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Identifying Best Practices for Snowplow Route Optimization

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Identifying Best Practices for Snowplow Route Optimization

University of Vermont



CLEAR ROADS

research for winter highway maintenance

Project 06741/CR14-07
December 2016

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Identifying Best Practices for Snowplow Route Optimization

Final Report

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16. Abstract <p>Well-designed winter maintenance routes result in snow and ice control service that is both more effective, because roads are cleared more rapidly, and more cost-efficient, because deadheading, route overlap and other inefficiencies are reduced or eliminated. There are an increasing number of computerized tools to facilitate the routing process, but these tools are not yet widely used by winter maintenance practitioners. The purpose of this report is to provide practitioners with an overview of computerized route optimization processes and concrete recommendations about how to ensure that route improvement efforts produce actionable results. Recommendations are synthesized from nine recent and ongoing snowplow routing projects using a variety of computerized routing tools. Project descriptions, based on interviews with project personnel, focus on project goals, optimization software features used, and lessons learned. Multiple route optimization projects report route length reductions on the order of 5% to 10%, with reductions as high as 50% reported in one case. These snowplow route optimization projects show that route optimization is a powerful tool for improving routing efficiency but that it does not replace the need for expert judgment in the route design process. Successful route optimization projects rely on close cooperation between experienced winter maintenance professionals and the individuals conducting the route optimization as well as a highly accurate, snowplow-routing specific representation of the road network. Successful projects also include time to review and revise new routes to identify potential problem spots prior to implementation.</p>			
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GLOSSARY

Approximate Solution Methods: A set of approaches to solving *route optimization* problems that produce routes that meet the technical and procedural *constraints* included in the optimization process but that are not always *optimal routes*. Approximate solution methods are less computationally intensive than *exact solution methods* and, therefore, frequently used in route optimization for snow and ice control operations.

Arc Routing Problem: A *route optimization* problem type with the goal of minimizing the total cost to service a set of road segments, or arcs, in a road network. Because the arc routing problem directly addresses road segment coverage, it parallels snow and ice control operations directly.

Base Routing Network: A representation of the road system that is used as an input for *route optimization*. The network must accurately reflect the direction and speed of travel along road segments as well as the turn actions that are permitted at road segment intersection in order for the optimization to produce realistic results. Optimization software packages frequently require individual lanes be represent as separate links in the road network.

Capacitated Routing: A type of *route optimization* that includes a *constraint* to account for the carrying capacity (either of fuel or of anti-/deicing materials) of the vehicles being routed.

Constraints: Restrictions on route, vehicle, or network characteristics that ensure routes reflect the real-world technical and procedural limits on snow and ice control operations. Vehicle salt capacity and plow orientation (right-side or left-side) are examples of technical constraints while maximum shift duration and prohibitions on U-turns are examples of procedural constraints.

COTS: Commercial off-the-shelf software.

Cycle Time: The length of time required to complete a set of a snow and ice control routes once. Cycle time is equal to the length of time needed to complete the longest single route.

Depots: Winter maintenance facilities that house snow and ice control vehicles and serve as the starting and end points for snow and ice control routes, also referred to as garages.

Dynamic Routes: Routes that are adjusted on a storm-by-storm or real-time basis to reflect short-term weather forecasts or real-time conditions.

Exact Solution Methods: A set of approaches to solving *route optimization* problems that produce *optimal routes* for the constraints included in the optimization process. Because of their computational complexity, exact solution methods are not generally feasible for real-world route optimization for snow and ice control operations.

Heterogeneous Vehicle Routing: A type of *route optimization* that includes *constraints* that account for differences in vehicle characteristics in a mixed vehicle fleet. Variable vehicle characteristics can include material capacity, speed, plow type, or other features.

Hierarchical Routing: A type of *route optimization* that includes a roadway-priority *constraint* requiring that high-priority roads are serviced before low-priority roads.

Heuristic: A type of *approximate solution method* that uses a set of practical (and often simple) rules to generate and/or improve upon possible snow and ice control routes.

Metaheuristic: A type of *approximate solution method* frequently used to improve upon possible snow and ice control routes generated by simpler heuristics.

Modeling: Using mathematical equations to represent a real-world process for the purpose of investigating alternate scenarios that may improve upon the ability to meet performance standards for the process.

Objective Function: A mathematical expression that defines a quantity that will be maximized or minimized in an optimization. For snow and ice control, it is a mathematical representation of the cost of snow and ice control operations that is minimized in the *route optimization* process. Costs may be measured in monetary terms or in terms of travel time or travel distance. The objective function in snow and ice control operations is often focused on minimizing the *total service time* or the *total cycle time*.

Operations Research: A discipline that deals with the application of analytical methods to help make better decisions. The terms “management science” and “analytics” are sometimes used as synonyms.

Optimal Routes: The set of routes that minimizes the cost of snow and ice control operations. Given the complexity of the *route optimization* process for snow and ice control, it is not always possible to determine truly optimal routes.

Post Processing: Adjustments made to the results of a *route optimization* to improve upon routes produced using approximate solution methods to move them closer to *optimal routes* or to account for real-world constraints not captured by the optimization. Post processing is generally a manual process.

Route Review: Expert inspection of the feasibility or efficiency of a set of routes. Route review may be facilitated by computerized tool that help track and visualize important route characteristics.

Route Optimization: The process of creating *optimal* or improved routes by minimizing the cost of snow and ice control operations as defined in an *objective function*. Routes must be consistent with technical and procedural *constraints*. Route optimizations can be performed using either *exact* or *approximate solution methods* though exact methods are generally not feasible for snow and ice control routing.

Static Routes: A set of fixed snow and ice control routes that do not vary weather conditions.

Stops: Intermediate points on a road segment where a service is performed. When snow and ice control *route optimization* is formulated as a *vehicle routing problem*, stops are added to road

segments that require service and represent the plowing/material demand for the entire road segment.

Time Windows: A *constraint* that requires a road segment to be serviced within a specific time frame.

Total Service Time: The length of the time required to complete all snow and ice control routes once, calculated by summing the duration of all individual routes.

Vehicle Routing Problem: A *route optimization* problem type with the goal of minimizing the cost to service a set of *stops* or nodes (rather than road segments) on a road network. This approach requires specific destinations or stops to be added to each road segment to be serviced by winter maintenance vehicles prior to running the optimization.

EXECUTIVE SUMMARY

During winter months, snow and ice control is a top priority for snow-state DOTs. The safety of the traveling public, emergency service response times, and on-going access to goods and services are all dependent on the effectiveness of winter maintenance operations. Well-designed snowplow routes result in snow and ice control service that is both more effective, because roads are cleared more rapidly, and more cost efficient, because deadheading, route overlap and other inefficiencies are reduced or eliminated. Historically, the route design process was a largely manual process, but today there are an increasing number of computerized tools to facilitate the routing process.

These tools can be categorized as either *route review* or *route optimization* tools. Route review tools display existing routes and facilitate manual route revisions by making it easier to visualize a route and track important route characteristics such as mileage and *cycle time*. Route optimization tools generate entirely new routes based on mathematical algorithms. DOTs have successfully used both route review and route optimization tools to improve winter maintenance performance and efficiency. Several route optimization projects report route length reductions on the order of 5% - 10% while reductions as high as 50% have been reported in one case. In-depth reviews of snowplow route optimization projects show that route optimization is a powerful tool for improving routing; however, it is not a magic bullet and cannot replace the need for expert judgement in the route design process. Several best practice for route optimization projects are provided here.

1. Successful route optimization projects rely on close cooperation between experienced winter maintenance professionals and the individuals conducting the route optimization (the “modelers”), especially when the optimization is conducted by an external team. Modelers may not fully understand all of the operational constraints that affect snowplowing, such as the limitations on where vehicles can safely turn around or size constraints that prevent certain vehicles from servicing narrow roads. Close communication between modelers and winter maintenance experts will improve optimization outputs and limit the need for route revisions.
2. Successful route optimization requires a highly accurate, *base routing networks* – representations of the road network created specifically for snowplow route optimization. For example, route optimization frequently requires that individual lanes be included separately in the model of the road network. Additionally, failure to include features like highway crossovers and safe turnaround locations at the edge of service territory boundaries will result in impractical routing results. It is essential to include sufficient time in the project to update the network to reflect the realities of snow and ice control operations prior to running any route optimization tool.
3. Computer generated routes are never perfect; successful projects include time to review and revise new routes. Testing routes with supervisors and operators in advance of the winter maintenance season can help to identify potential problem spots and help generate buy-in for new routes.

4. Automatic Vehicle Location/Global Position System (AVL/GPS) systems are highly complementary to route optimization and route review projects. AVL/GPS systems gather precise vehicle speeds for every road that is plowed; this information is a valuable input for the route optimization process. Additionally, systems that can provide drivers with turn-by-turn directions can help facilitate the implementation of new routes.

Given the high cost of providing snow and ice control services, even relatively small gains in efficiency can result in significant monetary savings. The improvements in route performance achieved by a route optimization project depend on the effectiveness of the optimization process itself and the efficiency of the existing routes. If these routes are already highly efficient then the benefits of route optimization will be comparatively small. One relatively simple indicator of the efficiency of existing routes is the distribution of route lengths. Widely varying route lengths may be indicative of opportunities for route improvement. Collecting route length data is straight-forward with GPS/AVL systems or even with smartphones or driver reports. Agencies that do not have up-to-date information about the lengths of existing routes should consider collecting this information prior to undertaking route improvement projects. It should be noted that route balance is a less effective indicator of route efficiency when the service territory is highly asymmetric relative to the location of the maintenance garage and when minimizing total vehicle hours of travel is a higher priority than minimizing cycle time.

Finally, the majority of projects featured in this review focus exclusively on optimizing routes given existing service territory boundaries and fixed garage locations. The tools for analyzing service territory boundaries and facility locations are less complex than for vehicle routing and may provide additional opportunities for improving snow and ice control performance.

CHAPTER 1: INTRODUCTION

During winter months, snow and ice control is a top priority for snow-state DOTs. The safety of the traveling public, emergency service response times, and on-going access to goods and services are all dependent on the effectiveness of winter maintenance operations. Given the importance of these activities and the extent of the road infrastructure that needs to be serviced, DOTs devote considerable resources to snow and ice control operations. Well-designed winter maintenance routes result in snow and ice control service that is both more effective, because roads are cleared more rapidly, and more cost efficient, because deadheading, route overlap and other inefficiencies are reduced or eliminated. Historically, the route design process was a manual one, but today there are an increasing number of computerized tools to facilitate the routing process. Though routing tools have been used for applications like package delivery for some time, these tools have only recently developed the sophistication needed for applications to snow and ice control. As a consequence, the benefits and challenges of using these tools are not yet well understood by winter maintenance practitioners.

The purpose of this report is to provide practitioners at state DOTs and municipal transportation agencies with an overview of computerized route optimization processes and concrete recommendations about how to ensure that route improvement efforts produce actionable results. These recommendations are synthesized from the experiences of recent and on-going projects at nine winter maintenance organizations (seven DOTs and two municipal Departments of Public Works) using a variety of computerized routing tools. The report summarizes the experience of each agency based on interviews with project personnel and published project documentation, when available. Project descriptions focus on the project goals, optimization software features used, and lessons learned. Since each project had a unique set of inputs (number of vehicles, road network configurations, etc.), it is not possible to make direct comparisons of the performance/effectiveness of the optimization software packages across these projects. Nonetheless, the best practices and lessons learned from these projects are widely applicable to future routing projects.

Throughout this report, routing tools are categorized as either *route review* or *route optimization* tools. Route review tools display existing or manually created routes and facilitate manual revisions by making it easier to visualize routes and to track important route characteristics such as mileage and *cycle time*. Route optimization tools generate entirely new routes based on mathematical algorithms intended to minimize the time or cost of providing snow and ice control services. Transportation agencies have successfully used both route review and route optimization tools to improve winter maintenance performance and efficiency.

In total, nine routing projects are included in this report. The description of these projects provided in this report are based on interviews with agency staff and, when available, other published reports on the projects. Five projects were identified by the Clear Roads Technical Advisory Team (TAC) and four additional projects were identified through a survey of North American winter maintenance agencies:

- Route Review
 - Iowa DOT
 - Pennsylvania DOT (PennDOT)
- Route Optimization
 - Indiana DOT (INDOT)
 - Centennial, Colorado Department of Public Works
 - Vermont AOT (VTrans)
 - Wisconsin DOT (WisDOT)
 - Niles, Illinois Department of Public Service
 - Kentucky Transportation Cabinet (KYTC)
 - Utah DOT (UDOT)

Six of the route optimization projects used commercially available, off-the-shelf software (COTS) packages – three projects used the software Fleet Route produced by C2Logix, two used ArcGIS produced by ESRI, and one used TransCAD produced by Caliper Corporation. One project used a custom route optimization software package. Four of the route optimization projects are still on-going and have not yet reached the implementation phase. Additional information about the effectiveness of these tools will become available as these and other projects are completed.

Generally, the sponsoring agencies reported positive project outcomes regardless of the route optimization or route review approaches used. Multiple route optimization projects report route length reductions on the order of 5% - 10%, with reductions as high as 50% reported in one case. Nonetheless, optimization projects are not without their challenges and the computer generated routes produced by the various optimization software packages all required *post processing* before the routes could be implemented on the ground. Post processing typically consists of revisions to the *base routing network* to improve the output or direct adjustments to the computer generated route for purposes such as avoiding unsafe turning movements. The shortcomings in the computer-generated results can be the results of inaccuracies in the inputs (e.g. missing turnarounds or unrealistic vehicle travel speeds) or in limitations inherent in the *approximate solution methods* used by the specific optimization software. These snowplow route optimization projects show that route optimization is a powerful tool for improving routing but that it cannot replace the need for expert judgement in the route design process.

The cost of route optimization projects vary depending on a number of factors including, the size of the base routing network being optimized (e.g. whether it is a city, county, or state level project), existing data quality, software availability, and whether the work is done in-house or with an external consultant. For the six route optimization projects conducted using COTS packages, project costs ranged from approximately \$30,000 to approximately \$120,000, not including in-house staff time.

Section 2 of this report describes the steps required to conduct an optimization project in general terms. A brief overview of the history of snowplow route optimization methods is presented in

Section 3.¹ Section 4 provides an overview of the survey of route optimization practices by winter maintenance organizations in North American. Sections 5 and 6 describe the route review strategies employed by PennDOT and Iowa DOT and the seven route optimization projects. Section 6 also includes two project matrices, the *Route Optimization Project Overview* and the *Route Optimization Project Features*, to provide interested readers with a concise comparison of the attributes of five route optimization projects. Key lessons learned are presented in Section 7. Finally, general conclusions are presented in Section 8, and Appendix A provides concrete recommendations about how to avoid several common optimization pitfalls.

CHAPTER 2: OVERVIEW OF A ROUTE OPTIMIZATION PROCESS

Route optimization is the process of creating a set of snow and ice control routes or paths that minimize the cost of snow and ice control operations. Costs may be measured in monetary terms or in terms of travel time or travel distance or some combination of these factors. The routes produced by the optimization process must be consistent with technical and procedural constraints such as vehicle salt capacity, vehicle size, and maximum shift durations. In general, all optimization problems have 1) an objective or set of objectives to minimize (or maximize) and 2) a set of constraints that restrict possible solutions to be consistent with real-world requirements.

Route optimization projects can be divided into five steps:

1. Selection of project team and project tools
2. Preparation of input data
3. Utilization of optimization tool
4. Review and revision of routes
5. Implementation of routes

The first step in a route optimization process is to determine whether the project will be conducted primarily by agency staff or by an external team in collaboration with the agency staff and what software to use. Generally, route optimization software packages offer similar sets of features so the decision about which software to use may come down to the expertise of the project team or to compatibility with other agency projects and existing licenses. Utah DOT, for example, issued a Request for Proposals for its route optimization project that specified that the optimization should be conducted using ESRI's ArcGIS since this program is widely used within the agency for other applications. Similarly, the VTrans route optimization was performed using TransCAD in part because the Agency's statewide travel-demand model is maintained in this program.

