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Improving Snowplowing Operations in Utah Through Optimization and Visualization

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Abstract. This paper describes efforts to improve snowplowing routes in 12 regions in northern Utah. Both exact and approximate methods are applied to determine snowplowing routes that decrease total travel time, turnaround time, and deadhead miles by an average of 5.04%, 15.01%, and 14.84%, respectively, across the 12 regions, which can significantly improve the efficiency of snow removal operations as well as the social welfare. Our models also evaluate the tradeoffs between different operational policies such as echelon versus nonechelon routing and centralized versus decentralized optimization and analyze various scenarios to understand the benefits of providing additional resources to different regions. These analyses enable local management teams to determine the best settings for their regions. In addition to optimization modeling, a major component of this work is the use of data visualization to demonstrate the effectiveness of the new routes (with comparisons to current practice) to the Utah Department of Transportation.

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Introduction

Frequent snowstorms during winter months significantly impact traffic safety and mobility in most North American cities (Yan et al. 2020). Accumulated snow on roads reduces pavement friction, leading to longer stopping distances and increased crash occurrences (Abohassan et al. 2022). Limited visibility and maneuverability force drivers to reduce their speeds, resulting in traffic congestion and travel delays (Doll et al. 2014). To address these negative effects of snowfall, transportation agencies deploy a fleet of snowplows to clear snow and spread deicing materials such as salt and sand on designated roadways as part of their winter road maintenance operations.

In the United States, individual states are responsible for snow removal from the road network under their jurisdiction, which requires a massive labor effort and considerable financial investment (Ahabchane et al. 2021). For example, the Utah Department of Transportation (UDOT) maintains a fleet of around 500 plow trucks and is responsible for snow removal on approximately 24,300 lane miles of roadways. The state of Utah spends approximately $25 million annually on snow removal, with an average cost of around $1 million per snowstorm (UDOT 2023). In addition to the significant investment in winter road maintenance, frequent snowfalls lead to substantial traffic delays and accidents. According to a report by the U.S. Department of Transportation (USDOT 2023), snowy or slushy pavements cause an average decline in arterial speeds of 30%–40%. Additionally, more than 1,300 people lose their lives, and over 116,800 individuals sustain injuries in vehicle crashes that occur on snowy or icy roads, annually. Therefore, even minor improvements in the efficiency of snow-clearing operations could result in significant benefits by reducing the snow-induced loss of time and harm to individuals.

This paper outlines a comprehensive 10-month-long endeavor aimed at optimizing snowplowing routes for 12 regions in northern Utah. The snowplow routing problem is approached as a capacitated vehicle routing problem (VRP) with different objectives, depending on the management's requests. The selection of objectives for snow removal depends on factors such as geographic features and traffic patterns. For example, some regions have asymmetric networks with long roadways into canyons that require immediate snow clearing, and thus the routes are optimized to minimize the turnaround time, ensuring that road conditions can be recovered as quickly as possible. Regions with a well-connected network and high traffic volume prefer to optimize routes with the goal of minimizing the overall time spent by plowing trucks traveling along roadways. As a result, the duration of travel disruptions caused by snow removal can be minimized. We use both exact and heuristic methods to solve these various routing problems and evaluate the solutions using three metrics. On average, our routes achieve reductions of 5.04%, 15.01%, and 14.84% in the three respective metrics. These improvements primarily benefit the social welfare: we estimate the travel-time savings resulting from snowplow operations using methods analogous to those used at UDOT (Moser et al. 2021), and project that they will save approximately $160,728 per snowstorm for the traveling public. We also prepare animations of both our proposed routes and those previously used by UDOT to validate the results and facilitate the implementation of the proposed routes by UDOT staff.

Literature Review

At a very high level, our paper is a practical implementation of vehicle routing methods in the domain of public sector operations research. Other work of this kind includes, for example, Chu et al. (2020) on school bus routing. The more directly related literature on snow removal, however, is much less abundant, and there have been relatively few studies explicitly considering the types of practical considerations and challenges posed by this complex problem.

Snowplowing is a specific instance of the arc routing problem (Golden and Wong 1981), which aims to determine the most efficient routes for a fleet of trucks to serve links or arcs of a given network with various objectives such as total travel time and turnaround time (Perrier et al. 2007, Salazar-Aguilar et al. 2012). Although researchers have developed various mathematical programming and heuristic techniques for designing snowplowing routes (see Corberán et al. 2021, for a recent review), there are relatively few real-world implementations of optimization algorithms for snowplowing operations. In this section, we will review papers that test the proposed models in realistic settings or deploy their algorithms in practice.

Perrier et al. (2008) propose a mathematical optimization model that utilizes a multicommodity network flow structure to determine the most efficient routes for snowplowing trucks in urban areas, with the primary objective of minimizing the time required to clear each road priority. The authors present two distinct approaches, a parallel algorithm heuristic and a cluster-first, route-second approach, and apply both methods to a realistic instance involving four different scenarios in the city of Dieppe, Canada. By comparing the proposed methods with the routes currently used by the city of Dieppe, the authors conclude that their solutions can reduce the turnaround time required to service all arcs by 3% and 13%, respectively. Although the improvements achieved by the second method are similar to those observed in our own work (a reduction of 15% in turnaround time across 12 different regions), the model presented by Perrier et al. (2008) does not consider truckload capacity used for ice melt. Additionally, their model imposes strict constraints on road hierarchy, mandating that higher-priority roadways must be serviced before lower-priority ones. In contrast, UDOT allows for road upgrading, which means that lower-priority roadways can be serviced earlier in order to minimize the overall completion time.

Salazar-Aguilar et al. (2012) tackle the challenge of improving the efficiency of snow clearance from multilane road segments by introducing a new approach to snowplow routing that involves echelon formations. This technique enables snowplows to work together in a synchronized and coordinated manner, allowing for efficient clearing of multiple lanes in a single pass. The authors formulate the problem as a mixed integer program with the objective of minimizing the time taken to clear the snow. To solve the problem, the authors propose an adaptive large neighborhood search heuristic and demonstrate its effectiveness through computational experiments on both artificial and realistic instances. In our study, we also consider echelon plowing routes on specific road segments, and find that this can sometimes enhance the efficiency of snow removal operations, particularly for high-priority roadways with multiple lanes. However, we find that it is crucial to properly set the number of trucks in the echelon: if this is too large, the snow removal efficiency of the entire network may suffer, because an excessive focus on multiple-lane roadways diverts resources from other roadways. Even then, echelon formations do not always help, and we even find one instance in which it is advantageous to break up an existing echelon formation.

Quirion-Blais et al. (2017) investigate a winter maintenance problem that involves road segments with different priorities, requiring plowing and gritting while adhering to practical constraints such as turn restrictions, varying truck capabilities, and travel speeds. They propose an adaptive large neighborhood search framework and apply it to optimize routes in a city in Quebec, Canada. Unlike our study, where all trucks are equipped to perform both plowing and spreading salt for ice melt, their trucks can only handle either plowing or spreading tasks. As a result, the optimization of routes for plowing and salt spreading needs to be carried out sequentially rather than simultaneously.

Previous research on snowplow routing has commonly relied on mathematical programming techniques, as demonstrated in studies like Hajibabai et al. (2014) and Liu et al. (2014). Kinable et al. (2020) propose an alternative approach using constraint programming to tackle the snowplow routing problem. The authors conduct extensive numerical experiments on real-world data from the city of Pittsburgh, and report a 33% reduction in turnaround time compared with routes previously operated in Pittsburgh. In our situation, there was less room for improvement as UDOT had already invested extensive effort into the design of routes for sparse networks in rural areas. However, optimization still provided valuable insights for other regions, and yielded significant improvements in the metrics of greatest interest to UDOT.

According to a survey by Perrier et al. (2006), snow removal operations in large geographical areas are traditionally decentralized by dividing them into several regions. Each region then operates its own fleet of trucks independently. This is also the case with UDOT's plowing operations in Utah. Some recent research suggests that more benefits could be obtained if district boundaries were ignored and resources shared between regions. For example, Blandford et al. (2018) optimize snowplow routes for four counties in Kentucky using a Geographic Information System that employs Esri's Network Analyst tool to tackle the vehicle routing problem. Their multicounty route optimization brought significant savings in operational costs (i.e., $225,000 per year) and completion time compared with the county-based routing strategy, in which the trucks only worked within their own jurisdictions. Similar findings are reported by Miller et al. (2018) and Xu et al. (2022) in their studies on centralized optimization and resource sharing in Ohio districts and Perth County municipalities, respectively. In our work, we also consider this question in the context of the Centerville region, which is divided into four independently operating subnetworks. We optimize plowing routes for each subnetwork, as requested by UDOT, but we also assess the potential benefits of centralized optimization for the entire region. We find that centralization can produce more efficient routes, though in practice this would come at the cost of more difficult and potentially expensive coordination of diverse road classifications, traffic volumes, and maintenance requirements.

