Report No. K-TRAN: KU-20-3 ▪ FINAL REPORT ▪ September 2023

Snowplow Route Optimization for the Kansas Roadway System

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1 **Report No.** K-TRAN: KU-20-3	2 **Government Accession No.**	3 **Recipient Catalog No.**

4 **Title and Subtitle** Snowplow Route Optimization for the Kansas Roadway System	5 **Report Date** September 2023 6 **Performing Organization Code**
7 **Author(s)** Dan Tran, Ph.D., P.E. Phuong Nguyen, Ph.D.	8 **Performing Organization Report No.**
9 **Performing Organization Name and Address** The University of Kansas Department of Civil, Environmental & Architectural Engineering 1530 West 15th St. Lawrence, KS 66045-7609	10 **Work Unit No. (TRAIS)** 11 **Contract or Grant No.** C2149
12 **Sponsoring Agency Name and Address** Kansas Department of Transportation Bureau of Research 2300 SW Van Buren Topeka, Kansas 66611-1195	13 **Type of Report and Period Covered** Final Report July 2019 – June 2022 14 **Sponsoring Agency Code** RE-0794-01

15 **Supplementary Notes**
For more information write to address in block 9.

16 **Abstract**

State departments of transportation (DOTs) spend substantial resources on snow and ice control activities and operations each year. The Kansas DOT (KDOT) spends from $7 million to $22 million annually. KDOT winter maintenance operations currently deploy a fleet of 591 snowplow trucks, including 1,182 drivers and approximately 200 engineering technicians, to maintain more than 25,000 lane miles. The deployment of so many trucks over a vast maintenance area makes it operationally difficult to determine optimal maintenance routes and fleet size.

The objective of this project was to develop a snowplow truck route optimization plan for one district (District 4) to help KDOT enhance snow removal efficiency by justifying the fleet size and efficiently allocating limited resources while maintaining roadway safety and reliability. The fleet optimization model was developed using geographic information system (GIS) base maps created by a commercial software package, ArcGIS, and its Network Analyst extension and vehicle routing problem toolset. By iteratively removing the least efficient trucks and updating a new GIS base map, the optimization model minimized the fleet size and maintained the current level of service (LOS) for all 144 snow and ice routes within District 4. The current LOS of 71% increased to 81% when relevant snow and ice routes were grouped without adding trucks to the current fleet optimization. The proposed optimization model also decreased the total travel time needed to treat all snow and ice routes in District 4 by approximately 29 hours for one treating iteration. These study results could also be applied to other districts in Kansas.

17 **Key Words** Snowplows, Snow & Ice Control, Snow Removal, Maintenance Practices, Optimization	18 **Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service www.ntis.gov.

19 **Security Classification (of this report)** Unclassified	20 **Security Classification (of this page)** Unclassified	21 **No. of pages** 146	22 **Price**

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Final Report

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A Report on Research Sponsored by

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

and

THE UNIVERSITY OF KANSAS
LAWRENCE, KANSAS

September 2023

PREFACE

The Kansas Transportation Research and New-Developments (K-TRAN) Program from the Kansas Department of Transportation (KDOT) funded this research project. K-TRAN is an ongoing, cooperative, and comprehensive research program that addresses transportation needs in Kansas using academic and research resources from KDOT, Kansas State University, and the University of Kansas. Transportation professionals at KDOT and the universities jointly develop projects included in the research program.

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Abstract

State departments of transportation (DOTs) spend substantial resources on snow and ice control activities and operations each year. The Kansas DOT (KDOT) spends from $7 million to $22 million annually. KDOT winter maintenance operations currently deploy a fleet of 591 snowplow trucks, including 1,182 drivers and approximately 200 engineering technicians, to maintain more than 25,000 lane miles. The deployment of so many trucks over a vast maintenance area makes it operationally difficult to determine optimal maintenance routes and fleet size.

The objective of this project was to develop a snowplow truck route optimization plan for one district (District 4) to help KDOT enhance snow removal efficiency by justifying the fleet size and efficiently allocating limited resources while maintaining roadway safety and reliability. The fleet optimization model was developed using geographic information system (GIS) base maps created by a commercial software package, ArcGIS, and its Network Analyst extension and vehicle routing problem toolset. By iteratively removing the least efficient trucks and updating a new GIS base map, the optimization model minimized the fleet size and maintained the current level of service (LOS) for all 144 snow and ice routes within District 4. The current LOS of 71% increased to 81% when relevant snow and ice routes were grouped without adding trucks to the current fleet optimization. The proposed optimization model also decreased the total travel time needed to treat all snow and ice routes in District 4 by approximately 29 hours for one treating iteration. These study results could also be applied to other districts in Kansas.

Acknowledgments

This project was made possible by the sponsorship of the Kansas Transportation Research and New-Developments (K-TRAN) Research Program and the Kansas Department of Transportation (KDOT). The authors of this report would like to thank the project monitor, Mr. Clay Adams, Director of Field Operations, Mr. John Hrenak, former District Maintenance Engineer, and Ms. Jaci Vogel, former Bureau Chief of Maintenance, for their essential help and support with the data collection model development guidance and suggestions. The authors also acknowledge the valuable assistance and technical guidance from members of the K-TRAN Research Committee in the course of performing this study.

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Chapter 1: Introduction

1.1 Background

The management of winter maintenance operations is a complex but critical process to achieve safe travel routes (Holik & Anderson, 2019). The Federal Highway Administration (FHWA) has provided general guidelines for state departments of transportation (DOTs) to improve reliability, safety, and mobility on roadways during winter months (Alfelor & Yang, 2011). In addition, several state DOTs have attempted to streamline their snow removal process using heuristic approaches, mathematical models, and off-the-shelf software packages (Liu et al., 2014; Dowds et al., 2013). For example, the Colorado DOT (CDOT) utilizes a snowplow route optimization procedure with what-if scenario modeling to develop a base map for its winter highway treatment routes in Region 4 (Harley, 2016). Similarly, the Ohio DOT (ODOT) employs a route optimization program based on the geographic information system (GIS) to model snow and ice routes and consequently optimize fleet size and determine if new truck facilities are needed to improve the level of service (LOS) for winter operations in three of their 10 districts (Schneider et al., 2016). Recent studies (Dong et al., 2020; Li et al., 2018; Blandford et al., 2017) have incorporated modern technologies (e.g., GIS) and modeling techniques (optimization algorithms) to collect and analyze spatial and geographic data to increase efficiency and reduce the number of trucks needed to accomplish snow removal operations.

1.2 Research Problem

The Kansas DOT (KDOT) spends $7 million to $22 million annually on snow and ice control activities and operations, and KDOT currently deploys a fleet of 591 snowplow trucks, 1,182 drivers, and approximately 200 engineering technicians to conduct winter maintenance operations on more than 25,000 lane miles throughout the state (KDOT, 2017). The deployment of so many trucks over a vast maintenance area makes it operationally difficult to determine optimal maintenance routes and fleet size and satisfy LOS requirements for snow and ice route removal operations. Therefore, this study investigated the current development and implementation of fleet optimization models for snow and ice route removal operations in the United States and Canada to identify the potential need for an advanced route optimization model to improve snow removal efficiency. The objective of this study was to develop a snowplow fleet optimization model for KDOT's winter maintenance operations in District 4. These study results could also be applied to other districts in Kansas.

1.3 Objectives

The primary goal of this study was to develop a snowplow route optimization plan for District 4 in Kansas to enhance snow removal efficiency by justifying the fleet size and specifying the allocation of limited resources while maintaining roadway safety and reliability. This project was designed with three main objectives: (1) digitize all snow and ice base routes and available truck facilities throughout District 4; (2) identify optimized routes and fleet size for current snow and ice route removal operations; and (3) determine the total number of operational trucks needed for District 4 to maintain current LOS requirements. The outcomes of this study are expected to benefit KDOT by providing information to optimize the fleet size of winter operational trucks and suggest snow and ice routes that meet LOS requirements.

1.4 Report Organization

This report consists of seven chapters. Chapter 1 introduces the subject area and covers the scope and objectives. Chapter 2 provides a literature review to support the understanding of existing snowplow fleet optimization models, including winter maintenance approaches in sample DOTs and current practices of GIS-based snow and ice route removal practices. Chapter 3 presents information on the project setting for District 4 and snow and ice model development. Chapter 4 includes the current state of the practice of snow and ice removal in District 4, results of the fleet optimization, and model verification processes. Chapter 5 presents future implementation plans for optimized trucks within District 4, and Chapter 6 includes research findings and deliverables. Finally, Chapter 7 briefly summarizes the information presented in previous chapters and offers conclusions and suggestions for future research.

Chapter 2: Literature Review

2.1 Introduction

This literature review focuses on snowplow optimization methodologies and models, with an emphasis on the current state of the practice for optimizing snow removal operations. Literature searches were conducted using academic search engines such as Engineering Village and Google Scholar, as well as research institutions such as the Transportation Research Board (TRB), the FHWA library, several state DOT websites, and general internet search engines. The literature searches specifically focused on obtaining documents that would support the development of snowplow optimization models. Typical keywords and search terms included snowplow, optimization, GIS-based route optimization, winter maintenance operations, fleet optimization, and snow removal activities. The research team reviewed and synthesized each document to obtain relevant information, including key summaries of past snowplow optimization practices, focusing on original work rather than summaries. Cross references of the literature helped identify essential advances in the domain.

Although an increasing number of computerized applications are used to facilitate snow and ice route optimization, these applications are not yet commonly implemented by winter maintenance operators. This study focused on the development of snowplow optimization models, utilized tools (e.g., GIS-based software packages), and the evaluation and assessment processes related to the anticipated winter operations budget. The following sections describe core components of snowplow optimization methodology, including snowplow optimization tools such as ArcGIS, Network Analyst, and vehicle routing problems. Key findings and effective practices from eight state DOTs (Colorado, Delaware, Iowa, Kentucky, Minnesota, Missouri, Ohio, and Vermont) that have investigated snowplow optimization models are presented in Appendix A.

2.2 Overview of Snowplow Optimization

Roadway snow and ice removal is an essential operation in many state DOTs, including KDOT. However, efficient implementation of winter maintenance activities involves complex decisions that depend on staging, routing, and reloading of vehicle fleets for plowing, as well as spreading anti-icing or deicing materials (Dowds et al., 2016). State DOTs have been searching for cost-effective approaches to optimize snow and ice removal operations while minimizing equipment, fuel, material (e.g., salt), and labor costs. Although most snow and ice removal decisions are made by expert DOT personnel, computerized route optimization models are promising tools to improve the efficiency of winter maintenance operations (Dowds et al., 2016).

Snowplow route optimization methodology typically involves three main tasks: (1) dividing the road network into service areas, (2) optimizing snowplow routes within each area, and (3) allocating winter maintenance resources (e.g., plow trucks, salt, or labor) for the service areas. For example, ODOT utilized a GIS-based route model with the ArcGIS software package, Ersi's Network Analyst, vehicle routing problem toolsets, and a Q-travel program to optimize snowplow routes (Schneider et al., 2016). In the first step of the methodology, the optimization model collected snow and ice route information and truck facility locations (e.g., garages, outposts, refill stations) via handwritten and digital maps from three districts. Second, vehicle routing problem toolsets were used to load all plowing locations within the snow routes to create the route optimization model. Third, after creating a base map of all necessary layers of road network information, initial optimization was performed to analyze the current state of the practice for snow and ice route removal operations in the three districts and establish a baseline for the subsequent fleet optimization. The results included district overview maps, snow and ice route maps, and snow and ice route descriptions for all three districts. The fourth step of the methodology completed the verification process by identifying differences in the initial optimization and current practices in each district. Finally, the least efficient trucks were iteratively removed to conduct fleet optimization (Schneider et al., 2016).