¹ A much more extensive treatment of this subject and a review of older route optimization projects can be found in the Literature Review included as Appendix D of this report.

Though the format may vary among software packages, all route optimization packages require a similar set of inputs. These inputs include locations of garages and other salt storage depots, an inventory of the winter maintenance vehicle fleet, a base routing network, and critical agency winter maintenance policies. Fleet information generally includes the number of vehicles at each garage as well as the material capacities of these vehicles and any limitation on the roads that they can service. The locations of garages where fleet vehicles are housed and any other locations where salt can be replenished must be geo-coded to a specific location on the serviceable road network. Creating the base routing network for the route optimization is one of the key steps in the optimization process and may require significant modifications to the original source data. For some optimization processes, each lane within the road may need to be represented as a distinct link within the base routing network. Each road link must also be coded to indicate whether or not it requires service by the agency, the travel speed of winter maintenance vehicles on that segment, and the quantity of salt or other materials required to service it. Preparation steps for the base routing network are discussed in greater detail in Appendix A of this report. Finally, acceptable cycle times, maximum shift lengths and other policy-based constraints must be obtained and incorporated into the routing process often through the application of *time windows* that specify how quickly a given link must be serviced.

Once the data preparation step has been completed, the automated optimization tool in the routing software can be run. This step is relatively rapid in comparison to the time required for data preparation and post-processing. The optimization software will normally provide both a map of each new route and turn-by-turn directions for following the routes (Figure 2.1).

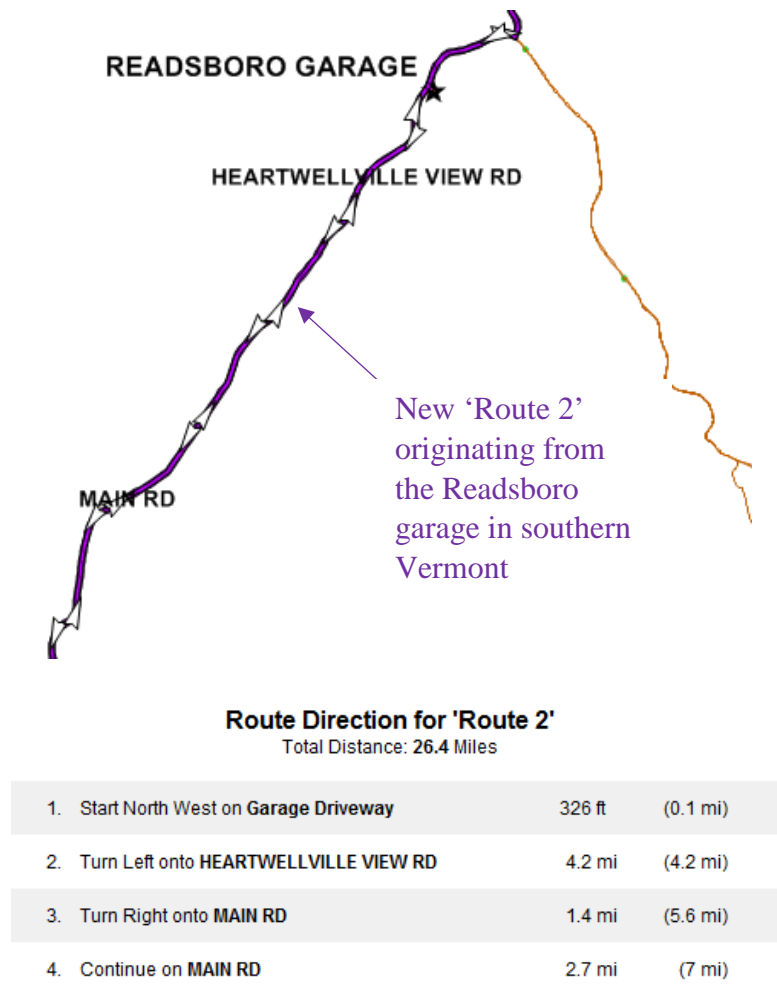


Figure 2.1. Examples of visual and turn-by-turn route optimization outputs from TransCAD

Routes produced by the optimization software should always be reviewed for unsafe or impractical vehicle movements. This review process may result in revisions of the base routing network and re-running the optimization tool or it may simply require manual edits to the optimized routes. This review and revision step was necessary in all of the projects included in this review. Examples of route revisions made during this review phase are included in several of the project descriptions in Section 6.

After a set of routes has been revised, these routes can be tested by supervisors and winter maintenance drivers under non-winter weather conditions. Testing these routes allows any remaining obstacles to implementation to be identified and promotes buy-in for the new routes by supervisors and drivers.

CHAPTER 3: BACKGROUND

Route optimization has been studied since the 1950s and, over time, the methods for solving these problems have become increasingly sophisticated both in terms of the objectives that can be examined and the specific types of constraints that are easily incorporated into the optimization. As computing power has increased and new solution methods have been developed, route optimizations have been applied to a variety of logistics and delivery systems, including package delivery and garbage pick-up services. Historically, the level of complexity associated with winter maintenance operations, which typically includes multiple depots and roads with varying numbers of lanes and priority levels, created substantial challenges for routing solution methods. However, as software has improved, DOTs have begun to use route optimization software with their snow and ice control operations. Some DOTs have made use of custom tools (1) while others have created iterative scripts to use with commercial, off-the-shelf software (COTS) packages (2).

The earliest snow and ice control routing studies are found in the operations research literature; however, as the field has matured since the mid-1990s, a growing number of studies have appeared in the transportation research literature, and a range of transportation agencies have undertaken optimization projects. Route optimization tools are available in COTS software packages, such as TransCAD, ArcGIS, and FleetRoute, though these tools are not designed specifically for snow and ice control routing. Several companies including Geo-Decisions, Route Optimization Consultants, and Vaisala offer routing services geared specifically toward winter maintenance operations.

Winter maintenance vehicle routing has matured to the point where it can produce valuable input for designing real-world routes while incorporating many of the most pertinent operational constraints. As noted in several of previous published optimization studies, however, routes produced by automated optimization processes frequently require some level of manual review and modification (post processing) before they can be implemented (1, 3, 4).

Additional details about route optimization can be found in the Literature Review included as Appendix D of this report.

CHAPTER 4: SURVEY OF WINTER MAINTENANCE ORGANIZATIONS

A snowplow route optimization survey was distributed to winter maintenance agencies in order to identify agencies that had recently engaged in route improvement efforts. In addition, the survey asked respondents to rate the desirability of a variety of route optimization features. These responses informed the project review process and the project evaluation matrix included in Section 6.8.

The initial invitation to participate in the survey was distributed via the Clear Roads Listserv, the AASHTO Winter Maintenance Listserv maintained by the University of Iowa, and by direct email to staff at each of the Canadian provincial DOTs. Invited recipients were also asked to forward the survey invitation to other practitioners experienced with snowplow routing. This “snowball” recruitment effort was intended to ensure as comprehensive a list of agencies using route optimization tools as possible. This method is commonly used to identify potential respondents with specific characteristics, in this case snowplow routing expertise.

In total 49 respondents from 31 agencies completed the survey (at seven of these agencies multiple respondents completed the survey). Table 1 categorizes respondents by agency type. As shown in Table 2, the majority of agencies that reported undertaking some sort of route improvement project reported using manual review for the project. Several agencies also contracted with external consultants or research teams to assist with the improvement process with only a small minority of respondents (five in the case of snowplow routing) reporting use of custom routing software.

Table 1. Survey Respondents by Agency Type

Agency Type	Number of Respondents
U.S. State DOT	33
Canadian Provincial DOT	7
Cities/Town/Local DPW	5
Other (university/consultant/other)	4

Table 2. Optimizations methods used by responding agencies

Optimization Project Type:	Optimization Method			
	Manual Review	Commercially Available Software	Custom Software	External Consultant/ Research Team
Facility Location	18 ^a	1	1	6
Service Boundaries	18 ^b	0	1	5
Fleet Size/Allocation	19	0	1	0
Routing	18 ^c	3	2	9

^a Includes 1 agency that used also custom software and two agencies that also used external consultant/research teams

^b Includes 3 agencies that also used external consultant/research teams

^c Includes 2 agencies that also used commercial software and 3 that also used external consultants

Respondents were also asked to rate the importance of different optimization objectives (Figure 4.1) and real-world routing constraints (Figure 4.2). Overall, the survey respondents placed greater importance on minimizing the time until all roads are cleared than on minimizing the number of routes/total vehicle hours traveled. Many respondents rated both objectives as important. These two objectives cannot always be achieved simultaneously however. Depending on the road network and other constraints imposed on the optimization, there may be unavoidable tradeoffs between minimizing vehicle hours of travel (e.g., by reducing deadheading/route overlap) and minimizing cycle time. In some instances, a route optimization may improve both cycle time and total vehicle hours traveled relative to existing routes, but agencies should be aware of the trade-offs between the goals. The top five most highly rated optimization features were 1) accounting for roadway prioritization schemes, 2) accounting for differing vehicle load capacities, 3) allowing vehicle to reload at remote material storage facilities, 4) lane specific routing, and 5) accounting for vehicle/road capability limitations.

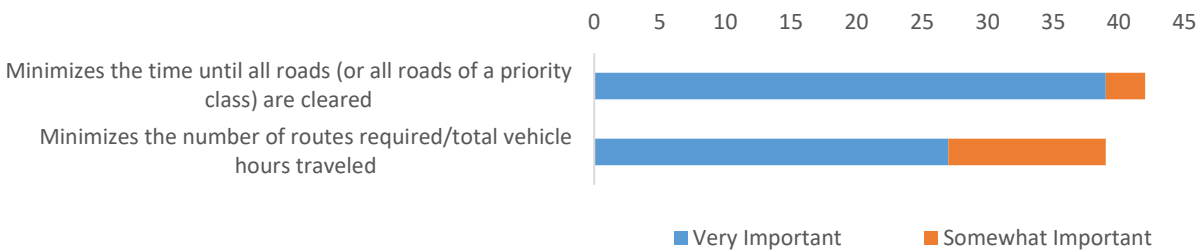


Figure 4.1. Importance ratings for route optimization goals



Figure 4.2. Importance ratings for route optimization constraints

CHAPTER 5: SUMMARY OF ROUTE REVIEW PROJECTS

5.1. Pennsylvania DOT

Project Contacts: Jonathan Flemming, Chief, Maintenance Technical Leadership Division – PennDOT
Sandra Tosca, District Executive – PennDOT

Project Tools: The Snow Route Planning Application – Geo-Decisions

Additional Project Description: *Pennsylvania Department of Transportation’s Snow Routes and Planning Process with GIS* – GIS in Transportation (5)

As part of an initiative to assess process and operations improvements undertaken in 2012, PennDOT’s winter maintenance team recognized the need for better data on the existing winter maintenance fleet, vehicle routing, and material usage (5). To address these data needs, PennDOT contracted with Geo-Decisions to develop a custom GIS-based tool capable of integrating with existing PennDOT systems, tracking relevant winter maintenance data, and generating route maps for the agency’s winter maintenance vehicles. The result, the *Snow Route Planning Application* tool, reduced the time required to generate the snowplow route maps from two weeks to two days. In addition, the tool improved the visualization of routes, including color coding routes by length, and enabled comparisons of material application practices across county lines. Making route-length information easily accessible to winter maintenance managers facilitated balancing the length of snow and ice control routes, improving overall performance.

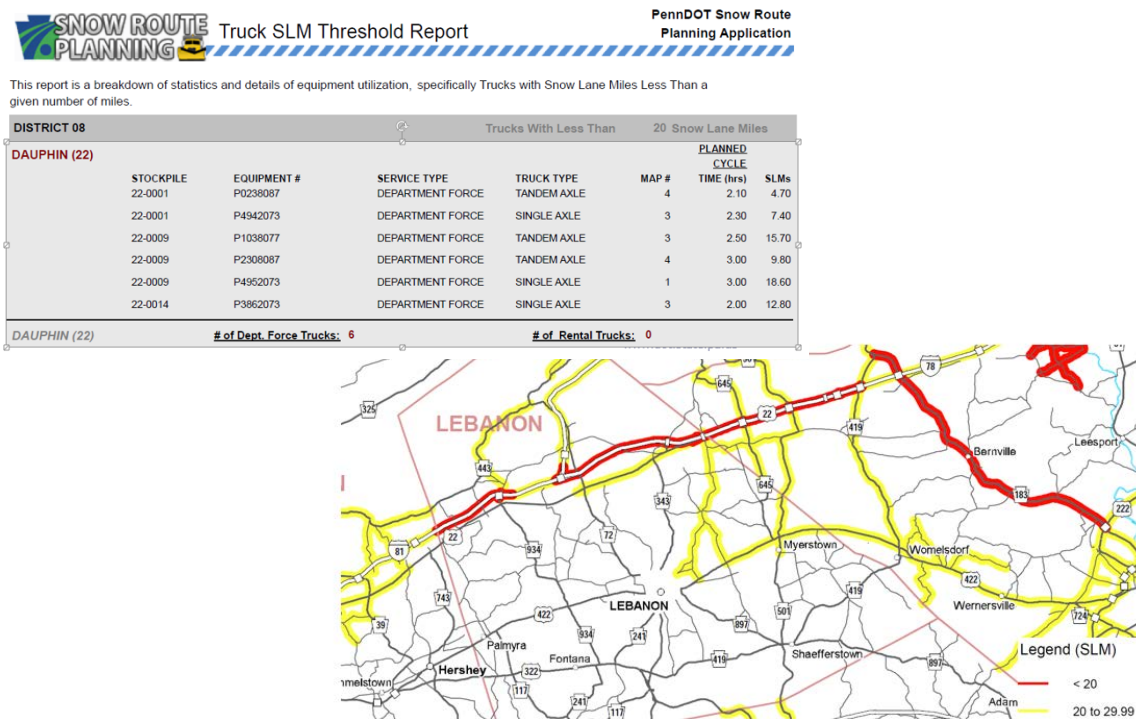


Figure 5.1. Tabular and visual reports from the Snow Route Planning Application

PennDOT is continuing to leverage this investment by integrating the program more closely with its AVL systems. The AVL systems can validate that the routes in the Snow Route Planning Application tool accurately reflect the snow and ice control activities happening in the field.

Tracking material application rates with the AVL and Snow Route Planning Application tool may enable improvements in the consistency of material application and reduce annual material costs.

In addition to its experience with the Snow Route Planning Application, PennDOT explored the possibility of using the Network Analyst route optimization tool included in ESRI ArcGIS in 2013. Due to issues with the base routing network used with the software and because the routes traversed municipal roads extensively in test optimizations, the agency opted not to continue with the project at that time.

5.2. Iowa DOT

Project Contact: Craig Bargfrede, Winter Operations Administrator – Iowa DOT

Project Tools: Automatic Vehicle Location (AVL) – SkyHawk Telematics

Additional Project Descriptions: *GPS/AVL System Upgrades Improve Reliability Of Data Used To Make Snowfighting Decisions* – Transportation Matters for Iowa (6).

In 2009/2010 Iowa DOT began equipping winter maintenance vehicles with AVL systems. The agency rapidly discovered that good cellular coverage was essential to the quality of the data collected. During this rollout, the AVL devices had a strong cellular signal along the Interstate 35 and Interstate 80 corridors but limited coverage in much of the rest of the state. Though the AVL systems are designed to record data internally when the cellular signal is insufficient to transmit it to the central server, this feature did not function reliably, resulting in significant data losses. In spite of the technical difficulties with data transmission, the data collected by the AVL systems had significant value to the agency.

In 2014 the DOT began testing a new data transmission system and, in 2015, launched a project to equip all 900 of its winter maintenance vehicles with next generation GPS/AVL systems. As part of this upgrade, the Iowa DOT switched cellular carriers for its AVL system which greatly improved the reliability of the AVL data transmission. The AVL system collects the real-time location of each vehicle (as shown in Figure 5.2) and data on the time, length, and material used along each route. This information helps supervisors assess and potentially reduce material usage as well as evaluate service gaps and adjust resource allocation as needed to address the gaps.

