Literature Review, Technology Scan, and Early Adopter Interviews: Adaptive Route Optimization

Report No. FHWA-HOP-21-098

October 2022

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

This literature review, technology scan, and collection of interviews with early route-optimization adopters serves to support development of foundational systems engineering documentation for adaptive route optimization (ARO). These engineering documents, provided separately, include a concept of operations and system requirements that describe a system or tool that incorporates real-time and historic data to develop an adaptive snowplow routing optimization solution. End users for this system (or tool) will include snowplow operators, maintenance supervisors, and related agency staff. This report highlights the existing gaps faced by agencies considering route optimization in terms of available software tools, the state of practice, and deployment.

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HOP-21-098	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Literature Review, Technology Scan, and Early Adopter Interviews: Adaptive Route Optimization		5. Report Date October 2022
		6. Performing Organization Code
7. Author(s) Neal Hawkins (InTrans), Jing Dong (InTrans)		8. Performing Organization Report No.
9. Performing Organization Name and Address Institute for Transportation at Iowa State University (InTrans) 2711 S. Loop Drive, Suite 4700 Ames, IA 50010 Leidos Inc. 11251 Roger Bacon Drive Reston, VA 20190		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFH61-16-D-0005, Task T-693JJ321F000066
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Technical Report, July 2021 through October 2021
		14. Sponsoring Agency Code HOP
15. Supplementary Notes David Johnson, TOCOR		

16. Abstract

This literature review, technology scan, and collection of interviews with early route optimization adopters serves to support FHWA in developing foundational systems engineering documentation for adaptive route optimization (ARO). These engineering documents, provided separately, include a concept of operations and system requirements that describe a system or tool that incorporates real-time and historic data to develop an adaptive snowplow routing optimization solution. End users for this system (or tool) will include snowplow operators, maintenance supervisors, and related transportation agency staff. This report highlights the existing gaps faced by agencies considering route optimization in terms of available software tools, the state of practice, and deployment.

17. Key Words Snowplow routing, static route optimization, adaptive route optimization, route optimization; snowplows; winter operations, node-based routing, arc-based routing, pickup and drop-off service industry, segment based services, road weather, road weather management program		18. Distribution Statement No restrictions.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 42	22. Price n/a

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

ARO	adaptive route optimization
ARP	arc routing problems
AVL	automated vehicle location
CARP	capacitated arc routing problem
COTS	commercial off-the-shelf
DOT	department of transportation
FHWA	Federal Highway Administration
GPS	Global Positioning System
MDSS	maintenance decision support system
OR-Tools	Google® optimization tools
RWIS	road weather information system
RWMP	Road Weather Management Program
TMC	traffic management center
VRP	vehicle routing problem

CHAPTER 1. INTRODUCTION

BACKGROUND

Adverse weather has a significant and measurable impact on roadway safety, mobility, and productivity. It increases driving risk and travel time and creates operational challenges for transportation agencies. Every year, adverse weather conditions cause more than 235,000 injuries and 6,000 fatalities on U.S. roadways. Although rainstorms are more common, winter weather events have a larger impact on the cost to agencies of maintaining roadway service levels. State departments of transportation (State DOTs) currently spend more than $2 billion per year on snow and ice control and more than $5 billion per year on repairs due to snow and ice operations, chemical use, and wear of the roadways. Figure 1 illustrates the challenging conditions both snowplow operators and motorists faced during winter conditions. Any efficiencies that get plow operators off the road quicker and travel lanes cleared faster have the potential to yield immediate safety benefits.

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Figure 1. Winter conditions often reduce visibility and available friction, which impact both snowplow operators and motorists alike.

The availability of road weather information can help reduce the operational impacts of adverse winter weather conditions. Drivers with access to timely and accurate travel information can make informed decisions regarding driving patterns, thus reducing the risk of crashes, injuries, and fatalities. State DOT winter operations and maintenance staff use pavement condition, atmospheric and pavement temperatures, and precipitation data to plan how to restore roads to pre-storm, clear-pavement conditions. These operations generally include plowing to remove snow and ice from roadways and using de-icing materials to improve the pavement state.

Each State DOT has its own goals and challenges in restoring roadways to pre-storm levels of service. In general, maintenance planning and routing builds on past practice and results, conditioned by the profile of each storm. Results for the road network as a whole depend on the State DOT's safety and mobility goals and routing of the available vehicles in the maintenance fleet. The results for a specific segment of roadway depend on factors such as the type of storm and precipitation, the timing of operations, and the type of roadway treatment. The time to plow and treat all road lanes on a route can be affected by the maintenance trucks' material capacities, the location of maintenance sheds, incidents on the roadway, changing winter storm conditions, traffic, staff shift changes, and other factors.

Changes in weather patterns, road network conditions, agency resources, and public expectations are posing challenges to past practices for winter maintenance planning and routing. Intense weather events—whether winter snow and ice, hurricanes, or droughts and dust storms—are becoming more common. Traffic in urban areas and along interstate corridors is more congested even while lane miles increase. Agencies continue to struggle with the budgets and staffing necessary to keep up with the increased need for maintenance resources. Moreover, public perceptions focus more on extreme events in which expectations may not have been fully met than on regular, consistent service.

These challenges create an opportunity to improve safety and mobility on roads subject to winter weather through efficient snowplow routing. However, route optimization is a complex science. Better winter maintenance routing requires research into models and methods that can improve the state of the practice.

OBJECTIVE

This literature review, technology scan, and collection of interviews with early route optimization adopters serves to support development of foundational systems engineering documentation for adaptive route optimization (ARO). The documents, to be released at a later time by FHWA, include a concept of operations and system requirements that describe a system that incorporates real-time and historic data to develop an adaptive snowplow routing optimization solution. End users for this system will include snowplow operators, maintenance supervisors, and related agency staff.

CHAPTER 2. ROUTE OPTIMIZATION

BACKGROUND

As shown in Figure 2, winter operations include the removal of snow and ice on roadways and the application of materials to improve road conditions for safe travel. In general, snowplow routes are developed based on past experiences and expected weather conditions. Route efficiency, over time, is dependent on these conditions remaining constant with no new lanes added to the route, storm severities staying within expectations, and available resources remaining consistent year after year (labor force, equipment, and materials). In reality, transportation agencies face a wide range of changing conditions each winter, which reduce route efficiency and lead to increased labor and materials costs, reduced roadway safety, and gaps in traveler expectations.

Figure 2. Removing ice and applying salt during winter operations.

While agencies do not need to be reminded of all the dynamic issues they face, they do need support in transitioning beyond fixed, or static, snowplow routing. Adaptive route optimization can provide agencies with the flexibility to adapt to new conditions (e.g., fewer trucks than expected, lack of staff, closed roadways, record storm intensities) in an efficient and timely way. This chapter explores the concepts of route optimization in question and answer format.

UNDERSTANDING ROUTE OPTIMIZATION

What goes into setting up a snowplow route?

Snowplow routes are typically set up based on agency resources (i.e., equipment, material storage, and labor) and service goals (e.g., the amount of time it takes the snowplow operators to plow and apply materials on all lanes of traffic along their route once). Routes may be modified due to added lanes, changes to material storage locations, the addition of equipment with new capabilities (e.g., tow plows[1]), or revised service goals.

Are an agency's current snowplow routes optimized if they are easy to understand and do not get many complaints?

Existing routes may meet public and agency needs for an area that is stable and not growing or adding new lanes. The route optimization process, however, looks at how the routing might be *improved* to reduce costs or time beyond current expectations.

What is route optimization?

Route optimization is the process for determining the most efficient route based on specific factors. It is more complicated than just finding the shortest path, because it considers factors like minimizing fuel costs, service times, or the number of trucks required. In terms of winter maintenance, an optimal snowplow route solution could minimize factors like driver hours, fuel costs, material use, or cycle times. Solving for an optimized route requires repetitive mathematical comparisons of feasible solutions to find the most favorable option.