Similarly, the Delaware DOT (DelDOT) established a route optimization model using the commercial software package ArcGIS and its extension Network Analyst with the vehicle routing problem toolset. The GIS-based snowplow route optimization included seven steps:

1. Create the base map with ArcGIS and input all necessary reference maps.
2. Establish roadway layers and target areas.
3. Review the roadway layers.
4. Update the roadway network.

5. Create plowing nodes for the routing problem.
6. Build the network dataset using Network Analyst.
7. Develop optimized snow routes using vehicle routing problems.

Figure 2.1 illustrates snowplow route optimization for DelDOT. First, a number of inputs were considered to develop the model, including road classification (interstates, primaries, secondaries, locals, and subdivisions), number of lanes, and intersection modifications. Then model parameters were defined, including length measurement (using ArcGIS to measure the length of each segment), travel time calculation (travel time = length/speed limit), and direction information (one-way or two-way) to determine an optimal fleet size for snowplow operations.

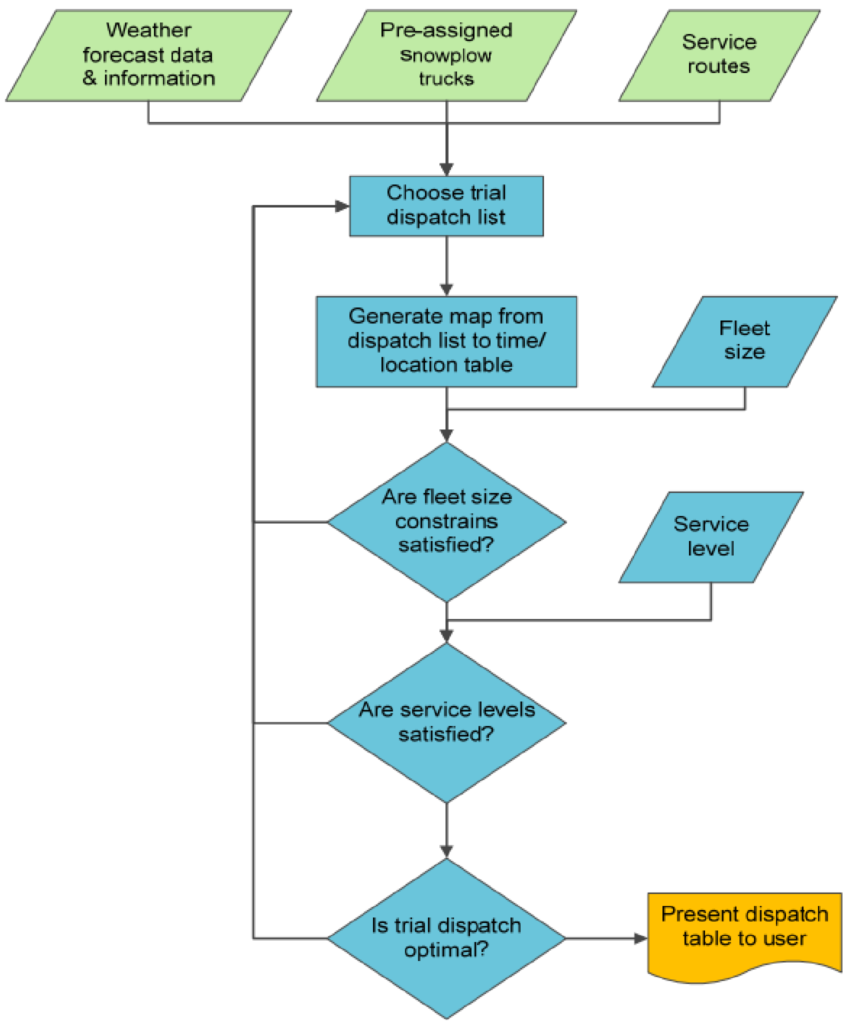

Figure 2.1: Standard Snowplow Operating Process at DelDOT
Source: Li et al. (2018)

2.3 Factors Affecting Snowplow Optimization Models

The primary goal of snowplow route optimization models is to identify efficient treatments for snow and ice routes to meet a set of targets or objective functions. The objective function may vary from state to state depending on the goals of fleet operators and a set of service standards. Typical objective functions include exceeding and maintaining the required LOS, optimizing winter maintenance resource reallocation (e.g., minimizing total service time and relevant costs associated with labor, materials, and equipment), and enhancing public safety. The National Cooperative Highway Research Program (NCHRP) Report 889 (2019) states that defining an LOS helps establish an expectation based on event severity and roadway type and increases effective monitoring of snow removal activities. However, collecting LOS data during a snow event is a complex task depending on the nature of the operational strategies involved (NCHRP Report 889, 2019). Figure 2.2 illustrates a linear relationship between LOS satisfaction, the severity of snow and ice events, and route priority. As shown in the figure, maximum LOS satisfaction is often obtained when the severity of the snow and ice event is low, and the highest route priority is fully treated. Therefore, the treating time and distance of snow routes must be optimized to maximize LOS satisfaction in winter maintenance operations.

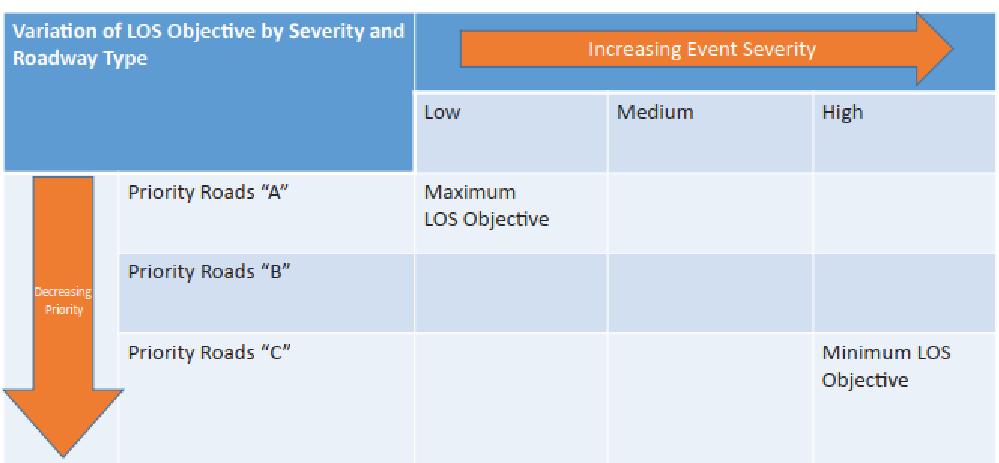

Figure 2.2: Relationships Between LOS Satisfaction and Roadway Priorities
Source: NCHRP Report 889 (2019)

As mentioned, LOS standards vary by state. For example, CDOT considers the following five LOS categories in their winter operations (Harley, 2016):

- Level A represents the highest LOS to maintain wet pavement throughout a storm on highly traveled highways and snowpack or icy but passable conditions on low-volume roads.
- Level B represents a high LOS to maintain wet pavement as much as possible on highly traveled highways with snowpack/icy conditions on low-volume roads.
- Level C represents a moderate LOS to maintain wet pavement as much as possible to patches of snow or slush on highly traveled highways and keep patches of snow or ice to predominately snowpack/icy conditions on low-volume roads.
- Level D represents a marginal LOS to maintain patches of "oatmeal" snow, packed snow/ice on highly traveled highways to predominately snowpack/icy conditions on low-volume roads.
- Level F represents poor LOS with limited clearing, plowing, and de-icing applications, resulting in impaired mobility on all roadways with patches of snow/ice on the highest-standard roads, potentially degenerating to snowpack/icy conditions and resulting slowdowns and/or delays.

Developing a snowplow route optimization approach often requires consideration of a range of factors to capture the dynamics of snow and ice operational activities and control. Dowds et al. (2016) identified the following factors or operational constraints for developing a snowplow optimization model:

- Vehicle capacity—Winter maintenance vehicles are limited to only the amount of fuel and materials needed to treat the route length;
- Mixed vehicle fleets—Fleets often include vehicles of various types, capacities, speeds, and equipment specifications;

- Vehicle and roadway compatibility—Not all winter maintenance vehicles are used for all types of roadways or lanes;
- Road service jurisdiction—Vehicles may need to traverse roads that are serviced by another agency to reach the start of their routes;
- Variable travel times—Speeds of vehicles may vary depending on whether they are actively servicing or deadheading;
- Multi-lane service—Roads with multiple lanes may require more passes to service or simultaneous service;
- Road prioritization—Road prioritization categories influence the allocation of vehicles among depots based on the mileage of high priority roadways in each depot's service area;
- Remote material supply—Remote salt domes can be used to extend the maximum route length for vehicles;
- Maximum cycle time—Maximum cycle time is the maximum time window in which roads or segments of a specific prioritization level must be serviced; and
- Maximum route length and workload balance—This factor involves shifting lengths or seeking to balance workloads across routes.

Because snow and ice control operations vary substantially from storm to storm, winter maintenance personnel prioritize each of the factors according to current state practices and available resources. However, factors or operational constraints can vary from state to state or between districts within a state. For example, some DOTs intentionally set maximum routes or shift lengths of specific routes to balance workloads across routes (Dowds et al., 2016).

2.4 Snowplow Optimization Methodology

Snowplow methodology is often based on approximate methods (e.g., constructive heuristics, two-phase heuristics, or metaheuristics) and exact methods. Constructive heuristics include path-scanning, construct and strike, and merging algorithms, while two-phase heuristics include cluster first, route second, route first, and cluster second approaches. The metaheuristics method includes simulated annealing, tabu search, extensive neighborhood search, or memetic search (Figure 2.3). Exact methods with the complex computational process, such as dynamic programming, branch and bound/cut approach, or constraint programming, have shown a higher solution quality for snow and ice control than approximate methods (Dowds et al., 2016).