The system also collects engine diagnostic information that can help keep vehicles on the road. Since each vehicle is assigned a specific route, any vehicle down time during a winter weather event requires re-

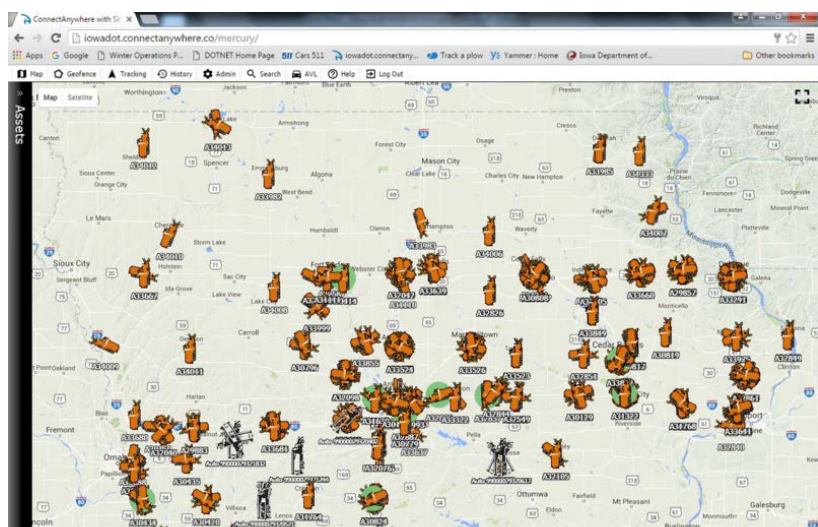


Figure 5.2. Web interface for Iowa DOT's AVL system.

routing the remaining vehicles to ensure that all roads are serviced.

Currently, IOWA DOT routes are designed and revised based on the experience and judgement of agency personnel. The agency is exploring options with its AVL provider, SkyHawk Telematics, to develop a system for analyzing snowplow routing.

CHAPTER 6: SUMMARY OF ROUTE OPTIMIZATION PROJECTS

6.1.Indiana DOT

Project Contact: Tony McClellan, Deputy District Commissioner – INDOT

Project Tools: Computer Aided System for Planning Efficient Routes – Purdue University (*discontinued*)

Additional Project Descriptions: *Evaluation of Computer-Generated Routes for Improved Snow and Ice Control – Transportation Research Record (1).*

Indiana DOT was one of the earliest DOTs to use computerized route optimization tools. From 1993 through 1995, INDOT tested the implementation of a routing program – the Computer Aided System for Planning Efficient Routes (CASPER) – developed by researchers at Purdue University (15). CASPER included hierarchal routing, turn restrictions, and synchronized plowing constraints. During the winter of 1993-1994, INDOT maintenance staff field tested the CASPER generated routes. Overall, 72% of the routes were implemented after varying levels of manual modification and 28% of the routes were rejected as infeasible. At that time, implementation of the feasible routes resulted in a 10% reduction in winter maintenance fleet size and was estimated to generate \$5 million in savings over 10 years (15).

However, the CASPER program is no longer in use at INDOT. While the tool demonstrated initial promise, it was complicated to use and the routes generated were not always feasible in the real-world. As with other optimization programs it was highly dependent on the quality of the input data. Over time, normal personnel turnover reduced the institutional familiarity with the program and its operation. Today, routing is largely handled at the district level using manual route review practices, in some cases facilitated by GIS visualizations.

6.2.City Centennial, Colorado

Project Contact: Monty Sedlak, Director of Project Services, (formerly Centennial Operations Manager) - CH2M

Project Tools: FleetRoute, C2Logix

Additional Project Descriptions: *Checking Priorities: Colorado City tests optimized snowplow routing solution – Roads & Bridges (7)*

Since 2007, the City of Centennial, Colorado has contracted with CH2M Hill to provide public works services to the city. The city's roadways are divided into two priority classes and are serviced by 10 plow trucks. Prior to 2012 winter season, CH2M Hill created a histogram of existing route lengths for each winter maintenance vehicle. These histograms showed that the Priority 1, Priority 2, and total road lengths assigned to each vehicle were significantly unbalanced.

In order to improve route balance and reduce the time required to service the city's streets, CH2M Hill worked with C2Logix to optimize the city's snowplow routes using C2Logix's FleetRoute software package. The optimization incorporated the roadway prioritization system

using hierarchical routing and included tandem plow routes for the Priority 1 streets. Vehicle capacity restrictions were accurately reflected in the optimization. Prohibitions on u-turns and turn penalties were also included as constraints.

After the optimization was completed, a two-phase route review process was conducted. First, maintenance supervisors then drove the routes and provided feedback to the optimization team, including identifying problematic turnaround locations. The optimization process was then repeated, and a second set of routes was shared with vehicle operators who provided additional feedback to the optimization team. This iterative process helped eliminate problem spots in the computer-generated routes and improved buy-in from winter maintenance personnel.

The optimized routes were then implemented in the winter of 2012. Using the new routes, the time required to complete snow and ice control operations for a 15-inch storm in February 2012 was 5.5 hours as compared to 8 hours for a 12 inch storm in December 2011 using the old routes. Overall, total vehicle mileage and labor hours were estimated to be reduced by approximately 50% on an annual basis.

Given the small size of the City of Centennial (relative to DOT service territories), several features that may be important in other contexts were not relevant here. Specifically, since the city routes its vehicles from a single garage, optimizing service boundaries and resupplying salt at remote locations were not applicable to this project nor were there any vehicle/roadway compatibility constraints – all of the vehicles could be used to service any of the roadways.

6.3.Vermont AOT

Project Contact: Wayne Gamell, Assistant Bureau Director for Maintenance and Operations – VTrans
Todd Law, Maintenance Transportation Administrator – VTrans.

Project Tools: TransCAD by Caliper Corporation

Additional Project Descriptions: *Optimization of Snow Removal in Vermont* – University of Vermont (2) and *Strategic Location of Satellite Salt Facilities for Roadway Snow and Ice Control* – Transportation Research Record (8)

VTrans funded two related winter maintenance optimization projects with the University of Vermont Transportation Research Center (these projects were conducted by the authors of this report). The first project was a route optimization project performed using the Vehicle Routing tool in TransCAD, a COTS transportation GIS software produced by Caliper. The second project was to identify potential sites for salt resupply facilities that would reduce the distance winter maintenance vehicles needed to drive to reload salt (and potentially other winter maintenance materials).

In contrast to many of the optimization projects here, this route optimization project first redefined the garage service territories and each garage's vehicle allocation instead of using existing boundaries and allocations. To ensure that all roads could be serviced as quickly as possible, each road segment was assigned to the garage that it was closest to as measured by the travel time for a winter maintenance vehicle to drive from the garage to the road segment. Once the optimal service territories for each garage were determined, two alternative vehicle allocations were considered for this routing project. Vehicles were allocated based on the total

lane-miles in each garage's service territory and based on lanes-miles weighted by the roadway's importance. The project also created separate sets of routes for three different salt application rates, for a total of six distinct sets of routes. These routing alternatives were created to illustrate the impact of differing storm conditions/salt application rates and vehicle allocation on optimal routing. The optimization used vehicle numbers and salt capacities that reflected the current composition of the VTrans winter maintenance fleet. Lane-specific routing and tandem plowing were not priorities for VTrans and were not included in this optimization.

The facility location component of the optimization process identified locations for remote materials depots that would reduce the distance winter maintenance vehicles needed to travel to resupply with salt or other materials. This was done by minimizing the longest distance between all state-maintained roadways and the nearest state garage or material storage depot. Figure 6.1 shows the time required to travel from all state maintained roadways in Vermont to the closest salt storage facility. The project took place after the route optimization so the remote storage depots were not used in the optimization process.

Given project time constraints, the large number of routes developed, and the difficulty of selecting from among the six different routing scenarios, review and comparison of these routes and the existing routes was limited and the new routes have not been implemented. On the basis of the vehicle allocation results, however, VTrans has reallocated winter maintenance vehicles to support snow and ice control operations at a garage that is responsible for a high proportion of high-priority lane miles and is in the process of constructing a new, remote salt re-supply facility to support snow and ice control operations on a remote section of Interstate 89.

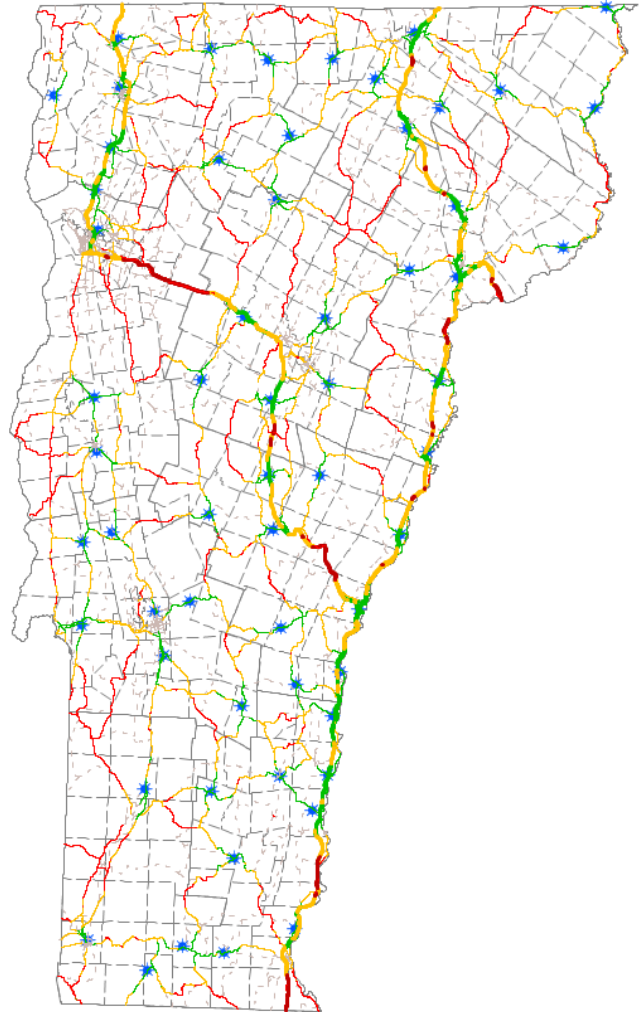


Figure 6.1. Proximity to salt storage locations for all state maintained highways in Vermont. Road links in red are more than 20 minutes removed from a salt storage location.

6.4. Village of Niles, IL DPS

Project Contacts: Bob Pilat, Streets

Fred Braun, Streets Superintendent – Village of Niles

Project Tools: FleetRoute – C2Logix

The Niles, IL Department of Public Services contracted with C2Logix to perform a route optimization project in 2015. Niles DPS routes snow and ice control vehicles from a single maintenance garage. Its snow and ice control guidelines divided the Village's streets into five priority classes.² The optimization was intended to improve route balance and, in conjunction with the installation of GPS systems to provide drivers with turn-by-turn directions, improve route consistency.

The optimization generated lane-specific routes using the Village's roadway prioritization scheme and the actual material capacities of its winter maintenance vehicles. The optimization was tested both with and without prohibitions on u-turns.

Three main issues arose during the route review and revision phase. First, vehicle/roadway compatibility constraints were not adequately represented in the initial optimization. As a result, some plow trucks were assigned to service alleyways that were too narrow for these trucks to service. Second, several plow routes included extensive detours into adjacent towns, which was not acceptable. Third, when u-turns were not prohibited in the optimization, the routes called for u-turns in locations that were not safe (e.g. across multilane highways) or not physically possible (at the end of dead-end streets without cull-da-sacs).

Limited testing of the revised routes occurred in the winter of 2015 – 2016. Testing was limited because of a delay equipping the winter maintenance fleets with GPS systems and by a relatively mild winter season. More complete implementation of the new route systems is anticipated for the winter of 2016 – 2017.

6.5. Kentucky Transportation Cabinet

Project Contacts: Michael Williams, Snow & Ice Program Coordinator – KYTC

Eric Green, Research Engineer – Kentucky Transportation Center

Ben Blandford, Research Associate – Kentucky Transportation Center

Project Tools: ArcGIS - ESRI

Starting in the fall of 2015, the KYTC funded a two-year snowplow route optimization undertaken by researchers at the Kentucky Transportation Center. The optimization process is being piloted on District 7 with implementation of these test routes anticipated for the 2016 – 2017 winter season.

The research team is using the Vehicle Routing tool in the COTS package ArcGIS distributed by ESRI. The optimization accounts for the material capacity of individual trucks in the winter maintenance fleet, the state's three-tier roadway prioritization scheme and lane-specific routing. Initial optimization tests did not account for vehicle/roadway compatibility constraints, resulting in routes that sent contract trucks servicing roads that were too narrow to accommodate them. A

² <https://www.vniles.com/DocumentCenter/View/2977>

vehicle/roadway constraint (called the “Specialties” parameter in ArcGIS) was used in subsequent optimizations to avoid this problem. Developing an accurate base routing network and route reviews were both labor-intensive phases of the optimization process.

The optimization results showed an estimated time savings of approximately 8% of total vehicle hours relative to the existing routes but some route revisions are still in progress and this figure is based on the estimated speeds used in the optimization. These assumptions and the realized time saving are anticipated to be tested during implementation in the 2016 – 2017 winter season.

6.6. Wisconsin DOT

Project Contact: Peter Wisniewski, Bureau of Highway Maintenance - WisDOT

Project Tools: FleetRoute – C2Logix

WisDOT is currently conducting a route optimization project with agency staff using FleetRoute, a COTS optimization package distributed by C2Logix. It is the only agency to conduct route optimization in-house among the agencies featured in this report. The goals of the optimization were to balance cycle length, reduce deadheading, and reduce cycle time. To date, WisDOT has generated new routes for the highway departments in Dane, Green, and Brown counties to be piloted in the winter of 2016 – 2017. The agency hopes to have routes completed for up to six more counties before the start of the winter maintenance season.

The base routing network used for the optimization project was derived from the individual counties’ GIS files used for emergency response. These networks were displayed over satellite images of the road network to help identify any feasible turn-around locations that were omitted from the county maps. The optimization process incorporates the salt capacity limitations of the existing fleet vehicles and allows vehicles to resupply with materials at remote salt sheds. Roadway prioritization was not a major consideration in the pilot counties and was not considered in the optimization.

Routes produced by the optimization software did require additional user review and post-process to be implementation ready. This post-processing included removing unnecessary turning movements and minimizing left-hand turns. Though FleetRoute includes time penalties for left-hand turns, additional opportunities to eliminate turns were identified during the route inspection. The route inspection and post-processing was more time intensive than the optimization process itself.

Implementation of the new routes is planned for the 2016 – 2017 winter season. Based on comparisons between the lengths of the new and existing routes, WisDOT conservatively estimates a reduction in route length of between 4 and 10% in the three pilot counties. In one case, additional cost saving were realized because the new routes enabled a county to forgo planned truck purchases in spite of a 23% increase in its highway lane-miles due to the completion of a major highway project.

6.7. Utah DOT

Project Contact: Brandon Klenk, Methods Engineer – UDOT

Project Tools: ESRI ArcGIS

In spring of 2016, UDOT contracted with Spatial Matters to optimize the agency's snowplow routes. The project used the Vehicle Routing tool included in the COTS package ArcGIS. The agency elected to use ArcGIS for the project since UDOT uses the program for a variety of other mapping application including UPLAN, a web-based portal that supports information-sharing and decision-making within the agency.³ The optimization produced lane-specific routes that adhered to the agency's cycle-time targets and accurately reflected the salt capacity of UDOT's vehicles. The optimization adjusted the boundaries between garages and also re-allocated vehicles to improve route performance. Re-supply of salt at remote locations and vehicle/roadway compatibility constraints were not included in the application.

The initial set of routes produced by the optimization project covered the area from Ogden to Provo. These routes required a variety of revisions to be more compatible with real-world conditions. In part, this post-processing reflected inaccuracies in the average vehicle speeds used for the routing. This initial routing optimization significantly reduced the number of trucks used in winter maintenance operations but given the uncertainty about the assumed vehicle speeds it is unclear that new routes would provide the current level of service. Trade-offs between potential cost savings and reductions in snow and ice control performance require additional consideration. Some turning actions included in the routing were also impractical for winter maintenance vehicles. Revision to the routes are on-going, and implementation of new routes is not expected before the winter of 2017 – 2018.