It is important to consider the difference between static and dynamic routing. Static route optimization uses a point-in-time snapshot to develop routes based on available resources and service goals. These static routes, however, are fixed, and the efficiency of each route degrades with any changes to the assumed conditions. Without manual intervention, static route optimization does not account for extreme weather events, unexpected resource issues, or operational problems that occur during winter storms.

In contrast, dynamic route optimization provides the flexibility to adapt to changing conditions (resources and service goals) and to generate revised optimal routing based on the changes faced in real-time. The ability to generate routing solutions from dynamic conditions is called adaptive route optimization (ARO).

In the package delivery business, ARO finds the most efficient routes within a matter of seconds given a change in conditions. For example, if a delivery truck breaks down between deliveries, fleet dispatchers or managers can re-optimize routes quickly by reassigning jobs to nearby drivers. This quick response is possible because of the real-time dynamic-routing software. ARO software can also redirect drivers to other roads or find the most efficient routes when there are sudden downpours, road closures, or vehicular accidents.

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[1] Tow plows are steerable trailers usually pulled behind a dual-axle snowplow.

Are any agencies currently using adaptive route optimization for winter operations?

The authors completing this literature review is not aware of any U.S. State DOT currently using ARO for winter operations, but no formal survey exists to verify this assumption.

Do we know how many agencies have tried static route optimization for winter operations?

A 2016 survey identified agencies that had recently engaged in snowplow routing optimization projects (Dowds et al. 2016). The findings show that 18 agencies reviewed their snowplow routes manually, 9 agencies relied on external consultants to review their routes, and 5 agencies reported using a custom static-route optimization tool to complete their projects.

What data does the ARO process need to work?

Moving from static-route optimization to the dynamic capabilities of ARO requires data. The sources of that data depend on the factors that influence routing plans. Figure 3 illustrates some of the information available today to improve route efficiencies. These include current weather and pavement conditions, traffic speeds, and event data (e.g., lane closures, crashes, stalled vehicles).

Figure 3. Potential information for ARO (e.g., weather, traffic, crashes, road closures).

How are route optimization tools used in businesses?

Route optimization tools are common across transportation-based companies that deliver goods and services. Static route optimization is the most common; however, there is a clear transition toward adaptive route optimization solutions for several reasons:

- Shifts in consumer demand – Consumer demand for package delivery is accelerating along with demand for next-day delivery, product tracking, and alerting. The number of ecommerce shipments in June of 2020 were 30 percent higher than in June of 2019 (Berthene 2020). One large company noted that its average daily shipping volume rose 21 percent in one quarter of 2020 during the pandemic, faster than the company has ever recorded, with a 65-percent increase in shipments to homes (Ziobro 2020).

- Business challenges – Meeting customer demands today requires that businesses overcome a number of challenges related to labor (hiring and retaining staff), unexpected events (increased frequency of disruptive events like weather), unexpected events like the pandemic (impacts to supply, labor, and safety), and the need to be able to react immediately to changed conditions.

Businesses are constantly finding ways to reduce their costs, increase profitability, and gain a competitive edge. Route optimization is one way to make this happen, although agencies must keep in mind that routes that do not change to reflect new conditions are not optimal by definition (DispatchTrack 2021).

The pickup and drop-off package industry applies ARO in real-time globally every day. These tools produce fast, efficient, and accurate optimized routes in real-time and in reaction to change. A global company noted that ARO presents its 55,000 U.S. delivery van drivers with the sequence in which they should pick up and deliver packages for the customers assigned to them that day (Holland et al. 2017). ARO is also used in other surface transportation-related businesses from waste collection to utility meter reading.

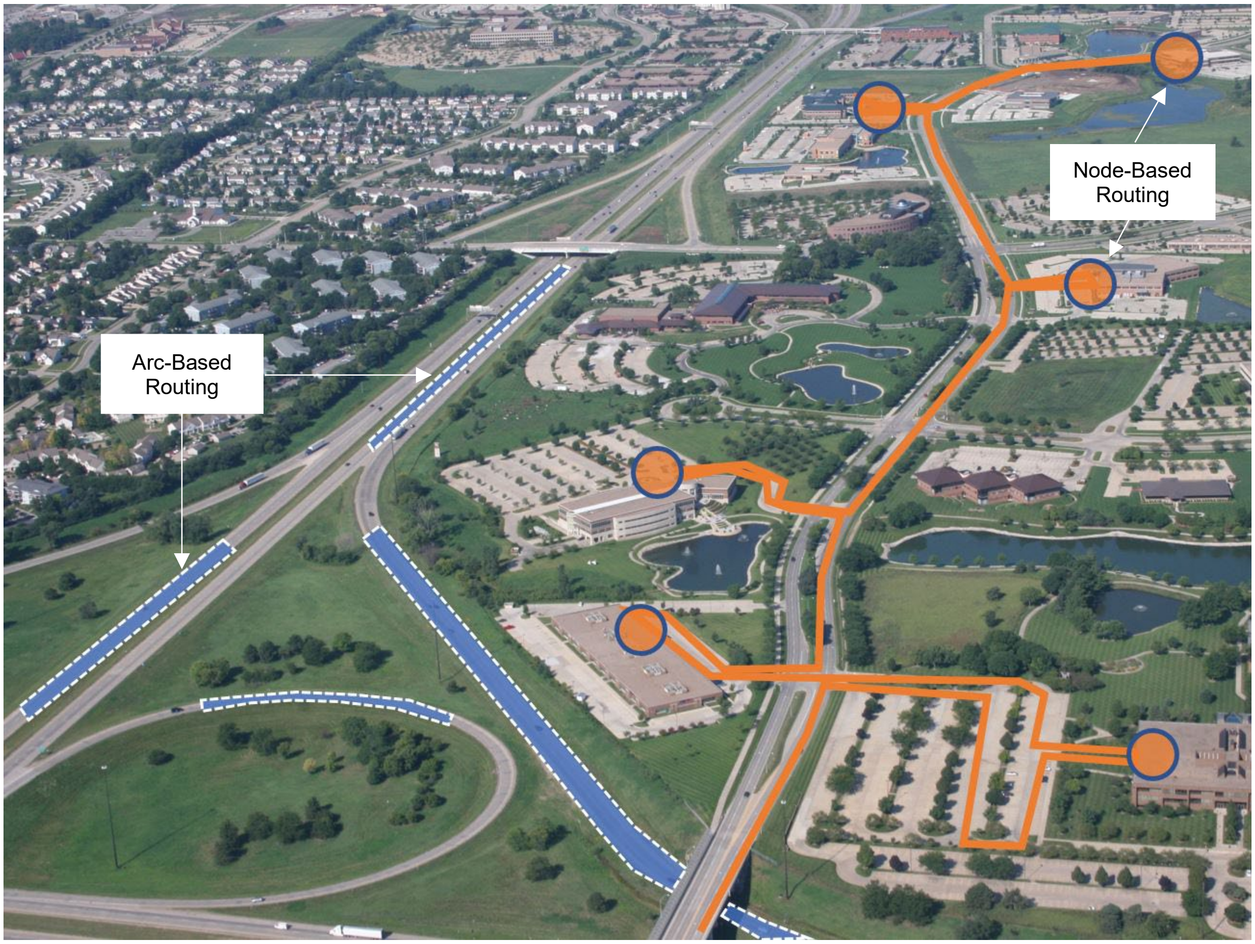
In terms of financial impact, one analysis found that a large package delivery company using its own ARO experienced a reduction of 100 million miles driven, with driver-cost avoidance and fuel savings of between $300 million and $400 million annually (Holland et al. 2017). A few non-financial benefits include operators being able to concentrate on driving safely and a reduction in carbon dioxide (CO_2) emissions.