The aforementioned research primarily focuses on designing vehicle routes with the assumption that all parameters are known with certainty, a premise shared by our current work. Nonetheless, some researchers have incorporated various sources of uncertainty in their route planning. For instance, Ahabchane et al. (2021) employ robust optimization to address the capacitated vehicle routing problem for winter road maintenance under uncertain demand for deicing material. They develop a metaheuristic and evaluate its performance in two Quebec cities. Similarly, Hajibabai and Ouyang (2016) investigate the assignment of snowplow trucks to routes while considering uncertainties in demand and service disruption. They do not consider routing, but instead focus on multiperiod assignments using up-to-the-moment data on, for example, weather conditions and traffic patterns. Similar dynamic paradigms were considered by Fu et al. (2009) and Li et al. (2021). Both of these papers dynamically adjust service routes based on real-time travel speeds and road weather conditions, and find that this can improve the efficiency of operating plans. However, even if reliable and accurate data are available, it is often quite challenging to incorporate them into operational decisions because of the robust real-time communication and computational capability that would be required. Because of these challenges, UDOT currently has more preference in improving snow removal efficiency based on deterministic optimization, and thus dynamic reoptimization falls beyond the purview of the present study. The development of a dynamic model can be considered a possible future research direction.

Most existing research on routing optimization for snow removal typically focuses on a small number of regions, such as four cities involved in Blandford et al. (2018) or three districts of Ohio in Miller et al. (2018). In contrast, we consider 12 regions with diverse network configurations and truck types. Management in different regions has varying interests in different types of operational policies. Thus, our study brings together diverse scenarios including investigation of echelon routes, centralized optimization and decentralized optimization, fleet size extension, etc. The assessment of these scenarios indicates that there is no "one-size-fits-all" solution: for instance, echelon routes enhance snow removal efficiency in one region (North Logan), but are detrimental to it in another (Centerville). Our comparisons between these scenarios highlight the heterogeneity between regions, and are themselves of significant practical interest.

Snowplowing Route Optimization

In this section, we begin by providing an overview of the essential data sources and constraints for snowplowing route optimization. We then describe how we transform the snowplowing route problem into the node routing problem using graph transformation, based on a realistic road network.

Data Collection

Our project aims to improve snowplowing operations for 12 nonoverlapping regions in northern Utah. Each region is equipped with a dedicated maintenance station located within its designated area and manages maintenance resources to service a set of responsible roadways, with the type and number of trucks allocated typically dependent on the size of the region and road classes within its jurisdiction. These trucks start and end their trips at the maintenance station and are not permitted to offer services in other regions. At the beginning of the study, we held several meetings with the manager for road winter maintenance in each region to gather the required data, including:

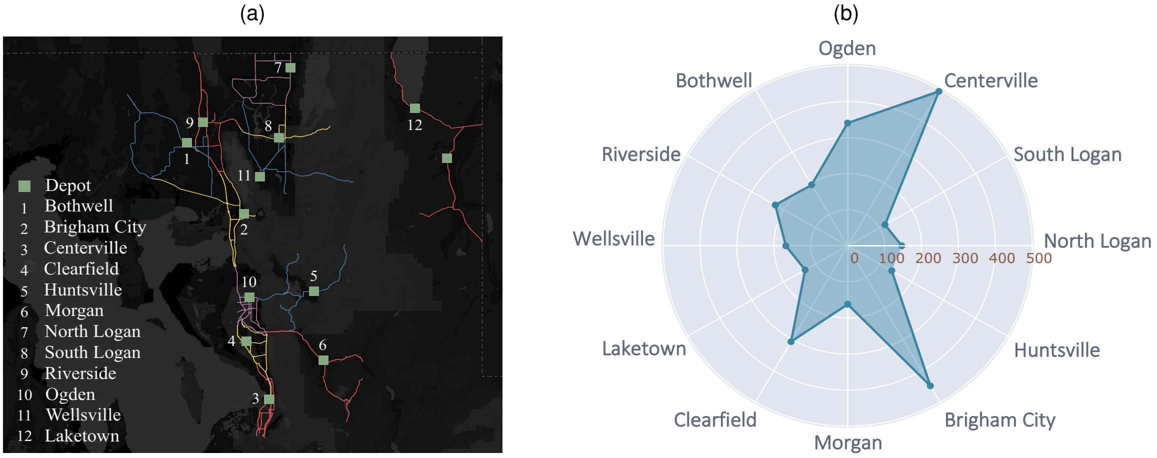
- **Road network.** We extract the number of lanes, length of each road link, and speed limits from the OpenStreetMap data. We then verify the required number of passes for each road link, which depends on the number of lanes and the presence of wide shoulders. Although we assume a vehicle speed of 70% of the speed limit, we occasionally modify it, such as for roads where higher truck speeds could damage mailboxes while pushing snow or for icy canyon roads. Additionally, we assign a designated priority to each road. Road priorities are predetermined by UDOT; typically, roads with higher road classification and traffic volume receive higher priority. Figure 1 illustrates the road network, and also shows the total number of lane miles that each region is responsible for servicing. Further details such as the number of lanes, travel speed, and road priorities of the road segments in each region are provided under "Results."
- **Fleet composition.** We confirm the fleet composition for each region because snow removal operations require trucks with different types and capabilities. The UDOT fleet is comprised of single-wing trucks that clean one lane at a time, double-wing trucks that clean one and a half lanes at a time (e.g., the rightmost lane and a shoulder), and tow-plow trucks that can simultaneously clean two lanes (see Figure 2). The latter two groups account for about 15% of the overall fleet and are usually assigned to major roads only. For example, two tow-plow trucks in Centerville are only permitted on Interstate 15 (I-15), where they operate in echelons, ensuring simultaneous snow removal across all the lanes.
- **Automatic vehicle location (AVL) data.** All state-owned snowplow trucks come equipped with an AVL system that collects data on vehicle operation. This includes truck identification (ID), time, location, heading, and travel speed, with a fixed refresh rate of 30 seconds. Figure 3(a) presents an example of AVL data produced by a single-wing truck after a snow event. This also demonstrates that location errors are common with AVL technology. To correct these errors, we conduct map matching using the OpenStreetMap routing tool. This tool leverages a hidden Markov model to reconstruct the most likely route taken by a truck. By analyzing and animating AVL data, we are able to visualize the plowing routes implemented by UDOT. This makes it easy to validate the routes with local management.

Constraints and Objectives

In our consultations with regional managers, we also sought to identify essential constraints and objectives. The main points of these discussions are summarized below.

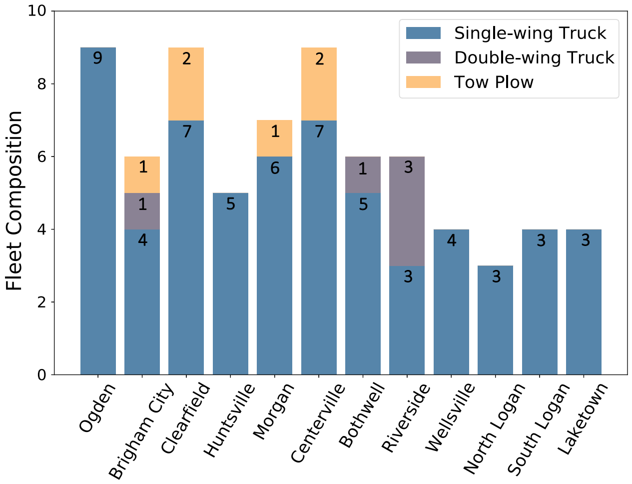
- **Operational policies.** Each region presents a unique set of operational policies that necessitate consideration when designing the snowplowing routes. For instance, managers in some regions (e.g., Logan, Centerville) advocate for the implementation of echelon formations, which involve clearing multiple lanes simultaneously. These formations are particularly essential for multilane interstates to prevent snow accumulation on the road surface (see Figure 2). Furthermore, maintaining

Figure 1. (Color online) The Responsible Road Network and the Total Amount of Lane Miles in Each Region



Notes. (a) State-owned roadways within 12 regions. (b) Responsible lane miles across 12 regions.

