Adaptive Route Optimization for Operations: Feasibility and Readiness Report

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16. Abstract Adaptive route optimization (ARO) is a method of dynamically and effectively routing winter maintenance vehicles across all segments of a road network to meet an agency's maintenance goals, subject to real-time disruptions from atmospheric and road weather conditions, traffic congestion, incidents, work zones, and resource constraints. ARO could enable agencies to respond more quickly and efficiently to changing storm conditions, resource constraints, and service expectations than is possible with current routing systems. ARO has the potential to restore pavement conditions faster, reducing weather-related risk and improving mobility. State departments of transportation 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. Given these costs, even minor improvements to snowplow routing can produce savings through reduced staff time, material use, and equipment hours. This report describes readiness for developing ARO capabilities for winter maintenance operations in terms of technical, market, financial, and institutional feasibility and considerations for prototype demonstration and potential national rollout.		
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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 yards	0.836	square meters	m^2
ac	Acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		Volume (volumes greater than 1,000L shall be shown in m^3)		
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
		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/m^2	0.2919	foot-Lamberts	fl
		Force and Pressure or Stress		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009.)

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
API	application programming interface
ARO	adaptive route optimization
ARP	arc-routing problem
AVL	automated vehicle location
ConOps	concept of operations
DOT	department of transportation
FHWA	Federal Highway Administration
GIS	geographic information system
ITS	intelligent transportation system
MDODE	Managing Disruptions to Operations Data Exchange
RWIS	road weather information system
SyRS	system requirements specification
TMC	traffic management center
VRP	vehicle routing problems

CHAPTER 1. INTRODUCTION

State departments of transportation (DOTs) spend over $2 billion per year on snow and ice control, and they allocate over $5 billion annually for repairs related to snow and ice operations, chemical use, and wear. Winter maintenance operations can incur significant expenses, so any improvements in snowplow route efficiency can yield considerable savings.

Adaptive route optimization (ARO) uses dynamic routing tools to find the most efficient winter maintenance routes considering road conditions and resource constraints. These conditions and constraints could include real-time route disruptions such as traffic congestion, incidents, and work zones, changing weather forecasts and conditions, and shortages of drivers, trucks, or materials.

ARO integrates agency level-of-service goals, route and segment priorities, cycle time expectations, and forecasted roadway conditions into its route optimization process. The optimized set of routes can account for practical constraints specific to snowplowing operations, such as access to fuel and material depots, turnarounds, U-turns, clearing snow within intersections, and driver deadheading. The more effective routing can provide benefits for agencies and the public. It restores driving conditions more quickly, reduces the amount of time that agency staff spend working in hazardous conditions, thus lowering risk, and results in decreased costs per storm event by adapting route priorities to actual resource, roadway, and weather conditions.

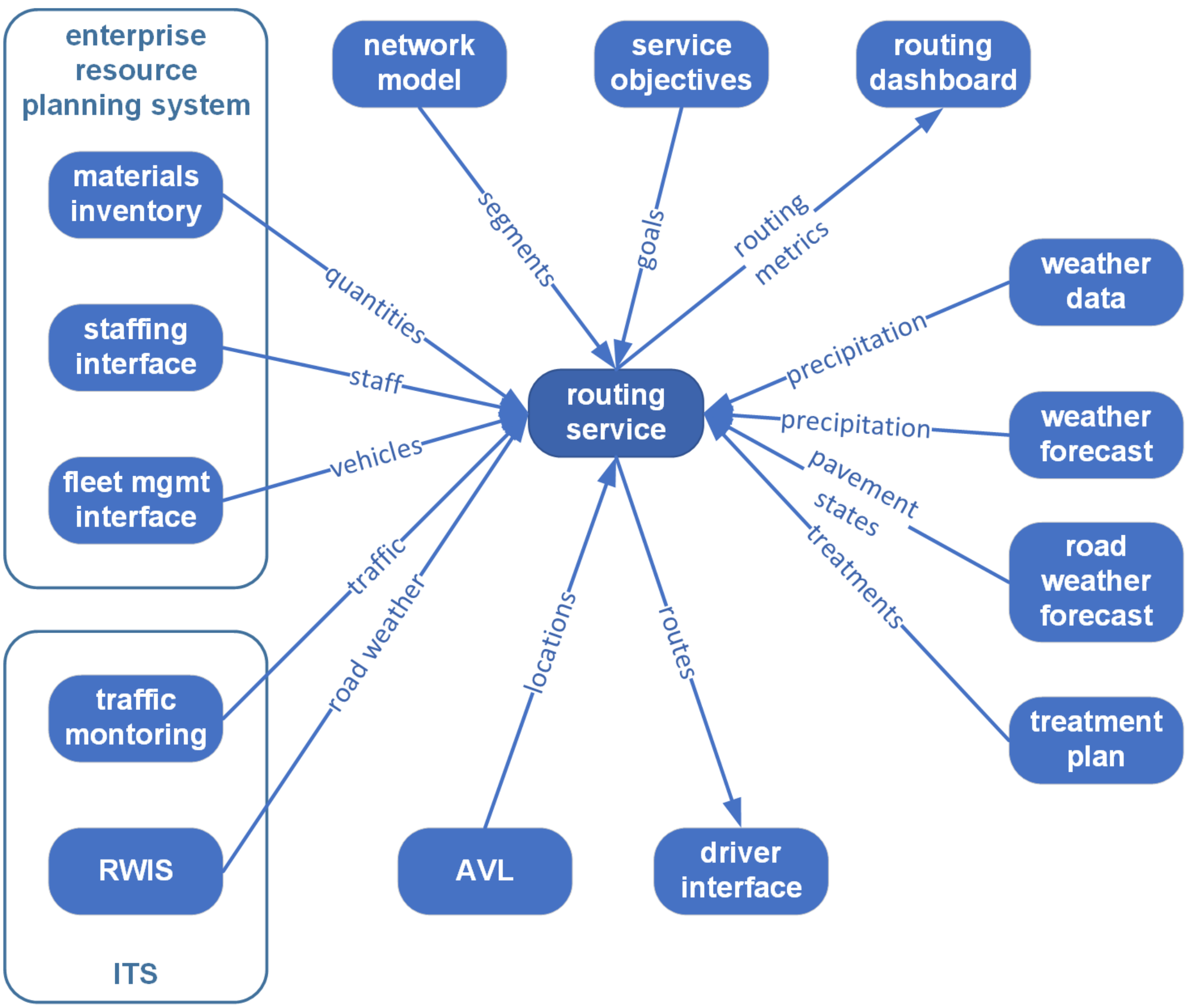
BACKGROUND

Winter storms create challenging driving conditions across large areas of a road network. State and local transportation agencies work together within their jurisdictions to preserve safety and mobility across the network during and after the storms. Their routes, planning, and activities are typically based on winter maintenance technologies and practices that have matured over decades of development and operating experience. ARO can update routes to match the forecasted storm characteristics and available resources across the road network.