ARO also supports the airline industry by determining optimal flight paths. Each optimal route depends on the actual conditions for each flight, including forecasted upper air winds and temperatures, the amount of payload, the value of the payload, and the restrictions for the crew and airplane. However, not all airlines use optimized routes. While nearly all computerized flight-planning systems can optimize routes, many airlines still use fixed “company routes” most of the time. The use of ARO has been limited due to permissions and company policies that place restrictions on routing in certain areas. However, most flight-planning systems contain models of all these restrictions, which allow the flight plan to be optimized with dynamic data on winds, temperatures, and costs while still complying with all restrictions. One study of an airline determined that using routes optimized with the most recently forecasted winds, with numerical constraints modeling all requirements, would save about 1 million U.S. gallons of fuel per year and reduce annual CO_2 emissions by about 20 million pounds (Altus 2009).

CHAPTER 3. ROUTE OPTIMIZATION TOOLS AND ACADEMIC LITERATURE

TYPES OF ROUTING PROBLEMS

The calculations behind route optimization are solving either node- or arc-based problems. Solutions to the node-routing problem, often referred to as the vehicle-routing problem (VRP), identify service points (like customer address) as nodes in a network and find the best routes to service each of the customers (nodes). On the other hand, solutions to arc-routing problems (ARP) find the best routes to visit all the segments (called arcs) of a network. Figure 4 provides an illustration comparing these two types of problems, with node-based routing in orange and arc (segment)-based routing in blue.



© 2021 CWIMS at Iowa State University (annotations to show routing added).

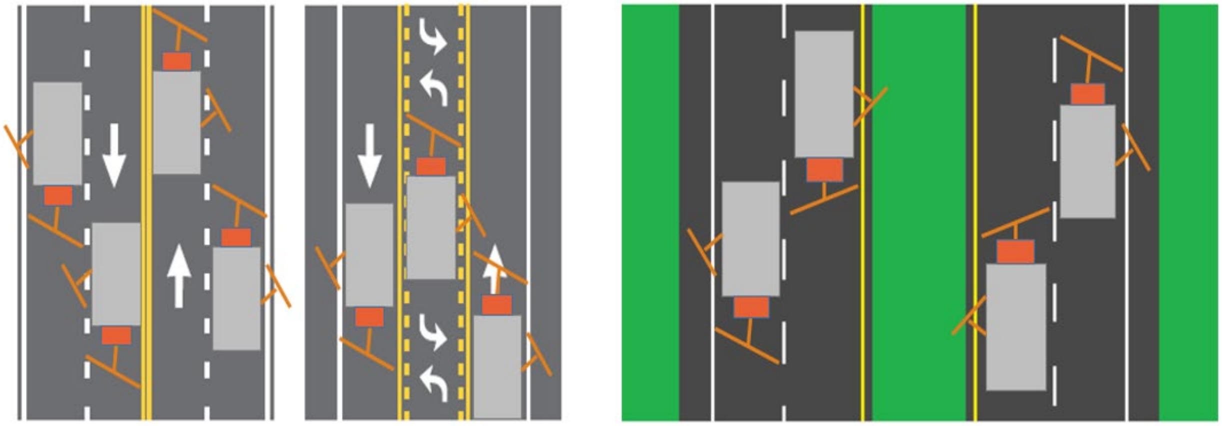
Figure 4. Node-based routing example (orange) contrasted with arc- or segment-based routing (blue).

Node Routing

Node-routing problems are solved to generate routes for fleets of vehicles to visit nodes for delivery, pickup, or service calls. Given the wide applications in both the public and private sectors, the solutions to the node-routing problem are based on ample research extending back several decades. Algorithms are solving node-routing problems in real-time, which leads to implementation in commercial off-the-shelf (COTS) software packages and integration with customized fleet-management tools.

Arc-routing

ARPs, on the other hand, have received less attention than node-routing. Some familiar examples of ARPs include postal service and newspaper delivery, household meter reading, solid waste (trash) collection, and package delivery in very dense urban areas. Very few commercial off-the-shelf tools exist specifically for solving an ARP (Dowds et al. 2016). As a workaround, transforming an ARP to a node-routing problem and solving with a COTS route-optimization tool is possible. However, problems can arise when trying to incorporate ARP-specific objectives and constraints. For example, Figure 5 shows a unique constraint where roadways that do not have a wide median to hold snow need to be serviced by right-wing snowplows.



Notes: Left: undivided multilane road, all snowplows with right-wing plows. Right: divided multilane road, inner-lane snowplows with a left-wing plow, and outer-lane snowplows with a right-wing plow).

Figure 5. Snowplow blade direction constraints based on roadway configuration example.

POPULAR COTS TOOLS

There are several popular COTS tools for solving the route optimization challenge primarily geared towards pickup- and delivery-route design. The following features of these tools are relevant to snowplow routing optimization.

- Real-time route modification feature in which a user can insert last-minute orders, adjust stop sequences, and adjust routes if a driver calls in sick.
- Manual adjustments that automatically trigger new routes.
- Route optimization based on user-defined outer boundaries of an area.
- Route optimization based on real-time traffic conditions
- A feature allowing users to insert new stops on existing routes.

- An avoidance zone feature that allows a user to specify places to avoid, such as high-crime areas and accident-prone intersections

- Predictive weather information that automatically updates estimated delivery times to account for poor weather conditions and tells drivers about the weather along their routes.

- Traffic application programming interface (API) that returns a list of traffic incidents and an image of the current traffic situation for a particular area.

Many tools have implemented algorithms that are efficient enough to recalculate new routes in real-time in response to changes in demand or traffic conditions. They can be used for both static and adaptive route optimization in the context of pickup and delivery (i.e., solving node-routing problems).

Since snowplow route optimization is an ARP (because it requires vehicles to traverse road segments versus service nodes), agencies can either use tools specifically designed to solve the ARP or convert the ARP to a node-routing problem and then solve it using tools designed for solving node-routing problems. There are several COTS software applications currently being used for static snowplow route optimization. Some features of these tools are summarized as follows.

- Use of priority levels in the route design whereby trucks apply salt and sand prior to snowfall, beginning with snow emergency routes before moving on to treat major roads, and finally, neighborhoods and local streets.

- Considers avoiding dumping snow into intersections, servicing side streets, covering multilane roadways, and servicing one-way roads. Provides turn-by-turn directions and route statistics and tracks material use and truck loading plans.

- Some tools include functions that solve node-routing problems. These tools can be used to solve the snowplow route optimization ARP by reprocessing the network. For example, to generate snowplow routes for Kentucky Transportation Cabinet, Blandford et al. (2018) converted road segments to salt delivery points that included fields indicating the amount of salt needed for application on each segment. Midpoints had to be created for every road segment shown as a salt-delivery point located to the right of the direction of travel. Multilane roads required parallel arcs with salt delivery points for each lane.

- Some tools allow users to specify heterogeneous capacities of the fleet and thus were selected by agencies operating snow plot trucks with different capacities (e.g., Dowds et al. 2013).

Although static weather and traffic information can be incorporated into the tools (e.g., the salt demand of each road segment can be dependent on the forecasted storm intensity), road weather information systems (RWIS), integrated mobile observations and sensors, and real-time traffic information have not been incorporated into snowplow route optimization. In addition, recurring problem areas due to weather and historic crash data have been considered in the Colorado DOT Network Optimization framework by introducing a hazard-map representation (Walsh 2018).

Incorporating the hazard-map data into the route optimization, however, requires custom route-optimization software. The impact of maintenance shed locations and maintenance resource availability (e.g., equipment, personnel, and materials) can be evaluated using the static route-optimization tools by changing the network structure (e.g., different locations of maintenance sheds) or constraints (e.g., the number of trucks available and the length of the shift) and solving the problem for various scenarios.