Figure 2. (Color online) The General Types of Plowing Trucks and Fleet Composition in Each Region

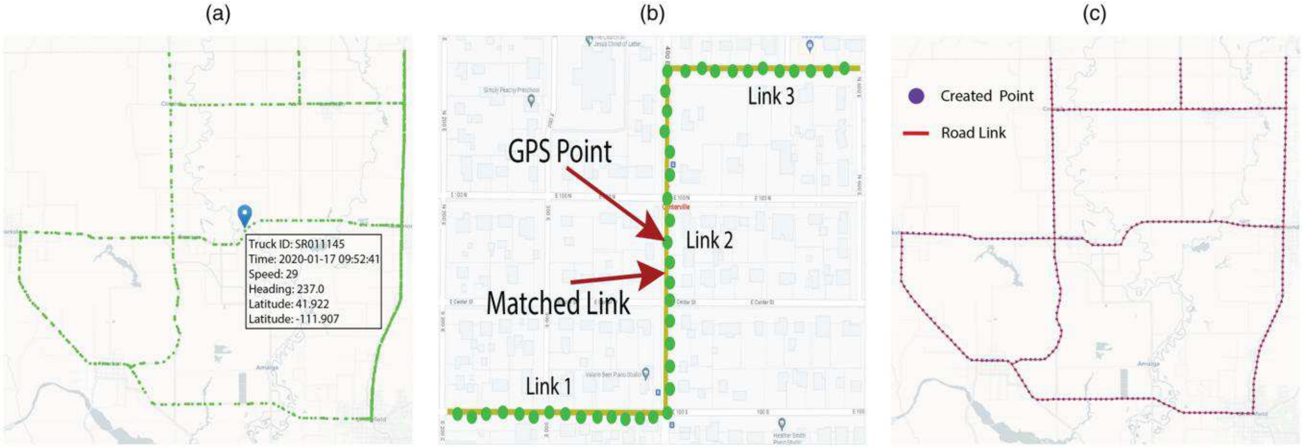


Note. The graph shows the number of trucks in each region.

the current subpartitioning of regional networks is emphasized by some managers (e.g., Centerville and Ogden) as a crucial requirement for decentralized optimization. These operational policies emerge because of the road network structure. In cases where certain regions have road segments with multiple lanes and high priority levels, echelon formations allow for simultaneous clearance of multiple lanes and can significantly enhance snow removal efficiency. In regions where the network is divided into several subnetworks with similar road classifications, such as highways or local streets, drivers do not need to frequently adjust their travel speeds when transitioning between different road classes. This consistency in road class facilitates smoother and more efficient travel for snowplow drivers. Though we largely follow the wishes of the managers, we also aim to evaluate the effectiveness of these operational policies. By considering different scenarios, we can identify cases where, for example, better performance can be obtained by deviating from echelon formations. These situations are discussed under "Results."

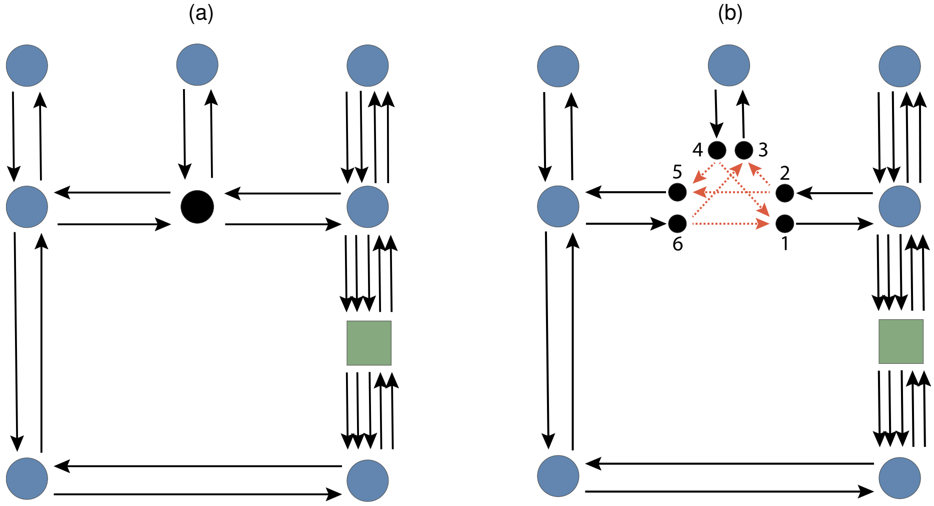
- **Salt load capacity.** The capacity of the salt spreader is a common constraint in snow removal operations. A single-wing truck has a 7-ton capacity and applies 250 lbs of salt per lane mile. This means that each truck can clean 56 lane miles before needing to return to the depot to refill. Because salt capacity is found to be more constraining than fuel, there is no need to explicitly consider fuel constraints.
- **U-turn prohibition.** Because of the increased dimensions of snowplowing trucks compared with regular vehicles, U-turns are restricted at small intersections. As a result, we incorporate this constraint into the graph representation of the snowplow routing problem. Figure 4 demonstrates the construction of a graph that takes into account the prohibition of U-turns at an intersection.
- **Performance measures.** The performance measures of greatest interest to UDOT are total travel time, deadhead miles, and turnaround time. Total travel time measures the duration in minutes to complete the snow removal. Deadhead miles refer to the distance traveled by snowplow trucks without performing snow removal, for example, on roads that have already been cleared. Turnaround time refers to the duration of the longest route (i.e., the time needed to clear the entire network). However, optimization objectives vary depending on the unique needs of each region.

Figure 3. (Color online) AVL Data and Responsible Road Links



Notes. (a) The raw AVL data collected after one snow event in North Logan. (b) Matching the responsible road links and AVL data points. (c) The responsible road links and projected points along links. We edit the plow map in ArcGIS Pro and create point features along each link for plowing route animations.

Figure 4. (Color online) An Illustrative Example of a Directed Graph with Prohibited U-Turns at an Intersection



Notes. (a) This directed graph represents the road network in North Logan. The black node indicates an intersection where U-turns are not permitted. (b) The transformed directed graph, in which U-turns are not allowed. Six artificial nodes are introduced to facilitate left turns, right turns, and through movements, excluding U-turns (no connection between node pairs (1,2) and (5,6)). It is important to note that arcs indicated with red dashed lines between artificial nodes have no assigned demand for snow removal. The blue circles denote intersections accessible to plowing trucks, while the black arrows indicate directed road links connecting adjacent intersections. The green squares represent the depots.

For example, regions with long roadways into canyons require immediate snow clearing to minimize turnaround time for preventing accidents and maintaining traffic flow. Managers in regions with larger road networks and adequate resources prioritize minimizing total travel time to reduce costs (e.g., labor, equipment maintenance, and fuel) as well as the impact of plowing activities on travel mobility.

Network Transformation

The snowplow routing problem addressed in this work is a variant of the capacitated arc routing problem in which efficient routes are determined to traverse all the necessary road links. In this work, we take advantage of the efficiency and robustness of existing solution methods for various practical applications of node routing problems (Hu et al. 2022, Khodabandeh et al. 2022) by implementing a graph transformation. Specifically, we transform the arc routing problem into an equivalent node routing problem to leverage the strengths of existing solution methods.

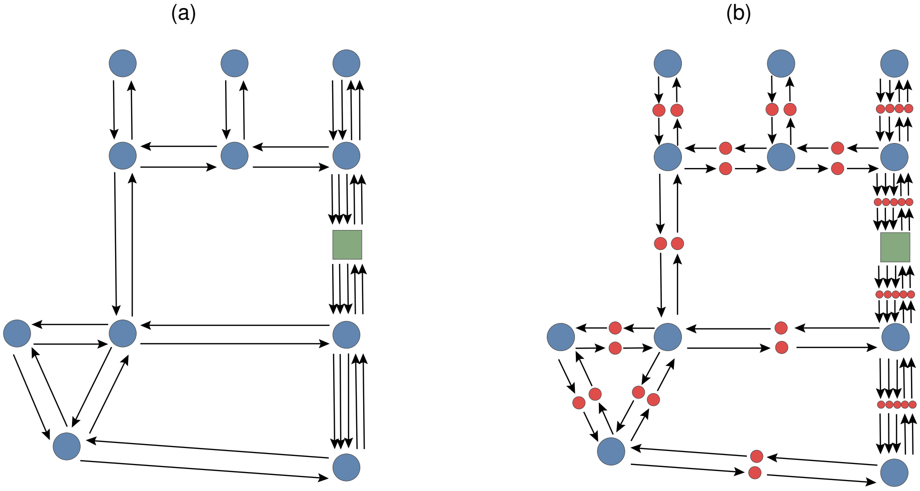
We demonstrate the graph transformation approach using data from North Logan. Figure 5(a) shows the directed network comprising responsible road segments in North Logan, with black arrows representing travel lanes and blue nodes denoting intersections. To transform this graph, we add a "customer" node in the middle of each arc, resulting in the modified graph illustrated in Figure 5(b). By designing routes that visit all the newly inserted customer nodes, we can ensure that all the travel lanes from the original graph are traversed.