6.8. Project Matrix Overview

This Project Matrix consists of two tables that assess a wide range of project characteristics. Note that the discontinued INDOT project and UDOT project, which is still in the comparatively early stages, are not included in the Matrix. Table 3, *Route Optimization Project Overview*, provides information about how each project was conducted, the outputs produced by the optimization process, whether alternate routing scenarios were considered, and the project's current implementation status. Table 4, *Route Optimization Features*, describes the operational constraints that were included in the mathematical optimization for each project. Clicking on the text in individual cells in each table provides additional information about the characteristic described in that cell and how it was incorporated into each project.

Each of the characteristics assessed in the Project Matrix is color-coded from green (more desirable) through red (less desirable), reflecting its straightforwardness and/or effectiveness in the optimization process. For example, COTS is assumed to be readily available and to require less technical expertise than developing a custom application. Thus, it is rated as more desirable than custom software. Similarly, project results that have been successfully implemented by agency personnel are known to be effective in the real world and are rated more highly than results that have yet to be implemented or have only been partially implemented. In some cases,

³ <http://onlinepubs.trb.org/onlinepubs/conferences/2012/MakingProgress/casestudyutah.pdf>

certain operational features (e.g. reloading vehicles at remote material storage facilities) cannot be modeled by the optimization software and require post-processing after the computerized optimization has been completed. For this evaluation, it is assumed that it is more desirable for a feature to be part of the computerized optimization rather than being included in the project results through manual post processing. The general feature/output color coding is summarized as follows:

Green – The feature is included in the software and was used in the project.

Yellow – The feature is not included in the software but was incorporated into the project through manual revisions to the network or routes.

Red – The feature was not incorporated into the project. The feature may not be a priority for the winter maintenance organization or may be difficult or infeasible to include in the route optimization process. The following matrix entries are used:

- *Feature not applied* – when the software includes an option feature, but it was not used in the project because it was not applicable or not a project priority
- *Not included* – when the software does not include an option for the feature (note that manual route revisions could still be used to implement these features).
- *Not Considered* – status in software unknown.

No single project includes all possible operational constraints. In most cases, the sponsoring agencies have derived significant benefits from these projects regardless of how they are rated here.

Table 3. Route Optimization Overview

		Project				
		Centennial. CO	Vermont Agency of Transportation	Village of Niles, IL	Kentucky Transportation Cabinet	Wisconsin DOT
Project Personnel		External Team	External Team	External Team	External Team	Agency Staff
Project Software		COTS – Minimal modifications required	COTS – Additional coding required	COTS – Minimal modifications required	COTS – Minimal modifications required	COTS – Minimal modifications required
Route Performance Metrics	Route Mileage & Service Time	Standard output	Standard output	Standard output	Standard output	Standard output
	Operating Cost	Not considered	Feature not applied	Not considered	Not considered	Not considered
	Methods for comparing new and historical routes	Validated time compared to validated time	Not considered		Estimated time compared to validated time	Estimated mileage compared to estimated mileage
Additional Model Outputs	Service Territory Boundaries	Not considered	Included in optimization	Not considered	Not considered	Not considered
	Vehicle Allocation	Not considered	Included in optimization	Not considered	Not considered	Not considered
	Facility Location	Not considered	Locations for material storage identified	Not considered	Not considered	Not considered
Alternate Routing Scenarios		Not considered	Routes generated for three different material application rates	Separate plowing and spreading routes generated	Not considered	Not considered
Implementation Status		Results fully implemented	Results partially implemented	Results partially implemented	Results to be implemented in the future	Results to be implemented in the future

Table 4. Route Optimization Features

Feature	Project				
	Centennial, CO	Vermont Agency of Transportation	Village of Niles, IL	Kentucky Transportation Cabinet	Wisconsin DOT
Route Prioritization	Incorporated in routing	Incorporated in routing	Incorporated in routing	Incorporated in routing	Feature not applied
Mixed Vehicle Fleets	Incorporated in routing	Incorporated in routing	Incorporated in routing	Incorporated in routing	Incorporated in routing
Remote Material Resupply	Not considered	Not included	Not considered	Incorporated in routing	Incorporated in routing
Lane-specific routing	Incorporated in routing	Not considered	Incorporated in routing	Incorporated in routing	Partially incorporated in routing
Vehicle/Roadway Compatibility	Not considered	Feature not applied	Incorporated in route revisions	Incorporate in routing	Not considered
Maximum Route Durations		Incorporated in routing	Not considered	Incorporated in routing	Manually reviewed
Tandem Plowing	Incorporated in routing	Not considered		Not included	Manually reviewed
Turn Constraints	Incorporated in routing and in manual route revisions	Feature not applied	Incorporated in route revisions	Some turn constraints incorporated in routing	Incorporated in routing and in manual route revisions
Multipass Routes	Not considered	Not included	Not considered	Incorporated in routing	Not considered

CHAPTER 7: LESSONS LEARNED AND IMPLICATIONS FOR FUTURE PROJECTS

Though the projects reviewed here employed a variety of different route optimization software packages, several “lesson learned” themes recurred across the optimization projects. Specifically:

Successful route optimization projects rely on close cooperation between experienced winter maintenance professionals and the individuals conducting the route optimization (the “modelers”), especially when the optimization is conducted by an external team. Modelers may not fully understand all of the operational constraints that affect snowplowing, such as the limitations on where vehicles can turn around safely or size constraints that prevent certain vehicles from servicing narrow roads. Close communication between modelers and winter maintenance experts will improve optimization outputs and limit the need for route revisions.

Successful route optimization requires a highly accurate, snowplow-routing specific representation of the road network. For example, route optimization frequently requires that individual lanes be included in the road network separately. Additionally, failure to include features like highway crossover and safe turnaround locations at the edge of service territory boundaries will result in impractical routing results. It is essential to include sufficient time in the project to update the network to reflect the realities of snow and ice control operations. See Appendix A for additional information about preparing the base routing map.

Computer generated routes are never perfect; successful projects include time to review and revise new routes. Testing routes with supervisors and operators in advance of the winter maintenance season can help to identify potential problem spots and help generate buy-in for new routes.

Automatic Vehicle Location/Global Position System (AVL/GPS) systems are highly complementary to route optimization and route review projects. AVL/GPS systems gather precise vehicle speeds for every road that is plowed; this information is a valuable input for the route optimization process. Additionally, systems that can provide drivers with turn-by-turn directions can help facilitate the implementation of new routes.

Finally, while many of the agencies that participated in the survey, described in Section 4, expressed interest in a range of scenario-specific routes to address issues such as out-of-area deployments, equipment shortages or variable storm intensity, this option may not be practical feasible for most DOTs at this point in time since the time and effort required to inspect and revise routes can be considerable. Creating a single (or limited number of) base routes and allowing district manager to modify these routes in response to current conditions may be a more practical option.

CHAPTER 8: CONCLUSIONS

In recent years, an increasing number of transportation agencies have completed or initiated route optimization or route review projects in an effort to improve the delivery of snow and ice control services. Agencies reported positive project outcomes regardless of the approach used with optimization projects reporting route length reductions from 5% to 10%, with reductions as high as 50% reported in one case. Additional estimates of route efficiency improvements will be available as on-going projects are completed. Given the high cost of providing snow and ice control services, even relatively small gains in efficiency can result in significant monetary savings.

The improvements in route performance achieved by a route optimization project depend on two factors. First, any improvement depends on the performance of the routes produced by the optimization software. The performance of these routes, in turn, depends on the quality of the routing inputs, the effectiveness of the route optimization software's solution algorithm, and the post-processing conducted by the project team. Appendix A includes specific recommendations for improving the quality of optimization inputs (specifically the routing base routing network). Direct comparisons of the effectiveness of the solution algorithms used by different software packages would require running optimizations with the same sets of inputs with each software package and is outside the scope of this project. The second factor that impacts the improvement that can be achieved by the route optimization project is the efficiency of the existing routes. If these routes are already highly efficient then the benefits of route optimization will be comparatively small.

One relatively simple indicator of the efficiency of existing routes is the distribution of route lengths. Widely varying route lengths may be indicative of opportunities for route improvement. Assessments of route-length balance was an early step in both the PennDOT route review and City of Centennial's route optimization projects. Collecting route length data is straight-forward with GPS/AVL systems or even with smartphones or driver reports. Agencies that do not have up-to-date information about the lengths of existing routes should consider collecting this information prior to undertaking route improvement projects. It should be noted that route balance is a less effective indicator of route efficiency when the service territory is highly asymmetric relative to the location of the maintenance garage and when minimizing total vehicle hours of travel is a higher priority than minimizing cycle time.

The optimization software used in the projects reviewed here offer broadly similar features. Of the five features sets rated as most important by survey respondents, FleetRoute, ArcGIS and TransCAD are all capable of incorporating road prioritization schemes, variable vehicle salt capacity, lane-specific routing and vehicle/roadway compatibility into the routing process. Remote material resupply can be implemented with ArcGIS and FleetRoute, but is not currently a feature in TransCAD.

Finally, the majority of projects featured in this review focus exclusively on optimizing routes given existing service territory boundaries and fixed garage locations. The tools for analyzing

service territory boundaries and facility locations are less complex than for vehicle routing and may provide additional opportunities for improving snow and ice control performance.

CHAPTER 9: REFERENCES

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Appendix A
PRACTICAL STEPS FOR PREPARING FOR ROUTING PROJECTS

An accurate base routing network is essential to successful route optimization. Snowplow routing networks differ significantly from maps provided by many GIS vendors. Individual roads lanes must generally be represented as separate links within the base routing network and safe plow speeds are slower than the free flow travel speeds typically coded into travel models and other mapping applications. In all five of the completed route optimization projects included in this report, project personnel stated that the initial computer generated routes required additional revisions in order to be implementable in practice. Common causes for these revisions included unrealistic or unsafe vehicle turning behaviors, mismatches between roadways and snow and ice control vehicles, and extensive use of roadways outside of the routing agency's jurisdiction. While it is unlikely that the need for post processing revisions can be completely eliminated, the extent of these revisions can be reduced through careful review of the base routing network prior to running the optimization. A number of concrete steps for avoiding common routing problems are described here.

A.1. Turning Behavior

Many of the revisions required for routes generated by optimization software are related to how and where plow trucks turn in the suggested routes. In some cases, plow routes may fail to take advantage of safe turnaround locations that are regularly used by plow drivers because the locations are not included in the base routing map (see below). In other cases, plow routes may suggest turns that are unsafe or impractical in the real world. A number of these issues can be preempted by modifications to the base map or the use of software settings that regulate allowable turning movements.

A.1.1. Inclusion of Safe Turnaround Locations

The base road networks supplied by many public and commercial sources, such as the Census Bureau's TIGER road layer or Google Maps, are designed to map travel on the public road network. Because of this, turnaround locations that are not useable by the general public are often excluded from these maps. If these turn around locations are not included in the base routing map, the optimization software is likely to produce inferior results.

A.1.1.1. Highway Cross Overs

Figure A.1 A. shows an example of a highway cross over north of Exit 17 on I-89 in Colchester Vermont. Figure A.1 B. shows the same exit, with the highway cross over excluded in the base map provided by Caliper with TransCAD. Finally Figure A.1 C. shows the exit as it should be represented in a snowplow routing model, with the cross over included in the road network.

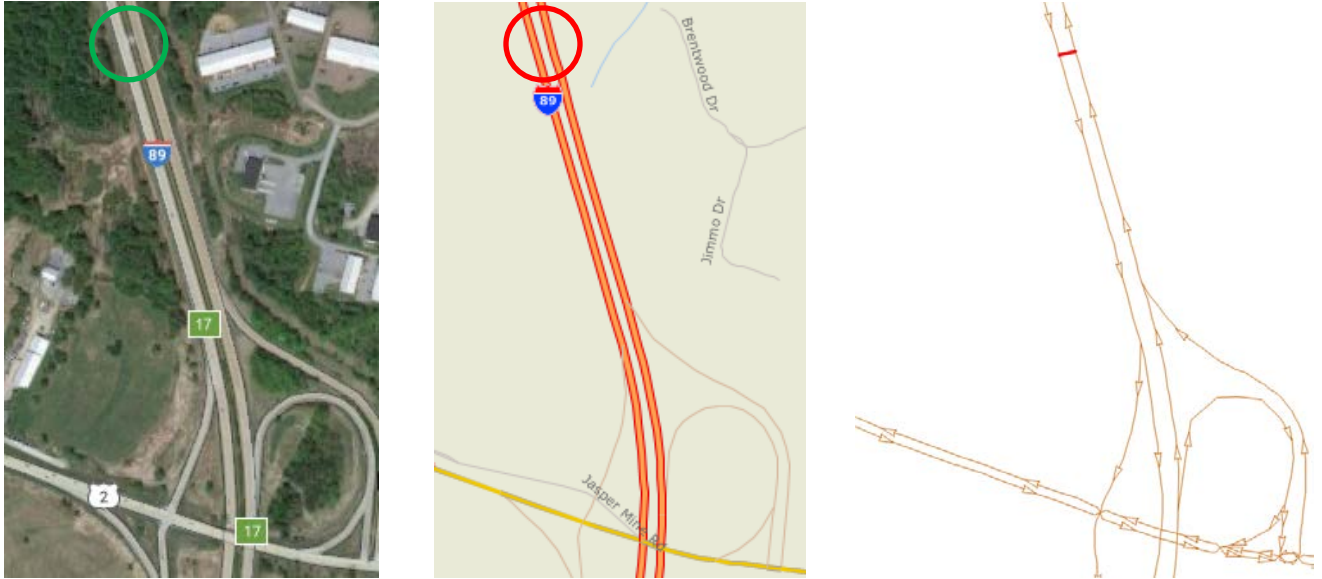


Figure A.1. Exit 17 on Interstate 89 in Colchester Vermont from A. Google Maps B. TransCAD and C. Routing base map

A.1.1.2. Service Territory Boundaries

Service territory boundaries are another area where turnaround locations may be omitted from common base maps. Winter maintenance organizations generally coordinate plowing at jurisdictional boundaries to ensure that there is not gap in snow and ice control coverage and that vehicle can turn around safely. Winter maintenance vehicles may turn around at off-road turnaround sites, in parking lots, or at a side road near the end of a route. Because parking lots and off-road turnaround sites, such as the one shown on the left in Figure A.2, will not appear in many base maps, the road network will frequently need to be modified to allow vehicles to turn around at these areas. As shown at right in Figure A.2, this modification is extremely straightforward but if omitted can result in (potentially lengthy) travel across jurisdictional borders in search of turn around locations.

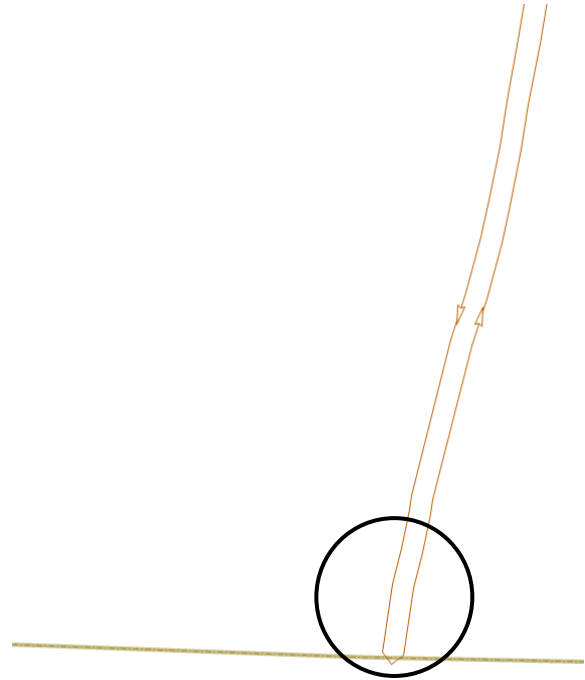


Figure A.2. Turnaround location on Route 5 at the Vermont/Massachusetts border

A.1.2. Exclusion of Hazardous/Unnecessary Turnaround Locations

Similarly, because many sources of mapping data are not geared toward snowplow routing, the networks may allow vehicles to make turn in locations that are unsafe or impractical for winter maintenance vehicles. This can occur when turn lanes are not accurately included in the base routing map, resulting in plow trucks making left turns across multiple lanes of traffic. Where appropriate, intersections can be modified so that only the leftmost lane can turn left at any given intersection.