ACADEMIC LITERATURE

Given that there are only a few COTS software tools available, one might be surprised to see the significant amount of academic research devoted to formulating and solving a variety of snowplow-routing problems. The snowplow routing problem has been widely formulated as a capacitated arc-routing problem (CARP) and solved using various exact and heuristic algorithms. This section reviews the algorithms developed for CARP, its variations, and the applications in winter road-maintenance routing problems.

In this section, multiple technical terms will be used. An overview of these terms is defined below:

- Algorithm – A procedure for solving a problem or accomplishing a task.
- Exact Algorithm – An algorithm that solves an optimization problem to optimality.
- Heuristic Algorithm or Problem-Specific Heuristic Algorithm – A procedure that determines good or near-optimal solutions to a specific optimization problem. It is designed to solve a problem in a faster and more efficient fashion than an exact algorithm by sacrificing optimality.
- Metaheuristic Heuristic Algorithm – A high-level problem-independent algorithmic framework that provides a set of guidelines to develop heuristic algorithms.

Exact algorithms are guaranteed to find the optimal solution for the problem, but it may take a long time. For example, the navigation app on a smart phone may take several minutes to find the absolute optimal route. By contrast, heuristics do not guarantee an optimal solution, but require shorter computation times. Using the smart phone example, the navigation app can use heuristics to recalculate and change a suggested route based on a wrong turn.

Various exact algorithms have been developed to solve the classical CARP optimally on small networks of less than 150 road segments (Bode and Irnich 2012; Bartolini, Cordeau, Laporte 2011). However, as illustrated in the smart phone example above, the exact algorithms cannot always find optimal solutions within a reasonable time. On large-sized networks, it is computationally impractical to find exact solutions. Thus, both metaheuristic[2] and problem-specific heuristic algorithms have been used to find near-optimal solutions (Brandão and Eglese 2008; Mei, Tang, and Yao 2009; Martinelli, Poggi, and Subramanian 2011).

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[2] Metaheuristic algorithms are those that can be applied to a broad range of problems.

At a strategic and tactical level, route optimization is an integral part of facility location and sector design; that is, determining the best locations for maintenance sheds and assigning road segments to each shed (i.e., defining the responsibility area of each shed). At an operational level, routes are optimized based on fixed maintenance shed locations and responsibility area. Various operational constraints have been incorporated in the CARP formulation, which are solved using a custom heuristic algorithm. For example, the following constraints have been considered:

- Road-truck dependency – Snowplow trucks can usually be equipped with either a left-wing or a right-wing plow. Road-truck dependency arises when snow and ice must be pushed to a specific side, either to the median or to the shoulder. Roadways that do not have a wide median need to be serviced by right-wing plow trucks. For roadways with a median that is wide enough to hold snow, the snow on the inner lane can be pushed to the left (Dong, Zhang, and Yang 2019). In addition, some agencies are using tow plows, which can clear two lanes in one pass and should be assigned to multilane roads. Refer to Figure 5 above as an example.

- Service continuity – The service-continuity constraint requires connected service links with possible deadheading[3] from the garage to the service beginning node and deadheading from the service end node to the garage (Haghani and Qiao 2002). The service continuity constraint requires a truck deadhead only when going to or from the garage rather than in the middle of a route (i.e., the truck cannot skip a few road segments and then plow or treat again). Similarly, Lystlund and Wohlk (2012) solved the service-time-restricted CARP that required the road segment be serviced by the first truck traversal (i.e., deadheading is not allowed before the road is plowed or materials spread).

- Road hierarchy – Some agencies require roads to be plowed and/or materials spread in a sequence depending on road prioritization. These road prioritization schemes are usually based on road classification systems or traffic volume. Accordingly, hierarchical routing algorithms have been developed that incorporate a roadway-priority constraint requiring that high-priority roads be serviced before low-priority roads (Perrier et al. 2008).

- Tandem plowing – Multilane roads sometimes need to be plowed simultaneously by synchronized vehicles traveling in the same direction (Salazar-Aguilar et al. 2012). When the entire route requires synchronized service, matching multiple vehicles to a specific route is sufficient to account for synchronization. However, if only a subsection of a route requires synchronized service, inter-route coordination is needed in the optimization model.

In real-time operations, prevailing or forecasted weather conditions and real-time traffic conditions have been considered in ARO. Handa Chapman, and Yao (2005) incorporated a road-weather system into their route optimization. The weather system provides road temperature forecasts and then yields service-demanding roads based on road temperature as an input for CARP. Tagmouti, Gendreau, and Potvin (2011) considered the case of a dynamic storm moving across the road network. In this example, the cost and time for treating road segments

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[3] Deadheading occurs when the truck travels on a road segment without plowing or spreading material.

changes with the storm's movement. Xu et al. (2017) optimized routes based on the benefit of plowing and deadhead costs. The benefit is calculated based on the difference between the total predictive travel time with and without plowing. In particular, impacts to travel speed and capacity resulting from snow accumulation on roadways (with and without plowing) are used to estimate travel times.

Table 1 summarizes the models researchers have proposed over time trying to solve CARP in the context of winter road maintenance.

Table 1. CARP literature review for winter operations.

Level	Source	Objective	Special constraints
Strategic and tactical	Muyldermans et al. (2002, 2003)	Allocate road segments to maintenance sheds	None
	Cai, Liu, and Cao (2009)	Determine maintenance shed locations, allocate road segments to sheds, and route design	None
	Jang, Noble, and Hutsel (2010)	Determine maintenance shed locations, allocate road segments to sheds, design route, and schedule fleet	Heterogeneous capacity, fleet size, and road service frequency
Operational	Haghani and Qiao (2001)	Design routes to minimize deadhead distance	Service start time, route duration, time windows, and servicing one or two lanes in a single pass
	Haghani and Qiao (2002)	Design routes to minimize total number of trucks and to minimize deadhead distance	Service continuity
	Omer (2007)	Design routes to minimize total travel distance	None
	Tagmouti, Gendreau, and Potvin (2007) and Tagmouti, Gendreau, and Potvin (2010)	Design routes to minimize the sum of travel and service costs	Time-dependent service cost
	Perrier, Langevin, and Amaya (2008)	Design routes to minimize the service completion time of the first priority class, then second priority class, and so on	Different service and deadhead speed, class upgrading, road-vehicle dependency, load balance, and turn restrictions
	Salazar-Aguilar, Langevin, and Laporte (2012)	Design routes to minimize the makespan[1] (i.e., all road segments are serviced within the least possible time)	Road segments with two or more lanes in the same direction are plowed simultaneously by different synchronized vehicles

Level	Source	Objective	Special constraints
	Lystlund and Wohlk (2012)	Design routes to minimize the total cost	Road segment is serviced by the first truck traversal (i.e., any deadheading on a road segment must take place at a later time than the time of service)
	Dussault et al. (2013)	Design routes to minimize total travel cost	Plowing uphill takes a much longer time than plowing downhill
	Hajibabai et al. (2014)	Design routes to simultaneously minimize the total deadhead travel time and the longest individual truck cycle time	Turn delay and material replenish at salt satellite facilities
	Liu et al. (2014)	Design routes to minimize total travel time	Work shift limit
	Hajibabai and Ouyang (2016)	Design routes to minimize the cost for truck deadheading and maximize the level of service	Replenish material at salt satellite facilities, uncertain maintenance demand, and uncertain service disruption
	Kinable, van Hoeve and Smith (2016)	Design routes to minimize the makespan	Heterogeneous capacity and fuel and salt limits
	Quirion-Blais, Langevin, and Trepanier (2017)	Design routes to minimize the makespan and deadhead travel time	Turning restriction, various speed by truck type, road class operations, and road-vehicle dependency
	Gundersen et al. (2017)	Design routes to minimize the total operation time	Precedence relations between the driving lanes and the sidewalks and forbidding or penalizing U-turns
	Dong, Zhang, and Yang (2019)	Design routes to minimize deadhead distance	Heterogeneous capacity, fleet size, road-truck dependency, and road service frequency
Adaptive	Handa, Chapman, and Yao (2005)	Design routes to minimize the total cost	Predicted road temperature and condition
	Tagmouti, Gendreau, and Potvin (2011)	Design route to minimize the sum of service costs and travel costs	Time-dependent service costs
	Xu, Mahmassani, and Alfelor (2017)	Design routes to maximize benefit of plowing (travel time savings with and without plowing) and minimize deadhead	Predictive weather and traffic information

[1] Makespan is the completion time of the last job.