Animation of Plowing Routes

The conventional practice of visualizing snowplowing routes through static figures is of limited use for practical implementation because static figures have limitations in presenting routes in higher granularity and capturing the temporal aspect of routing. In route animations, the timestamps and moving icons representing plowing trucks can tell the service sequence and the times it takes for the snowplows to clear the snow from different roadways. Consequently, a major portion of this study is devoted to generating animated representations of both UDOT's routes and the proposed routes for each region. These animations offer the following benefits:

- **Enhanced understanding.** By visually illustrating the sequence of road segment servicing and turn locations, animations effectively convey the intricacies of truck movement during the plowing process. This level of detail allows managers to better understand and evaluate the efficiency and effectiveness of the routes.
- **Comparative analysis.** By presenting, in animated form, the proposed routes side by side with UDOT's current routes, a direct and intuitive comparison can be made. This enables practitioners to observe the differences in route patterns, workload distribution, and potential improvements offered by the proposed routes. Route animations can be particularly helpful in highlighting and illustrating the disparities in service orders, turn locations, and other relevant aspects.
- **Practical implementation.** Animations serve as a practical tool for implementing the proposed routes. Practitioners can follow the animated sequences to replicate the optimized routes in the field, ensuring a more

Figure 5. (Color online) Example Transformation for North Logan Based on the Road Network Information (see Figure 7)



Notes. (a) The graph for arc routing problem. (b) The transformed graph for node routing problem. We create a directed graph where the arc routing problem is defined. The black arrows denote lanes between adjacent intersections indicated with blue circles. The corresponding node routing problem is obtained using a standard transformation (Hajibabai et al. 2014) where "customer" nodes are inserted in the middle of each arc.

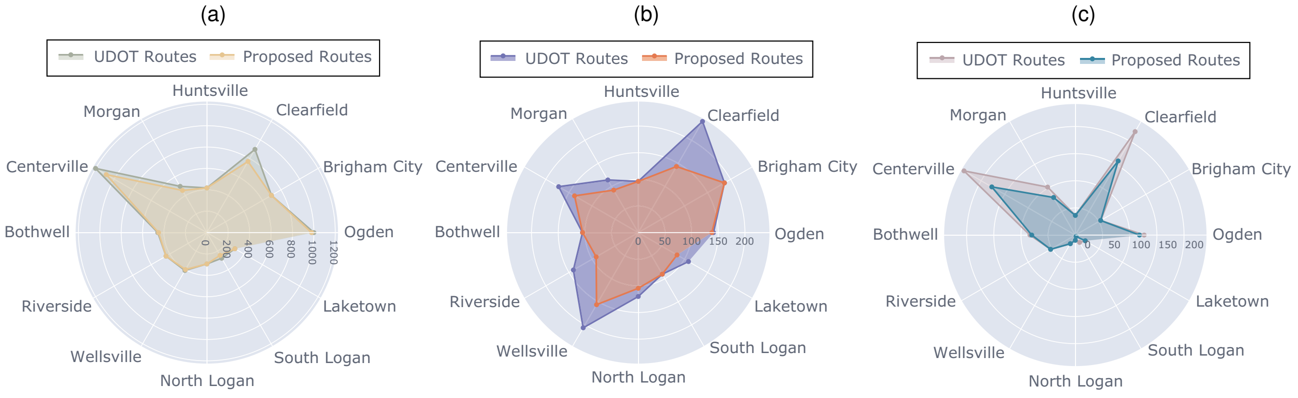
seamless and accurate implementation. The managers expressed satisfaction when reviewing the animations, appreciating their accurate depiction of the two sets of plowing routes. Additionally, they planned to use the animations (specifically, the visualized trajectories of the plowing trucks) to verify that drivers were adhering to our proposed routes.

Results

We evaluate Utah's snowplowing operations, which were based on manually designed routes created by UDOT, and compare them to the optimized routes. Figure 6 provides a summary of the improvements in total travel time, turnaround time, and deadhead miles, which are reduced on average by 5.04%, 15.01%, and 14.84%, respectively. The proposed routes play a crucial role in reducing turnaround time, as most managers prefer to have balanced plowing routes (that is, the routes should have similar durations of snow removal). Because such routes aim to distribute workload evenly, they may not have much effect on total travel time. On the other hand, the savings in deadhead miles are comparable to the improvements in turnaround time. This is because balanced routes ensure that trucks are actively providing snow removal service for a higher portion of their journey, minimizing the instances of travel without any service and consequently reducing deadhead miles.

The primary impact of these improvements is on the social welfare. Optimized routing, under the same fleet size and infrastructure, can produce only modest savings in operational costs (such as fuel and labor). However, the savings to the traveling public can be quite substantial. Using a methodology similar to the one

Figure 6. (Color online) Comparison of UDOT's Routes and Proposed Routes in Terms of Total Travel Time, Turnaround Time, and Deadhead Miles



Notes. (a) Total travel time. (b) Turnaround time. (c) Deadhead miles.

Table 1. Estimation of Travel Delay Cost Reduction for Each Region

Region	No. of trips	ΔTurnaround Time (min)	ΔDelayCost, $	Region	No. of trips	ΔTurnaround Time (min)	ΔDelayCost, $
North Logan	230	15	1,150	Wellsville	837	50	13,950
South Logan	857	19	5,427	Ogden	4,557	0	0
Clearfield	1,868	97	60,398	Morgan	268	22	1,965
Centerville	6,046	34	68,521	Bothwell	616	0	0
Riverside	543	49	8,869	Laketown	56	24	448

Notes. ΔTurnaroundTime and ΔDelayCost denote the reduction in turnaround time and delay cost resulting from the implementation of our proposed routes. No further improvements could be made to the routes in the Brigham City and Huntsville regions. Therefore, this table only includes the savings in travel delay for the remaining 10 regions.

used by UDOT, we estimate trip volumes based on comprehensive historical trajectory data from Utah, assuming trips are generally avoided during severe storms, and using a conservative estimate of $20 per vehicle-hour (as argued in the Online Appendix). Table 1 presents the projected savings, which add up to $160,728 per snowstorm across 12 regions. With an average of 25 heavy snowstorms annually, our proposed routes have the potential to save approximately $4 million per year in trip delay costs for public road users. For a detailed explanation of the approach taken to estimate these numbers, please refer to the Online Appendix.

We utilize both exact and heuristic approaches, as detailed in the Online Appendix. Most regions are modeled using min-max VRPs, which optimize turnaround time; we use this model in North Logan, South Logan, Wellsville, Laketown, Bothwell, Morgan, and one subnetwork within Clearfield. In some instances where only one truck is available for the subnetworks (Ogden, Centerville, and Clearfield), the problem reduces to a traveling salesman problem (TSP). In one instance (Riverside), we use a min-sum VRP because that network happens to be particularly well connected.

The remainder of this section focuses on four specific cases where our analysis yields particularly interesting insights into such issues as the formation of echelon routes, fleet sizing, the establishment of satellite replenishment stations, and centralized optimization. Within the remaining eight regions, a comprehensive analysis and comparison of the existing routes by UDOT and our proposed routes for six specific regions—namely, South Logan, Ogden, Riverside, Clearfield, Morgan, and Bothwell—can be found in the Online Appendix. Lastly, in the remaining two regions, Huntsville and Brigham City, the routes currently used by UDOT coincide with those obtained through optimization, so no changes were required. Additional details pertaining to these two regions can also be found in the Online Appendix.

North Logan: Route Balance and Investigation of Echelon Routes

Logan is a city located in Cache County, in the northernmost part of Utah. UDOT has divided Logan into two regions to simplify operations management: North Logan and South Logan. UT-23, UT-61, UT-142, and UT-218, as well as a large portion of US-91, are located in North Logan, whereas South Logan encompasses UT-30, US-89, and UT-252, along with a short section of US-91. Figure 7 displays the number of lanes that require clearing and the recommended travel speed. UDOT has allocated three single-wing plows to North Logan and four to South Logan. We discuss North Logan in detail here and defer the analysis of South Logan to the Online Appendix.