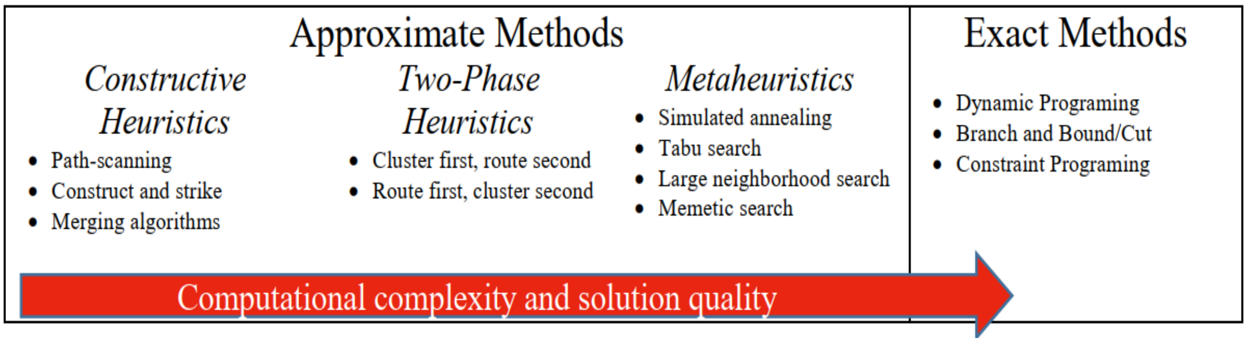

Figure 2.3: Methods for Snowplow Optimization
Source: adapted from Dowds et al. (2016)

State DOTs have used both approximate methods and exact methods for snowplow optimization modeling. For example, in 2013, the city of Centennial, Colorado, revised snowplow allocation based on research showing significant variability of trucks in miles traveled and coverage of priority-level roads. As part of the reallocation, routes were divided into two priority levels. Optimization was based on time to complete the route and involved clearing all Priority 1 roads before starting on Priority 2 roads. Routes were developed using a mathematical version of the "postman problem," in which deliveries are made via an optimized route. The reallocation reduced miles traveled, decreased fuel costs, cut labor hours, and lowered CO_2 emissions (Roads & Bridges, 2013).

Similarly, in 2005, the Iowa DOT implemented a web-based Winter Maintenance Decision Support System (WMDSS) that integrates ArcIMC ActiveX Connector with ArcIMS RouteServer Extension and various other web technologies. The tool evaluates different snow removal procedures by integrating geospatial analytical techniques, the existing snow removal asset management systems (SRAMS), and spatial decision support systems (SDSS). WMDSS, which creates, manipulates, and deletes routes manually, also manages resources and provides expert advice to assist with complex decision-making, such as routing, optimal resource allocation, and monitoring live weather information. Expert knowledge is required to determine estimated snowplowing times, how many snowplow runs are needed, and the total snowplowing time (Sugumaran et al., 2005). To solve routing problems, the optimization methodology was built on capacitated arc routing problems (CARPs), which use a memetic algorithm to perform optimization with constraints of treatment cycle time, heterogeneous truck capacities, fleet size, road conditions, and work-shift duration. The optimization process included two tasks: (1) determine optimal snow routes with the same LOS requirements and unchanged fleet size, and (2) identify a combination of optimal snow routes and service areas simultaneously while allowing a truck to refill at another facility or refill station other than their own (Dong et al., 2020). The dataset used in the optimization process included:

- Weather data (e.g., snow dates and storm severities) from 2016 to 2018;
- Maintenance truck operation data (e.g., GPS location, treating locations, truck capacity, truck speed and direction, spreading rate and type, and timestamp); and
- Traffic network data (e.g., roadway information, reference posts, facility type, and LOS requirements).

In 2011, the FHWA performed a study to identify DOT tools, or weather responsive traffic management (WRTM) solutions, to address road weather conditions via public advisory, traffic control, and snow-removal treatment, as shown in Figure 2.4 (Alfelor & Yang, 2011). WRTM consists of four fundamental areas (traffic density, speed, capacity, and precipitation) that DOTs can utilize to enhance highway system performance in severe weather conditions. For snowplow operations, routing can be manipulated to treat heavily trafficked roads, resulting in improved decision-making by DOTs and motorists and improved reliability, safety, and mobility on the roadway system during adverse weather.

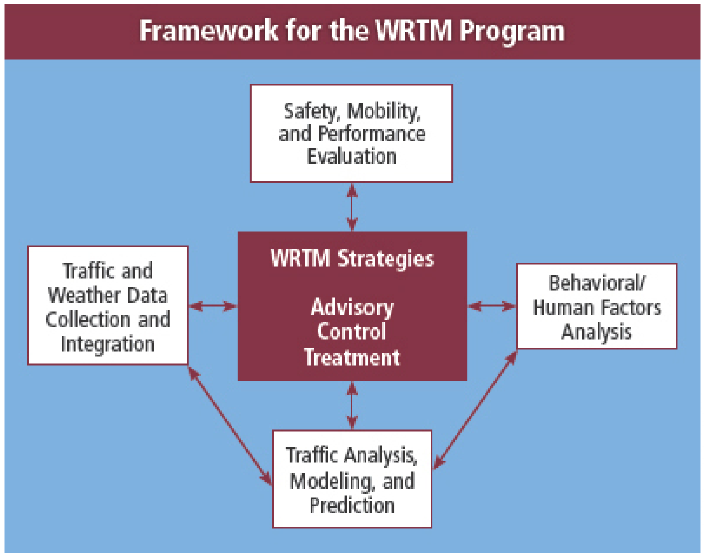

Figure 2.4: FHWA Framework for Weather-Responsive Traffic Management
Source: adapted from Alfelor & Yang (2011)

The transportation authority in Quebec, Canada, used a combination of methods to improve snowplow vehicle routes in 2008. Their primary approach used a model comprised of a multi-commodity network flow structure. In addition, they examined two heuristic solution methods based on mathematical optimization for vehicle routing. Service to each route satisfied a set of operational constraints, real-life restrictions, and a time objective. Although the model was helpful for small areas, larger networks could not be solved, and route priorities were not addressed (Perrier et al., 2008). A more recent study in Alberta, Canada (Liu et al., 2014), created a set of routes that improved safety and mobility for road users while satisfying agency-directed operational constraints. The Ministry of Transportation replaced the network optimization method, which can be limiting for areas with unique conditions and restraints, with a mathematical optimization model based on the CARP to minimize total travel distance for snowplows. A metaheuristic algorithm was used to solve this model, which was tested in one city and proved sensitive to the depot location and number of routes (Liu et al., 2014).

2.5 Snow and Ice Route Optimization Tools

Based on the literature review of computerized tools for optimizing snow and ice route removal operations, this study utilized advanced GIS-based tools to solve the snow and ice route removal optimization problem in District 4. The mechanism of applied tools included ArcGIS software program and its extension, Network Analyst, and vehicle routing problem function.

2.5.1 ArcGIS

Developed by Esri, a GIS company based in California, ArcGIS is a software package built on a GIS platform with geodatabase management applications and its extensions. ArcGIS can digitally produce optimized snow and ice routes as GIS-based maps. ArcMap, one of the main components of ArcGIS, provides a comprehensive toolset for spatial analysis, management of geographic data, and building digital maps. ArcGIS allows users to review relevant attributes of the road network, including time, cost, and associated resources. GIS-based outcomes can then be used to produce a digital data bank for long-term management and monitoring of winter maintenance activities.

ArcGIS can handle complex optimization algorithms without profound coding or programming skills from end-users, which simplifies the implementation of optimization outcomes for transportation personnel. Since many DOTs have established an online database with GIS data of all road networks, utilization of the ArcGIS software package has become increasingly accessible. Because ArcGIS can also incorporate road prioritization scenarios, variable truck capacity for carrying salt applications, lane-specific routing solutions, and roadway-truck compatibility into the routing optimization process; transportation agencies often use ArcGIS to improve their winter maintenance operations. For example, the Utah DOT (UDOT) requested a proposal for their route optimization project, specifying that ArcGIS must be used as an optimization tool (Dowds et al., 2016). With practical and user-friendly outcomes and reports from ArcGIS, KDOT personnel can quickly review and implement optimized routes for snow and ice conditions.

2.5.2 Network Analyst Extension

The ArcGIS Network Analyst extension allows users to investigate route conditions and conduct analyses based on transportation networks (Esri, 2016). The extension functions as a complex algorithm (metaheuristic tabu search-based algorithm) that identifies and evaluates all possible outcomes to determine the shortest travel time and cost solutions for a particular routing problem. Consequently, creating a network dataset can be time-consuming and requires a thorough understanding of the network's components and attributes. There are various functions within the Network Analyst extension that support the identification and assessment of optimal routing alternatives for network optimization, including:

- Service area,
- Route and closest facility,
- Location-allocation,
- Origin-destination cost matrix, and
- Vehicle routing problem.

The service area function generates drive-time polygons to enhance the accuracy of travel directions in the road network. The route and closest facility function identifies the shortest path between the treating areas and truck facilities in snowplowing operations, while the location-allocation function determines the most appropriate truck facility (garages or outposts) for treating surrounding snow and ice routes. The origin-destination cost matrix function measures the travel time between the treating areas and truck facilities in the network. Finally, the vehicle routing problem function optimizes the treating schedule for a fleet of snowplow trucks.

2.5.3 Vehicle Routing Problem Function

The vehicle routing problem function determines the best routing pathway for a fleet of snowplow trucks to service a set of snow and ice plowing orders or deliveries of salt applications (Blandford et al., 2017). This function, proven to be one of the most suitable methods to optimize snow and ice clearance routes, is a generalization of the Traveling Salesman Problem, which aims to identify the optimal routing solution for a fleet of vehicles to service a set of orders under a series of constraints, as shown in Table 2.1 (Dong et al., 2020; Schneider et al., 2016; Holik & Anderson, 2019).

Table 2.1: Typical Constraints in Vehicle Routing Problems

Constraint Type	Classification
Location	Time to service a location
	Number of depots
	Nature of demands – deterministic or stochastic
	Location of demands – points, arcs, or polygons
	Operations – pickups or drop-offs
Vehicle	Number of depots
	Fleet size
	Heterogeneous vehicle capacity
	Maximum vehicle route times
Pathway	Underlying network – directed or undirected
	Time to travel a given network segment
	Vehicle type limitations on network segments

Vehicle routing problems can be categorized as node routing, in which demand is on nodes on the graph. Another is arc routing, where the focus is on the route itself (Minge et al., 2020). Liu et al. (2014) presented an example of a vehicle routing problem in snow removal operations that includes identifying and evaluating a road network with an associated fleet storage facility to ensure that all road links are serviced during a snow and ice event and that operational constraints are satisfied with minimal cost and time (Figure 2.5). The figure illustrates the road network, with node 0 being the truck facility. Optimized snow routes begin and end at node 0 with complete service performed for all road links in the network.

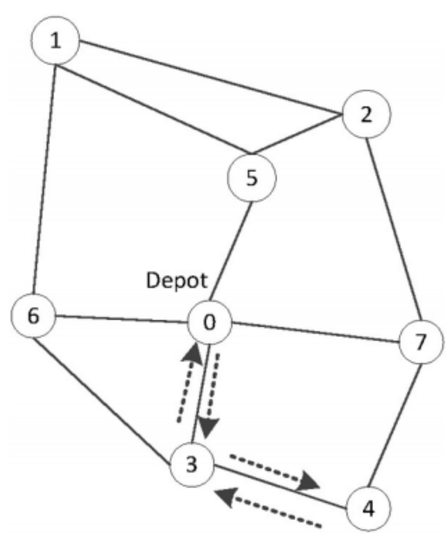

Figure 2.5: Example of a Vehicle Routing Problem in Snow Removal
Source: adapted from Liu et al. (2014)

To solve a vehicle routing problem, optimization algorithms must solve both arc and node problems simultaneously. The vehicle routing problem function integrated with ArcGIS consists of multiple layers that store the inputs, parameters, and outputs for a given vehicle routing problem. A routing network dataset must be prepared to enable the use of the ArcGIS Network Analyst extension. The developed vehicle routing problem analysis layer in this study required a set of input classes, including plowing points with snow and ice routes, locations of truck facilities (salt domes and remote sites), snow and ice route network, boundaries of service areas, and route boundaries. Using these classes, the vehicle routing problem function accurately directed snowplow trucks to treat areas with optimal routes and minimal travel time. The roadway-vehicle compatibility feature of the vehicle routing problem toolset also matched roadways to specific truck types, limiting trucks with widest plows to major roadways.