In terms of algorithms, about half of the reviewed papers used problem-specific constructive heuristics. This might be due to the faster computational time these algorithms provide. Given that the instances used in these studies are problem specific, it is difficult to compare the effectiveness and efficiency of the algorithms. The heuristic algorithm, by its nature, does not guarantee a global optimum (i.e., the best solution among all the alternatives). Instead, it can find a nearly optimal feasible solution much quicker than exact methods.

CHAPTER 4. AGENCY EXPERIENCE WITH ROUTE OPTIMIZATION

AGENCY INTERVIEWS

The FHWA Road Weather Management Program (RWMP) recently conducted interviews with five transportation agencies that have considered or are using route optimization. This includes three State DOTs and two local agencies, as shown in Figure 6.

© Map data 2021 Google. Shading, pins, and text added by FHWA to indicate surveyed agencies.

Figure 6. Locations of the five agencies interviewed (three State DOTs and two local agencies).

Interview questions focused on the state of the art, challenges, gaps, and opportunities to enhance adaptive route optimization capabilities. The agencies represent varied geographic locations, snowplow truck fleet sizes, and lane miles covered as noted in table 2.

Table 2. Agencies interviewed along with fleet size and lane miles.

Agency	Fleet Size (Trucks)	Lane Miles
Ohio DOT	1,700	43,000
Wisconsin DOT	755	35,000
North Dakota DOT	350	17,250
City of Pittsburgh, PA	110	2,400
City of West Des Moines, IA	16	8,000

Note: In Wisconsin, the fleet is owned by each county and is subsidized by the Wisconsin DOT.

The research team first contacted each agency via email to provide background information on the project and identify the most appropriate person or people in the agency to interview. A brief description of the project objective and interview questions were included in the email and are provided in the appendix. A 60-minute virtual meeting was scheduled for each interview. Interview questions covered three areas:

- Current operations and resources, available data, and performance goals.
- Experience with route optimization deployment.
- Needs and expectation for the adaptive route optimization system.

The agency responses are summarized below.

Q1: Tell us how you handle snowplow routing in your State/city.

Key findings: All agencies have a set of static routes; route optimization by combining State and county roads has resulted in significant improvements in efficiency.

All agencies have a set of static routes. Route adjustments are made pre-storm to account for staff being sick or late, equipment issues, etc. It is not uncommon for up to 10 percent of expected staff to be unavailable. During the storm, supervisors and operators might change material application rates and routes based on weather and road conditions. Most districts, counties, or zones operate independently and typically do not cross boundaries. The Wisconsin DOT does not own its own snowplows, so it compensates the counties to plow State roads. Three counties in Wisconsin conducted route optimization by combining State and county roads, which resulted in significant improvements in efficiency. However, keeping track of salt use by roadway requires counties to equip their trucks with equipment for location tracking—including automatic vehicle location (AVL) and GPS, material monitoring, and communications to transmit the information back to the office. Not all Wisconsin counties have this equipment, so the practice is not widely deployed. The Ohio DOT also looked at ways to remove district borders. Currently, when hit hard with snow, the agency has invisible boundaries. For example, if District 12 near Erie is struggling, District 3 will share its resources.

Maintenance decision support systems (MDSS) or similar services or products are used for treatment recommendations along with direct conversations with private weather service providers. Agencies are also considering opportunities to share roadway surface data with these services. For example, the City of West Des Moines has four mobile observation units mounted on snowplows to collect and transmit data on road surface state, friction, and temperature. The devices are currently used to capture road conditions on arterials and share this information with MDSS. The city also has a project, starting in winter 2021, to adjust material spreader rates on arterials based on MDSS application recommendations.

Q2: Do you consider winter storm forecasts as part of your routing plan?

Key findings: All five interviewed agencies manually adapt their snowplow routing based on input from their respective weather service providers, MDSS, or agency guidelines. Ohio DOT and Pittsburgh are not using MDSS. Ohio DOT has material guidelines, and their weather provider takes this information and builds it into treatment plan. The City of Pittsburgh uses a table for application rates based on best practices.

All five interviewed agencies work with a weather service provider to get storm forecasts, which support route planning. Although the routes are predetermined, the staffing, selection of routes, and treatment options are adjusted based on the weather forecast. For example, the Wisconsin DOT helped counties set up different routing scenarios using a route-optimization program that helps schedule staff and overnight crews. In particular, Milwaukee County has developed routing and equipment scenarios that describe everything from the deployment of a single truck to full fleet deployment based on graduated levels of winter storm impact. Scenarios are selected in response to weather, crew availability, and traffic conditions.

Q3: What happens when an incident occurs that hinders a snowplow from continuing on its planned route?

Key findings: Each agency noted that snowplow operators generally stay on their assigned routes. However, operators are typically on their own, and are encouraged to make safe, independent decisions when routing around unexpected issues. Agencies also schedule their work to apply materials or plow the roads ahead of peak-hour traffic or major shift changes at factories.

In Wisconsin, disruptions are handled through county management hubs, with some urban counties having preset alternative routing scenarios. The North Dakota DOT has one traffic coordinator during winter storms to support operator decisions given that there is currently no State traffic management center (TMC). The Ohio DOT relies on its TMC in Columbus to monitor traffic conditions and potential issues. TMC staff then communicate with snowplow supervisors, highway patrol, and local sheriffs when major issues impact winter operations. Dense urban areas tend to have more issues, so both the City of West Des Moines, IA, and the City of Pittsburgh, PA, mentioned empowering their operators to determine a safe path around obstacles and to use their judgement as to when communication with their supervisor is needed. Agencies also noted efforts to avoid peak-hour volumes, especially in urban settings. The Ohio DOT noted that it also tries to get materials applied ahead of shift changes at major factories. West Des Moines tries to clear its major arterials prior to 6 a.m. and before 4 p.m. to avoid delays in rush-hour traffic.

Q4: What communication methods or systems are used for rerouting?

Key findings: Among the agencies interviewed, two-way radios are the standard for communications with operators. The City of Pittsburgh is using in-cab, turn-by-turn guidance, while the City of West Des Moines, although interested in this technology, is not currently using it.

Two-way radio systems are used by each of the interviewed agencies for communication between supervisors and operators. Of the two agencies that have MDSS-equipped trucks, neither system's in-vehicle units include a display screen. The City of West Des Moines made a point to share that a new operator asked an important question: "When will we get to the point where we have turn-by-turn directions provided to us in the cab?" At that point, the city had tablets within the trucks but was not using them. The tablets resulted from an earlier effort by a company to optimize the city's routes. The city did not end up using the routing recommendations, but is open to future pursuits, including in-cab directions. The City of Pittsburgh uses in-cab, turn-by-turn directions to support operator routing and any rerouting when necessary. Getting its crews to accept this new technology was not automatic. The most effective approach was when supervisors helped each other understand the technology. Seasoned operators started to appreciate the in-cab guidance when working in unfamiliar areas of the city, with even a seasoned operator noting, "You know, this isn't too bad." Temporary and new drivers seem to appreciate the in-cab guidance, especially at night.