Currently, one notable issue with UDOT's routes in North Logan is the lack of balanced route durations. It is evident from the left portion of Table 2 that truck 3 took at least 34% longer to complete its route compared with the other two trucks. In order to identify more balanced

Figure 7. (Color online) The Number of Lanes, Plowing Speed, and Priority of Responsible Roads in Logan

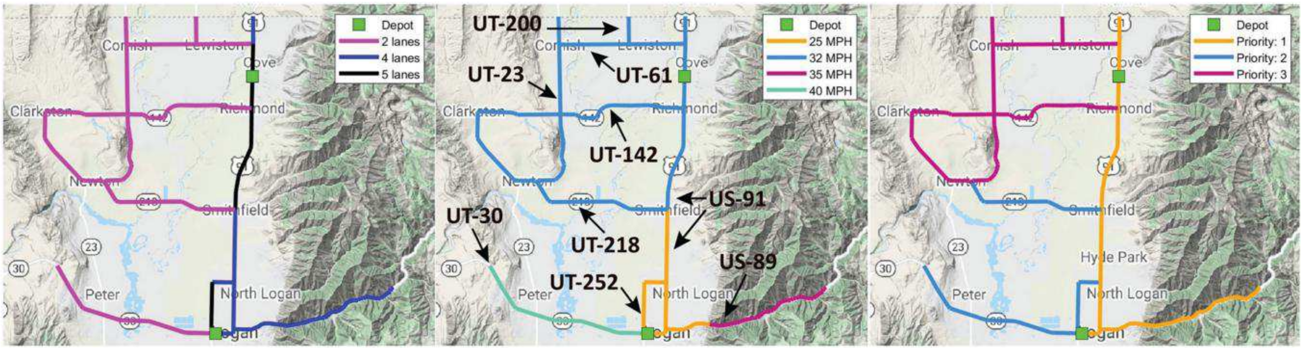


Table 2. Performance Comparison Between UDOT's Routes and Proposed Routes in North Logan

UDOT routes						Proposed routes					
			Deadhead						Deadhead		
Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)	Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)
1	84.3	44.9	0.0	0.0	5.6	1	84.3	44.9	11.2	5.9	4.8
2	89.0	47.4	3.4	1.8	5.7	2	104.5	55.7	3.4	1.8	6.7
3	119.9	63.9	14.6	7.8	7.0	3	104.4	55.6	3.4	1.8	6.7
Total	293.2	156.2	18.0	9.6	18.3	Total	293.2	156.2	18.0	9.5	18.3
Max	119.9	63.9	14.6	7.8	7.0	Max	104.5	55.7	11.2	5.9	6.7

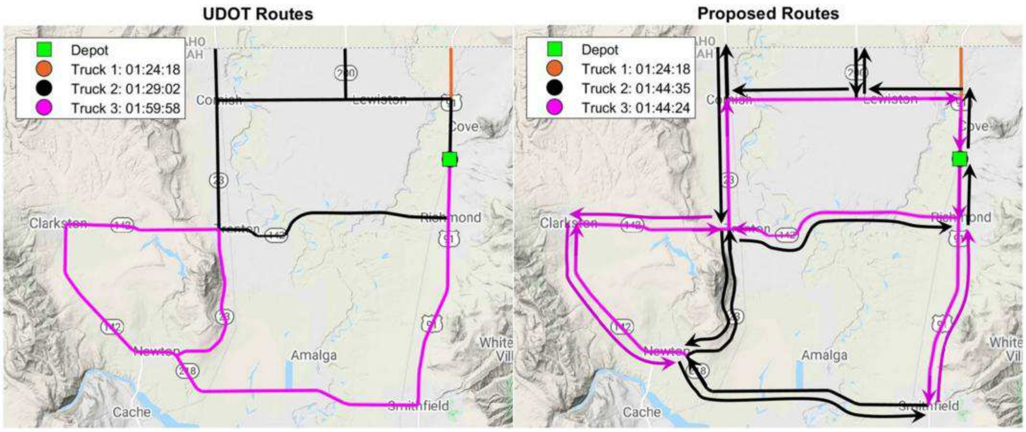
routes, we formulate and solve a **min-max VRP** where the objective is to minimize the duration of the longest route for North Logan.

The resulting routes produce identical performance in terms of total travel time and deadhead miles, but reduce the turnaround time by about 13% compared with UDOT's current routes (see Table 2). As shown in the left panel of Figure 8, UDOT utilized truck 3 to clear snow from roadways represented by pink lines, resulting in longer route durations compared with truck 2, which serviced the roadways indicated by black lines. In contrast to UDOT's unbalanced assignment, our proposed routes for truck 2 and truck 3 include exchanges of roadways previously assigned by UDOT. For a more detailed, side-by-side comparison of the truck movements along the two sets of routes, please refer to the video available at NorthLogan_BasicSetting.mp4.

Because of the high traffic volume on US-91, which has first priority, and the potential mobility issues caused by snow accumulation, the local management teams want to reduce the completion time for snow removal operations on the highway. Given that US-91 features a total of five lanes implementing echelon routes would be a suitable strategy to enhance the efficiency of snow removal on this road segment. Echelon routes involve multiple trucks working in parallel, with each truck assigned to clear a specific lane or set of lanes. This approach enables focused and synchronized snow removal on road segments with multiple lanes. There is, however, a potential tradeoff between improved efficiency on these segments and the overall efficiency across the region, as the vehicles that make up the echelon formation will not be available for other routes until the echelon route is completed.

Joint optimization of echelon and nonechelon routes is quite difficult because of the high degree of coordination between trucks that would be required. We use a heuristic but practicable two-step optimization approach. In the first step, we create a directed graph for the targeted segment (in this case, US-91) where an echelon route is required; the precise procedure is outlined in the Online Appendix. We then solve a **TSP** on this graph to determine an optimal route for clearing it. Subsequently, we solve a **min-max VRP** to find the most efficient routes for the remaining road segments, with the objective of minimizing the turnaround time. We repeat this procedure for different echelon sizes and select the best. This

Figure 8. (Color online) Static Visualization of UDOT's Routes and Proposed Routes for North Logan



Notes. In the proposed road network, a road link represented by a single line without arrows (or two arrow lines in identical color) indicates that both directions are serviced by one truck. Conversely, a road link depicted by two different colored lines with arrows signifies that one truck services one lane while another truck cleans the lane in the opposite direction.

Table 3. Performance of the Proposed Routes with Varying-Size Echelons in North Logan

Two-truck echelon routes						Three-truck echelon routes					
			Deadhead						Deadhead		
Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)	Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)
1	102.8	54.8	3.4	1.8	6.6	1	121.8	64.9	30.9	16.5	6.0
2	95.2	50.8	6.9	3.6	5.9	2	95.2	50.8	6.9	3.6	5.8
3	102.0	54.4	14.6	7.8	5.8	3	125.2	66.7	29.3	15.6	6.3
Total	300.0	160.0	24.9	13.2	18.3	Total	342.2	182.4	67.1	35.7	18.3
Max	102.8	54.8	14.6	7.8	6.6	Max	125.2	66.7	30.9	16.5	6.3

Note. The animations of routes with two-truck and three-truck echelons are available at NorthLogan_Two-truckEchelon.mp4 and NorthLogan_Three-truckEchelon.mp4.

approach cannot be guaranteed to produce optimal plowing routes, but is straightforward to compute and implement, and the results significantly outperform the current routes used by UDOT.

Table 3 reports the performance of proposed routes with echelon sizes of two and three trucks. Using a two-truck echelon, turnaround time is reduced by 1.6% compared with UDOT's routes, whereas travel time and deadhead miles actually increase by 2.3% and 38%, respectively. However, the advantage of the echelon formation is that it is able to clean all road lanes of US-91 in only 46 minutes, representing a 45% reduction compared with optimal routes that do not use the echelon approach. For this reason, UDOT opted to use a two-truck echelon for US-91. Nevertheless, it is necessary to pay careful attention to the number of trucks used in the echelon formation. A three-truck formation is able to clean US-91 in 42 minutes (down from 46 for two trucks), but now there is a 14% increase in total travel time and a 22% increase in turnaround time, because the focus on US-91 leaves no trucks available for other road segments.

As mentioned previously, we give a detailed discussion of South Logan in the Online Appendix. It is worth noting that our methods similarly lead to significant improvements there, including an 11% reduction in total travel time. However, echelon routing is far less beneficial in South Logan than in North Logan: the improvement obtained on US-91 is not sufficient to outweigh the loss in region-wide efficiency.

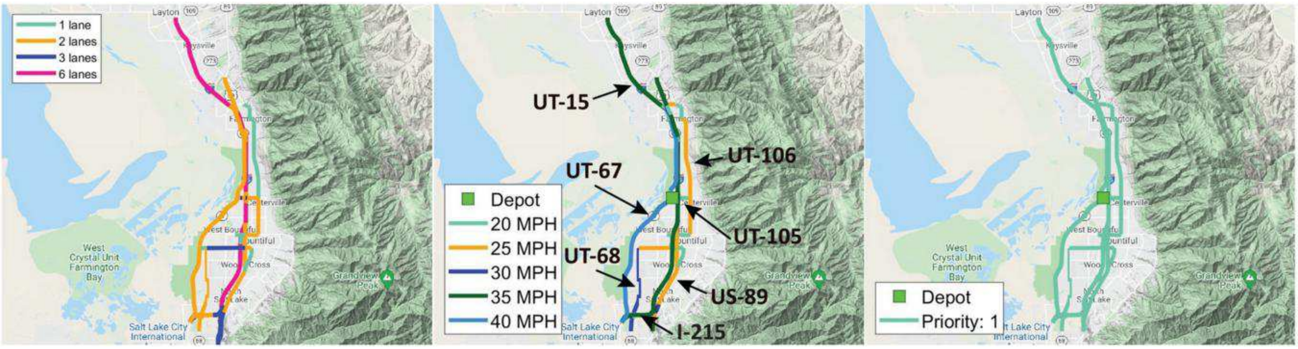
Centerville: Decentralized Optimization vs. Centralized Optimization

Centerville has a well-developed road network that connects the city with surrounding areas. The serviced roadways, including I-15, I-215, UT-67, UT-68, US-89, UT-105, and UT-106, are detailed in Figure 9, which provides information on the number of lanes, plowing speed, and road priority for each. UDOT divides the Centerville road network into four subnetworks based on considerations of functionality, traffic volumes, and network connectivity. This division serves to streamline operations and reduce complications when plowing across diverse road classifications.