A.1.3. Limitations on Turning Movements

FleetRoute, ArcGIS and TransCAD each allow the user to prohibit U-turns and to impose turn penalties that reduce the desirability of left hand turns. Use of these feature can minimize problematic turning actions.

A.2. Vehicle/Roadway Compatibility

In some cases, specific snow and ice control vehicles are poorly suited to or entirely incompatible with servicing certain roads within the network. Some larger plow/ truck combinations that are configured to clear wide lanes or multiple lanes simultaneously are too wide to service smaller, single lane state highways. Roundabouts, bridges and alleyways may also impose maximum size constraints on snow and ice control vehicles. Smaller trucks, used by some agencies to help clear on and off-ramps are not well suited to clearing wide, multi-lane highways.

Fleet Route, ArcGIS, and TransCAD all allow the user to set restrictions on the type of vehicle that can service a particular road segment. Documenting these restrictions at the start of the

optimization process and inputting them into the optimization software is likely to reduce the amount of post processing that is required.

A.3. Limiting Travel on Local Roads

Generally speaking, agencies try to minimize the amount of time that their vehicles spend traversing roads that are outside of their jurisdiction. While it may be necessary to traverse some of these roads (e.g. traveling on town roads between a garage location and the state road network is unavoidable in some cases), deadheading snow and ice control vehicles can be a source of public frustration when the public does not understand the rationale for this behavior. Several strategies can be used to limit the use of roadways that fall outside of an agency’s jurisdiction.

As discussed in Section A.1, ensuring that the base network includes safe turnaround locations near service territory boundaries will prevent the optimization software from creating routes that extended deep into adjacent service territories before turning around. In addition, the travel speeds of roads that fall outside the jurisdiction of an agency can be significantly reduced (making travel on these roads less attractive to the optimization software) or the roads can be removed from the base network entirely (preventing routes from traversing them at all).

Figure A.3 shows state highways 118 and 105 in Franklin County Vermont as well South Richford Road, a local road that is not maintained by the state. Since, at VTrans’s suggested maximum operating speeds, the time required to travel from South Richford Rd’s intersection with 118 (Point A) to its intersection with 105 (Point B) is slightly faster via South Richford Rd than with the state highways, route optimization software may

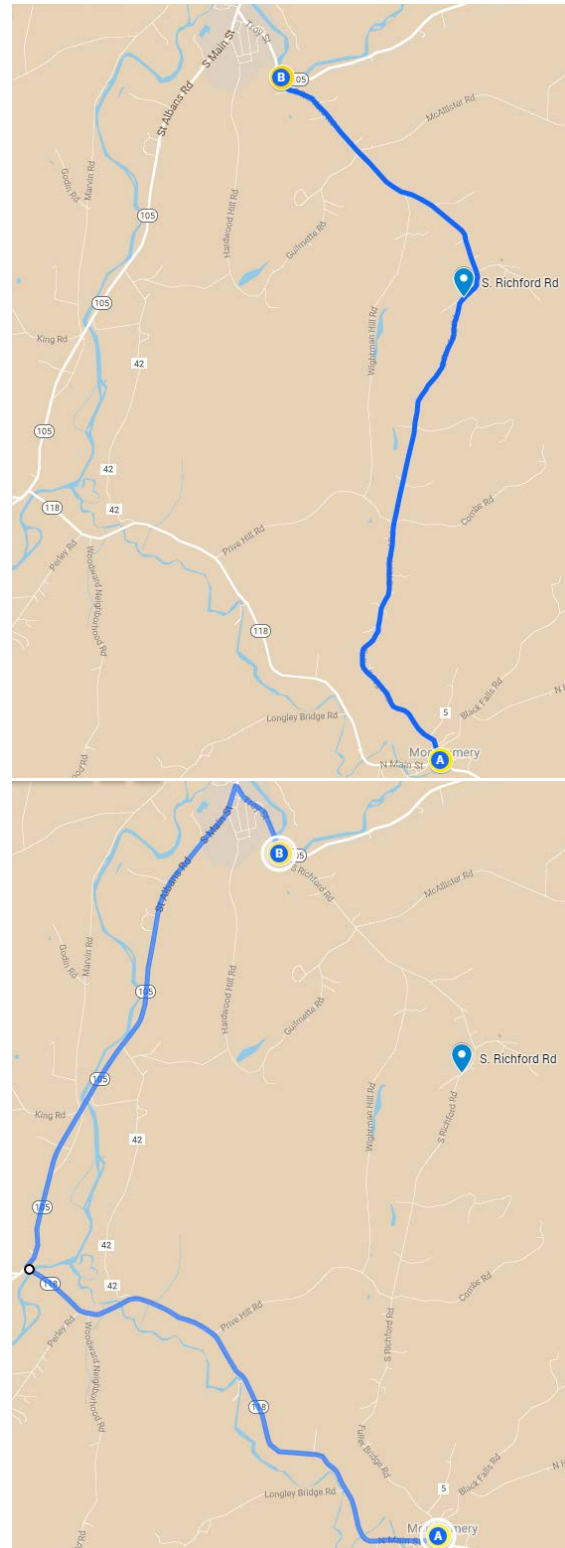


Figure A.3. Fastest route generated using default plow speeds (top) and Fastest routing using modified plow speeds (bottom)

(depending on the number of available plows and other factors) generate routes that traverse South Richford Road. Reducing the speed of travel on such local roads will make this less likely to occur, and removing local roads will eliminate the possibility entirely. Both of the strategies, however, do run the risk of eliminating potentially time savings that could be realized by using the local road system, so these competing ends need to be carefully considered.

Appendix B
PROJECT MATRIX EVALUATION CRITERIA

Personnel: Many projects featured in this study were undertaken with external consulting or research teams while other projects were undertaken exclusively with agency personnel. The choice of whether to use external expertise depends on the technical capacity within each given agency.

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Software: There are an increasing number of commercially available, off-the-shelf, software (COTS) packages that include various route-optimization features. Some of these COTS packages require significant modifications (additional coding) to meet the needs of the agency. Custom software can also be used but may require considerable development work.

The following three options are ranked in terms of the technical expertise that is required to use them where 1 requires the least technical expertise and 3 requires the most technical expertise:

1. COTS - Minimal modifications required (green)
2. COTS - Additional coding required (yellow)
3. Custom software package (red)

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Route Mileage & Service Time: Route length, measured by either travel time or distance traveled, is a standard route-optimization output. This output information can be used to compare new routes to existing routes and to ensure that service is timely and that route lengths are safe and compatible with drivers' shifts. Travel times and distances are extremely important factors contributing to the cost of snow and ice control activities.

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Operating Cost: The monetary cost associated with the selected snowplow routes, including various combinations of material, fuel and labor costs, can be calculated in some route optimization software and can be used to compare the effectiveness of routing alternatives.

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Method for Comparing the Performance of New and Historical Routes: Comparing the performance of new proposed routes to previously existing routes is essential for evaluating whether route changes will be beneficial. Generally routes are compared in term of mileage or travel time. In this matrix the term “estimated time/distance” refers to the route length values calculated by the routing software and “validated time/distance” refers to route lengths measured when winter maintenance vehicle are actually performing snow an ice control on a given route. Because models rely on fixed travel speed estimates for each road segment but real-world vehicle speeds depends on the weather, traffic conditions, and driver behavior time it is expected that estimated and validated times will not be identical. Some small variability might also occur between estimated and validate route distance. Consequently, caution should be exercised comparing estimated and validated route lengths. We rate the comparison methods as follows:

1. Validated time/mileage for new routes compared to validated time/mileage for historical routes (green)
2. Estimated distance for new routes compared to estimated or validated distance for historical routes (yellow)
3. Estimated time for new routes compared to validated times for historical routes (red)

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Service Territory Boundaries: Setting boundaries on service territories is a very important step in the snowplow route-optimization process. When a fleet of snowplows are assigned to and routed from multiple depots, optimal results will be most achievable when each of the road segments is assigned to the depot that is closest to it. Some optimization projects include a separate step that focuses on optimizing the service territory boundaries so that each link is assigned to its nearest depot, while other projects use existing service territory boundaries.

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Vehicle Allocation: The number of snow and ice control vehicles assigned to each depot will directly impact the routes that are created for it. Vehicles may be assigned to a depot based on a variety of factors such as the total number of lane-miles or the number of high-priority lane-miles the depot is responsible for. Some optimization projects include an explicit step for optimizing the allocation of vehicles at each depot, while other projects treat the vehicle allocation as fixed based on the existing allocation.

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Facility Location: The location of depots and the location of material resupply facilities has a substantial influence on the efficiency of snowplow routes. Ideally winter maintenance facilities will be centrally located within the various service territories, although this is not always possible in reality. Some optimization projects include a step for identifying optimal facility locations (depots and/or satellite materials storage locations) while other projects take the location of depots and any satellite material resupply facilities as fixed.

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Alternate Routing Scenarios: Optimal routing depends on a number of factors such as the number of available vehicles/drivers, weather conditions, and the travel speed of winter maintenance vehicles. Alternative routes can be generated for to account for changes in these factors. Potential routing scenarios include:

1. Equipment shortages/out-of-area deployments: Since the routes generated by a route optimization process is influenced by the number of available vehicles, equipment shortages or out-of-area deployment are likely to require routes that differ from the baseline routes.
2. Differing storm conditions/material spread rates: Different weather conditions require different anti-icing and de-icing strategies, including changes in material application rates. These changes may alter how far a plow can travel before running out of materials and therefore alter the optimal routing.

3. Variable Travel Speeds: Time of day/traffic conditions may impact vehicle speeds and therefore travel times.

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Implementation: The benefits associated with the optimization of routes, service territories, vehicle allocations, and/or facility locations that are generated in the route optimization modeling process are only realized if the results are implemented in practice. Several of the projects highlighted here are still on-going or only recently completed and have not yet reached full implementation.

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Road Prioritization: Many transportation agencies have road prioritization schemes based on road classification systems or based on traffic volume. Strictly hierarchical routing procedures require that all of the lane miles within a particular priority class are serviced before the roads belonging to a lower priority class. Some route optimization software often allows limited upgrading to service lower priority roads on higher priority routes if these upgrades improve the overall service performance. Road prioritization may also influence the allocation of vehicles among depots based on the mileage of high priority roadways in each depot's service territory.

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Mixed Vehicle Fleets: Vehicle fleets typically include vehicles of different types; all of which have different material storage capacities, speeds and equipment specifications. Consequently, vehicles will vary in terms of maximum route length and/or the roads that they can service.

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Remote Material Resupply: Remote materials storage facilities such as salt domes can be used to extend the maximum route length for winter maintenance vehicles and can be integrated into the routing procedure.

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Lane-specific routes for multi-lane roads: Servicing roads with multiple lanes often require multiple independent routes, each servicing a specific lane. Generally, lane specific-routes can be created in any software pack so long as each lane included as a separate entity in base road network.

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Vehicle/Roadway Compatibility: Not all snow and ice control vehicles are suitable for all roads. Some road infrastructure, such as smaller highways, roundabouts, and alleyways, impose maximum vehicle and plow size restrictions. Tow plows, fixed left or right side plows, and other equipment configurations limit the roads and lanes that a vehicle can service. Some route optimization software allows the user to specify what vehicle types are acceptable on a given road link.

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Limits on Maximum Route Duration: Maximum route lengths may be set in order to ensure that routes can be repeated at target intervals or that driver shift limits are not exceeded. Maximum route duration limits ensure that the routes generated in the optimization process comply with these constraints.

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Tandem Plowing: In some instances, multiple lanes must be serviced simultaneously, as when a middle and right lane are plowed in tandem. In cases where the entire route requires synchronized service, matching multiple vehicles to a specific route is sufficient to account for synchronization. If only a subsection of a set of routes require synchronized service; however, inter-route coordination must be included in the optimization model or manual route revisions.

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Turn Constraints: Snow and ice control routes may seek to avoid left turns and U-turns in order to avoid dropping snow in the roadway as well as to avoid safety issues and reduce the amount of time the vehicles spend waiting to make a turn.

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Multipass Routes: Frequently, routes must be repeated multiple times over the course of a storm to restore roadways to target conditions. Routes designed for multiple passes may differ from routes designed for a single pass since they require additional material and since the deadheading time from the depot to the start of a route constitutes a smaller proportion of total service time than if a route only needs to be serviced once.

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Appendix C
PROJECT MATRIX DETAILS

C.1. Centennial, CO – Route Optimization

Project Overview: The city of Centennial Colorado contracts with CH2M Hill to provide public works service to the city. In 2012, CH2M Hill implemented a new set of snow and ice control routes developed by C2Logix using its commercially available FleetRoute software. The new route reduced total vehicle mileage and labor hours by approximately 50%.

[Back to Table](#)

Personnel: The route optimization was conducted by personnel at CH2M Hill and C2Logix.

[Back to Table](#)

Software: This route optimization is being performed using FleetRoute, a commercially available routing software package produced by C2Logix.

[Back to Table](#)

Route Mileage & Service Time: Route mileage and service times are standard outputs from FleetRoute.

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Operating Costs: Operating cost were not directly calculated for this optimization process.

[Back to Table](#)

Method for Comparing the Performance of New and Historical Routes: Time savings the new routes were calculated by comparing the time to complete snow and ice control for two major storms (12 and 15 inch respectively) in December 2011 and February 2012.

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Service Territory Boundaries, Vehicle Allocation, and Facility Location: This project used existing service territory boundaries, vehicle allocations and facility locations in the routing process. Since the service boundaries are the city boundaries, territory optimization is not applicable in this case. Optimization of vehicle allocation and facility location was not considered for this project.

[Back to Table](#)

Alternate Routing Scenarios: Alternate routing scenarios were not considered for this project.

[Back to Table](#)

Implementation: The optimized routes were implemented in the winter of 2012.

[Back to Table](#)

Road Prioritization: Road prioritization designations were applied to this optimization.

[Back to Table](#)

Mixed Vehicle Fleets: FleetRoute allows the user to input material capacities for each vehicle in the optimization. This project used vehicle capacities that reflected the composition of the city's winter maintenance fleet.

[Back to Table](#)

Remote Material Resupply: Since the Centennial routes all vehicles from a single garage, remote resupply was not an applicable feature for this project.

[Back to Table](#)

Lane-specific routes for multi-lane roads: Lane specific routes were constructed for tandem routes.

[Back to Table](#)

Vehicle / Roadway Compatibility: Vehicle/roadway compatibility constraints were not required for this project.

[Back to Table](#)

Limits on Maximum Route Duration:

[Back to Table](#)

Tandem Plowing: Tandem plow routes were generated for Priority 1 roads.

[Back to Table](#)

Turn Constraints: Prohibitions on U-turns and time penalties for other turning actions can be incorporated into the FleetRoute. The resulting routes were also manually reviewed to remove unnecessary movement and to maximize right turns.

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Multipass Routes: Multipass routes were not considered for this project.

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C.2. VTrans – Route Optimization & Facility Location Project Details

Project Overview: The Vermont Agency of Transportation (VTrans) sponsored two related winter maintenance optimization projects. The first project generated new snow and ice control routes for the state’s 60 winter maintenance garages using TransCAD, a commercially available software package. This project created separate sets of routes for three different salt application rates and three different vehicle allocation systems, for a total of nine distinct sets of routes. The second project was to identify potential sites for salt/material resupply facilities that would reduce the distance winter maintenance vehicles need to drive to reload salt and other winter maintenance materials.

[Back to Table](#)

Personnel: The authors of this review performed the route optimization and facility location projects for VTrans.

[Back to Table](#)

Software: This route optimization was performed using the Vehicle Routing Procedure in TransCAD, a commercially available GIS software package produced by Caliper. While the Vehicle Routing Procedure can be run using only drop down menus, minimizing the cycle time for each garage required a repeating process of running the routing procedure and then adjusting the maximum allowable route duration. Conducting this process manually for each garage for each of the nine scenarios would be time prohibitive. In order to use the repeated process, the research team created separate scripts in TransCAD and MATLAB that automated this process.