Q5: What options or barriers do your plow drivers have to reroute based on the configuration of the roadway?

Key findings: None of the agencies interviewed noted issues with rerouting trucks. The City of Pittsburgh already matches up its fleet with accommodating roadway widths given its narrow roads in residential areas and steep grades across the city.

No specific concerns were noted among the three State DOTs interviewed. They can use city or county roads for rerouting as needed. The City of Pittsburgh, however, is an older city with a variety of roadway widths and steep grades. Its winter operations strategy relies on a fleet of vehicles ranging from large, tandem-axle trucks to pickup trucks for the narrowest of roadways. The city noted that matching truck sizes to roadway widths would be a major consideration for any future ARO to be applied successfully.

Q6: What are the performance goals for your snowplow operations? Do you have level-of-service policies or procedures that govern winter operations at your agency?

Key findings: Agencies currently use, or are implementing, a variety of performance measures and goals for winter operations.

Agencies report using performance goals based on targeted pavement conditions, cycle time, and speed recovery, as shown in Table 3.

Table 3. Winter maintenance performance measures and goals by agency.

Agency	Performance Measure	Performance Goal
Ohio DOT	Speed recovery	Regain normal speeds within 2 hours after precipitation ends and wind speed drops below 15 mph
Wisconsin DOT	Cycle time	Maximum cycle time is 3 hours for State highways and 2.5 hours for interstates
North Dakota DOT	Speed recovery	Currently set at 85 percent normal speed
City of Pittsburgh, PA	Coverage	Reach every street segment, which can take 12 hours
City of West Des Moines, IA	Pavement conditions	Keep major arterials open all the time, that is, "mostly bare"

Pavement condition describes what the roads should look like after the snow and ice control operations are completed. For example, the City of West Des Moines has a snow manual that illustrates performance outcomes like “mostly bare” pavement on the arterials and “some snowpack” remaining on the residential roads.

Cycle time describes how frequently a road segment is serviced. For example, the Wisconsin DOT requires a maximum cycle time of 3 hours on State highways and 2.5 hours for interstates. They are also considering a minimum cycle time of 2 hours to allow the rock salt to melt.

The North Dakota DOT is implementing an automated-speed recovery performance measure based on data from sensors (loop and radar detectors). The system will use 16 sites (8 districts with 2 sensor sites per district), and North Dakota DOT is looking to add more sites over time. The Ohio DOT (ODOT) uses average speed as a performance measure based on third-party probe data sources. The agency’s goal is for drivers to regain normal speed within 2 hours after a storm. ODOT traffic management staff track this performance measure per storm.

Q7: What data do you currently collect for winter operations; for example, AVL (plow speed, idle times, application rates, and cycle times), RWIS, or traffic (speed, travel time)? Also, in your opinion, what datasets are necessary to deploy an adaptive snowplow routing system, and what additional datasets would be helpful?

Key findings: All five of the agencies interviewed collect AVL and GPS data.

Each of the agencies interviewed collect AVL and GPS data with partial- or full-fleet deployment. The three State DOTs and the City of West Des Moines also collect RWIS station data. The three State DOTs have traffic data available. The Wisconsin DOT AVL data includes truck speed, location, plow status, and application rates. They have not incorporated traffic data in the flow models for route optimization. The Wisconsin DOT route optimization model accounts for intersection delay by adding 30 seconds for stop signs, 60 seconds for traffic signals, 30 seconds for left turns, and 120 seconds for U-turns along a route. No cameras are installed on these trucks. The Ohio DOT has 1,700 trucks equipped with AVL and GPS capabilities.

To deploy ARO, integration of traffic data in urban areas and timely notification of incidents is necessary. These agencies suggested additional data might include mobile pavement sensors mounted on trucks to collect surface condition and pavement temperatures; traffic data, including live incidents, integrated into the route optimization system; and MDSS, if applicable, connected with ARO.

Q8: What is your experience with route optimization deployment? Which software tool do/did you use? How is/was the performance? Do you feel there are any drawbacks to the optimization software outputs and, if so, what?

Key findings: The five agencies have tried, or are working on, static route optimization with implementation remaining a challenge.

All five interviewed agencies have conducted static route optimization in recent years to various levels of implementation, as shown in Table 4. In general, this requires running the program and then making changes for practical maneuvers. This iterative process works well with static route optimization but won't be applicable for ARO. With ARO, routes need to be optimized automatically in real-time and communicated with turn-by-turn directions to the snowplow operator. Agencies that have tested or partially implemented static optimized routes have observed savings in fleet travel time. The static-route optimization program has also been used both to generate routes for different scenarios, which can be used adaptively based on storm and staffing conditions (Wisconsin DOT), and to determine garage locations (North Dakota DOT and Ohio DOT).

Table 4. Route optimization efforts by agency.

Agency	Implementation Status of Optimized Routes
Ohio DOT	Route development in progress
Wisconsin DOT	Partially implemented
North Dakota DOT	Routes developed but not implemented
City of Pittsburgh, PA	Routes developed with continued testing with crews
City of West Des Moines, IA	Routes developed but not implemented

Three reasons were given for not implementing the optimized routes:

- Practicality – For example, the City of West Des Moines felt the output from the route optimization software needed quite a bit of modification to account for local operational issues such as avoiding left turns so as not to leave a row of snow. Thus, the route-optimization effort provided some learning points but ultimately did not meet the city's needs.

- Impact – For example, the North Dakota DOT included both routes and garages in the route optimization project. In its optimization results, some small garages would be eliminated. The impact these closures might have in local rural areas was a big concern, especially at higher levels within the State, which prevented implementing the optimized plan. North Dakota DOT was able to use the optimization results for reworking some routes at district levels but did not mandate any change.

- Operator/supervisor resistance – All the agencies that have partially implemented or are in the process of implementing optimized routes have faced great pushback from crews, who have concerns for their jobs and safety. With less deadheading, static route optimization generally reduces the number of routes compared to the agency's current practice, so there is a potential to need fewer operators. Also, route guidance can be seen as a distraction, especially to seasoned drivers on familiar routes. If garage locations are also included in the optimization process (e.g., North Dakota DOT), it could also eliminate some garages.

Q9: How do you envision the following groups utilizing ARO? What user groups might benefit from ARO? For example, snowplow operators, maintenance supervisors and managers, TMC operators, emergency responders, and planners?

Key findings: Users most likely to benefit from ARO are operators and supervisors with improved route guidance helping to reduce driver workload and material use.

The Wisconsin DOT noted their route optimization project received a lot of positive feedback after drivers tried the new routes, but that it was difficult to initially convince drivers to try these new routes. If the State Patrol and TMC staff were supporting ARO, they might be able to relay impactful crash information to supervisors and drivers quicker for the road segments that are about to be plowed. State Patrol and TMC staff tried to feed AVL information to TMCs in the past, but the project was shut down due to the lack of mutual understanding regarding who leads winter operation activities.

The City of West Des Moines noted the importance of sharing the status of snowplow operations with the public and first responders so they can plan their work and emergency response routes. The city holds a pre-season meeting to reinforce the message that winter operations staff will support police, emergency medical services (EMS), and other emergency responders, but the winter operations staff are the authority in terms of route priorities and winter operations.

North Dakota commented that ARO could help operators adjust for weather and treatment options in addition to supporting supervisors to strategically move snowplow operators around.

The Ohio DOT felt ARO would be beneficial in coordinating winter operations with the TMC, turnpike authority, and local agencies.

None of the interviewed agencies discussed planners as a potential user group.

Q10: What changes, if any, would be needed to deploy ARO in your agency (e.g., procedures, policies, hiring, and training)?

Key finding: To deploy ARO, these state and local transportation agencies suggest having buy-in from management, leadership, and the legislature, as well as operators. Agency champions need to understand ARO to then successfully explain and promote change with the agency.