2.6 State of Practice of Snowplow Optimization Models

The authors conducted a comprehensive review of eight state DOTs that have investigated snowplow optimization models, including a comprehensive analysis of manuals, guides, and other related documents from DOT websites. Table 2.2 summarizes the snowplow optimization approaches from the eight state DOTs. A detailed discussion of the state of practices of snowplow optimization models is provided in Appendix A.

Table 2.2: Summary of Snowplow Optimization Methods

State DOT	Project Goals	Optimization Approach	Key Findings
Colorado (Harley, 2016)	Establish a base map of winter highway treatment routes to improve service levels, optimize resource reallocation, and monitor changes to overriding constraints in Region 4, Colorado.	Developed a snowplow route optimization procedure with what-if scenario modeling.	Optimized the fleet size in snowplow operations, replaced old fleets, and recommended the use of mobile weather monitoring.
Delaware (Li et al., 2018)	Solve vehicle routing and scheduling problems of snow and ice removal practices for three counties in Delaware.	Developed a GIS-based optimization model for snowplow routing to reduce the total travel distance and travel times.	Reduced the total cycle times for completing each snowplow route and provided different scenarios for snow and ice control activities.
Iowa (Dong et al., 2020)	Design winter maintenance truck routes for single and multiple depots under the responsibility maps in District 3, Iowa.	Used a memetic algorithm to solve capacitated arc routing problems with constraints of cycle times, fleet size, truck capacities, and work duration.	Reduced 13.2% of deadhead distance compared to current practices.
Kentucky (Blandford et al., 2017)	Identify strategies to enhance snow and ice removal operations for four counties within two districts in Kentucky.	Utilized ArcGIS software packages with the Network Analyst extension and vehicle routing problem toolset to investigate current snowplow routing practices.	Minimized the operational trucks required to treat all snow and ice routes. Potential cost savings could reach $225,000 per year.
Minnesota (Holik, & Anderson, 2019)	Summarize optimization methodology to solve vehicle routing problems of snowplow operations in Minnesota to reduce total operational costs.	Three common snowplow programming software packages, including Fleet Route software produced by C2Logix, ArcGIS developed by Esri, and TransCAD created by Caliper Corporation.	Using GIS-based applications can optimize the snow and ice route removal operation by reducing the snowplow route length 5%–50%.

State DOT	Project Goals	Optimization Approach	Key Findings
Missouri DOT (Jang et al., 2011)	Enhance the level of service of winter maintenance operations by optimizing snow and ice routes and fleet allocations in Missouri.	Developed an integrated heuristic-based optimization algorithm for a state transportation agency to identify the most efficient route plans and determine sufficient fleet allocations.	Determine specific service routes that trucks can follow and optimal truck allocation scenarios with minimum cycle times and deadheading miles.
Ohio DOT (Schneider et al., 2016)	Optimize snowplow routes and fleet size for three districts in Ohio by removing county borders.	Developed a GIS-based snow and ice route optimization model using the ArcGIS software package and its extensions.	Achieved total travel time savings of 837 minutes per treating cycle. Recommended adding 13 more plow trucks to two districts to maximize the LOS.
VTrans (Dowds et al., 2013)	Improve service efficiency while minimizing labor hours and fuel for winter maintenance operations in Vermont.	Developed a specific snow-route base map to optimize the service areas for each truck garage based on total travel time and surrounding roadways.	Efficient vehicle allocations based on detailed roadways allowed the agency to optimize man-hours and reduce fuel consumption.

Chapter 3: Methodology

3.1 Introduction

The objective of this project was to improve KDOT snow and ice route removal operations in District 4 using a scientific, mathematical methodology built on GIS applications. First, a literature review was conducted to summarize current practices in winter maintenance of snow and ice route removal operations. Second, geospatial data related to geography, route networks, LOS requirements, and recent snow and ice route removal practices were collected. Third, a snowplow fleet optimization model was developed to determine the minimum number of operational trucks needed to treat all snow and ice routes while maintaining the current LOS satisfaction percentage in District 4. A snow and ice removal optimization model was developed based on Esri's ArcGIS software platform. Finally, the optimized fleet size for the snow and ice routes in District 4 was determined, as well as total travel time savings and potential for cost savings and man-hours for winter maintenance operations.

3.2 Research Approach

The methodology of this project was established based on an integrated research framework consisting of seven main tasks: literature review, project settings, snow and ice model development, model results, route verification, fleet optimization, and final report. Figure 3.1 illustrates the research framework and associated tasks. The applied research framework initially reviewed the current state of the practice of snow and ice route removal operations, and then the research team collected relevant snow and ice route removal data to create a base map for subsequent analyses. The snow and ice removal model was run and then verified to establish baselines for fleet optimization. Finally, recommendations for improving current snow and ice removal practices in District 4 were input into a final report.

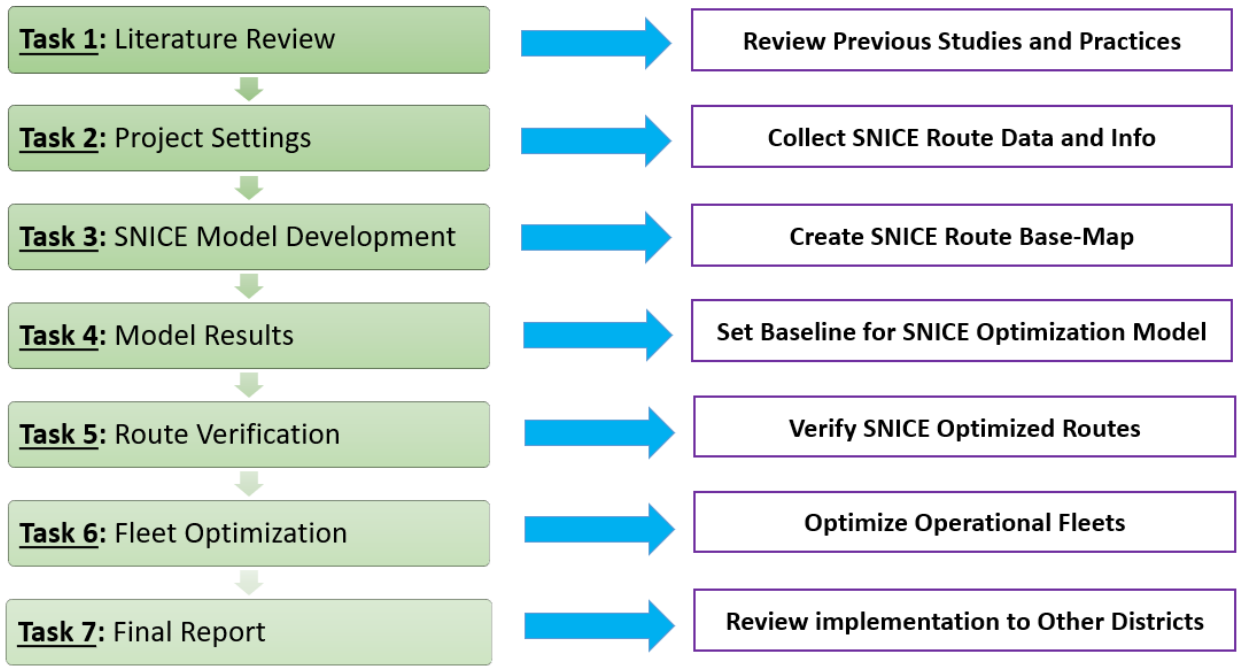

Figure 3.1: Research Framework

Task 1 involved a literature review of snowplow optimization models developed by other state DOTs, with an emphasis on the current state of the practice for optimizing snow removal operations in eight states (Colorado, Delaware, Iowa, Kentucky, Minnesota, Missouri, Ohio, and Vermont). The research team focused on relevant technical articles to better understand how optimization models are created and implemented. The review concentrated on the model development process, utilized tools (e.g., ArcGIS Network Analyst and vehicle routing problem), and the evaluation and assessment process for the anticipated winter operations budget, which provided the research team with snow and ice route removal data to develop the model.

Task 2 collected geographical information (e.g., numbers of counties, highway miles, elevation difference, terrain types, and highway base maps), precipitation data (e.g., snowfall ranges), and current snow routes and facilities (e.g., garages, outposts) in District 4 to establish project parameters. The research team also obtained current LOS categories from KDOT to evaluate the vulnerability of each route to snow plowing, as well as the challenges that face every route in the network. Based on this information, a priority for winter maintenance operations was assigned for each road in the network. The collected data were translated into a district map to develop a digital base map developed in Task 3.

Task 3 developed a GIS-based map for the initial route optimization model based on obtaining road and network datasets, digitizing snow routes and facility data, creating the route optimization-based model, and conducting the snow route removal optimization process. Data collected in Task 2 were used to create various layers for the base map of District 4 with additional layers for snow removal attributes. An additional layer of snow and ice operation routes was created using ArcGIS software. This layer contained all digitally optimized routes in the district map. A suitable salt application rate for operational snowplow trucks was determined based on historical data and discussion with KDOT personnel.

Task 4 included an initial run of the developed snow and ice removal model to establish relevant baselines of model parameters for the fleet optimization process, including total travel time, treating time, deadhead time, refill time, LOS requirement time, route efficiency, and LOS satisfaction percentage of the current snow and ice route removal practice. This task aimed to analyze current snowplow routes in District 4 based on optimized routes in the base map developed in Task 3. Accordingly, the task determined the number of trucks currently employed, expected time, and percentage of routes that satisfy the LOS requirement, or the maximum time required for a road to be treated in District 4. The LOS is a primary factor for comparing current routes with optimized routes. A route satisfies the LOS requirement if a truck leaves the facility, treats the assigned roads, and returns to the facility to refill. Task outcomes produced a district overview map, individual route maps, and individual route descriptions for current and optimized situations.

Task 5 verified model results, including the snow and ice route network, time-related parameters, and percentage of LOS satisfaction in District 4. Due to the impact of COVID-19, the verification process included multiple meetings with KDOT experts and personnel of snow removal operations in District 4 and regional staff to thoroughly assess total travel times, treating times, deadhead times, number of trucks available, and LOS requirements. Specifically, this task identified variations or abnormal circumstances between current travel times in four operational areas of District 4 and times calculated by the optimization model from Task 4. Handwritten maps of current snow and ice route removal operations in District 4 were also provided to compare to the results of the developed model.

Task 6 implemented the optimization model according to the truck inventory in District 4, and the research team provided the area operated by each facility to maintain the required LOS within the district's network. The fleet of snowplow trucks was optimized by removing the least efficient trucks from the initial model results to determine the minimum number of trucks required at each facility to maintain the required LOS at each road in the network. The optimizing truck fleet process was based on route priority, route efficiency, refill locations, total salt application used, deadhead time, and sub-area boundary. The outcome of this task was recommendations for the total number of trucks needed to maintain the current percent of LOS satisfaction and/or maximize the percent of LOS satisfaction for snow and ice route removal operations.