Winter maintenance processes start with setting maintenance objectives before the season. Agencies estimate, acquire, and allocate human, capital, and material resource needs (e.g., drivers, equipment, and materials) for maintenance facilities across the area of service for the coming winter season. ARO can provide preseason route recommendations based on the maintenance objectives and resource plans for typical storm conditions. As the season starts, agencies monitor weather conditions for approaching storms. ARO can develop prestorm and real-time route recommendations tailored to weather, pavement, and traffic conditions based on service-level priorities and the timing and severity of the storm.

Agencies that adopt ARO can develop routing plans that make the most efficient use of staff time, materials, and equipment. The ARO capability could consider level-of-service goals, route and segment priorities, cycle time expectations, and current and forecasted roadway conditions in route optimization. ARO capabilities, strategies, and technologies could incorporate real-time and historic data in a snowplow routing solution for maintenance and operations to use during adverse winter weather. The solution could support a strategic view of maintenance planning and a tactical view of real-time operations. Dashboards could be provided for users, such as managers, maintenance supervisors, and drivers.

ARO capabilities could address near-real-time conditions including atmospheric weather, road weather, incidents, work zones, and traffic volume (or demand). Forecasted conditions to be considered could, at a minimum, include atmospheric weather and road weather conditions. Incorporating traffic and operational predictions could improve optimizations for cycle time, staff utilization, and priority locations with time-of-day traffic demand and congestion. Routes could further consider historical crash data, traffic bottlenecks, problematic road geometries, and known weather-related recurring problem areas for their routing risk implications. Routing could consider constraints specific to snowplowing operations, such as access to fuel and material depots, difficult maneuvers, turnarounds, U-turns, intersection snow clearance, and driver deadheading. Figure 1 illustrates interfaces and data flows supporting the ARO capability.



AVL = automated vehicle location; ITS = intelligent transportation system; mgmt = management; RWIS = road weather information system.

Source: FHWA.

Figure 1. Diagram. Interfaces and data flows for adaptive route optimization.

The ARO capability could enable DOTs to better respond to changing winter weather events and associated congestion. Scenarios in which ARO could improve agency responses include, for example:

- Storms hitting some areas with more snow than other areas in the same region or State. Optimizing snowplow routes with reallocation of plowing resources among maintenance sheds and regions could improve the overall recovery.
- Staff and equipment availability changing before and during a storm. Adaptively optimizing routes to compensate for resource unavailability could reduce effects on recovery time.
- Severe storm conditions increasing the likelihood of crashes. Tactically reoptimizing snowplow routes around active incident sites and the resulting congestion could improve cycle times and safety of operations.

A successful ARO deployment could lead to faster restoration of clear pavement, safer roadway conditions for the traveling public, and improved mobility under winter driving conditions. An ARO capability uses more complete and timely views of operations and winter maintenance activities across the road network than static route plans provide. ARO deployment could improve awareness within and across the transportation agency and could enable timelier and more effective communications with the public.

Within an agency's operations, ARO could improve utilization of human and equipment resources in winter operations. The improved routing could reduce the total route miles and deadheading, which in turn could improve snowplow operator satisfaction and morale with the use of their work hours. Better knowledge of and planning for storm conditions and routing could result in using less treatment materials and reduced environmental effects than on nonoptimized routes in the absence of a decision support system.

FUNCTIONAL AND INTERFACE NEEDS FOR ADAPTIVE ROUTE OPTIMIZATION

The concept of operations[1] (ConOps) and system requirements specification[2] (SyRS) for ARO provide descriptions of a future ARO capability. Descriptions of system components such as the routing service, plow truck, and driver interface and their interactions are foundational to analyzing potential costs and value of ARO for broad operational use. The ConOps provides context for assessing potential deployments and use cases relative to current and future transportation agency practices with ARO. The SyRS describes the intended ARO capabilities as a basis for further evaluation of existing systems and future research. Needs for the ARO capability, summarized in table 1, are identified in the ConOps and further developed in the SyRS.

[1]Garrett, K., N. Hawkins, J. Dong, and R. Schaefer. 2021. *Adaptive Route Optimization for Operations – Concept of Operations*. Report No. FHWA-HOP-22-004. Washington, DC: FHWA.

[2]Garrett, K., N. Hawkins, J. Dong, and R. Schaefer. 2022. *Adaptive Route Optimization for Operations—System Requirements Specification*. Report No. FHWA-HOP-22-029. Washington, DC: FHWA.

Table 1. Adaptive route optimization system needs.

The System Needs a Means of	• Communicating between the traffic management center (or traffic operations center) and the maintenance vehicle. • Presenting route information to the maintenance vehicle driver (e.g., via a driver interface) in near-realtime. • Specifying maintenance operations objectives. • Specifying maintenance resources (e.g., vehicles, drivers, material and fuel depots, and materials). • Specifying the extent of the road network over which routing will be performed.
The System Needs Sources of	• Atmospheric weather condition forecasts (e.g., precipitation type and rates; temperature). • Atmospheric weather condition information. • Historic operations data (e.g., crash data; recurring problem areas). • Road weather condition forecasts (e.g., pavement status and temperature; friction). • Road weather condition information. • Traffic condition information. • Maintenance vehicle geoposition information.
The System Needs to	• Assess road weather conditions (e.g., pavement status, pavement temperature, and friction). • Enable maintenance managers to allocate maintenance resources (e.g., vehicles, drivers, material and fuel depots, and materials) for State, county, and municipal agencies to and among agency districts, and within districts to and among maintenance sheds or depots. • Enable maintenance managers to set maintenance operations objectives (e.g., level of service; cycle time). • Monitor atmospheric weather conditions (e.g., precipitation type and rates; temperature). • Monitor maintenance vehicles in route (i.e., to receive telematics data, such as latitude and longitude, from those vehicles). • Monitor traffic conditions (e.g., incidents, work zones, closures, traffic speeds and volumes). • Optimize routes based on changing resource availability. • Optimize routes based on resources, atmospheric weather conditions, road weather conditions, and traffic conditions. • Optimize routes to changing atmospheric and road weather conditions. • Optimize routes to changing traffic conditions (e.g., incidents, work zones, closures, traffic speeds and volumes). • Provide optimized routes to vehicle drivers in near-realtime. • Accommodate and recover from intermittent communication outages between vehicles and the system.