[Back to Table](#)

Route Mileage & Service Time: Route mileage and service times are a standard output from TransCAD’s Vehicle Routing Procedure.

[Back to Table](#)

Operating Cost: The TransCAD Vehicle Routing Procedure does allow the user to specify the cost of operating each vehicle, but this feature was not used for this process.

[Back to Table](#)

Method for Comparing the Performance of New and Historical Routes: Total travel time and cycle lengths were compared among the nine routing scenarios using TransCAD routing outputs. Route length and service times for existing VTrans routes were available for comparison purposes.

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Service Territory Boundaries: The first step in the optimization process was to set the service territory for each of the 60 state garages. To ensure that all roads could be serviced as quickly as possible, each road segment was assigned to the garage that it was closest to as measured by the travel time for a winter maintenance vehicle to drive from the garage to the road segment.

[Back to Table](#)

Vehicle Allocation: Once the service territories for each garage were determined, two alternative vehicle allocations were considered for this routing project. Vehicles were allocated based on the total lane miles in each garage and based on a combination of the lanes miles and roadway importance.

[Back to Table](#)

Facility Location: The facility location component of the optimization process identified locations for remote materials depots that would reduce the distance winter maintenance vehicles needs to travel to resupply with salt or other materials. This was done by minimizing the longest distance between all state maintained roadways and the nearest state garage or material storage depot. The project took place after the route optimization so the remote storage depots were not used in the optimization process.

[Back to Table](#)

Alternative Routing Scenarios: This project generated a total of 9 different set of route sets. These routing alternative were created to illustrate the impact of differing storm conditions/salt application rates and vehicle allocation on optimal routing. Three salt applications rates were modeled for each of three vehicle allocation strategies.

Implementation: On the basis of this work, VTrans has reallocated winter maintenance vehicles to support snow and ice control operations at a garage that is responsible for a high proportion of high priority lane miles. In addition, the Agency is in the process of constructing a new, remote material storage facility to support snow and ice control operations on a remote section of Interstate 89. New routes have not been adopted, due to the difficulty of selecting from among the nine different routing scenarios and the difficulty of conveying clear turn-by-turn directions for each of these scenarios.

[Back to Table](#)

Road Prioritization: This project accounted for road prioritization in the vehicle allocation phase of the project. Road prioritization could also be implemented in TransCAD using a “time windows” feature that required each road to be treated within the time prescribed by the VTrans winter maintenance guidelines. The approach allows a single route to cover roadways of multiple priority classes in any order so long as each road segment is serviced with its specific time window.

[Back to Table](#)

Mixed Vehicle Fleets: The TransCAD Vehicle Routing Procedure allows the user to input material capacities and vehicle costs for each vehicle in the optimization. This project used vehicle capacities that reflected the current composition of the VTrans winter maintenance fleet.

[Back to Table](#)

Remote Material Resupply: The TransCAD Vehicle Routing Procedure does not support this feature. Incorporating vehicle reload would require manual route adjustments.

[Back to Table](#)

Lane-specific routes for multi-lane roads: Lane-specific routes can be created by modifying the road network to represent each lane as a separate link, but this was not done for this project.

[Back to Table](#)

Vehicle / Roadway Compatibility: The TransCAD Vehicle Routing Procedure allows the user to restrict which vehicles can service each road link. This feature was not used for this project.

[Back to Table](#)

Limits on Maximum Route Duration: User specified maximum route durations were used for all scenarios in this project.

[Back to Table](#)

Tandem Plowing: Tandem plowing is not a priority for VTrans, so it was not considered for this project.

[Back to Table](#)

Turn Constraints: Prohibitions on U-turns and time penalties for other turning actions can be incorporated into the TransCAD Vehicle Routing Procedure, but were not used for this project.

[Back to Table](#)

Multipass Routes: The TransCAD Vehicle Routing Procedure does not support multipass routes.

[Back to Table](#)

C.3. Village of Niles, IL. – Route Optimization

Project Overview: The Village of Niles contacted with C2Logix to generate new snow and ice control routes for the Department of Public Services. Reduce deadhead time and route overlap.

[Back to Table](#)

Personnel: The route optimization is being conducted by an external team at C2Logix.

[Back to Table](#)

Software: This route optimization was performed using FleetRoute, a commercially available routing software package produced by C2Logix.

[Back to Table](#)

Route Mileage & Service Time: Route mileage and service times are standard outputs from FleetRoute.

[Back to Table](#)

Operating Cost:

[Back to Table](#)

Method for Comparing the Performance of New and Historical Routes: Unknown.

[Back to Table](#)

Service Territory Boundaries, Vehicle Allocation, and Facility Location: This project used existing service territory boundaries, vehicle allocations and facility locations in the routing process. Optimization of these aspects of snowplow routing was not consider for this project.

[Back to Table](#)

Alternate Routing Scenarios: This project generated separate plowing and spreading routes.

[Back to Table](#)

Implementation: Routes were initially tested in the winter of 2015 – 2016 but this was a very mild winter in Niles. Additional testing will take place in the winter of 2016 – 2017.

[Back to Table](#)

Road Prioritization: Road prioritization designations were applied to this optimization.

[Back to Table](#)

Mixed Vehicle Fleets: FleetRoute allows the user to input material capacities for each vehicle in the optimization. This project used vehicle capacities that reflected the current composition of the Village’s winter maintenance fleet.

[Back to Table](#)

Remote Material Resupply: Since the Village of Niles routes all vehicles from a single garage, remote resupply was not an applicable feature for this project.

[Back to Table](#)

Lane-specific routes for multi-lane roads: This optimization project generated lane-specific routes.

[Back to Table](#)

Vehicle / Roadway Compatibility: Vehicle/roadway compatibility constraints were required to ensure that alleys were serviced by smaller vehicles. C2Logix revised the initial routes it provided to the Village to account for this constraint.

[Back to Table](#)

Limits on Maximum Route Duration: Limits on route duration were not consider for this project.

[Back to Table](#)

Tandem Plowing: Tandem plow routes were generated for the state highways.

[Back to Table](#)

Turn Constraints: Prohibitions on U-turns can be incorporated into the FleetRoute. Ultimately, this feature was not used since prohibiting U-turns cause winter maintenance vehicles detour through adjacent towns to turn around.

[Back to Table](#)

Multipass Routes: Multipass routes were not considered for this project.

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C.4. KYTC – Route Optimization

Project Overview: The Kentucky Transportation Cabinet (KYTC) sponsored a two year project with the Kentucky Transportation to generate new routes for its 12 winter maintenance districts with a goal of reducing deadheading time. The optimization for this project is being conducted in ArcGIS, a commercial available software package produced by ESRI. KYTC anticipates testing routes for District 7 in the winter of 2016 – 2017.

[Back to Table](#)

Personnel: The route optimization is being conducted by Eric Green and Benjamin Blanford at the Kentucky Transportation Center.

[Back to Table](#)

Software: This route optimization was performed using the Vehicle Routing Problem (VRP) feature in ESRI's ArcGIS.

[Back to Table](#)

Route Mileage & Service Time: Route mileage and service times are standard outputs from the VRP in ArcGIS.

[Back to Table](#)

Operating Cost: Operating cost was not considered in this project.

[Back to Table](#)

Method for Comparing the Performance of New and Historical Routes: Preliminary evaluations of the new routes was made by comparing estimated travel time for new route with validated historical travel times but some route modifications are still underway. These preliminary results showed an improvement of over 8%. A final evaluation of time saving will not be made until the validated route times can be compared directly.

[Back to Table](#)

Service Territory Boundaries, Vehicle Allocation, and Facility Location: This project used existing service territory boundaries, vehicle allocations and facility locations in the routing process. Optimization of these aspects of snowplow routing was not considered for this project.

[Back to Table](#)

Alternate Routing Scenarios: Alternate routing scenarios were not considered for this project.

[Back to Table](#)

Implementation: Initial route implementation is anticipated to take place in the winter of 2016 – 2017.

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Road Prioritization: Road prioritization was incorporated into this project by using a “time windows” feature that required each road to be treated within the time prescribed by the KYTC winter maintenance guidelines. The approach allows a single route to cover roadways of multiple priority classes in any order so long as each road segment is serviced with its specific time window.

[Back to Table](#)

Mixed Vehicle Fleets: The VPR allows the user to input material capacities for each vehicle in the optimization. This project used vehicle capacities that reflected the current composition of the District 7 winter maintenance fleet.

[Back to Table](#)

Remote Material Resupply: The VPR included remote resupply in the optimization process.

[Back to Table](#)

Lane-specific routes for multi-lane roads: This optimization project generated lane-specific routes.

Vehicle / Roadway Compatibility: The VPR has a feature that allows roadways to be matched to specific truck types. This feature was used to restrict the trucks with the widest plow to major roadways.

[Back to Table](#)

Limits on Maximum Route Duration: Limits on route duration were incorporate in the project through the use of time windows.

[Back to Table](#)

Tandem Plowing: Tandem plow routes were not considered for this project and would be difficult to create in the ArcGIS software without manual revisions.

[Back to Table](#)

Turn Constraints: Mid-block U-turns were prohibited but U-turns were allowed at intersections and at dead ends.

[Back to Table](#)

Multipass Routes: Multipass routes were incorporated into this routing process by using recurring time windows that required a vehicle to cover its route multiple times.

[Back to Table](#)

C.5. WisDOT – Route Optimization

Project Overview: The Wisconsin Department of Transportation (WisDOT) is developing new route for several of the counties that provide snow and ice control in the state using FleetRoute, a commercial available routing software package produced by C2Logix. To date, new routes have been generated for three of Wisconsin’s 72 counties and it is anticipated that routes for six counties will be completed for the current winter maintenance season. The first set of routes produced by WisDOT will be implemented in the winter of 2016 – 2017.

[Back to Table](#)

Personnel: The route optimization is being conducted by WisDOT staff.

[Back to Table](#)

Software: This route optimization is being performed using FleetRoute, a commercially available routing software package produced by C2Logix.

[Back to Table](#)

Route Mileage & Service Time: Route mileage and service times are standard outputs from FleetRoute.

[Back to Table](#)

Operating Cost: Operating costs were not directly calculated as part of this optimization process.

[Back to Table](#)

Method for Comparing the Performance of New and Historical Routes: New and historical routes were compared in terms of estimated route mileage, as calculated in the FleetRoute software. Preliminary results suggest that the new routes could reduce total vehicle mileage by 4 – 10% per cycle.

[Back to Table](#)

Service Territory Boundaries, Vehicle Allocation, and Facility Location: This project used existing service territory boundaries, vehicle allocations and facility locations in the routing process. Optimization of these aspects of snowplow routing was not considered for this project. Since snow and ice control is provided by the counties in Wisconsin, service territory boundaries cannot easily be altered but facility location optimization may be considered in future projects.

[Back to Table](#)

Alternate Routing Scenarios: This project produced a single set of routes. No alternative routing scenarios were considered in the pilot phase of this project.

[Back to Table](#)

Implementation: New routes will be implemented in the pilot counties for the winter of 2016 – 2017.

[Back to Table](#)

Road Prioritization: A road prioritization designation is included in FleetRoute, but was not applicable in the pilot counties so not used in this project.

[Back to Table](#)

Mixed Vehicle Fleets: FleetRoute allows the user to input material capacities for each vehicle in the optimization. This project used vehicle capacities that reflected the current composition of the winter maintenance fleets in the pilot counties.

[Back to Table](#)

Remote Material Resupply: FleetRoute allows winter maintenance vehicles to reload salt or other materials at alternate locations.

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Lane-specific routes for multi-lane roads: Lane-specific routes can be created by modifying the road network to represent each lane as a separate link. This modification was made for major highways in the pilot counties. For lower priority roadways and roadways lane specific routing was not explicitly included in the routing procedure.

[Back to Table](#)

Vehicle / Roadway Compatibility: Vehicle/roadway compatibility was not an applicable constraint in the pilot counties so not considered in this project.

[Back to Table](#)

Limits on Maximum Route Duration: All route durations were compared to recommendations after the routes were generated to make sure that they were consistent with guidelines.

[Back to Table](#)

Tandem Plowing: The FleetRoute software did not explicitly generate tandem plow routes.

[Back to Table](#)

Turn Constraints: Prohibitions on U-turns and time penalties for other turning actions can be incorporated into the FleetRoute. The resulting routes were also manually reviewed to remove unnecessary movement and to maximize right turns.

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Multipass Routes: Multipass routes were not considered for this project.

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Appendix D
LITERATURE REVIEW

D.1. Literature Review Introduction

Roadway snow and ice control operations cost over \$2 billion every year (1) and are among the most high-profile responsibilities for DOTs in snow states. Properly maintaining the roadways in these states involves complicated decision-making regarding the staging, routing, and refueling/reloading of the vehicle fleets that are responsible for plowing roadways and spreading anti-icing, deicing and friction enhancing materials. For the sake of brevity, this report will refer to these materials collectively as simply “salt” or “materials.” The timing, type and extent of snow and ice control operations in a particular jurisdiction depend on climate, weather, site and traffic conditions (1). Faced with the high costs of fuel, material, and labor, state DOTs are increasingly looking for new approaches and tools to improve the efficiency of these operations as a means of managing costs. Currently, the expert judgment of DOT personnel is the most common method of decision-making (2) but computerized route optimization models show increasing promise as tools for improving the efficiency of winter maintenance operations. This report reviews the history and current state of snow and ice control route-optimization research and practice with a focus on recent advances in route modeling. The final report for this project will provide an in-depth review of applied route optimization projects by state DOTs and other transportation agencies.

The optimization of snow and ice control operations includes three distinct problems: 1) how best to divide the road network into service territories, 2) how best to allocate winter maintenance vehicles among these territories, and 3) how best to route these vehicles within each service territory. Since the optimal routes for winter maintenance vehicles depend on the service territories selected and the size and composition of the vehicle fleet used in each territory, some snow and ice control optimization projects include facility siting and vehicle allocation as either preliminary steps or as an integrated part of the optimization process. Other projects have created vehicle routes based on existing or hypothetical facility locations and fleet compositions. In addition to the location of winter maintenance facilities and the characteristics of the vehicle fleet (e.g., number and salt/fuel capacity of vehicles, plow configuration), routing solutions depend on the layout and makeup of the road network (e.g., configuration of ramps, distribution of road types), road prioritization criteria, specific performance targets of the DOT (e.g., recovery time and acceptable level of service), and storm-specific characteristics (e.g., intensity, duration, snow/ice mix).

Route optimization has been studied since the 1950s and, over time, solution methodologies have evolved to become increasingly sophisticated in terms of the objectives that are examined and the specific types of constraints that are incorporated into the optimization problem. As computing power has increased and new solution methods have been developed, both exact and approximate solution methods have been applied to all types of logistics and delivery problems, including package delivery and garbage pick-up services. Historically, the level of complexity associated with winter maintenance operations, which typically include multiple depots and service roads with varying numbers of lanes and priority levels, created substantial challenges for routing solution procedures. As newer solution methods have been developed that are capable of addressing these complicating factors, several DOTs have begun to incorporate route optimization into their snow and ice control management plans. Some of these approaches have

made use of custom tools (3) while others have created iterative scripts to use with commercial, off-the-shelf software (COTS) packages (4).

Sections D.2 through D.5 of this report provide an overview of how snow and ice control route optimizations are conducted while Section D.6 provides a synopsis of recent routing applications from the academic literature and from DOT projects. Specifically, Section D.2 reviews the technical and operational constraints that need to be accounted for in the modeling process as well as the trade-offs between dynamic and static routes in terms of the simplicity of implementing model generated routes. Section D.3 discusses different snow and ice control goals and how these goals impact optimization results. Section D.4 provides an overview of routing methodologies, including different solution approaches and problem formulations. Section D.5 discusses the data preparation requirements needed to conduct a route optimization project in a real-world setting as well as for comparing model outputs and existing route performance. After the synopsis of recent routing work in Section D.6, Section D.7 presents the conclusions of this review.