Task 7 developed the final report with recommendations for route groupings and fleet size for the snow and ice route removal network in District 4. An implementation plan for the snow and ice route optimization model in this district was also suggested and discussed.

3.3 Mathematical Model Algorithms and Tools

This project utilized advanced algorithms and tools to solve a snowplow optimization vehicle routing problem for snowplow removal operations in District 4 in Kansas. This section presents the mathematical insights of the vehicle routing problems and proposes the implementation of GIS applications, including ArcGIS software and its extension package, Network Analyst. The objective of the snowplow optimization vehicle routing problem was to minimize the total travel time of the snow and ice removal operation in the network. The problem can be described using a graph theory language; where,

- $G = (V, A)$ is a connected directed graph consisting of V (set of nodes) and A (set of arcs), with s_{ij} as the treating time for an arc (i,j),
- t_{ij} is the deadhead time for an arc (i,j),
- T is the work-shift duration,
- K is a set of snow and ice routes,
- m is the number of routes, and
- o is the facility location.

The graph theory provided the core of the vehicle routing problem defined in this project. The decision variables of the problem are defined as:

x_{ij}^{k} = 1 if route *k* is treated from *i* to *j*, otherwise x_{ij}^{k} = 0,

y_{ij}^{k} = 1 if route *k* is traversed without treating, otherwise y_{ij}^{k} = 0, and

u_{kh} = 1 if the h^{th} truck treats route *k*; otherwise u_{kh} = 0.

The objective function of the minimal travel time is defined as follows:

$$Min\sum_{k=1}^{m}\sum_{(v_i,v_j)\in A}\left(t_{ij}\times x_{ij}^{k}+s_{ij}\times y_{ij}^{k}\right)$$

Equation 3.1

The vehicle routing problem was solved for each facility (e.g., garage and/or outpost); including where the truck must depart from and return for each treating cycle within a specific area. The optimization vehicle routing problem in this project was set up with the following constraints:

$$\sum_{(v_i,v_j)\in A} x_{ij}^{k}-\sum_{(v_i,v_j)\in A} y_{ij}^{k}=0\ (v_i\in V;k=1,2,...m)$$

Equation 3.2

$$\sum_{k=1}^{m} y_{ij}^{k}=1 \text{ with } (i,j)\in V$$

Equation 3.3

$$x_{ij}^{k}\geq y_{ij}^{k} \text{ with } (i,j)\in V$$

Equation 3.4

$$\sum_{(i,j)\in A}\left(s_{ij}\times y_{ij}^{k}+t_{ij}\times x_{ij}^{k}\right)\leq T \text{ with } \forall k\in K$$

Equation 3.5

$$\sum_{(0,i)\in A}\left(y_{0i}^{k}+x_{0i}^{k}\right)=1 \text{ with } \forall k\in K;i\in V$$

Equation 3.6

$$\sum_{(i,0)\in A}\left(y_{i0}^{k}+x_{i0}^{k}\right)=1 \text{ with } \forall k\in K;i\in V$$

Equation 3.7

$$\sum_{(i,j)\in A} q_{ij}\times x_{ij}^{k}\leq\sum_{h\in H_1\cup H_2} Q_h\times u_{kh} \text{ with } \forall k\in K$$

Equation 3.8

$$\sum_{h\in H} u_{kh}=1$$

Equation 3.9

$$\sum_{k\in K,h\in H} u_{kh} \le m$$

Equation 3.10

$$f_k \le f_{ij} \times x_{ij}^k$$

Equation 3.11

$$\sum_{(i,j)\in A} \left(x_{ij}^k \times t_{ij}^{'} + y_{ij}^k \times t_{ij} \right) \le f_k$$

Equation 3.12

Where q_{ij} is the demand of arc (*i,j*); *H* is a set of snowplow trucks; Q_h is the truck capacity; *m* is the number of routes; f_k is the treating cycle time for route *k*; f_{ij} is the treating cycle time for arc (*i,j*); and $t_{ij}^{'}$ is the treating time of arc (*i,j*).

Equation 3.2 shows the continuity for each snow and ice route in the network. Equation 3.3 ensures that all the routes are treated only once, and Equation 3.4 ensures that the snowplow trucks travel through the edges of all snow and ice routes. Equation 3.5 provides a constraint for the work shift of each snowplow truck. Equations 3.6 and 3.7 ensure that all snow and ice routes start and end at the facility. Equation 3.8 refers to the capacity constraint of the snowplow truck. Equation 3.9 ensures that each snow and ice route is treated by exactly one truck, while Equation 3.10 is the fleet size constraint. Equation 3.11 ensures that the treating cycle time of a route is greater than the treating cycle time of an arc within that route. Equation 3.12 states that the deadhead time of each route never exceeds the treating time. All developed constraints were used to set up and solve the snowplow optimization vehicle routing problem in this project.

To solve a vehicle routing problem, a set of orders typically is calculated and assigned to a set of routes with a specific number of vehicles departing from a set of depots such that the overall travel time and cost are minimized. In this project, the set of orders included the plowing points and the snow and ice routes in District 4, while the depots represented the snowplow truck storage facilities. This project utilized Dijkstra's algorithm, which accommodates the single-source, shortest-path problem on a weighted graph. Dijkstra's algorithm identifies the shortest path from starting location *A* to destination location *B* using a set of junctions, *P*, with a calculated final shortest path from *A*. The algorithm iteratively determines a particular junction in the set of initial junctions that has the minimum calculated shortest path and adds it to the set of junctions *P*. Then, the shortest calculated path of all neighbors of this junction that are not in *P* is updated. The algorithm continues calculating the shortest path until the junction of the destination location is added to *P*. Dijkstra's algorithm was incorporated into the ArcGIS Network Analyst function, as shown in Figure 3.2.

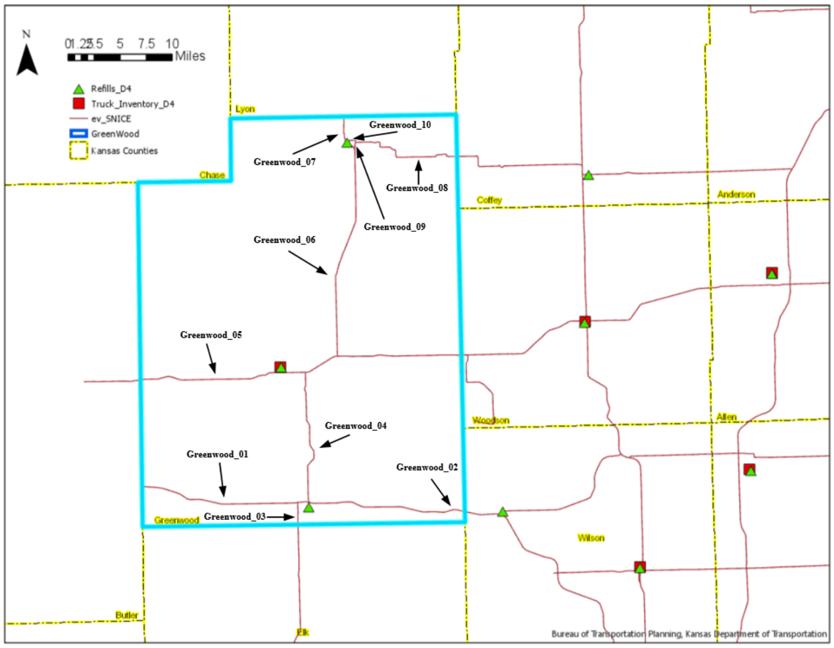

Figure 3.2: Using ArcGIS to Solve a Vehicle Routing Problem

ArcGIS is a software package built on a GIS platform with geodatabase management applications and extensions. ArcGIS digitally produces optimized snow and ice routes as GIS-based maps that can be used to produce a digital data bank for long-term management and monitoring of winter maintenance activities. ArcGIS can handle complex optimization algorithms without profound coding or programming skills from end-users, which simplifies the implementation of optimization outcomes for transportation personnel. This study developed a fleet optimization model using the ArcGIS Network Analyst extension and the vehicle routing problem tool. The ArcGIS Network Analyst extension allows users to investigate route conditions and conduct analyses based on transportation networks (Esri, 2016). The Network Analyst extension can accurately create multiple network datasets to optimize snow and ice routes in District 4. A typical network dataset includes route information, such as turning points, travel speeds, and elevation data that represent real-world route conditions. The vehicle routing problem toolset in ArcGIS assesses and generates optimized routes with network datasets created by the Network Analyst extension. This tool allows users to determine the most efficient fleet size to service specific maintenance orders to save time and money.

Chapter 4: Snowplow Model Development

4.1 Introduction

This chapter describes the development of the snow and ice route removal optimization model built on the mathematical algorithms and tools to solve the vehicle routing problem. The contents of this chapter include project settings, data collection, and a description of the developed optimization model parameters. Project settings describe the district involved in the snow and ice route removal optimization process, specifically data collection and preparation of inputs to the proposed optimization model.

4.2 Project Settings and Data Collection

Snow and ice removal optimization requires substantial data preparation because routing results rely on underlying network characteristics. Therefore, this study collected and analyzed geographical information (e.g., numbers of counties, highway miles, elevation difference, terrain types, and highway base maps), precipitation data (e.g., snowfall ranges), and current snow routes and facilities (e.g., garages, outposts) from District 4 in Kansas to develop a snow and ice route removal optimization model. This research also assessed current winter maintenance operations and KDOT requirements in the district. For example, KDOT classifies the LOS on its roads network into three categories depending on the number of average annual daily traffic (AADT) and the number of lanes combined on the network's roads (KDOT, 2017).

Figure 4.1 highlights District 4 out of the six districts in Kansas. Because District 4 has unique geographic demands for snow and ice route removal operations, this district is responsible for construction and maintenance activities (e.g., snow and ice removal) on the 3,958 miles of state highways throughout the 17 counties in the district. The snow and ice route removal area is divided into 16 sub-areas with various numbers of operational trucks located at each facility.