DOCUMENT PURPOSE AND OVERVIEW

The purpose of this document is to describe the feasibility of developing and the readiness of deploying ARO, as described in the ConOps, for an agency that performs winter maintenance and operations. Assessing ARO feasibility and readiness is based on analysis of the state of technology and agency operations relative to the needs identified in the ConOps and SyRS, and discussions with stakeholders.

CHAPTER 2. TECHNICAL FEASIBILITY AND READINESS

Development and deployment of ARO capabilities could create new opportunities for agencies to improve their winter maintenance operations. It could also create new ways of performing and facilitating winter maintenance. This section describes and assesses the technical (i.e., functional) aspects of ARO development and deployment relative to current agency environments and practices in terms of agency operations, data, and systems.

AGENCY OPERATIONS

In general, winter maintenance processes follow consistent patterns across most transportation agencies. Some agencies have advanced in almost all ways the practices described in the American Association of State Highway and Transportation Officials' (AASHTO's) 1999 *Guide for Snow and Ice Control*.[3] The National Cooperative Highway Research Program's *Guide for Snow and Ice Control Operations Final Report*[4] discusses expansion of the 1999 guide, such as levels of service, prewinter preparations, personnel, equipment, materials, and technologies.

Static snowplow route plans are typically seen as default bases for winter maintenance planning and operations. ARO adds adaptive routing to the toolkit for actively managing winter maintenance operations. Routes can be adjusted with ARO in the same way that equipment and driver assignments or material application rates may be changed to meet service goals for a particular storm. ARO creates opportunities for responding more flexibly to changing objectives and conditions.

Currently, most agencies interviewed for this assessment use a fixed set of route plans that are generally not revised unless roadways are changed or added to the network, equipment is changed and affects their route assignments, or equipment and material storage locations are changed. Route changes during a weather event are typically managed through communications with supervisors, and some of these route plans may include contingencies for drivers and equipment being unavailable. Agencies have sometimes revised route plans looking for better levels of service, particularly when weather conditions and disruptions to operations may change routes from the plans.

Agencies' search for improved service levels suggests a potential interest in ARO. ARO can enable agencies to move beyond previous routing practices as quickly as they are willing and able to implement process, data, and systems changes. ARO capabilities can support an incremental approach to route optimization as the associated agency data and systems become available for improved integration and real-time adaptive application.

AGENCY DATA

A variety of data are needed to support ARO. This section describes the types, interfaces, availability, and other attributes of data needed to build ARO capabilities. Data types include

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[3]AASHTO. 1999. *Guide for Snow and Ice Control*. Washington, DC: AASHTO.

[4]Haberman, J. A., W. Holik, W. Hwang, S. Das, E. Rista, and D. Clonch. 2022. *Guide for Snow and Ice Control Operations Final Report*. Washington, DC: The National Academies Press.

performance measures, maps, resources, treatment plans, vehicle location, and traffic data. Use of standardized interfaces for these data types could reduce the complexity and cost of developing and deploying ARO capabilities.

Maintenance and level-of-service objectives often function as optimization criteria in ARO. As such, corresponding winter maintenance and level-of-service performance measures are important for ARO. Workable route optimizations should reflect achievable levels of service across the entire service area and all road classifications.

Accurate, current maps are important for ARO technological readiness. Although map data for routing are generally available, they may not be integrated into any one database. For example, maps of road centerlines generally exist in geographic information systems (GISs), but other road attributes for snowplow routing might be captured in a decision support system. These maps need to be routable for winter maintenance operations, including maneuvers for snowplows and identify challenging locations such as shading, traffic bottlenecks, and railroad crossings. Maps created for navigation generally do not include some features relevant to snowplow operations and routing, such as type of plow equipment needed, locations of bridge joints and rails over which an operator might need to raise the plow blade, numbers of lanes and lane widths, and radii of curbing at intersections.

Data on maintenance staff availability, equipment, and material resources are important for ARO capabilities. While most agencies have asset and resource management databases, they may not be integrated and accessible from other agency systems and may not provide real-time inventories.

Treatment plans need to be specified across the network for use in ARO computations. Most agencies have specific treatment plans based on precipitation rates and pavement temperatures. Agencies using a decision support system are likely to have segment-specific treatment plan data and are likely to benefit from making the plans available for use in ARO.

Real-time ARO needs snowplow location data, which an automated vehicle location (AVL) system typically provides. Agencies with AVL systems typically have the location data, with varying degrees of latency. Rural areas may have communication blank spots where vehicle location data become unavailable or delayed until communications are restored, although satellite-based communication systems provide more ubiquitous service than cellular systems. An ARO capability would need interfaces to the location data from the AVL service.

Real-time ARO needs information about traffic and incident conditions to clear emergency response paths to the incident or route snowplows around congestion. An advanced transportation management system in which operators have verified and accurately located the events would typically provide the traffic data.

AGENCY SYSTEMS

Agencies typically use a fixed set of static routes throughout their winter maintenance seasons. Agencies update the fixed routes when there are updates to the road network model, such as the number of lanes on segments, intersection configurations, recurring problem areas, or maintenance facility or materials storage locations. ARO computes new routes for those road networks and other changes using data from other agency systems, such as AVL, decision support, asset management, and advanced transportation management systems. An agency deploying ARO would need computing infrastructure, applications, third-party services, or all of these, to provide data to support an ARO capability.

Real-time ARO capability needs to be able to provide navigational instructions to snowplow drivers. Currently, the majority of agency snowplow vehicles rely on voice radio communications among drivers and supervisors for situational awareness, with only a minority of snowplows having incab data communications and graphical interfaces that might be used for navigational routing updates. Onboard systems for ARO could provide turn-by-turn voice navigational instructions and just-in-time hazard avoidance alerts or maps showing current locations, intended routes, and alerts depending on agency constraints on the incab systems and interfaces.