Subnetwork 1 consists of I-15 and I-215, both of which have six lanes in each direction. To clear all lanes simultaneously and ensure that no snow remains on the interstates, two tow plows and two single-wing plows must work in an echelon formation. Because of these strict constraints, no improvements could be made to UDOT's existing routes for these roads.

Subnetwork 2 consists of UT-67 and a short section of US-89, which were cleared by two single-wing trucks in an echelon formation devised by UDOT. The echelon formation allowed the trucks to clear snow from this

Figure 9. (Color online) The Number of Lanes, Plowing Speed, and Priority of Responsible Roads in Centerville



four-lane controlled-access parkway, including the ramps, in two passes. One drawback of this strategy, however, is that the two trucks that formed the echelon continued along UT-67, which had already been cleared, to reach US-89, thus incurring a significant number of deadhead miles. This cost is a consequence of the echelon formation and cannot be reduced by tweaking the routes. To address this issue, we heuristically solve a **min-max VRP** without any echelon routing at all. The resulting routes significantly reduce the total travel time, turnaround time, and deadhead miles by 22%, 20%, and 40%, respectively. Because all roads in this subnetwork have the same priority, breaking up the echelon formation does not have any adverse effects. This is another clear illustration that echelon routes should be used selectively, on a case-by-case basis.

Subnetwork 3 encompasses UT-68 and US-89, which were cleared by two single-wing trucks utilizing an echelon formation. To optimize operations in this subnetwork, we construct a new graph accounting for the echelon routing setting and solve a **TSP** to minimize the total travel time. Unlike subnetwork 2, the favorable layout of UT-68 and US-89 facilitates a more streamlined snow removal operation, where trucks can progress along their designated routes without having to frequently traverse roads that have already been cleaned. Consequently, the proposed echelon route achieves a 7% reduction in total travel time, accompanied by a 27% decrease in deadhead miles.

In subnetwork 4, which comprises UT-105 and UT-106, only one single-wing truck is assigned to undertake the snow removal operations. To optimize the plowing routes that minimize the travel time, we construct a **TSP** based on the input data specific to this subnetwork. The resulting route achieves substantial reductions in travel time and deadhead miles (e.g., 16% reduction in travel time).

Table 4 shows that the proposed routes obtained via decentralized optimization for Centerville lead to significant benefits in terms of reducing total travel time, turnaround time, and deadhead miles. These improvements not only make snow removal cheaper but also increase safety and mobility for drivers. Across the whole road network, the 9% reduction in total travel time and 24% reduction in deadhead miles help lower fuel costs and minimize wear and tear on equipment, whereas the 19% reduction in turnaround time enables crews to clear snow more quickly, reducing travel delays and improving safety.

We also considered a centralized approach where the boundaries between subnetworks were completely removed. The results, shown in Table 5, suggested that even greater improvements could be obtained (e.g., an 18% reduction in total travel time compared with UDOT's routes). However, centralized routing would also increase the complexity of snow removal operations. In a decentralized setting, trucks typically travel along road segments that fall into the same classification, minimizing the need for frequent adjustments to ensure safe plowing activities. Conversely, centralized routes may require trucks to navigate road segments with varying classifications, necessitating closer attention from drivers and more frequent changes in driving speed, which may adversely impact safety. For these reasons, local management was hesitant to implement these routes, and elected to go with an optimized set of

Table 4. Performance Comparison Between UDOT's Routes and Proposed Routes Obtained via Decentralized Optimization in Centerville

UDOT routes						Proposed routes					
			Deadhead						Deadhead		
Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)	Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)
Subnetwork 1: I-15 & I-215 (Centerville_Subnetwork1.mp4)											
_1_	_111.6_	_60.4_	_25.9_	_14.2_	_13.3_	_1_	_111.6_	_60.4_	_25.9_	_14.2_	_13.3*_
_2_	_111.6_	_60.4_	_43.6_	_21.3_	_12.4_	_2_	_111.6_	_60.4_	_43.6_	_21.3_	_12.4*_
3	126.8	66.1	49.8	24.4	5.2	3	126.8	66.1	49.8	24.4	5.2*
4	126.8	66.1	44.2	22.6	5.4	4	126.8	66.1	44.2	22.6	5.4*
Subnetwork 2: UT-67 & US-89 (Centerville_Subnetwork2.mp4)											
5	172.3	96.3	82.9	49.2	5.8	5	131.3	71.3	66.4	34.5	4.6
6	172.3	96.3	94.2	53.1	5.3	6	137.9	79.9	39.9	27.1	6.5
Subnetwork 3: UT-68 & US-89 (Centerville_Subnetwork3.mp4)											
7	126.4	56.7	30.1	13.7	5.3	7	117.1	52.1	18.7	8.4	5.4
8	126.4	56.7	52.2	23.8	4.1	8	117.1	52.1	42.9	19.9	4.0
Subnetwork 4: UT-105 & UT-106 (Centerville_Subnetwork4.mp4)											
9	126.3	50.7	34.2	13.6	4.6	9	104.9	42.3	12.9	5.2	4.6
Total	1,200.5	609.7	457.1	235.9	61.4	Total	1,085.1	550.7	344.3	177.6	61.4
Max	172.3	96.3	94.2	53.1	13.3	Max	137.9	79.9	66.4	34.5	13.3

Notes. The asterisks in the rightmost column indicate that the proposed route for the truck is identical to UDOT's route. The italicized cells indicate that the truck is a tow-plow truck.

Table 5. Performance of the Proposed Routes Obtained via Centralized Optimization

Truck no.	Duration (min)	Distance (miles)	Deadhead (min)	Deadhead (miles)	Salt (tons)
1	*111.6*	*60.4*	*25.9*	*14.2*	*13.3**
2	*111.6*	*60.4*	*43.6*	*21.3*	*12.4**
3	111.2	67.8	14.3	4.5	7.9
4	112.8	57.9	50.2	24.4	4.1
5	103.0	45.4	14.8	3.6	5.2
6	89.8	40.4	22.5	7.4	4.1
7	133.5	79.2	56.9	32.1	5.8
8	99.1	46.8	31.2	12.8	4.2
9	102.4	57.3	44.1	22.0	4.4
Total	975.0	515.6	303.5	142.3	61.4
Max	133.5	79.2	56.9	32.1	13.3

Notes. The asterisks in the rightmost column indicate that the proposed route for the truck coincides with the one designed by UDOT. Italics indicate that the truck is a tow-plow truck.

routes for the original, decentralized partition of the network.

Wellsville: Benefits of Increasing Fleet Size

During the winter seasons, the region experiences frequent snowfalls, making it critical to implement efficient snow removal operations to maintain traffic mobility and safety, particularly along the long road leading into the canyon (see Figure 10). UDOT services US-91 and several state roadways within the area, including UT-23, UT-101, UT-165, and UT-252, using four single-wing trucks. Of these roadways, UT-23 and UT-101 are two long arms that access Newton town in Logan and Uinta-Wasatch-Cache National Forest, respectively.

We analyze UDOT's routes and discover an extreme imbalance in workload distribution (see the left part of Table 6). Specifically, truck 4 had the longest duration among the four trucks, lasting approximately 206 minutes, because of its additional task of clearing snow from UT-101 through the canyon while also servicing UT-23. To address this issue, we solve a **min-max VRP** with the current fleet configuration. The resulting routes reduce the turnaround time by 24%, without significantly increasing the total travel time and deadhead miles. Table 6 presents the performance of the two sets of plowing routes. As shown in the animation (Wellsville_BasicSetting.mp4), the proposed routes assign truck 2 to service the segment of UT-105 in the north after completing work on UT-91, while truck 4 focuses solely on cleaning UT-23. This helps reduce the workload on truck 4 and ensures a balanced workload distribution among the plowing trucks.