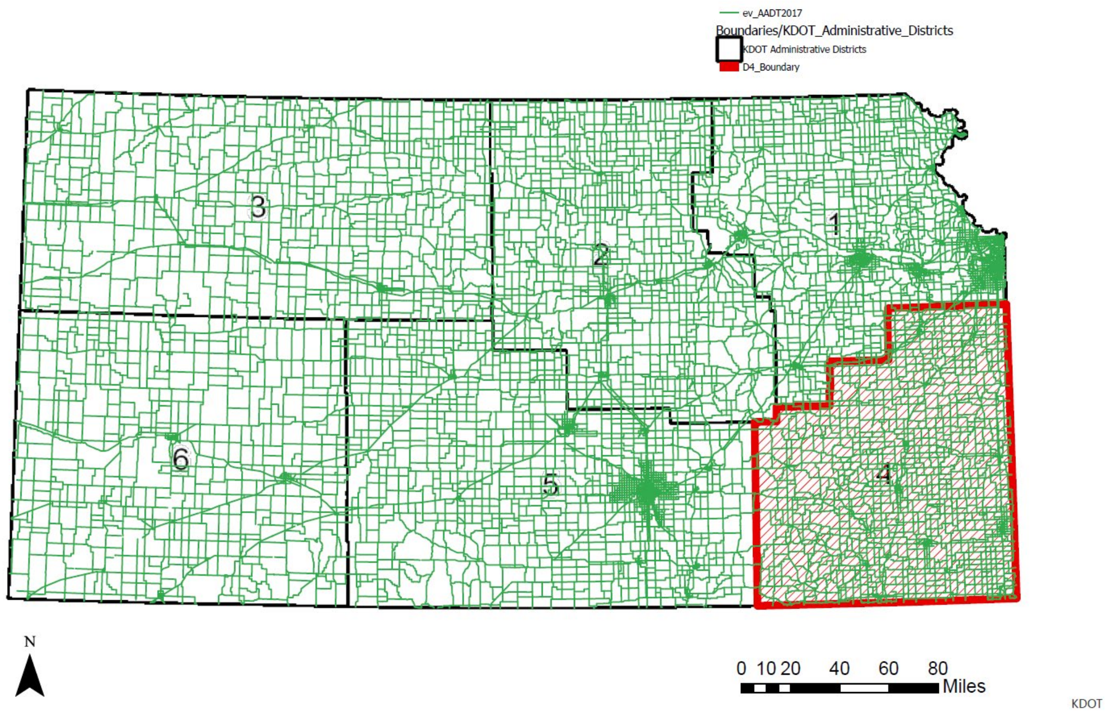

Figure 4.1: Snow and Ice Route Optimization Model for District 4, Kansas

The research team developed four initial sets of data required for model development. Group 1 contained data related to the district topography and geography, including county limits, elevations, terrain types, snow precipitation ranges, and freeze-thaw cycles. Group 2 included data related to the road network of District 4; specifically, highway miles, road hierarchy, network base map, LOS across the network, traffic data (AADT, speeds, classes), lane distribution (e.g., number of lanes at each road), travel directions, travel times, start and end points of each road, turning locations, turning restrictions, and elevation differences among network roads. Group 3 was comprised of data related to snow routes, including, current snow routes (e.g., GIS, pdf), snow facility locations, truck inventory at each facility (e.g., number, type, and capacity), salt capacities at each facility, materials used during winter maintenance (e.g., type, procedures, and distribution locations), garages and/or outpost locations, LOS requirements during snow events, amount of snow removed every year (data for the last five years), salt application rates at each location, frequency of maintenance operations for snow removal (preferred for five years or longer), truck distribution (number and locations during snow removal), and cycle times for snow removal trucks. Group 4 contained data related to other projects in the study area, making it an essential data group to account for current or future projects. This group includes current projects in District 4, future maintenance projects, long-term projects, plans to modify location, capacity, or size of snowplow truck facilities, and plans to upgrade the truck inventory.

The request for these four groups of data was sent to the KDOT experts and personnel of snow and ice removal operations in District 4. Several meetings with KDOT experts responsible for winter maintenance operations were conducted to review and collect data from relevant snow and ice routes. KDOT also provided printed maps with hand-drawn routes and digital maps created using spatial GIS software for snow and ice removal routes in District 4.

After verifying the data with KDOT experts, the research team determined terrain type, elevations, precipitation, and the LOS to evaluate the vulnerability of each route to snow plowing, as well as any route challenges, and then winter maintenance operations were prioritized for each road in the network. The collected data were then translated into a district map to develop a digital base map, which is required to develop the optimization model. The collected data included *geographical information,* such as the number of counties, county border limits, elevations, terrain types, and precipitation information. *Route network information* was also collected, which included AADT flow maps, highway length, roads hierarchy, travel directions, road distance, start and end points of each road, turning locations/turn-around, turning restrictions, elevations differences along network roads, number of lanes (e.g., one-way, two-way, multi-lane divided), and roadway width. *LOS information* included the number of lanes at each road in the network, the AADT, traffic classes, snow and ice route priorities for maintenance, typical salt application rates (lbs/ln mile), and frequency of maintenance operations for snow removal. The required LOS, which is a primary factor in comparing current routes and optimized routes, represents the maximum time required for a road to be treated. A route satisfies the LOS requirement if the truck is able to leave the facility, treat the assigned roads, and return to the facility and refill. The final collected data, *snow and ice route removal information*, included the number of snow and ice routes throughout the district, lane miles treated of each route, recent total travel times for treating all snow and ice routes, average travel and treating speeds, average refill time at truck facilities, current fleet size (i.e., total number of operational trucks), number and locations of truck facilities (e.g., garages, outposts, and refill stations), number, type, and capacity of trucks stationed at each facility, and salt capacities at each facility. Travel times were obtained as a function of travel speeds and distance at every road in the network during snow events. Table 4.1 presents an overview of current truck inventory and facilities in District 4.

Table 4.1: Overview of Truck Inventory and Facilities in District 4

Area ID	*Responsible Area*	*Sub-area ID*	*Truck Garage*	*Number of Remote Sites*	*Number of Trucks*
1	Iola	411	Eureka	3	5
		412	Ft. Scott	3	6
		413	Iola	2	5
		414	Yates Ctr	2	5
2	Garnett	421	Garnett	2	5
		422	Louisburg	2	8
		423	Mound City	3	5
		424	Ottawa	2	7
		425	Waverly	1	5
3	Independence	431	Altoona	2	5
		432	Independence	4	6
		433	Sedan	2	4
4	Pittsburg	441	Altamont	1	5
		442	Columbus	1	7
		443	Erie	3	5
		444	Pittsburg	2	7

Figure 4.2 shows a full GIS map of 144 snow and ice routes and 17 truck facilities (i.e., truck inventory) with remote sites or refill stations in District 4. The current KDOT snow removal plan divides roadways to be treated during snow events into three categories based on the targeted LOS: Priority 1 routes include multi-lane roads with more than 3,000 vehicles daily; Priority 2 routes include two-lane roads with 1,000–3,000 vehicles daily; and Priority 3 routes include two-lane roads with less than 1,000 vehicles daily. The current fleet size of winter operations for snow and ice route removal includes 90 plow trucks with tandem and same-size spreader units. Some trucks are equipped with wing plows, but their use is restricted to clearing shoulder areas and widened pavement areas such as ramps. KDOT does not deploy wing plows to clear traveled lanes in the district. Only one tow-plow truck is available for plows on Interstate 35 (I-35).

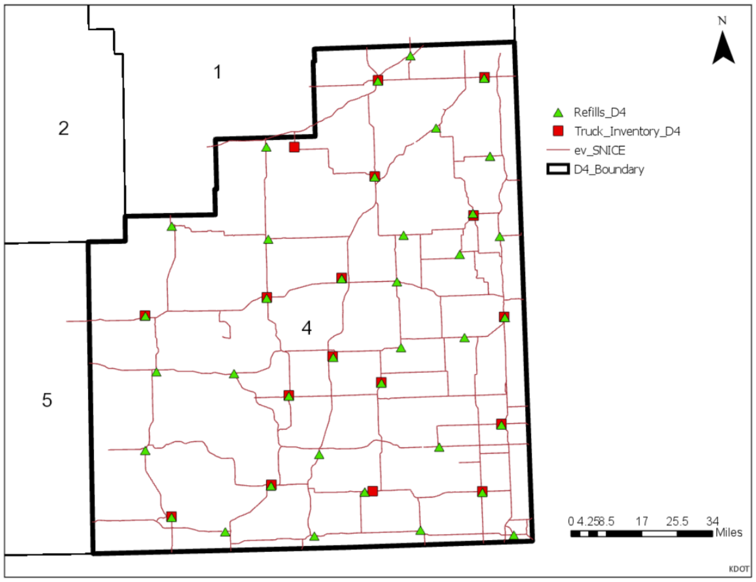

Figure 4.2: Locations of Truck Facilities (Salt Domes and Remote Sites) on Snow and Ice Route Map

4.3 Developing a GIS Base Map and Model Parameters

Many snow and ice control operational constraints were required to construct the snow and ice removal optimization model. These constraints are typically employed to establish model parameters. Before establishing parameters for the proposed optimization model, this study used the following steps to create a GIS-based map with all road layers and detailed information for model development:

1. Collect routing network datasets,
2. Digitize snow routes and facility data,
3. Create the route optimization-based model, and
4. Conduct the snow route removal optimization process.

Step 1 involved analyzing the collected data (see Chapter 2) to create different layers of information for District 4. For example, a layer containing a dataset of all the roads and elevation differences for the entire district was developed. The layers incorporated the attributes of each road within the network, including road hierarchy (e.g., freeway, arterial, etc.), travel direction, speeds, distances (start and end points of each route), and times. Travel times were then obtained as a function of travel speeds and distance at every road in the network during snow events. Traveling and plowing speeds varied based on factors such as highway type (e.g., multi-lane divided and two-lane), shoulders, driveways, and mailboxes and signs. The data revealed that KDOT snow and ice route removal operators typically increase their travel speeds between areas of treatment and/or plowing to clear remaining areas. Trucking speeds also increased during post-storm operations compared to intermittent operations during a snow event. Condition and road type were shown to be the primary factors that dictate plowing speeds, which are limited to 25 mph for two-lane highways and up to 35 mph for multi-lane divided highways.

Step 2 involved digitizing all routes treated by snowplow trucks for winter maintenance operations. Data related to snow and ice routes in District 4 contained route information in various formats, including digital and hard copies of operational maps from field staff and KDOT online GIS databases. Figure 4.3 shows the digitalization of four areas correlated with snow and ice route removal operations in District 4. Once snow and ice route data were obtained, another layer of snow and ice operation routes was created using the ArcGIS software package. This layer included all routes used for digital optimization. Results of this step also included digitalized information about route classifications throughout the district. Five major factors shown to affect route classification are daily traffic (e.g., volumes of trucks and autos), route continuity (e.g., consistency in the level of safety and service throughout the route’s entire length), access to major cities (e.g., linking major cities and access to communities), route spacing (e.g., higher classified routes), and trip length.