There are also challenges for communications among data systems and between services and field user interfaces. Voice and data communications may be spotty, especially in rural areas, but also potentially on urban roads flanked by tall buildings. Agencies may not have data communications on snowplow vehicles, or they may have insufficient bandwidth for sending camera images from field locations or maps back to vehicles. The trend is generally for communication deserts to fill in over time, but typically at lower bandwidths than high-traffic areas, creating potential challenges for the real-time communication needed to implement ARO.

TECHNICAL READINESS SUMMARY

Current agency winter operations practices vary widely, but all are based on having a set of routing plans determined before the start of the winter maintenance season. ARO can enable an agency's routing plans to change in response to conditions but needs data from many other systems to produce the adaptive route results. Most of the data are available for agencies with mature winter maintenance operations, although not yet integrated to support ARO capabilities:

- Route priorities and level-of-service performance objectives are set as part of the route plans and are implicitly available in most agencies.
- Map data needed are widely available; these data may need to be supplemented with additional information specific to snowplow routing to be sufficient for ARO.
- Resource management data for staff, equipment, and materials needed to support ARO are available in most agencies.
- Treatment plans range from static recommendations to sophisticated decision-support system deployments, with most agencies allowing snowplow operator discretion.
- AVL data including treatment and plowing status are available in some agencies.
- Pavement condition data are available to agencies with road weather information system deployments and mobile sensors, although coverage of the road network may not be continuous.

- Real-time operational data on traffic conditions and incidents are available in most agencies, although not necessarily on all roads.
- Communications and in-vehicle systems to support ARO deployment into maintenance vehicles are available in a minority of agencies.
- Integration of data across agency systems is challenging but doable.

ARO development and deployment is technically feasible for agencies with mature processes and data systems. Table 2 summarizes the relative readiness factors. The challenges to potential deployment are primarily in integrating data from multiple sources within the agency on time scales consistent with seasonal, storm-based, and real-time ARO optimizations. The datasets needed for ARO feasibility typically have other applications within agency operations and maintenance, reducing potential technical barriers to readiness and providing some economic benefit to cultivating, storing, and processing the needed datasets.

Table 2. Technical relative readiness.

	Relative Readiness		
Technical Factor	**Basic**	**Developing**	**Mature**
Established level-of-service goals	Common for all roads	Prioritized	Prioritized with operational goals
Map and network data	Routable road level	Lane level	With turnarounds and other details
Resource management: staffing	Historic	Prestorm by service area	Near-realtime, agencywide
Resource management: equipment	Historic	Prestorm by service area	Near-realtime, agencywide
Resource management: materials	Historic	Prestorm by service area	Near-realtime, agencywide
Treatment plans	Static	Based on conditions	Decision support system
Automated vehicle location data	None	Location only	Location plus plow plus spreader

Table 2. Technical relative readiness. (continuation)

Technical Factor	Relative Readiness		
	Basic	**Developing**	**Mature**
Traffic and incident data	Public websites	Agency traveler information and advanced transportation management system	Agency near-realtime data portal
Routing plans	Static	Modified prestorm	Adaptive near-realtime
Incab support	Driver/supervisor radio only	Radio plus incab display	Incab interactive
Data integration	Independent data systems	Some integration for winter operations	Integrated data portal

CHAPTER 3. MARKET FEASIBILITY AND READINESS

Market feasibility and readiness describe the availability and fit of solutions with the deploying agency's needs for ARO capabilities. This section assesses the market aspects of ARO development and potential deployment relative to product and service availability, agency demand for those services, and their fit with other agency systems needed for complete ARO deployments.

ROUTE OPTIMIZATION PRODUCTS AND SERVICES

Most existing route optimization software packages are designed to solve vehicle routing problems (VRP) with the goal of finding optimal routes for multiple vehicles that are visiting a set of locations. Because the objective of ARO is to find optimal routes for winter maintenance vehicles to traverse a network of arcs, it is considered an arc-routing problem (ARP). An ARP can be converted to a VRP by creating locations on arcs that the vehicles need to visit.[5] This conversion allows the use of established VRP algorithms and methodologies developed for solving routing and logistics optimization problems.

Some route optimization software packages include algorithms specifically designed to solve ARPs. But none of the available commercial-off-the-shelf software packages can account for all constraints specific to winter maintenance operations. Thus, current practice in snowplow route optimization usually involves iteratively adjusting optimized routes to meet operational considerations. This process hinders the application of commercial-off-the-shelf route optimization algorithms in realtime. Some agencies use customized software services to optimize their snowplow routes. Because these route optimization algorithms are specifically developed for winter maintenance operations, they might be suitable for ARO, although current applications seem to be limited to static route optimization.

Advances have been made to solve dynamic ARPs in the context of winter maintenance operations,[6] some of which have produced open-source software.[7] However, the project team is unaware of any implementation of these algorithms for ARO in the United States. In Sweden, Arvidsson, Bäckström, and Wärme implemented a dynamic route optimization program to determine routes for preventative salting based on forecasted road weather conditions. The authors found a 15–25 percent cost reduction over a whole season compared with the static routing practice.[8]

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[5]Blandford, B., E. Lammers, and E. Green. 2018. "Snow and Ice Removal Route Optimization in Kentucky." *Transportation Research Record* 2672, no. 45: 294–304.

[6]Fröhlich, G. E. A., M. Gansterer, and K. F. Doerner. 2023. "A Rolling Horizon Framework for the Time-Dependent Multi-Visit Dynamic Safe Street Snow Plowing Problem." *Networks* 83, no. 2: 236–255.

[7]Tong, H., L. Minku, S. Menzel, B. Sendhoff, and X. Yao. 2023. "A Novel Generalized Metaheuristic Framework for Dynamic Capacitated Arc Routing Problems." In *GECCO '23 Companion: Proceedings of the Companion Conference on Genetic and Evolutionary Computation* 45–46.

[8]Arvidsson, A. K., A. Bäckström, and M. Wärme. 2019. "Dynamic Forecast Controlled Winter Road Maintenance." In *26th World Road Congress 2019*. Abu Dhabi, UAE: World Road Association (AIPCR/PIARC).