D.2. Snow and Ice Control Operational Considerations

In the context of winter maintenance, route optimization efforts often must consider a wide range of operational constraints in order to accurately capture the dynamics of real-world snow and ice control operations. These include

- Mixed vehicle fleets with differing material and fuel capacities,
- Restrictions on which vehicle/plow combinations can service which road or road lane,
- Agency roadway prioritization schemes and performance goals.

Table D.1 summarizes operational constraints that the research team has encountered in our work with operations' staff at state DOTs and that are frequently cited in the literature. The project summaries in Section D.6 highlight which of these constraints are included in each study.

Table D.1. Operational Consideration for Routing Models

Vehicle Capacity	Winter maintenance vehicles are limited in the amount of fuel and materials that they can carry. For spreading operations, vehicle capacity is often a limiting factor in route length, and locations where additional material can be loaded are limited.
Mixed Vehicle Fleets (Fleet Heterogeneity)	Vehicle fleets typically include vehicles of different types, with different capacities, speeds and equipment specifications. Consequently, vehicles will vary in terms of maximum route length and/or the roads that they can service.
Vehicle/Roadway Compatibility	Not all snow and ice control vehicles are compatible with all roads/lanes. Roads with roundabouts or other features may only be serviceable by smaller vehicles. Tow plows or left-side plows may be limited to servicing specific lanes on multilane roads.

Table D.1 Operational Consideration for Routing Models Continued

Road Service Jurisdiction	Winter maintenance vehicles may need to traverse roads that are serviced by another agency in order to reach the start of their own routes or while traveling between route segments. Service jurisdictions must be included in the optimization in this case.
Variable Travel Times	Vehicles may travel at different speeds depending on whether or not they are actively servicing a roadway or whether a road that they are deadheading has been previously serviced. Time of day/traffic conditions may also impact vehicle speeds.
Turn Restrictions	Snow and ice control routes may seek to avoid left turns and U-turns in order to avoid dropping snow in the roadway as well as to mitigate safety concerns and the amount of time the vehicles spend waiting to make a turn.
Lane Specific/Multilane Service	Roads with multiple lanes may require multiple passes to service (especially when plowing) or may be serviced in a single pass (especially when spreading or when using tow plows).
Synchronized Service	In some instances, multiple lanes must be serviced simultaneously, as when a middle and right lane are plowed in tandem. In cases where the entire route requires synchronized service, matching multiple vehicles to a specific route is sufficient to account for synchronization. If only a sub-section of a set of routes require synchronized service, however, inter-route coordination must be included in the optimization model.
Road Prioritization (Hierarchical Routing)	Many transportation agencies have road prioritization schemes based on road class or traffic volume. Hierarchical routing, which accounts for road prioritization, can be strictly imposed, requiring that all roads of a given class be serviced before roads of a lower class, or may be flexible, allowing limited upgrading to service lower priority roads in higher priority routes if these upgrades improve overall performance. Road prioritizations may also influence the allocation of vehicles among depots based on the mileage of high priority roadways in each depot's service territory.
Repeated Routes	For many storms, routes must be repeated multiple times before the storm ends to restore roadways to target conditions. In the context of repeated routes, the deadheading time from the depot to the start of a route constitutes a smaller proportion of total service time than if a route only needs to be serviced once.

Table D.1 Operational Consideration for Routing Models Continued

Remote Material Resupply	Remote salt domes and other non-depot facilities can be used to extend the maximum route length for winter maintenance vehicles and can be integrated into the routing procedure.
Maximum Cycle Time (Time Windows)	Many agencies set a maximum cycle in which all roads (or roads of a particular prioritization level) must be serviced.
Maximum Route Length/ Workload Balance	Agencies may set maximum route or shift lengths and/or seek to balance workloads across routes in order to ensure that drivers remain safe and alert.

Ultimately, the relative importance that winter maintenance personnel place on each of these constraints is likely to vary from agency to agency and could change over time. For example, synchronized service is only a consideration for roadways where multiple lanes need to be plowed simultaneously, as when multiple plows are pushing to the same side on a multilane highway. The increasing prevalence of wing-, tow-, and left-side plows for servicing multilane highways may make the synchronization constraint less important than it may have been historically. In fact, some DOTs intentionally stagger, rather than synchronize, left-side and right-side plows on multilane highways in order to enable traffic to pass winter maintenance vehicles more freely. As another example, the ability to model the impact traffic congestion on winter maintenance operations using time-of-day specific speeds is more likely to be a significant constraint for snow and ice control operations in more highly urbanized areas.

From a practical standpoint, snow and ice control operations also vary considerably from storm to storm. Storm duration, precipitation mix, and the temperatures of the precipitant and the road surface all influence the rate and type of material spreading and the number of cycles that are required to meet an agency’s snow and ice control performance standards. Table D.2 defines two approaches to creating storm-specific routes. However, the implementation challenges inherent in having a number of different route scenarios may outweigh the efficiency benefits that scenario-based or dynamic routes provide. Newer in-vehicle technologies could enable drivers to receive new routes in real time, but the value of a driver’s familiarity with a specific route may have safety and efficiency benefits that are not captured in route optimization modeling.

Table D.2. Storm Specific Routing Approaches

Scenario-Based Routing	Fixed sets of routes are created for different material spread rates and/or vehicle allocations
Dynamic or Real-Time Routing	Short-term weather forecasts or real-time conditions are used to create unique sets of routes for each winter storm event

D.3. Snow and Ice Control Optimization Goals

Broadly speaking, route optimizations seek to meet a set of service standards as efficiently as possible by minimizing an objective function, a mathematical representation of the cost of providing service. The objective function may define cost in terms of monetary costs (e.g. of

labor, materials, and equipment) or in terms of travel time or distance. The objective functions for snow and ice control route optimization projects often focus on minimizing total service time or total cycle time. The routes that an optimization process produces depend on the goals of fleet operators and how the objective function is defined.

For example, a multi-vehicle route optimization process could focus on minimizing total service or vehicle operating time (which is achieved by minimizing the number of vehicle routes), or it could focus on minimizing cycle time, the time required to service all roadways in a service territory (which is achieved by minimizing the length of the longest routes). The first objective is commonly used for private-sector route optimization applications. However, given the fact that winter storms compromise the safety of the traveling public, a primary objective of public snow and ice control operations is to return the road network to safe operating conditions as quickly as possible given a finite set of resources (vehicles, personnel, material, etc.) available in a given winter.

These contrasting optimization goals are illustrated in Figure D.1. Figure D.1A shows the optimal routing solution for two winter maintenance vehicles to minimize vehicle operating time on a simple network. The routing solution depicted in 1A eliminates all deadheading but leaves a vehicle behind and increases the cycle time for plowing the entire network. Many DOTs would consider the solution illustrated in Figure D.1B, which minimizes the cycle time for plowing the entire network at the cost of some deadheading, to be the better solution. Weighted optimizations that balance contrasting goals, like reductions in total service time and cycle time are also possible.

Many standard COTS routing tools minimize total vehicle operating time, as shown in Figure D.1A. Consequently, these tools may not be ideal for snow and ice control operations since they provide solutions that leave vehicles idle and thereby increase the cycle time for winter maintenance operations. Thus, using the standard vehicle routing solutions in COTS requires the user to clearly understand what routing methods and objectives the software employs by default, and to clearly understand and carefully consider their own specific optimization objectives. In general, it is important to understand that simply running a routing optimization tool without a detailed understanding of the problem objectives and constraints is unlikely to support informed decision-making.

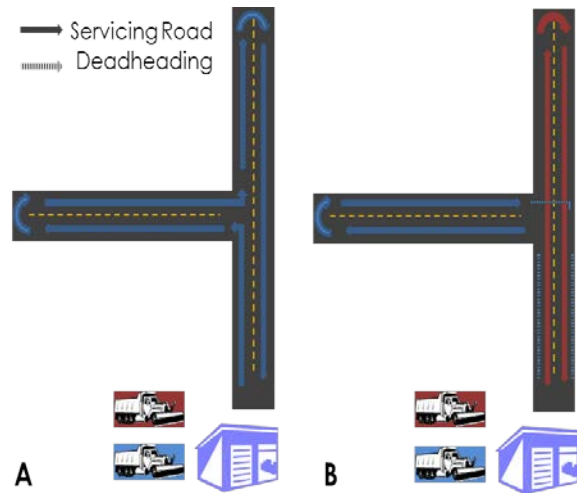


Figure D.1. Snow and ice controls routes optimized to minimize A) total vehicle operating time and B) cycle time.

D.4. Routing Methodologies

D.4.1. Solution Approaches

As noted in Section D.1, routing problems can be solved using either exact or approximate solution methods. Exact methods produce mathematically optimal routes but are generally not feasible for real-world snow and ice control routing problems due to the size and computational complexity of these problems (5). Approximate methods are designed to produce “good-enough” results for complex problems, like snow and ice control routing, but are not guaranteed to generate optimal solutions (6).

Approximate methods for solving snow and ice control routing problems frequently include separate route creation and route improvement phases. The route creation phase generates a set of initial routes that conform to the operational constraints included in the optimization (e.g. vehicle material capacity), while the route improvement phase repeatedly rearranges road segment between routes to search for more efficient solutions. Common approximate methods include constructive heuristics and two-phase heuristics (generally used in the route creation phase), and metaheuristics (generally used in the route improvement phase) (7). Examples of these methods, as well as the general relationship among them in terms of computational complexity and solution quality, are shown in Figure D.2. Researchers studying routing problems have increasingly used metaheuristic solution methods (8, 9). Additional information about how constructive heuristics, two-phase heuristics, and metaheuristics are used is provided in Appendix D-1.

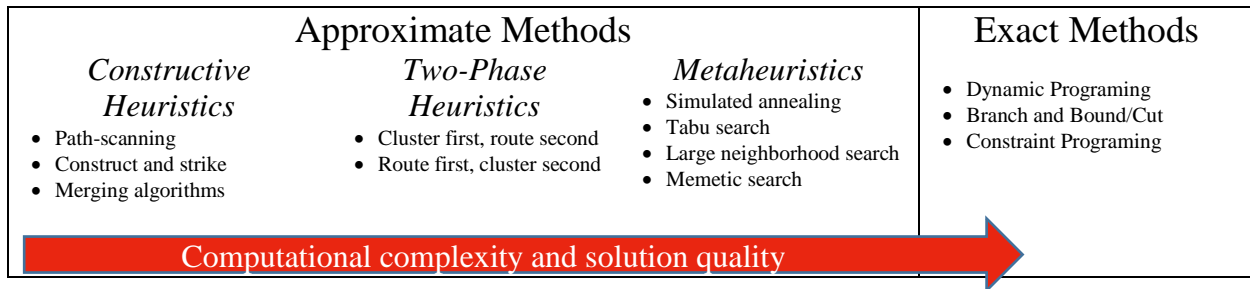


Figure D.2. Solution Methods for Snow and Ice Control Routing

D.4.2. Problem Formulation

The snow and ice route optimization process is generally set up either as a vehicle routing problem or an arc routing problem (9). From a practical perspective, vehicle and arc routing problems differ primarily in terms of their data preparation requirements. The vehicle routing problem creates a set of routes that minimize the cost associated with visiting specific points or stops on a road network (10). Since this approach requires that vehicles travel to a set of specific points, stop locations must be added to each road segment that requires snow and ice control before the optimization can be conducted. In contrast, the arc routing problem creates routes that minimize the total cost to service a set of road segments or arcs in a road network (10). Because the arc routing problem directly addresses road segment coverage, it translates to snow and ice control routing more directly than the vehicle routing problem and is commonly used for snow

and ice control route modeling (9). Mathematically, the arc routing problem can be converted to an equivalent vehicle routing problem, as shown in (11), and thus either approach is feasible for snow and ice control route optimization.

Early vehicle and arc routing models created a single route that serviced all target stops or road segments in a network. These early optimization did not create separate routes for multiple vehicles and did not consider material spreading. Subsequent research has generated a large number of routing problem variations capable of addressing many of the constraints identified in Table D.1. Crucially, current routing applications are able to create routes for each vehicle in a mixed, or heterogeneous, vehicle fleet routed from a single depot or from multiple depots. *Capacitated* routing problems specifically account for the material carrying capacity of winter maintenance vehicles. These problems track the amount of material loaded on each vehicle and the rate that the material is being applied while servicing road segments, making it possible to optimize spreading routes as well as plowing routes. *Hierarchical* routing allows for roadway prioritization to be included in the optimization process. Routing with *time windows* makes it possible to incorporate some winter maintenance performance targets by requiring that roadways are serviced within a specific time frame. Time windows can also be used to limit maximum shift lengths. Additional information on variations of the vehicle and arc routing problems can be found in reviews by Eksioglu et al. (12) and Wøhlk (8).

D.5. Data Preparation

Performing snow and ice control route optimization on real-world networks requires a significant amount of data preparation before the optimization can be conducted. In addition to detailed information about the vehicle fleet, accurate road networks are required and must be represented in a manner that is consistent with the problem formulation. The challenges associated with creating an appropriate representation of the road network are discussed in Section D.5.1.

Additionally, comparing the routes produced by the optimization process with existing routes is an important method for evaluating the efficiency gains of the new routes. However, this comparison requires detailed information about the existing routes, which may or may not be readily available. The challenges of route digitization are discussed in Section D.5.2.

D.5.1. Representation of the Road Network

Routing results are dependent on underlying network characteristics so accurate road network data are essential to the route optimization process. Initial road network data are often obtainable from agency sources or a variety of commercial sources such as ESRI, but these data often need to be altered in order to be compatible with optimization modeling. As depicted in Figure D.3A, lane specific routing requires each lane be represented by an individual arc in the network. Similarly, requiring repeated passes over a given lane can be accomplished by replicating the arc representing that lane once for each required pass. Any limits on the turning motions that are possible or allowable at road segment intersection must also be represented in the road network. Figure D.3B shows the representation of a four-way intersection with left turn and U-turn prohibitions. As mentioned in Section D.4.1, additional stop nodes must be added to each road segment, if the route optimization is set up as a vehicle routing problem. This process is described in (11).

In some cases road network data files must be converted from one file format to another in order to be compatible with the routing software. When this occurs, overpasses and underpasses should be reviewed carefully to ensure that no improper turning movements have been introduced in the conversion process. Network errors are often introduced at overpasses because elevation and turn restrictions are treated differently in different GIS and network-routing COTS applications.

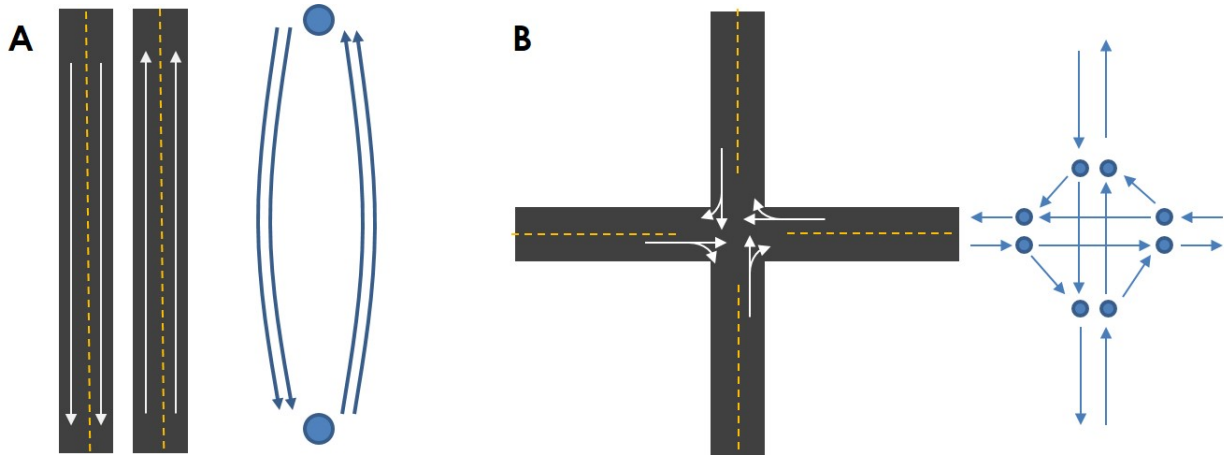


Figure D.3. Network representations (A) allowing lane-specific routing and (B) prohibiting left and U-turns. Modified from Hajibabai et al. (13)

Restrictions on where and how winter maintenance vehicles can safely turn around can also have significant impacts on routing results. Safe turnaround locations are particularly important in the context of snow and ice control operations for on- and off-ramps on limited access highways since servicing interchange ramps is time-intensive and may require considerable deadheading on highways with long distances between exits. To reduce the amount of deadheading required to serve these ramps, many DOTs have constructed turnarounds just upstream and downstream of an interchange that allow winter maintenance vehicles to safely change directions on the highway system (see the example shown in Figure D.4). Since these turnarounds are not part of the public road network, they are often excluded from commercially available GIS road layers. If they are available for use by winter maintenance vehicles, these turnarounds must be manually added to the road network to ensure that they are included in the route optimization and that the routing results are as efficient and realistic as possible.