In terms of training, operators need to understand the benefits of ARO. One-on-one peer training has proven to be effective at improving acceptance, although it tends to be a slow process. It is best to identify a champion, preferably a respected peer, to explain and promote the new technology.

In terms of hiring, it is generally easier to make changes when new staff and new managers begin. In general, younger drivers are more adaptable to new technologies. Sometimes supervisors hired from outside who did not rise through the ranks can be more open to change. When promoting from within, it is best to consider people who have shown themselves willing to embrace new technologies.

CHAPTER 5. CONCLUSIONS

The technology scan, literature review, and early adopter interviews provide insight on gaps within the state of the practice, the issues faced by agencies, and challenges ahead in considering implementation of ARO for winter operations.

GAPS IN THE STATE OF PRACTICE AND EXISTING TOOLS

Current gaps in the ability to implement ARO are:

- Availability – There is a gap in the availability of tools to solve snowplow routing problems. There are more COTS tools available to solve node-based (pickup and delivery) routing problems than arc-based (road segment-based) snowplow solutions. This report describes seven node-based solutions in contrast to three solutions for snowplow routing. Although an ARP may be transformed to a node-routing problem and solved by these innovative COTS tools, it might be difficult to incorporate some problem-specific objectives and constraints unique to snowplow operations.

- Demand – There is a gap in the demand for route optimization solutions. The pickup and drop-off package industry applies ARO in real-time globally every day. These tools produce fast, efficient, and accurate optimized routes even in reaction to change (e.g., weather, roadway, equipment, staffing, consumer demands). By contrast, roadway authorities in the United States are not using ARO at all. In fact, it is unusual to find an agency that has implemented static route optimization for snowplow operations.

- Data – A gap exists between the data requirements for static versus dynamic (adaptive) route optimization. ARO requires identifying and connecting to live data feeds, which trigger route changes based on changed conditions. Once connected, agencies will need to consider what data and trigger points justify revising snowplow routing. For the system to be effective, it has to be in real-time because any latency in receiving dynamic data (e.g., crashes, closed roads) will prevent the system from recalculating new routes in a timely manner.

- Peer Examples – There is a gap in being able to point to peer agency experiences with either static or dynamic route optimization as applied to snowplow operations. In one example, the Colorado DOT Network Optimization framework did consider recurring problem areas due to weather and historic crash data, but incorporating these data sources requires custom software and a base routing network that supports snowplow operations with details including the number of lanes and crossover points.

- Research – There is a gap in the level of academic research focused on the snowplow routing problem. The ideal yet slower problem-independent algorithms (a common tool applied to many locations) cannot meet the computational time requirements of ARO. Using the alternative and much faster problem-specific algorithms requires building them based on an agency's specific winter maintenance goals and operational constraints. This will preclude applying a common tool among different agencies.

CHALLENGES FOR DEPLOYMENT

This list of ARO implementation challenges is the result of interviews with five agencies:

- Comprehension – ARO is a new, dynamic, technical solution. Agency staff need to understand ARO in terms of how it will work, and the data required to make it dynamic. They need to know how it complements existing efforts and how it could fundamentally change or improve operational strategies. Practitioners need to understand the benefits of ARO compared with static route optimization when it comes to meeting service goals and public expectations.

- Leadership – Gaining leadership support is always a challenge. Winter operations management staff need to be confident that the expected ARO benefits and costs are reasonable, sound, and not subject to constant change. They need to be able to communicate the concept and opportunities ARO provides. They also need to be able to assure leadership that they understand and are working through the coordination requirements for ARO, including sharing data among departments, with other agencies, or establishing computational support internally with information technology staff and resources.

- Supervisors and Operators – Agency staff need supporting information that conveys what ARO is, how it will be implemented, opportunities for feedback and modification, and how it helps meet agency goals. Supporting information specific to job security and a loss of autonomy will be required to manage frustration and prevent any loss of critical staff. In addition, ARO will be used by both seasonal, new, and experienced drivers. Each group will have different expectations for the system, so a design challenge will be to provide detailed guidance while allowing for some operator discretion. A successful implementation will require input from this group of winter maintenance professionals in terms of understanding local constraints, testing new routes to identify potential issues, training staff, developing policies, and completing new guidance.

- Real-Time Data – The value of ARO is that routes can be optimized based on dynamic data. Agencies will need support in finding, selecting, and accessing these dynamic data sources. Instead of every agency being on their own, guidance should be provided towards establishing national-level data sources that are always available, as is currently the case for the trucking industry (e.g., weather, traffic, slow-downs). In another example, flight-planning systems all use wind forecasts from the U.S. National Weather Service and U.K. Meteorological Office, updated every 1 to 6 hours, to access wind information for every flight plan calculation.

REFERENCES

Altus, S. 2009. "Effective Flight Plans Can Help Airlines Economize." *AERO, Special Issue on Operational Efficiency and Environmental Performance*, No. 5, Qtr. 03: 27–30.

Badger Maps. 2021. "The #1 Route Planner for Field Sales." https://www.badgermapping.com/. Last accessed September 1, 2021.

Bartolini, E., J.-F. Cordeau, and G. Laporte. 2013. "Improved Lower Bounds and Exact Algorithm for the Capacitated Arc Routing Problem." *Mathematical Programming*, 137: pp. 409–452.

Berthene, A. 2020. "Ecommerce Shipment Volume Surges While On-Time Deliveries Plummet." *Digital Commerce* 360, July 31. https://www.digitalcommerce360.com/2020/07/31/ecommerce-shipment-volume-surges-while-on-time-deliveries-plummet/.

Blandford, B., E. Lammers, and E. Green. 2018. "Snow and Ice Removal Route Optimization in Kentucky." *Transportation Research Record*, *2672* (45): pp. 294–304.

Brandão, J. and R. Eglese. 2008. "A Deterministic Tabu Search Algorithm for the Capacitated Arc Routing Problem." *Computers & Operations Research*, *35*(4): 1112–1126.

Bode, C. and S. Irnich S. 2012. "Cut-First Branch-and-Price-Second for the Capacitated Arc-Routing Problem." *Operations Research*, *60*(5): 1167–1182.

Cai, W.P., G. Liu, and W.S. Cao. 2009. "A Study of Vehicle and Materials Depot Location Problems for Winter Road Maintenance." *Proceedings of the 9th International Conference of Chinese Transportation Professionals, ICCTP 2009*, *Critical Issues in Transportation System Planning, Development, and Management*, *358*: pp. 1530–1535.

DispatchTrack. 2021. "Static vs Dynamic Routing: What's the Difference?" *DispatchTrack Blog*, February 1. https://www.dispatchtrack.com/blog/static-vs-dynamic-routing.

Dong, J., L. Zhang, and Y Yang. 2019. *Iowa DOT Office of Maintenance Snowplow Optimization.* Center for Transportation Research and Education, Institute for Transportation, Iowa State University, Ames, IA.

Dowds, Jonathan, James Sullivan, Darren Scott, and David C. Novak. 2013. *Optimization of Snow Removal in Vermont* (No. 2013-12). Vermont Agency of Transportation.

Dowds, Jonathan, James Sullivan, David C. Novak, and Darren Scott. 2016. *Identifying best practices for snowplow route optimization*. No. CR 14-07. Minnesota. Dept. of Transportation. Research Services & Library.

Dussault, B., B. Golden, C. Groer, and E. Wasil. 2013. “Plowing with Precedence: a Variant of the Windy Postman Problem.” *Computers and Operations Research*, *40*: 1047–1059.

Gundersen A.H., M. Johansen B.S. Kjær, H. Andersson, and M. Stålhane. 2017. “Arc Routing with Precedence Constraints: An Application to Snow Plowing Operations.” In: Bektaş T., Coniglio S., Martinez-Sykora A., Voß S. (eds) *Computational Logistics*. ICCL 2017.