AGENCY INTEREST

There appears to be both demand and need within the transportation agency community for snowplow and maintenance vehicle routing solutions, though need and demand vary among State and local agencies and their areas of operation. This research interviewed 14 State and local agencies to gauge their general interest and perceived challenges in deploying ARO capabilities. The research found that interest seems to be higher for agencies dealing with network complexity, resource management challenges, and storm variability.

While agencies generally adapt as needed during events with supervisors tracking and reallocating resources, some agencies have routing contingency plans for limited resource operations, even to the level of specific numbers of vehicles and drivers being available. One agency described using different routing plans depending on how many drivers were available in a shift, down to as few as 25 percent. Other agencies described varying their resource allocations on routes based on snow intensity. These real-time adaptations typically reflect resource reallocation or route reprioritization rather than dynamically altering the planned routes, and generally ensure priority routes are fulfilled before limited resources are shifted to lower priorities.

Agency interest in ARO seems to parallel interest in winter maintenance performance assessment and optimization efforts where one or more service goals drive optimization. Agencies that actively assess their maintenance performance can have a heightened interest in improving that performance. One agency that tracks winter maintenance performance provided supervisors and drivers with a comparison between expected results when drivers followed the planned routes and treatment recommendations and the actual results from their routes. ARO can provide both methods and measures for enhanced performance assessment.

Agencies have expressed a variety of opinions on the frequency of optimization. Some have reoptimized their routing when service areas and facilities have opened, combined, or closed, and a few revisit their routing regularly. One agency has a staff route planner who provides updated route maps to the counties at their request. At least half of the 14 interviewed agencies could envision reassessing routes on a seasonal basis if a cost effective tool were available, and some shared that they saw value in prestorm route optimization to address storm characteristics and resource availability.

Interviews with the agencies revealed that many agencies understood the real-time ARO concept and were guardedly optimistic of being able to route around events as the events occur while being concerned that real-time ARO applications would be too complex to configure and difficult to implement in practice. Table 3 lists some of the agency-perceived challenges and questions about ARO.

Table 3. Agency-perceived challenges, questions, and concerns.

Agency	Technical Challenges	Institutional Challenges	Questions and Concerns
A	-	Effects of optimization on potentially reduced equipment	Potential issues with deadhead and turnaround locations
B	-	Adoption by maintenance districts, not just a statewide mandate	Using ARO to assess road prioritization
C	Lack of local knowledge in technology tools; issues with connectivity	Labor agreements	Safety concern in drivers interacting with complex tools; diversion of driver attention to the tools
D	-	Need for and effects of training	Preference for tools that support drivers but are not prescriptive; supportive of tools for supervisors
E	Integrating data across systems	Difficulty of culture change; labor agreements; overlapping jurisdictions	Benefits of what-if analysis; labor shifts and overtime as optimization constraints
F	Uneven communications	-	-
G	Spotty communications, especially in rural areas	Legacy routes and route knowledge	Using friction as a level-of-service indicator
H	-	-	Have their own routing tool but would be interested in additional integrated support
I	-	Skeptical of ARO as a concept	-
J	Knowledge of local road features (e.g., curbs and medians)	-	Have developed some incab capabilities for route guidance and monitoring

ARO = adaptive route optimization; AVL = automated vehicle location; - = no entry.

Table 3. Agency-perceived challenges, questions, and concerns. (continuation)

Agency	Technical Challenges	Institutional Challenges	Questions and Concerns
K	-	-	Might be more useful in urban than rural areas
L	Incab turn-by-turn routing may not be effective	-	-
M	-	-	Tried a commercial routing product but developed their own route solution
N	-	-	Interested; currently evaluating application of sanitation route optimization methods

ARO = adaptive route optimization. AVL = automated vehicle location. - = no entry.

INDUSTRY INTEREST

Although this research has not identified any commercial providers of real-time ARO capabilities or services for winter maintenance, discussions with technology companies have identified related capabilities and solutions that are available for integration. The research conducted conversations with five technology companies that are representative of industry capabilities. The interviews revealed broad support for data and analysis tools, as summarized in table 4, that could support an integrated ARO capability.

Table 4. Selected companies and their core technology offerings.

Technology	Company A	Company B	Company C	Company D	Company E
Geographical information systems	-	-	✓	✓	-
Automated vehicle location and telematics	✓	✓	-	-	-
Fleet management	✓	✓	-	-	-
Routing	-	-	✓	✓	✓
Data analytics	✓	✓	✓	✓	✓

✓ = technology offered; - = not specified.

Geographical information underlies all ARO capabilities. GISs provide databases, tools, and interfaces for managing and viewing the data on maps or through an application programming interface (API) for use in other systems. The interviewed companies provide extensive GIS capabilities, and other open-source GIS provide similar data and solutions. Agency candidates for ARO deployment should have GIS with which ARO capabilities can integrate.

AVL capabilities are needed for real-time ARO and are offered as services to agencies and companies for tracking their vehicle fleets. Data from the AVL solutions may include telematics data from the vehicle systems, including plow and spreader data for snowplows. The data may be available through an API, as was the case with two providers interviewed for this research. Fleet management solutions build on AVL and resource management for the fleet to provide awareness of vehicle availability, location, and operating conditions. Some of the agencies interviewed for this report are using fleet management and AVL solutions from the companies interviewed in this research.

Routing solutions build on the GIS to provide point-to-point routes that, as previously noted, can be extended to solve ARPs for winter maintenance of segments in a road network. None of the interviewed companies provide fully ARO for snowplows, although one provides static snowplow route optimizations based on maintenance facility locations. The two companies providing GIS offer VRP tools as part of their solution suites.

All the companies interviewed provide data analytics tools for their technologies and databases. As noted for GIS, agencies that might deploy ARO are likely to be using some of these technologies and data analytics in their operations. Some of those tools might be available for integration into an ARO capability through their APIs.

Conversations with technology providers indicated that their capabilities are generally ready for integration with ARO implementation in winter maintenance operations. Collaboration with technology solution providers could accelerate ARO development and potential deployment, ultimately supporting ARO adoption through a variety of market options and ongoing enhancements.

INTEGRATION WITH CURRENT AGENCY CAPABILITIES

Obtaining data from other agency systems to enable ARO is feasible but may be difficult. Data needed for the routing computations are generally available from existing agency systems since they are needed to support other agency operations and maintenance activities. The challenge is often that those systems may lack interfaces from which to access the data, or data from interfaces may need to be reconditioned for routing computations. In either case, additional work may be needed to get the data for ARO.