D.5.2. Digitization of Existing Routes

Comparing optimized routes with existing routes is important because it provides information about the efficiency gains that could be realized



Figure D.4. Winter maintenance vehicle turnaround near Interstate 89 Exit 5, VT

by implementing the new routes and because it may reveal short-coming in the route optimization process that need to be modified to produce realistic and usable results. Making this comparison requires detailed information about the existing routes, however, and this information is not always readily available. Some agencies do not have digitized route maps or written records of their routes. In some cases, route information is limited to a record of the set of roads that each vehicle must service and the specific routes used by those vehicles must be manually or computational derived (13). Frequently, route maps and route statistics are kept at the district level and may include erroneous location information (14).

D.6. Routing Studies

The earliest snow and ice control routing studies are found in the operations research literature but, as the field has matured, a growing number of studies have appeared in the transportation research literature and a range of transportation agencies have undertaken optimization projects since the mid-1990s. Routing procedures are available in COTS software packages, such as TransCAD, ArcGIS, and FleetRoute, though not all of these tools are designed explicitly for snow and ice control routing. Several companies including Geo-Decisions, Route Optimization Consultants, and Vaisala offer routing services geared toward winter maintenance operations. This section of the review provides a brief overview of DOT routing projects from the late 1990s and early 2000s. However, the focus of the section is on snow and ice control routing applications from the last five years.

In the 1990s, Indiana DOT (INDOT) and Minnesota DOT (MnDOT) led two of the earliest DOT supported snow and ice control optimization projects. From 1993 through 1995, INDOT tested the implementation of a arc routing program – the Computer Aided System for Planning Efficient Routes (CASPER) – developed by researchers at Purdue University (15). CASPER included hierarchal routing, turn restrictions, and synchronized plowing constraints. The program used a constructive heuristic to generate initial routes which could be improved using metaheuristic or by manual review. During the winter of 1993-1994, INDOT maintenance staff field tested the CASPER generated routes. Overall, 72% of the routes were implemented after varying levels of manual modification and 28% of the routes were rejected as infeasible. Implementation of the feasible routes resulted in a 10% reduction in winter maintenance fleet size and an estimated 10 year savings of \$5 million (15). In 1997, MnDOT published a review of COTS route planning and optimization software (16). The MnDOT review noted that while the benefits of automated route planning could be considerable, this process was not widely used for snow and ice control. The review included gdsICE, an improved version of the CASPER program. The review rejected gdsICE, however, because it was not compatible with MnDOT's computer system, the software ownership rights were uncertain, and the package did not allow the user to specify the number of passes per road segment. Ultimately, the review recommended using the arc routing tool in TranCAD while noting that the software (at that time) modeled only homogenous vehicle fleets and did not allow for the reallocation of routes among depots (16).

In 2003, Ohio DOT (ODOT) used winter plan WinterPlan, a COTS package used for route mapping and planning, in an effort to reduce route cycle times in Ohio (17). Ultimately the

ODOT found that the program had difficulty with complex interchanges and ramps and was too time consuming and costly to operate so the optimization project was terminated (18).

The team of Perrier et al. conducted a multi-part review of snow and ice control routing in 2006 and 2007 (19–21). Overall, the authors documented a trend from early route optimizations that applied simple constructive or two-phase heuristics but failed to incorporate many of the operational constraints that govern real-world problems to more sophisticated approaches that included many of these operational constraints (20). Despite these improvements in modeling, the authors noted that results from these studies were rarely implemented by transportation agencies (20, 21). They suggested that improved integration of facility siting and route optimization could improve real-world route performance. Finally, they suggested that future research should consider routing snowblowers and dump trucks for snow loading/hauling operations, as these activities have operating constraints that are distinct from spreading and plowing routes (21).

In an updated 2010 review (9), Perrier et al. pointed to a continued gap between route optimization model development in the research arena and implementations by transportation agencies in spite of generally positive results in limited testing. The authors speculated that the lack of widespread implementation reflected the difficulty of the snow and ice control routing problem, unfamiliarity in the practitioner community with the benefits of these models, and lack of adequate technology transfer. As well as emphasizing the need for snow and ice control routing implementation projects, Perrier et al. also highlighted three areas for future research. The first area was to leverage emerging information technologies, such as improved weather forecasting for dynamic (day-ahead) (22) and real-time routing based on prevailing or forecasted weather conditions (23). The second research area was to develop route optimization models that integrated other winter maintenance issues, including siting depots and material stockpiles, determining service territory boundaries, and personnel scheduling. The third area was to quantify the trade-offs between cost and level of service for different routing options.

Two DOT-sponsored research projects in 2010 and 2011 looked at route optimization. As part of a larger study of winter maintenance workforce needs for the MnDOT, Gupta developed a snow and ice control routing model that considers vehicle capacity, roadway prioritization, and turn restrictions (24). Routes generated by the model were used to estimate workforce needs but were not evaluated against existing routes. Missouri DOT (MoDOT) sponsored an snow and ice control optimization project undertaken by researchers at the University of Missouri (3). This project focused on the St. Louis District and considered facility closures and vehicle routing. The objective of the routing process was to minimize the total number of snow and ice control routes. The optimization was solved by applying a heuristic route improvement procedure to initial routes generated using a route-first, cluster-second two-phase heuristic. The study identified opportunities for cost saving by closing several depots and assigning responsibility for the roads serviced by these depots to other nearby depots.

In 2012, C2Logix, Inc. conducted a route optimization project for the city of Centennial, Colorado (25). The project used FleetRoute, a COTS package, to minimize the cycle time

required to serve all priority 1 and priority 2 roads within the city. The optimization considered road prioritization, synchronized plowing, and turn restrictions. The software outputs required significant post-processing but ultimately were implemented into practice. The new optimized routes produced significant reductions in the time required to complete winter maintenance operations, with multi-cycle service time reduced from 8 to 5.5 hours for two storms in winter of 2011-2012.

Salazar et al. (26) addressed the challenge of creating routes that synchronize multiple plows so that they can work in tandem to clear multilane roads without leaving snow in adjacent lanes. The model requires that all adjacent lanes with the same travel direction are plowed simultaneously. The optimization used minimizes the total cycle time required to service all roads, but it does not consider capacity constraints. The model was tested on several randomly generated networks and in a single-depot, eight vehicle scenario for the road network of the city of Dieppe in New Brunswick, Canada. The algorithm was able to successfully generate synchronized routes, but the performance of these routes could not be compared to the existing routes since the model did not account for the city's current roadway-prioritization classes and other constraints. The problem is formulated as an arc routing problem and solved using heuristic route creation and metaheuristic route improvement phases.

The authors of this review conducted a snow and ice control routing optimization project for the Vermont Agency of Transportation (VTrans) in 2013 (4) that made use of a COTS package, TransCAD, produced by Caliper. The study included the 60 garages and over 250 winter maintenance vehicles operated by VTrans and created routes for the full state-maintained highway network. Multilane services were not included in the model because tow-plows are expected to play an increasing role servicing multilane highways in Vermont. The initial step in the project was to delineate optimal service territories for each of the garages based on travel time from each garage to all other road segments. Thereafter, vehicles were allocated to each garage using several different allocation methods including a method based on the state's roadway-prioritization scheme. Routes were created for both low and high material applications rates using the vehicle routing problem tool in TransCAD. Because TransCAD's vehicle routing tool minimizes total service time but VTrans was not seeking to reduce the number of vehicles providing service, the team scripted an iterative process that used the time window constraint to route all winter maintenance vehicles and minimize the cycle time for completing winter maintenance operations. The software has the capacity to incorporate vehicle/road compatibility constraints and turn restrictions though these feature were not used in this project.

Holik et al. (27) also used a COTS routing package, ESRI's ArcGIS, to create a route optimization model for the Ohio DOT's District 4. The district has 33 garages and remote salt storage locations and 117 winter maintenance vehicles. The optimization included setting the service territories for each garage and then creating routes for each garage within the service district. The modeled time to complete these routes was compared to GPS records of winter maintenance vehicles on the routes to increase the accuracy of future model runs. The research team considered several different spread rates and storm-specific vehicle allocations. They showed that the total cycle time for a storm could be reduced by reallocating vehicles from

garages unaffected by the winter weather event to garage engaged in snow and ice control operations.

Pennsylvania DOT (PennDOT) and Geo-Decisions developed a GIS-based route planning tool that consolidated route and vehicle information from each of the Agency's districts (14). This process allowed agency staff to develop route maps more quickly and to identify inconsistencies (such as large variations in cycle times and difference in treatment standards) across service districts. The tool provided a clear visualization of route lengths, providing an opportunity to methodically reduce the number of trucks being deployed by eliminating routes with low snow-lane-mile assignments.

Liu et al. (28) conducted a study on the impact of depot location and number of vehicles routed on plowing efficiency in a neighborhood in the city of Edmonton in Alberta, Canada. They used a metaheuristic approach to solve a capacitated arc routing problem that minimized the total distance traveled by all vehicles. The model is strictly hierarchical, meaning that all routes consist of roads of a single priority class. It is assumed that roads of the same priority class have an equal number of lanes and thus that multilane coverage can be achieved by duplicating the routes of each priority class. As with several other projects, the problem was solved using a constructive heuristic for the route creation phase and a metaheuristic for the route improvement phase of the optimization. The authors tested six different depot locations, routing between one and six vehicles for a total of 36 model runs. Service time decreased as the numbers of routes increased, but the cost of adding routes and vehicles was not considered.

A recent paper by Hajibabai et al. (13) is noteworthy for incorporating both mid-route salt replenishment at remote salt domes and congestion effects on vehicle speed in its routing model. The model minimizes a weighted combination of total service time and cycle time by road priority class. The model accounts for multilane roads, fleet heterogeneity, and turn restrictions. The routing model was applied to the highway network of the Lake County, Illinois Division of Transportation and routed 25 vehicles from a single depot. In addition to the depot, the vehicles can replenish salt supplies at any of 12 remote salt domes. When compared to a shortest-path solution for existing roadway assignments, the model reduced deadheading travel by 4.1%. The problem is formulated as a vehicle routing problem and solved using a cluster-first, route-second heuristic to create initial vehicle routes and then a metaheuristic to improve these seed routes.

In 2015, Quiron-Blais et al. (7) conducted a case study of route optimization in a small city in northern Quebec with a single depot and eight winter maintenance vehicles of varying types. Their model incorporates many operational constraints including flexible hierarchical routing, vehicle/road compatibility, turning restrictions, and workload balance. It minimizes a weighted combination of the longest route and total service time by priority class. The optimization created set of initial routes using a simple constructive heuristic and improved on these routes using a metaheuristic. The authors noted although some post processing was necessary to make the routes completely functional, the results provided a template from which planners would be able to build efficient routes.

Colorado DOT (CDOT) commissioned Vaisala to perform a snow route review for CDOT Region 4, the Boulder maintenance area (29). The first stage of the project, completed in January of 2016, examined whether it would be possible to reduce the number of routes in this region while still achieving CDOT's snow and ice control performance goals. Vaisala concluded that a route optimization process could reduce the number of snow and ice control routes, but it did not produce new routes in the first project stage.

D.7. Conclusions

Winter maintenance vehicle routing has matured to the point where it can produce valuable input for real-world routes while incorporating many of the most pertinent operational constraints. Mixed vehicle capacities, vehicle/roadway compatibility, and turn restrictions are now routinely included in route optimizations. Increasingly these tools are available in COTS packages. Coordination between optimization modelers and operations personnel is essential to ensure the optimization objectives and constraints accurately reflect the needs of the agency.

Currently, there are several operational considerations that are frequently omitted from snow and ice control route optimization models. Multilane service is conceptually straightforward to integrate into these models but is often omitted. Relatively few studies incorporate remote material resupply when creating routes, and very few models consider that routes are generally repeated multiple times for each winter weather event. Additional research to provide guidance on the maximum or optimal number of vehicles that can feasibly be routed from a given depot is also warranted.

From an implementation perspective, static routes may be more valuable than a large number of scenario-based or dynamic routes, as most drivers and garage supervisors specialize in clearing a very limited number of (in most cases only one) specific, well-defined routes. Introducing changing routes with potentially different operating procedures can create confusion and reduce plowing efficiency, effectiveness, and safety. It may not be feasible to include all of the detailed safety and behavioral constraints in a routing optimization. Also, as noted in several of the optimization efforts (7, 15, 18), some of routes produced by automated optimization processes may not be implementable in practice without some level of manual review and modification. Consequently building final manual review time into optimization efforts may be necessary to achieve results that are useable by transportation agencies.

Finally, it should be noted that comparisons between modeled route times and current or historical route times should be undertaken with caution since assumptions about vehicle travel speeds and turn penalties embedded in the model may not accurately reflect the speeds of vehicles on the ground. Route mileage comparisons may be more reliable. In either case, the lack of repeated cycles in snow and ice control models also means that the importance of deadheading between the depot and route start is disproportionately large relative to the case where a winter maintenance vehicle travels to a route and stays on the route for multiple cycles before returning to the depot.

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APPENDIX D – 1

HEURISTIC ROUTING SOLUTION METHODS

Constructive heuristics use simple sets of rules to either sequentially or simultaneously create routes for each vehicle at the depot (20). Constructive heuristics include path-scanning, construct and strike, and a variety of merging algorithms (30, 31). Path-scanning creates routes by starting with a single link (e.g., the link closest to the depot) and iteratively extending the route according to a logic rule, such as adding whichever unserved, adjacent link terminates farthest from the depot. This process is repeated until a vehicle's capacity is exhausted and then the process is repeated for remaining unserved links for subsequent routes. The path-scanning algorithms are notable for their speed and simplicity (30). Merging algorithms start by creating a shortest path route for each network segment that requires service. Once this is completed, the longest route is examined to see if it encompasses other segments that need service. Overlapping routes are then merged, subject to capacity constraints, and the process is repeated iteratively (30).

Cluster-first, route-second and route-first, cluster-second are both two phase heuristics. The cluster-first, route-second method subdivides a network into a set of sub-networks (clusters) equal to the number of vehicles to be routed such that each cluster encapsulates an approximately equally number of road-miles. Once these clusters are created, a single vehicle route is created for each cluster. Route-first, cluster-second methods, in contrast, first create a single route that covers the entire network and then partitions that route into a set of shorter routes equal to the number of vehicles to be routed. Generally two phase heuristics produce better route optimizations than do constructive heuristics for multi-vehicle routing procedures (7).

Metaheuristics are general optimization algorithms that can be applied to a wide range of optimization problems. They have been demonstrated to be an effective means for solving complex problems for a number of different applications including routing (6). Broadly speaking, metaheuristics function by balancing random search processes with intensifying local searches related to promising solutions. In this way, metaheuristics are capable of finding near optimal solutions without searching all possible solutions sets. In the context of snow and ice control routing, metaheuristics are often applied to the results of constructive heuristics in ways that iteratively re-arrange these initial routes in search of better performing routes.

Metaheuristics that have been applied to snow and ice control routing include simulated annealing, Tabu search, elite route pool, adaptive large neighborhood search, memetic search, greedy randomized adaptive search and ant colony optimization (7, 8, 21). Additional discussion of these metaheuristics can be found in (6, 32)



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