We also find that, even after optimization, the resulting turnaround time of the proposed routes is the second highest among all the regions considered, at 156 minutes (see Figure 6(b)). Given that Wellsville is located at the intersection of several major highways and routes that provide access to neighboring cities like Logan and Brigham City, UDOT is interested in knowing the benefits of adding another truck to the fleet. By rerunning the same model with five trucks, we obtain a setup that reduces the turnaround time to 116 minutes, representing a significant 26% improvement. Importantly, this is achieved without increasing the deadhead miles, indicating the efficient utilization of all five trucks (see Table 7 for details). We have provided an animation of the five routes at Wellsville_FleetExtension.mp4. UDOT is currently considering increasing the fleet size for the upcoming winter season.

Laketown: Benefits of Adding a Satellite Replenishment Station

Laketown is situated near Bear Lake, a significant freshwater lake located on the Idaho-Utah border. UDOT is responsible for winter road maintenance on the state roadways in the area, including UT-16, UT-30, and UT-39 (see Figure 11), which are serviced by four single-wing trucks based at two depots to ensure safe driving conditions during the winter months when heavy snowfalls are frequent. Once more, we solve a **min-max VRP** to balance the workload. Upon closer inspection, it becomes evident that a significant number of deadhead miles cannot be eliminated, as one

Figure 10. (Color online) The Number of Lanes, Plowing Speed, and Priority of Responsible Roads in Wellsville

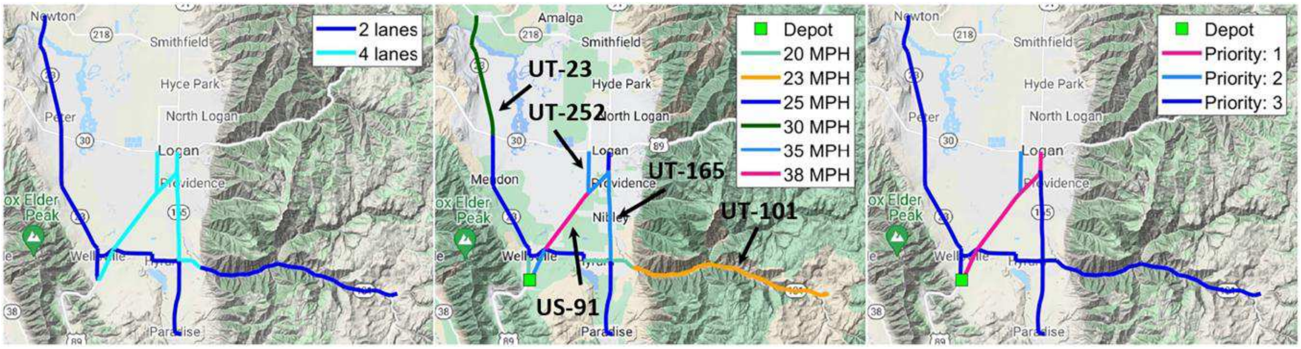


Table 6. Performance Comparison Between UDOT's Routes and Proposed Routes with Four Single-Wing Trucks in Wellsville

UDOT routes						Proposed routes					
			Deadhead						Deadhead		
Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)	Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)
1	75.6	29.0	4.8	1.6	3.4	1	116.0	45.4	7.6	4.4	5.1
2	63.7	36.9	0.0	0.0	4.6	2	63.7	36.9	0.0	0.0	4.6*
3	63.7	36.9	0.0	0.0	4.6	3	63.7	36.9	0.0	0.0	4.6*
4	206.4	82.9	44.9	16.6	8.2	4	156.3	66.6	32.3	13.8	6.5
Total	409.4	185.7	49.7	18.2	20.8	Total	399.7	185.8	39.9	18.2	20.8
Max	206.4	82.9	44.9	16.6	8.2	Max	156.3	66.6	32.3	13.8	6.5

Note. The asterisks in the rightmost column indicate that the proposed route for the truck is identical to UDOT's route.

truck needs to traverse a lengthy road segment that has already been serviced by another truck, to return to the depot. Therefore, we propose to reduce the fleet size by one truck and instead to add a salt replenishment station near the intersection of UT-16 and UT-39 to enable en route refill.

We observe an imbalance in the workload between trucks, as indicated in the left part of Table 8, with the plowing route for truck 4 taking 31% longer than the route for truck 3. Better and more balanced routes can be obtained by reassigning certain segments of UT-16 to the depot at Randolph. The optimal routes for the best-performing reassignment achieve a 23% reduction in turnaround time. The animation of the optimized routes is available at Laketown_BasicSetting.mp4.

Studying the proposed routes for four trucks, we find 21 deadhead miles on the road segment between Randolph and Woodruff arising because truck 3 returns to the depot along a lane that has already been cleared by truck 4. We might consider reducing the fleet size to three trucks, but, as can be seen from the animation at Laketown_ThreeTrucks_SaltStation.mp4, truck 3 will be unable to complete its route on UT-16 because it runs out of salt 1.37 miles from the depot. By adding a salt refill station at the intersection of UT-16 and UT-39 (see Figure 12), we can solve this issue and (as shown in the right part of Table 9) achieve a reduction of approximately 14% in total travel time compared with the current four-truck configuration. Importantly, our proposed routes achieve this improvement without incurring any deadhead miles, while maintaining the turnaround time—though it should be noted that this would be extended by the duration required to load 350 lbs of salt at the salt refill station.

Table 7. Performance of the Proposed Routes with Five Single-Wing Trucks in Wellsville

			Deadhead		
Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)
1	67.8	27.8	7.6	4.4	2.9
2	63.7	36.9	0.0	0.0	4.6
3	63.7	36.9	0.0	0.0	4.6
4	88.4	38.7	0.0	0.0	4.8
5	116.0	45.4	32.3	13.8	3.9
Total	399.6	185.7	39.9	18.2	20.8
Max	116.0	45.4	32.3	13.8	4.8

Conclusion

Over the course of this study, we engage with management across 12 distinct regions to identify insights and recommendations. The following key takeaways may be useful for comparable efforts in other regions worldwide:

- The animations of plowing routes offer a powerful tool for effective communication in meetings with managers. Prior to optimizing snowplowing routes for a specific region, we usually conduct a meeting with the manager to discuss the current configuration and existing plowing routes. To establish an accurate baseline, we create an animation showcasing the existing plowing routes and seek their confirmation. Following the optimization process, we reconvene with the manager and present our proposed routes, also in animated form. Both animations vividly illustrate the sequence of road segment servicing and provide details on truck turns. They serve as an engaging platform that encourages managers to actively participate, ask questions, and provide feedback.
- A complex network spanning a wide geographical area exhibits significant variety in road classifications and connectivity. For this reason, there is no "one-size-fits-all" approach that works well everywhere. Managers prefer a decentralized approach where the network is divided into smaller subnetworks, each with its own unique needs and service goals. Although greater centralization can improve efficiency on paper, the resulting routes can introduce additional complexity and operational risk, which are usually not preferred.
- Echelon routing can be a useful improvement in some situations, but the number of trucks allocated for this purpose must be carefully chosen. Even then, a case-by-case evaluation is required.

Figure 11. (Color online) The Number of Lanes, Plowing Speed, and Priority of Responsible Roads in Laketown

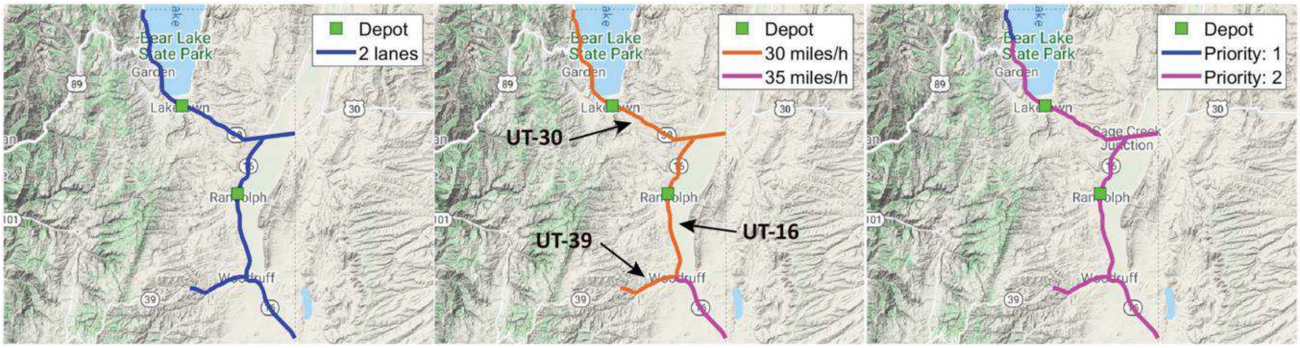


Table 8. Performance Comparison Between UDOT's Routes and Proposed Routes with Four Trucks in Laketown

UDOT routes						Proposed routes					
			Deadhead						Deadhead		
Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)	Truck no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)
1	56.8	28.4	0.0	0.0	3.5	1	56.8	28.4	0.0	0.0	3.5*
2	62.0	31.0	0.0	0.0	3.9	2	84.0	42.0	0.0	0.0	5.2
3	74.8	37.4	21.1	10.5	3.3	3	83.6	41.8	42.2	21.1	2.6
4	108.7	57.3	21.1	10.5	5.8	4	77.9	41.9	0.0	0.0	5.2
Total	302.3	154.1	42.2	21.0	16.5	Total	302.3	154.1	42.2	21.1	16.5
Max	108.7	57.3	21.1	10.5	5.8	Max	84.0	42.0	42.2	21.1	5.2

Note. The asterisk in the rightmost column indicates that the proposed route for the truck is identical to UDOT's route.