Two feasible approaches are available to obtain network maps and GIS data. Using the GIS data as a basis for the routing computations will rely on either: 1) building the ARO routing within the GIS environment or 2) getting interfaces to the database for use outside the GIS. All transportation agencies use GIS to plan, design, construct, operate, and maintain the road network. The current GIS database may not contain all the details needed to fully implement ARO, such as numbers of lanes, turnarounds, and vertical offsets for bridge joints or rails, but those data can be added to the GIS database.

ARO also needs to integrate with current asset and resource management systems. ARO needs information on personnel, equipment, and materials as inputs and potential constraints on optimal routing solutions. Many agencies are managing information about their resources and utilizations as part of other management applications. However, data for personnel, equipment, and material resources may not be kept in a single system or database, and the interfaces to those datasets would be needed or have to be created for the ARO capability. Accessing or building interfaces for resource data is feasible, with varied levels of complexity across the potential agency systems.

ARO tracks treatment material inventories on snowplows to ensure that recommended routes can be completed with the prescribed treatment rates. Agencies that perform winter maintenance operations have policies and procedures describing their plowing and treatment plans. The simplest plans can be captured in a treatment database or configuration file for ARO. Some agencies, typically in harsher climates, have invested in decision support systems for actively managing and optimizing treatment plans. A decision support system for those agencies would need to provide an interface to the treatment plan data for use in the ARO computations.

Some State and local agencies have invested in AVL systems for tracking and getting data, potentially including spreader rates and plow positions, from their vehicle fleets. Although most AVL systems have their own management interfaces and maps, the underlying data are similar to data in a GIS system and have similar interface opportunities. Integration with AVL may be feasible, especially for AVL systems designed for open data access. Agencies without AVL can be limited to seasonal and prestorm route optimization without real-time locations and adaptation to changing weather conditions and events.

Agencies typically use traffic management systems to manage information on traffic conditions and disruptions to operations in traffic management systems that traffic management center (TMC) operators use. Traffic management systems generally have interfaces for exporting traffic conditions and events as a center-to-center message or for traveler information. To be useful for ARO computations, data may need to be enhanced with details about the extent of an event (e.g., lane *x* affected from point *a* to point *b*). While traffic data interfaces for ARO are feasible, changes in event reporting may be needed to fully support real-time ARO.

ADAPTIVE ROUTE OPTIMIZATION SUPPORT

Software systems need support and maintenance over time. Whether built as a module within another environment or system (e.g., GIS) or a separate service, an ARO system needs maintenance to support its core capabilities and interfaces. Challenges include operating systems, data interfaces, and risk. Operating systems, development environments, and software libraries are upgraded over time and are not always backward compatible with previous versions. Data standards and interfaces can change as new technologies and applications develop. Risks may be higher when using third-party libraries and commercial tools outside the control of the developers. A system lifecycle management plan is recommended for ARO deployments to describe the future system operations and maintenance risks, system preservation strategy, and contingency plans.

MARKET READINESS SUMMARY

Currently no off-the-shelf arc-routing solution exists for snowplow routing in academic or commercial applications. Solutions based on node routing models are attainable, but with unknown performance characteristics. At least half of the agencies interviewed in this research are interested in cost effective routing solutions for developing sets of routing plans prior to the winter maintenance season or prior to particular storms. An agency’s experience with highly variable storms, network complexity, and meeting goals when faced with shortages in staffing, materials, or equipment may significantly influence an agency's interest in ARO. ARO integration with related data and services (e.g., resource management, decision support, or AVL) is a challenging but reasonable eventuality.

ARO solutions are feasible but have not been demonstrated with the full complement of considerations and constraints described in the ConOps and SyRS. The integrated nature of ARO datasets complicates development and support for deployment, and a prototype demonstration of ARO capabilities could help build interest in the ARO concept. Agencies that look for better winter maintenance resource utilization might see the opportunities in the prototype demonstration. Agencies that have mature winter operations capabilities and closely track operations performance might be more market ready for ARO implementation.

CHAPTER 4. FINANCIAL FEASIBILITY AND READINESS

Financial feasibility and readiness describe the potential costs and benefits of ARO deployment. This section assesses the financial aspects of ARO development and deployment relative to estimated ARO system costs and potential return on investment in ARO deployments.

ASSESSING COSTS OF AN ADAPTIVE ROUTE OPTIMIZATION SYSTEM

The costs to an agency associated with developing and deploying a new ARO system should be assessed throughout the entire system lifecycle. Federal sponsorship, a pooled fund, or a market-motivated commercial party could support development costs. Commercial development could depend on market feasibility and investment in developing technology. Agencies have typically changed resources rather than routes—due to lack of technology to create or change routing—in managing operational costs for winter maintenance. A cost effective automated routing solution could enable agencies to capture, as funding for deployment and operations, the saved cost from agency resource reductions.

Planning for potential deployment could include assessing the costs of assembling the services and data needed to support the AVL solutions. Agencies that have already deployed technologies that could provide data to ARO (e.g., AVL, asset management, and traffic management) would be leveraging previous investments and decreasing the incremental cost of ARO. ARO capabilities could be deployed as a system within an agency's information systems environment, or, in the case of commercial development, as a cloud-based service. Costs of those alternatives could be consistent with other in-house and service-based system deployments.

System maintenance and operations costs could accrue to whichever deployment alternative the agency selects. Training costs for ARO system deployment should include the direct cost of training users to create routing plans using the system and the cost of training staff to reorient winter maintenance planning around adaptive routing. The revised winter maintenance planning processes should affect management, supervisors, and drivers beyond whoever is charged with initiating and managing ARO results.

RETURN ON INVESTMENT

In general, winter maintenance operations have been shown to provide a great return on investment. Ye, Veneziano, and Shi developed a method to estimate the major benefits of winter maintenance, including safety improvements, travel time savings, and fuel savings.[9] The authors showed the benefits of Minnesota DOT's winter highway maintenance to be $227 million per winter season, including $168 million in safety benefits, $11 million in mobility benefits, and $48 million in fuel savings. The benefit–cost ratio was 6.2, considering material costs. A case study of I–90 and U.S. Route 12 in Idaho reported benefit ratios of 5.54 and 7.43, respectively.[10]

[9]Ye, Z., D. Veneziano, and X. Shi. 2013. "Estimating Statewide Benefits of Winter Maintenance Operations." *Transportation Research Record* 2329, no. 1: 17–23.