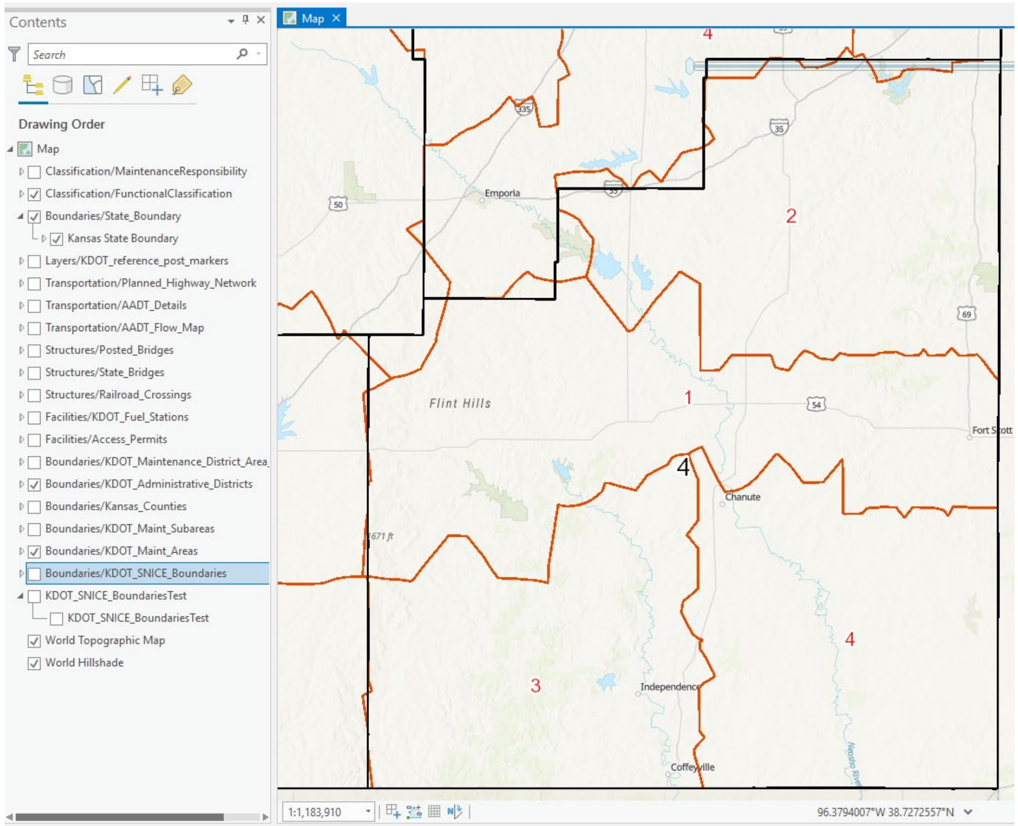

Figure 4.3: Digitalization of Routing Boundaries within Four Areas of District 4

Step 3 involved an initial optimization run to establish baselines for subsequent optimization processes. The first task of Step 3 was to locate all truck garages, outposts, and salt refill locations used by snowplow trucks during winter operations in the ArcGIS digital-based map developed in Step 2. The research team collected this data from KDOT maintenance personnel. According to the data, approximately 20 minutes are required to load a spreader at a truck facility when the material is broken and unfrozen. Depending on the size and temperature, which affects the hydraulics, the reloading time may double or increase by a factor of four, as the worst-case scenario, at KDOT remote sites with small mower tractors with loader buckets. Additional attributes were required for the model, including the number of trucks at each garage and outpost and typical plowing locations. The research team utilized fleet-related information, including the number of trucks and their assignments within each sub-area's facility, and then the Network Analyst extension of the ArcGIS software was used to define the service areas and snow and ice route network. The vehicle routing problem toolset was then utilized to finalize the initial route optimization model. The vehicle routing problem was used to account for plowing locations, route restrictions, and cycle times, as shown in Figure 4.4.

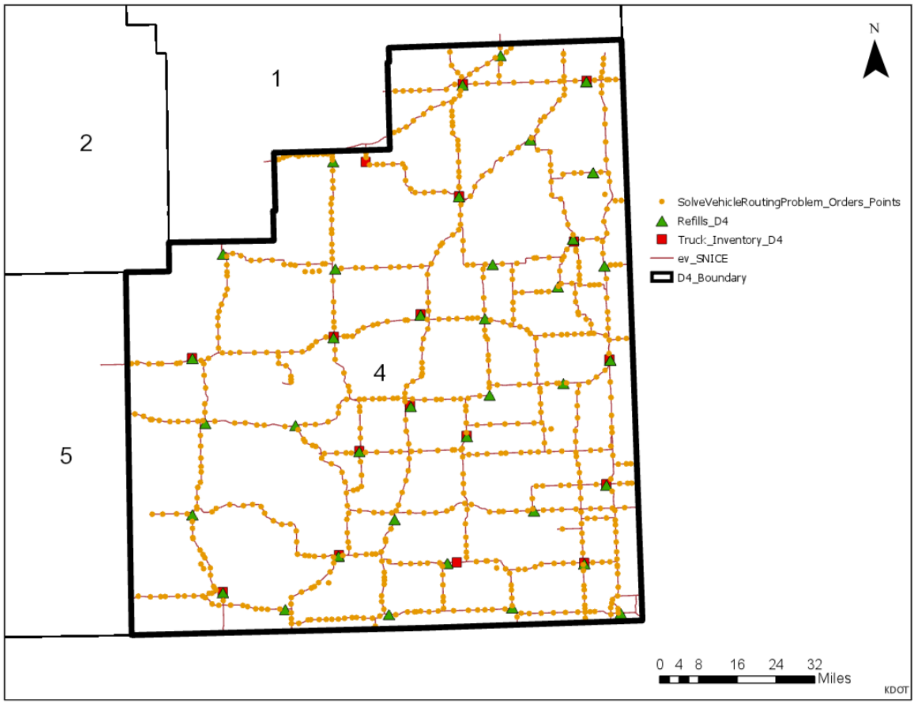

Figure 4.4: Plowing Points along Snow and Ice Removal Routes in District 4

Step 4 included a two-step optimization process for all District 4 snow and ice routes to minimize the fleet size and maximize LOS satisfaction. Optimization Method 1 aimed to remove the least efficient trucks while maintaining LOS satisfaction of KDOT's current snow removal practice. The optimization step aimed to maximize LOS satisfaction of the snowplow practice while retaining the number of KDOT operational trucks in District 4. Parameters of the snow and ice route removal optimization model included total travel time, or the total time to complete a full treatment cycle for a snow and ice route, which is the sum of treating time, deadhead time, and refill time of each treating cycle. Deadhead time is the time to drive to and from the treating area. Treating time is the time to drive and treat the snow and ice route. Refill time is the time to refill the truck at the facility. Lastly, LOS cycle time, which is the total time the truck needs to leave the facility, treat the assigned snow and ice routes, return to the facility, and refill to prepare for the next treating cycles. Optimization results provided several snowplow scenarios so KDOT decision makers can achieve optimal LOS satisfaction for future winter maintenance operations.

The LOS was a primary factor for comparing current routes with optimized routes. Results of the fleet optimization model were compared to thresholds included in District 4's LOS documents, including the treating speed priorities and LOS cycle time priorities of each snow and ice route. Treating speeds (mph) were classified into three route categories: Priority 1 with 35 mph, Priority 2 with 25 mph, and Priority 3 with 25 mph. LOS cycle time requirements (minutes) were shorter for high priority routes and longer for low priority routes (e.g., Priority 1 with 60 minutes, Priority 2 with 90 minutes, and Priority 3 with 120 minutes). The salt application used under normal conditions for each treating cycle remained at 250 lbs/ln mile.

Chapter 5: Model Results

5.1 Introduction

This chapter presents the results from the initial run of the snow and ice model developed in Chapter 4. The initial run was conducted with all digitalized routing data and the entire truck inventory throughout District 4 to provide a baseline for the number of trucks used within the treating areas of each truck facility and the percent of LOS satisfaction of snow and ice route removal operations. The snow and ice routing network was optimized using LOS time requirements for each route priority, a treating speed of 25 mph for two-lane highways and up to 35 mph for multi-lane divided highways, a refill time of 20 minutes at a truck garage (salt domes) and 40 minutes at remote sites, a salt application rate of 250 lbs/ln mile, and time-related factors such as 15 minutes to re-fuel, clean lights, and refill washer fluids per shift and a total of 20 minutes of operational break per shift during an active snow and ice event. The initial run used ArcGIS Pro version 2.7 with its Network Analyst extension and vehicle routing problem function.

5.2 Base Snowplow Operations in District 4

This section focuses on analyzing current snowplow routes in District 4 based on optimized routes developed in Chapter 4 to determine the number of trucks currently employed, expected time, and percent of routes that satisfy the LOS requirement. Detailed maps for current routes were digitized from Chapter 3; including, each route's start and end points, and route descriptions were developed for current routes. The route descriptions included the number of trucks currently operating in the network, the expected time to simultaneously treat all roads, and the percentage of routes satisfying the required LOS within District 4. The data required for the route description included road priority, total travel time, treatment cycle time, lane miles treated, route efficiency, and a description of where each route is treated, as shown in Figure 5.1.

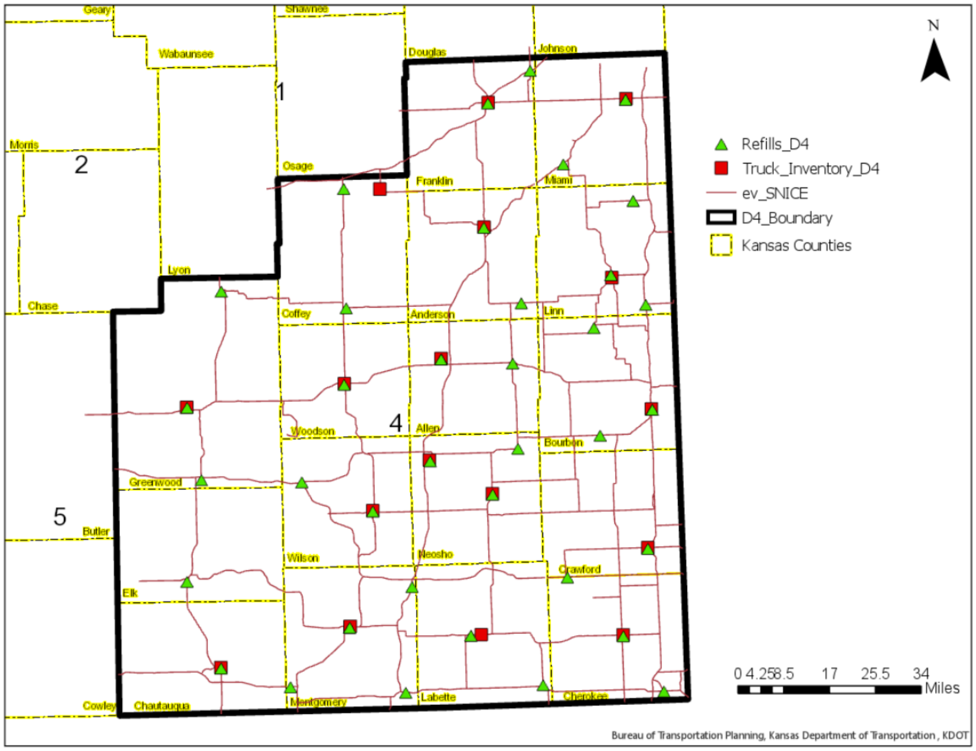

Figure 5.1: Snow and Ice Route Removal Practices with County Boundaries in District 4

The analysis of current practices also applied the optimization model to the truck inventory in District 4, as shown in Table 5.1. The research team utilized the entire truck inventory of the district to analyze the area operated by each facility to maintain the required LOS within the district's network. Initial route optimization considered route restrictions (county borders and township roads) and normalized the treating speed during winter operations in District 4. A suitable salt application rate was determined based on historical data and discussion with KDOT maintenance personnel. The required LOS represents the maximum time required for a road to be treated. The LOS is considered a primary factor in comparing current routes with the optimized routes. A route satisfies the LOS requirement if the truck is able to leave the facility, treat the assigned roads, and return to the facility and refill. If the truck completed a full cycle under LOS requirements, the truck satisfied the LOS. The outcomes of this task involved a district overview map, individual route maps, and individual route descriptions for both current and optimized situations.