Figure 12. (Color online) Static Visualization of UDOT's Routes and Proposed Routes for Three Single-Wing Trucks with a Satellite Refill Station in Laketown

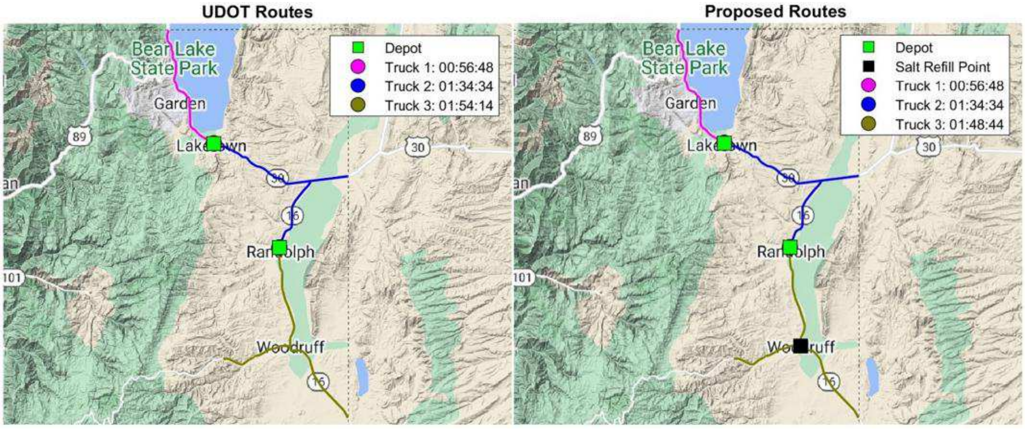


Table 9. Performance of the Proposed Routes for the Future-Coming Scenario in Laketown

Proposed routes without a refill station						Proposed routes with a refill station					
			Deadhead						Deadhead		
Route no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)	Route no.	Duration (min)	Distance (miles)	(min)	(miles)	Salt (tons)
1	56.8	28.4	0.0	0.0	3.5	1	56.8	28.4	0.0	0.0	3.5*
2	94.5	47.2	0.0	0.0	5.9	2	94.5	47.2	0.0	0.0	5.9*
3	114.2	60.0	5.4	2.7	7.1	3	108.7	57.3	0.0	0.0	7.1
Total	265.5	135.6	5.4	2.7	16.5	Total	260.1	132.9	0.0	0.0	16.5
Max	114.2	60.0	5.4	2.7	7.1	Max	108.7	57.3	0.0	0.0	7.1

Note. The asterisks in the rightmost column indicate that the proposed route for the truck remains the same under scenarios with and without a refill station.

- Minimizing the turnaround time for the entire region results in routes that provide improved service across roads of varying priorities. This observation simplifies the design of route optimization algorithms, as it eliminates the need to account for the priorities of different roads explicitly. Because this insight is gained from studying sparse rural networks, further testing is necessary to assess its applicability to more complex regions with a greater diversity of road priorities.
- Minimizing the turnaround time for the entire region additionally results in relatively short routes that do not exceed the capacity of salt spreaders. Similar to the previous case, this enables the application of optimization algorithms without the need to explicitly model salt (or fuel) constraints. In situations where such an approach produces a route with excessive plowing distance, the problem could be resolved by deploying a satellite salt pile to enable en route refill. This is easier to accomplish in rural areas with a large amount of state-owned land than in urban areas.
- The use of double-wing and tow-plow trucks is typically limited to major roads, such as interstates, where they must operate in echelon formations to clear all lanes at once. Consequently, there is limited room for improving their routes. In such scenarios, deploying algorithms that explicitly account for a heterogeneous fleet and optimizing routes for all vehicles may not be effective.

The work described is conducted as part of a time-sensitive project that aims at improving the efficiency of snowplowing operations in northern Utah while avoiding significant operational changes, such as relocating plows and drivers between regions. In the future, if UDOT or other relevant entities provide historical or real-time data that include information on weather patterns, road conditions, and other relevant factors, our research will incorporate uncertainty and/or real-time route updates into snow removal. This will enable us to adapt to the dynamic nature of realistic plowing operations, ensuring more effective and timely snow clearance.

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Verification Letter

Rhett G. Arnell, Winter Maintenance Engineer, Department of Transportation, Calvin Rampton Complex, 4501 South 2700 West, P.O. Box 141265, Salt Lake City, UT 84114, writes:

"I am pleased to provide information about the project 'Assessing and Improving Efficiency of Snowplowing Operations via Data and Analytics,' described in the article 'Improving Snowplowing Operations in Utah Through Optimization and Visualization,' which was funded and implemented by the Utah Department of Transportation (UDOT). As the project coordinator, I have worked with Yinhu Wang for about ten months on assessing and improving efficiency of snowplowing operations in 12 maintenance stations in northern Utah.

"Firstly, Yinhu met with the maintenance station foremen to obtain the first-hand knowledge of current plow routes implemented by UDOT and station specific information that pertains to their plowing activities such as fleet size and plow types as well as other plowing policies. With the important information, Yinhu reconstructed current snowplow routes for each station and evaluated route performance. The metrics used for performance evaluation included total travel time, deadhead miles and turnaround time. The performance of original snowplow routes provided a baseline to evaluate the efficiency of proposed routes.

"Then, Yinhu optimized the snowplow routes for each maintenance station and had meetings with maintenance station foremen to validate the proposed routes. For each station, the original and proposed routes were animated and compared 'side by side' (see the routes for north Logan via https://www.youtube.com/watch?v=BhgK-38UUiY), which were particularly helpful to see the difference between two sets of routes. The proposed routes improved the total travel time, deadhead miles and turnaround time by 5.04%, 15.01% and 14.84% on average across 12 Maintenance Stations, respectively (see https://youtu.be/Z1n-aXYtS18 and https://youtu.be/_up1UDmRqLg for two sets of snowplow routes). These improvements are considerable for snow removal operations.

"Please don't hesitate to contact me if you have any questions."

Yinhu Wang is currently a PhD candidate at the University of Utah, with a research focus on optimizing resource allocation and vehicle routing, particularly for the recovery of transportation systems following natural disasters.

Ye Chen is an assistant professor of statistical sciences and operations research at Virginia Commonwealth University. He received a PhD in statistics from the University of Maryland in 2018. His research interests include stochastic optimization, statistical learning, applied probability, and transportation science. He was a finalist in the Best Theoretical Paper Award competition at the 2016 Winter Simulation Conference, and a recipient of the 2022 INFORMS Transportation Science and Logistics Society Best Paper Award.

Ilya O. Ryzhov is a professor of operations management and management science in the Robert H. Smith School of Business at the University of Maryland. His research deals with business analytics with application to logistics and public sector operations. He coauthored the book *Optimal Learning* (Wiley, 2012) and received the 2017 Outstanding Simulation Publication Award from the INFORMS Simulation Society, as well as the 2022 Best Paper Award from the INFORMS Transportation Science and Logistics Society.

Xiaoyue Cathy Liu is an associate professor in civil and environmental engineering at the University of Utah. Her research expertise is in data-driven applications in transportation and multimodal transportation network modeling. Dr. Liu has authored and coauthored over 60 journal articles in such journals as *Transportation Research B, C, D*; *IEEE Transactions on Intelligent Transportation Systems*; *Computer-Aided Civil and Infrastructure Engineering*; *Computers, Environment and Urban Systems*; and the *Journal of Transport Geography*, among others. Her work stands at the forefront of integrating innovative technologies with transportation engineering to address complex challenges in the field.

Nikola Marković is an assistant professor of civil and environmental engineering at the University of Utah. His research uses operations research and data science to improve the efficiency of transportation systems. He was a recipient of the 2015 Glover-Klingman Prize and the 2022 INFORMS Transportation Science and Logistics Society Best Paper Award.