[10]Ye, Z., Y. Xu, D. Veneziano, and X. Shi. 2014. "Evaluation of Winter Maintenance Chemicals and Crashes With an Artificial Neural Network." *Transportation Research Record* 2440, no. 1: 43–50.

A similar approach can be applied to estimate the return on investment of ARO capabilities, including:

- Environmental effects and benefits from:
  - Reduced salt and chemical use in pretreatment and deicing.
  - Reduced fuel from more efficient routing and less deadhead to meet level-of-service goals.
- Infrastructure effects and benefits from reduced plow damage to pavements, pavement jointing, curing, bridges, and pavement markings.
- Equipment cost and use.
- Maintenance staff labor.
- Material use.
- Safety improvements, including reducing secondary crash risk.
- Reductions in congestion and travel time in inclement weather.

Previous studies have shown that static route optimization could reduce fleet size by better allocation and utilization of trucks. Miller et al. developed a static route optimization model using a commercial off-the-shelf system to assign assets and determine routes in three Ohio DOT districts. The study indicated the possibility of reducing the fleet size by 8.6 percent while maintaining the same level of service.[11] As noted earlier, Arvidsson, Bäckström, and Wärme implemented a dynamic route optimization program in Sweden to determine routes for preventative salting based on forecasted road weather conditions. The authors found a 15–25-percent cost reduction over a whole season compared with the static routing practice.[12]

FINANCIAL READINESS SUMMARY

Few studies exist on return on investment for route optimization; however, the evidence in those existing studies suggests potentially significant returns for agencies that routinely perform winter maintenance. Overall, ARO system development costs could be similar to other resource management and GIS application development efforts, and deployment costs could depend on whether ARO is intended for planning or real-time applications.

[11]Miller, T., B. Gleichert, H. Crabtree, J. Hendershot, R. Nuveman, and W. Schneider. 2018. "Role of Route Optimization in Benefiting Winter Maintenance Operations." *Transportation Research Record* 2672, no. 12: 232–242.

[12]Arvidsson, A. K., A. Bäckström, and M. Wärme. 2019. "Dynamic Forecast Controlled Winter Road Maintenance." In *26th World Road Congress 2019*. Abu Dhabi, UAE: World Road Association (AIPCR/PIARC).

CHAPTER 5. INSTITUTIONAL FEASIBILITY AND READINESS

Institutional feasibility and readiness address the openness and capacity of an agency's environment and culture to potentially deploy ARO. This section assesses the institutional aspects of ARO deployment relative to leadership and staff buy-in, socialization and agency culture change, operations support, and training.

INSTITUTIONAL ENGAGEMENT

To fully deploy ARO, institutional engagement could be needed at all levels of an agency's organization. The first steps to adoption could be taken at any level, with practitioners as much as with leadership, where ARO is seen as a potential solution to winter maintenance challenges or a tool for improving performance. New technologies, such as snowplow blades, liquids, and AVL, are continuously being integrated into winter operations. A champion who is motivated to demonstrate cost- or time-saving benefits could lead these integration efforts. Initiating ARO at an agency may follow a similar model, where a motivated supervisor or champion sees the opportunity in a support tool to find optimal routing given weather and road conditions.

Potential resource cost reductions, service improvements, and environmental benefits across the agency may motivate agency upper management. Potential service improvements, cost reductions, and resource management opportunities—to the extent that they benefit the manager's area of operations—may motivate middle management. Drivers might recognize the opportunities to improve learning curves for new and seasonal drivers, help avoid new or existing hazards, or perhaps provide awareness of events and emerging situations.

Stakeholder groups, forums, and webinars provide opportunities to engage with ARO subject matter experts, exchange fact sheets and reference materials, and hear from other practitioners. The ARO program has been working with a stakeholder group and with the Clear Roads Pooled Fund Study to gather perspectives and build awareness of ARO concepts. These engagements can continue to build and support discussions within interested agencies and help inform agency decisions to develop and deploy ARO.

SOCIALIZATION AND AGENCY CULTURE CHANGE

Efforts within an agency may need to start with a standalone demonstration prototype for optimization as a planning tool for a single maintenance service area. Comparing the optimized route lengths, cycle times, and material usage with results from the traditional route plans in that service area could provide experience and evidence for moving ahead with ARO, even if initially in a limited geography. Later applications could move from seasonal to prestorm to adaptive optimization. A small-geography pilot could move to a district and then statewide, showing the benefits of working across jurisdictions. The increasing geographic scale and frequency of optimization might be mapped to capability maturity framework plans to accelerate deployment and culture change.

Culture change within the agency could build on the champions' first proposals and on the evidence from the demonstration prototype. Results would need to be tested in operations, and changes would need to respect supervisor and driver concerns with the effect on procedures, practices, and work rules. One of the agencies interviewed in assessing agency interest in ARO found that their successful experience with changes to their maintenance processes in one service area created competitive pressure for other areas to improve their practices as well.

Private commercial contractors could provide an alternative path for proving and socializing ARO. Some agencies contract with commercial providers for winter maintenance operations. Those contracts may contain explicit service-level agreements and may contain technology clauses for methods and means. For example, agencies pursuing this approach could write contractual terms for performance specifications that require ARO features and performance measurement. Similar contractual terms could be specified for acquiring services for transportation management center operations and service patrols.

TRAINING SUPPORT

Understanding and effectively using ARO could need training at all levels within an agency's maintenance group. Other adjacent functions that provide or use ARO information may also benefit from ARO training. For example, TMC operations provide traffic and event data used by ARO and may benefit from seeing how routing priorities and results factor into traffic behaviors. Upper management could need to gain a clear understanding of the rationale, benefits, and investments for ARO. Training staff on ARO capabilities and interfaces with existing operations data sources could enable upper management to monitor the effect of ARO deployment on the agency.