Haghani A. and H. Qiao. 2001. “Decision Support System for Snow Emergency Vehicle Routing.” *Transportation Research Record*, *1771*: 172–178.

Haghani A. and H. Qiao. 2002. “Snow Emergency Vehicle Routing with Route Continuity Constraints.” *Transportation Research Record*. *1783*: 119–124

Hajibabai, L., S. Nourbakhsh, Y. Ouyang, and F. Peng. 2014. “Network Routing of Snowplow Trucks with Resource Replenishment and Plowing Priorities.” *Transportation Research Record*, *2440*: 16–25.

Hajibabai, L. and Y. Ouyang. 2016. “Dynamic Snow Plow Fleet Management under Uncertain Demand and Service Disruption.” *IEEE Transactions on Intelligent Transportation Systems*, *17*(9): 2574–2582.

Handa, H., L. Chapman, and X. Yao. 2005. “Dynamic Salting Route Optimization Using Evolutionary Computation.” In 2005 IEEE Congress on Evolutionary Computation. 1: 158–165.

Hill, D. 2021. “Dynamic Route Optimization: A ‘Must Have’ in Today’s Delivery Environment. Talking Logistics.” https://talkinglogistics.com/2021/02/18/dynamic-route-optimization-must-have-todays-delivery-environment/. Last accessed September 1, 2021.

Holland, C., J. Levis, R. Nuggehalli, B. Santilli, and J. Winters. 2017. “UPS Optimizes Delivery Routes.” *Interfaces*, *47*(1): 8-23. https://doi.org/10.1287/inte.2016.0875

Jang W., J.S. Noble, and T. Hutsel. 2010. “An Integrated Model to Solve the Winter Asset and Road Maintenance Problem.” *IIE Transactions*, *42*: 675–89.

Kinable, J., W.-J. van Hoeve, and S.F. Smith. 2016. “Optimization Models for a Real-World Snow Plow Routing Problem.” *Proceedings of Integration of AI and OR Techniques in Constraint Programming: 13th International Conference*, CPAIOR 2016, Banff, AB, Canada, 29 May – 1 June 2016. Edited by C.-G. Quimper. Springer International Publishing Cham. pp. 229–245.

Liu G., Y. Ge, T.Z. Qiu, and H.R. Soleyymani. 2014. “Optimization of Snow Plowing Cost and Time in an Urban Environment: A Case Study for the City of Edmonton.” *Canadian Journal of Civil Engineering*, *41*(7): 667–675.

Lystlund, L. and S. Wohlk. 2012. “The service-time restricted capacitated arc routing problem.” Centre of OR Applications in Logistics, Aarhus School of Business, Aarhus University, ˚Arhus, Denmark. https://pure.au.dk/portal/files/35929389/Lystlund_Woelk_Service_Time.pdf, accessed August 1, 2021.

Martinelli, R., M. Poggi, and A. Subramanian. 2011. “Improved Bounds for Large Scale Capacitated Arc Routing Problem.” *Math. Program, Ser. A*, *137*: 409–452

Mei, Y., K. Tang, and X. Yao. 2009. “A Global Repair Operator for Capacitated Arc Routing Problem. *IEEE Transactions on Systems, Man and Cybernetics*, *39*(3): 723–34.

Muyldermans, L., D. Cattrysse, D.V. Oudheusden, and T. Lotan. 2002. “Districting for Salt Spreading Operations.” *European Journal of Operational Research*, *139*(3): 521–532.

Muyldermans, L., D. Cattrysse, and D.V. Oudheusden. 2003. “District Design for Arc-Routing Applications.” *Journal of Operational Research Society 54*: 1209–1221.

Omer M., 2007. “Efficient Routing of Snow Removal Vehicles.” Master Dissertation. College of Engineering and Mineral Resources, West Virginia University.

Perrier, N., A. Langevin, and C.A. Amaya. 2008. “Vehicle Routing for Urban Snowplow Operations.” *Transportation Science*, *42*: 44–56.

Quirion-Blais, O., A. Langevin, and M. Trepanier. 2017. “A Case Study of Combined Winter Road Snow Plowing and De-Icer Spreading.” *Canadian Journal of Civil Engineering*, *44*(12): 1005–1013.

Salazar-Aguilar, M.A., A. Langevin, and G. Laporte. 2012. “Synchronized arc routing for Snow Plowing Operations.” *Computers and Operations Research*, *39*(7): 1432–1440.

Tagmouti M., M. Gendreau, J.-Y. Potvin. 2007. “Arc Routing Problems with Time-Dependent Service Costs.” *European Journal of Operational Research*, *181*(1): 30–39.

Tagmouti M., M. Gendreau, J.-Y. Potvin. 2010. “A Variable Neighborhood Descent Heuristic for Arc Routing Problems with Time-Dependent Service Costs.” *Computers and Industrial Engineering*, *59*: 954–963.

Tagmouti M., M. Gendreau, J.-Y. Potvin. 2011. “A Dynamic Capacitated Arc Routing Problem with Time-Dependent Service Costs.” *Transportation Research Part C, Emerging Technologies*, *19*: 20–28.

Walsh, C. 2018. Colorado Department of Transportation – Network Optimization and Thermal Mapping Project. Colorado Department of Transportation.

Xu, X., H.S. Mahmassani, Z. Hong, and R.M. Alfelor. 2017. “Dynamic Predictive Strategies for Urban Snowplow Routing.” Presented to the Transportation Research Board 96th Annual Meeting, Washington DC.

Ziobro, P. 2020. “UPS Rides E-Commerce Surge to 21% Jump in Package Volumes: Delivery Giant’s New Boss Sees Room to Raise Rates on Retailers Amid Coronavirus-Related Surge in Shipments.” *The Wall Street Journal*, updated July 30. https://www.wsj.com/articles/ups-rides-e-commerce-surge-to-21-jump-in-package-volumes-11596105832.

APPENDIX

Inquiry Letter to State DOTs and Local Agencies Requesting an Interview with FHWA

In collaboration with FHWA, we are conducting a study on Adaptive Route Optimization (ARO, pronounced "arrow") for snowplow operations. The project is funded by FHWA and will create foundational systems engineering documentation (concept of operations and systems requirements) for developing an adaptive snowplow routing optimization solution for maintenance and operations personnel to use during adverse winter weather. We would like to schedule a 60-minute interview to discuss your agency's experience with current routing practices, route optimization, and any other insights you may have on ARO. Here is a list of topics that we will discuss:

1. Tell us how you handle snowplow routing in your State/city.
2. Do you consider winter storm forecasts as part of your routing plan?
3. What happens when an incident occurs that hinders a snowplow from continuing on their planned route?
4. What communication methods or systems are used for re-routing?
5. What options or barriers do your plow drivers have to re-route based on the configuration of the roadway?
6. What are the performance goals for your snowplow operations? Do you have levels of service policies or procedures that govern winter operations at your agency?
7. What data do you currently collect for winter operations, e.g. AVL (plow speed, idle times, application rates, and cycle times), RWIS, traffic (speed, travel time)? In your opinion, what datasets are necessary to deploy an adaptive snowplow routing system and what additional datasets would be helpful?
8. What is your experience with route optimization deployment? Which software tool do/did you use? How is/was the performance? Do you feel there are any drawbacks to the optimization software outputs, if so what?
9. How do you envision the following groups utilizing ARO? Provide an example of a decision that ARO should be able to assist in making for the following user groups. Possible answers: snowplow operators, maintenance supervisors and management, TMC operators, emergency responders, planners.
10. What, if any, changes would be needed to deploy ARO in your agency (e.g. procedure, policy, hiring and training)?

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Office of Operations website
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Month Year
FHWA-HOP-21-098