Middle management could need to understand the data requirements and the implementation and training needs for ARO deployments. Maintenance managers and supervisors could be developing application and implementation plans that bridge the gap between current practice and a desired future reliance on ARO. This group may also be asked to produce return on investment that supports ARO use and expansion. Maintenance managers and supervisors could determine the types of dashboards needed and how and what to communicate to drivers. Training for middle management could describe the ARO capabilities, interfaces, and applications. Middle management could provide training in their own organizations on ARO applications within their operational context.

Drivers could need to understand and experience how ARO works to build confidence in the optimized route results. Training could focus on using the technology and emphasize the benefits to their roles, demonstrating a return on investment based on their acceptance of and belief in the recommended optimized routes. Drivers would have to bridge the gap between self-reliance and acceptance of incab route navigation and obstacle avoidance messaging.

Successful ARO depends on timely and consistent access to accurate operations data. An agency's information technology staff could be included in ARO training to understand the data flows and system support needs. Transportation operations staff may be included in ARO training to understand how the adaptive routing complements traffic operations. Alongside the benefits to winter maintenance, ARO could also benefit traffic safety and mobility with potentially faster pavement restoration and speed recovery times, reduced weather-induced congestion, and less crash risk from pavement conditions. Operators would need to understand how operations data are used in the optimization to prioritize routes and destinations and to route to and around events.

INSTITUTIONAL READINESS SUMMARY

The anticipated benefits of ARO may appeal to agency leadership who are willing to make institutional changes. Implementing ARO provides alternatives to the fixed routing plan basis of current practices. Use of ARO enables incremental evolution from prior methods. This cultural change may be challenging for some staff within the maintenance organization who are accustomed to the static routes. Adopting real-time ARO could entail reorienting and training all winter maintenance operations and adjacent staff.

CHAPTER 6. NATIONAL READINESS

As a novel concept, ARO needs ongoing engagement from practitioners to increase understanding and acceptance. Socialization of the ARO concept involves demonstrating viable ARO solutions at different network scales to facilitate buy-in. To successfully demonstrate an ARO deployment, one or more lead agencies with willing leadership, operational opportunities, and existing related data systems are needed. Demonstration with related system providers (e.g., AVL, decision support, or resource management) could accelerate the transition from research. Early adopter candidate agencies might include State agencies that provide maintenance on interstate and major highways and local agencies that have smaller but more complicated networks and higher rates of incidents, congestion, parked vehicles, and more route choices.

ARO for winter maintenance has not had extensive prior research or demonstrations. There have been some academic demonstrations with limited datasets and network geographies. As such, demonstrating ARO could be staged in three steps, with each step adding new capabilities:

1. Prototype demonstration of the arc-routing optimization for winter maintenance applications. The goal of the prototype would be to develop routes for a maintenance district network using static resource allocations, as might be done before the start of a winter season. The prototype would demonstrate the ability to efficiently generate routes for multiple vehicles covering a network of links with varying priorities and treatment characteristics. The routing results would be compared with previous static routes to demonstrate the potential improvements.

2. Pilot demonstration of adaptive routing methods over a road network of multiple districts and spatially varying weather conditions. The regional pilot demonstration goal would be to develop routes over multiple districts in a region or State with agency weather, traffic, work zone, incident, and resource conditions. The regional pilot would demonstrate the ability to efficiently generate routes using data from agency sources for prestorm planning conditions. Routing results would be compared with seasonal fixed plans to demonstrate the potential benefits of adaptive routing.

3. Pilot demonstration of near-real-time adaptive route optimization methods over an urban road network with complex road geometries, varying levels of service and road classification, and real-time conditions comparable to the regional demonstration. The urban pilot demonstration goal would be to assess the limits of real-time adaptation to changing conditions. Routing results would be compared with prestorm plans to demonstrate the potential benefits of real-time adaptive routing.

This rollout may be synergistic with development and deployment of Managing Disruptions to Operations Data Exchange (MDODE), a data exchange for disruptions to operations among agencies. To successfully use MDODE in the ARO demonstration, each participating transportation agency would need to incorporate its road weather, incidents, and work zone information into MDODE.

Potential and preferred candidate agencies for the prototype and pilot demonstration could have the following attributes, including in no particular order:

- A road network size large enough to include multiple facilities for equipment and materials.
- For longer corridors, having combinations of inclement weather with high traffic and commercial vehicle traffic risk.
- A deployed AVL system.
- Established routable maintenance network and routing maps.
- Issues with traffic congestion and traffic incidents during winter operations.
- Mature resource management systems.
- History of winter weather events requiring snowplow routing (figure 2).
- Some road network complexity in road classifications and routing alternatives.
- Multiple equipment types used in winter operations.
- Specific winter maintenance service goals to be tested.

Once ARO has been demonstrated for extensible real-time applications within and among agency jurisdictions, national deployment may need Federal seed funding through grant programs. Consistent with other Federal Highway Administration (FHWA) plans for MDODE and roadway digital infrastructure, transnational corridors could serve as a core for national rollout of ARO concepts across jurisdictions. This approach could look for a critical mass of State and local agencies that share operational goals and operations interests along the paths of winter weather events. Interstate highway corridors running west to east along I–94/90, I–80, I-70, and I–40 or north to south along I–5, I–15, I–25, I–35, I–75, and I–95 could be strong candidates for cooperative deployment. Large-scale deployments could also create downstream opportunities for resource and asset management, AVL, and decision support providers to participate in deployment or to develop their own ARO capabilities.

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GLOSSARY

adaptive	able to change in response to objectives (for example, cycle times), events (for example, traffic incidents) and changing conditions (for example, precipitation).
atmospheric weather	temperature, precipitation, visibility, and other conditions of the atmosphere above the Earth's surface.
automated vehicle location system	a system for monitoring and sending information about a vehicle's location and operating conditions (for example, salt inventory) to an operations center or system.
cycle time	how long it takes to service all lanes of a road segment along a planned route one time.
maintenance depot	a place where supplies and materials (for example, treatment materials) are stored.
maintenance shed	a site for storing and maintaining equipment used for winter maintenance operations.
optimization	techniques or algorithms for finding the optimal solution to a set of objectives (for example, the fastest routes over a set of roadways), subject to a set of constraints (for example, with a limited set of vehicles).
patrol	a group of vehicles (for example, snowplow trucks) operating together to achieve an objective.
road weather	temperature, precipitation condition, friction, and other conditions on a roadway surface.
route	an ordered set of segments.
segment	a linear link between nodes (intersections) in a network.

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