Table 5.1: Snow and Ice Route Removal Base Map Information of District 4

Parameter	*Current State*
Operational trucks/fleet size	90
Current number of facilities	17
Total coverage lane miles	3,958
Truck capacity (miles/truck)	32.18
Total route treated	144
Route length (lane miles/truck)	Priority 1 = 30 – 34 Priority 2 = 50 – 60 Priority 3 = 76 – 90
Roadway width (feet)	18 – 22
Cycle time per shift (1 shift = 12 hours with downtimes)	Priority 1 = 4 Priority 2 = 3 Priority 3 = 2
Average truck speed (mph)	12 – 18
Total travel time (minutes)	3,981 (high, medium, low classes)
LOS cycle time requirements (minutes)	Priority 1 = 60 Priority 2 = 90 Priority 3 = 120
Plowing speed (mph)	Priority 1 = 35 Priority 2 = 25 Priority 3 = 25

5.3 Model Baseline Outcomes

The model results provided a detailed set of overview district maps, individual route maps, and individual route descriptions with time-related parameters (total travel time, treating cycle time, and deadhead time), route efficiency, and percent of LOS satisfaction of the snow and ice route removal operations. The deadhead time was based on the distance between the truck facility and the treating route and the traveling speed of 35 mph during a snow and ice event. The treating cycle was based on the total responsible lane miles and the treating speed for each route priority. The total travel time was a sum of the treating cycle time, deadhead time, and refill time, and the route efficiency was calculated based on the total effective time for the snow removal operation over the deadhead time. These results were used as a baseline for subsequent fleet optimization.

Figure 5.2 shows all optimized routes in District 4 with detailed treatment sub-areas for 16 snowplow truck garages. Each truck garage has associated remote sites, where the snowplow truck can refill for the next treatment cycle. The developed model set up a constraint for the boundary of each sub-area so that a truck responsible for treating that sub-area does not traverse to other sub-areas. Table 5.2 shows the baseline outcomes for all routes for District 4.

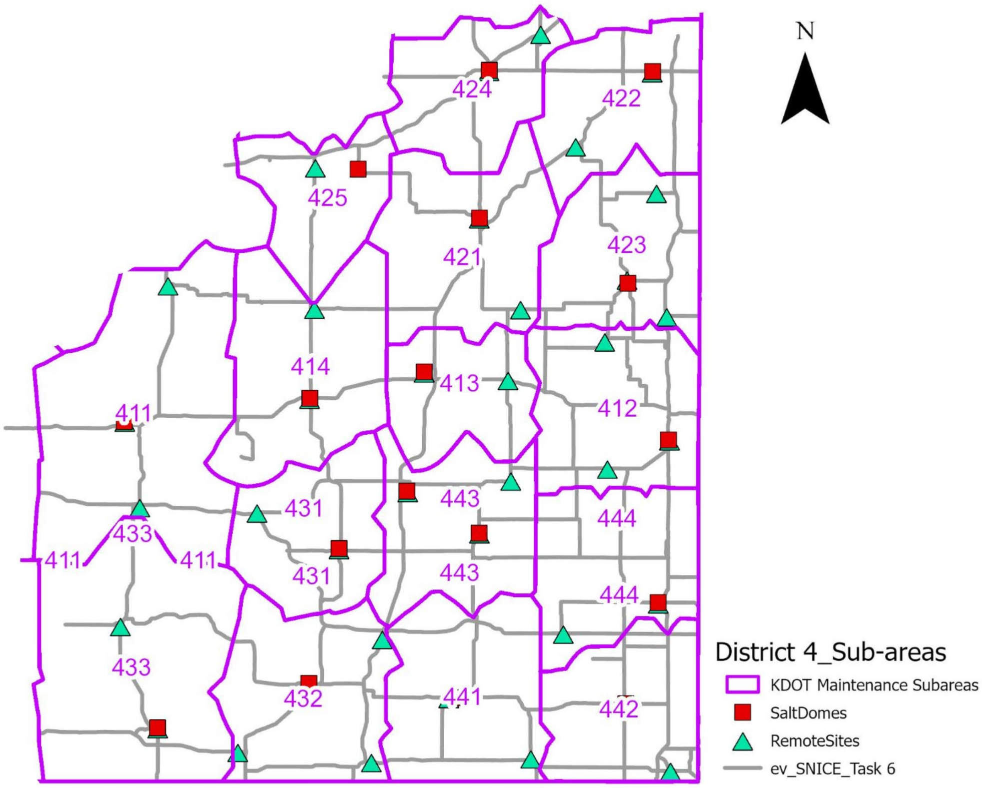

Figure 5.2: Overview of Snow and Ice Routes in District 4

Table 5.2: Baseline Outcomes for Snow and Ice Routes in District 4

SNICE ID	SNICE Route Start Point	SNICE Route End Point	Sub-Area	Responsible Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	LOS Req. Time (min)	Route Efficiency
850	JCT.K99/K249	JCT.K58/K249	411	Eureka	40	3.4	3.6	47.1	90	52%
1065	E.JCT.U54/K99	JCT.K58/K99	411	Eureka	40	0.0	102.2	142.2	90	100%
1067	JCT.U400/K99	JCT.U54/K99	411	Eureka	20	3.4	61.9	85.4	90	95%
11	BUTLER-GREENWOOD CO. LINE	11 MI.E.E.JCT.U400/K99 (FALL RIVER)	411	Eureka	40	0.0	95.2	135.2	60	100%
570	WCL ROSALIA	JCT.U54/K105	411	Eureka	20	0.4	125.8	146.2	60	100%
1638	W.JCT.U54/K3	JCT.K3/K65	412	Ft. Scott	20	26.3	33.6	79.9	120	56%
1640	JCT.K3/K39	E.JCT.U54/K3	412	Ft. Scott	20	20.7	50.6	91.3	120	71%
557	ECL Bronson	KS-MO STATE LINE	412	Ft. Scott	20	17.6	92.4	130.0	60	84%
1284	E.JCT.K7/K31	JCT.U69/K31	412	Ft. Scott	20	19.1	33.5	72.6	120	64%
1286	JCT.K31/K65	W.JCT.K7/K31	412	Ft. Scott	40	1.7	16.0	57.8	120	90%
1252	E.JCT.K3/K39	JCT.K7/K39	412	Ft. Scott	40	0.0	39.7	79.7	120	100%
1255	E.JCT.U59/K39	W.JCT.K3/K39	412	Ft. Scott	40	8.4	47.7	96.1	120	85%
1166	JCT.K3/K65	JCT.K31/K65	412	Ft. Scott	40	0.0	52.4	92.4	120	100%
1564	JCT.U54/K7	E.JCT.K7/K31	412	Ft. Scott	20	14.7	71.3	106.0	120	83%
1566	JCT.K7/K39	JCT.U69/K7	412	Ft. Scott	20	4.3	36.4	60.7	120	89%
422	JCT.U54/U69	JCT.U69/K239	412	Ft. Scott	40	0.0	100.9	140.9	60	100%
425	JCT.U69/K7	JCT.U54/U69	412	Ft. Scott	20	0.4	35.7	56.1	60	99%

SNICE ID	SNICE Route Start Point	SNICE Route End Point	Sub-Area	Responsible Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	LOS Req. Time (min)	Route Efficiency
123	JCT.U169/K39	JCT.U54/U169	413	Iola	20	8.3	63.0	91.2	60	88%
2016	JCT.U54/U169	JCT.U58/U169	413	Iola	20	0.0	38.2	58.2	60	100%
2013	ECL YATES CENTER	JCT.U54/U169	413	Iola	20	0.0	37.1	57.1	60	100%
2014	LA HARPE	ALLEN-BOURBON CO. LINE	413	Iola	20	0.0	66.8	86.8	60	100%
2015	NCL Moran (JCT.U54)/U59	JCT.U59/K31	413	Iola	20	1.4	52.8	74.2	90	97%
474	E.JCT.U59/K39	SCL Moran	413	Iola	20	0.0	66.7	86.7	90	100%
1196	S.JCT.U75/K58	JCT.U169/K58	414	Yates Ctr	40	0.0	96.7	136.7	90	100%
1198	GREENWOOD-COFFEY CO. LINE	N.JCT.U75/K58	414	Yates Ctr	20	3.4	63.0	86.5	90	95%
1199	JCT.K58/K249/SOUTHWEST RD	GREENWOOD-COFFEY CO. LINE	414	Yates Ctr	20	0.0	54.0	74.0	90	100%
2501	JCT.K58/K99	JCT.K58/K249	414	Yates Ctr	40	0.0	5.2	45.2	90	100%
567	JCT.U54/K105	ECL YATES CENTER	414	Yates Ctr	20	0.0	48.0	68.0	60	100%
1040	JCT.K105.FALL RIVER RD	JCT.U54/K105	414	Yates Ctr	20	48.6	50.1	118.6	120	51%
364	W.JCT.U75/K39	JCT.U54/U75	414	Yates Ctr	20	0.0	48.7	68.7	60	100%
2017	JCT.U54/U75	N.JCT.U75/K58	414	Yates Ctr	40	0.0	51.4	91.4	60	100%
1291	S.JCT.U59/K31	JCT.K3/K31	421	Garnett	40	0.0	28.9	68.9	120	100%
468	S.JCT.U59/K31	S.JCT.U59/U169	421	Garnett	20	10.4	58.0	88.4	90	85%
1294	ECL Waverly	N.JCT.U59/K31	421	Garnett	20	0.5	124.3	144.8	120	100%

SNICE ID	SNICE Route Start Point	SNICE Route End Point	Sub-Area	Responsible Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	LOS Req. Time (min)	Route Efficiency
114	N.JCT.U59/U169	JCT.U169/K7	421	Garnett	20	0.0	76.5	96.5	60	100%
136	JCT.U59/U169BUS	JCT.U169/U169BUS	421	Garnett	20	2.9	6.7	29.6	90	69%
460	ANDERSON-FRANKLIN CO. LINE	JCT.U59/I35	421	Garnett	20	32.2	44.9	97.1	60	58%
464	N.JCT.U59/U169	ANDERSON-FRANKLIN CO. LINE	421	Garnett	20	0.5	31.2	51.7	60	98%
1957	S.JCT.U59/U169	N.JCT.U59/U169	421	Garnett	20	9.2	14.3	43.4	60	61%
467	JCT.U169/K58	S.JCT.U59/U169	421	Garnett	20	22.9	36.4	79.3	60	61%
818	JCT.U169/K279	STATE HOSPITAL	422	Louisburg	20	20.5	2.4	42.9	120	10%
108	JCT.U169/K7	MI.S.MIAMI-JOHNSON CO. LINE	422	Louisburg	20	3.4	138.6	162.0	60	98%
1154	JCT.U69/K68	KS-MO STATE LINE	422	Louisburg	20	13.9	21.6	55.6	90	61%
1155	JCT.U169/K68	JCT.U69/K68	422	Louisburg	20	0.4	26.2	46.6	60	98%
1157	JCT.K33/K68	JCT.U169/K68	422	Louisburg	20	4.5	64.4	88.9	90	93%
415	JCT.U69/K68	0.5 MI.S.MIAMI-JOHNSON CO. LINE	422	Louisburg	20	0.0	39.0	59.0	60	100%
417	JCT.U69/K152	JCT.U69/K68	422	Louisburg	20	3.4	131.5	155.0	60	97%
973	JCT.K7/K152	JCT.U69/K152	423	Mound City	40	0.0	61.7	101.7	120	100%
418C	North Jct US-69/K-52	JCT.U69/K152	423	Mound City	0	0.0	43.2	43.2	60	
1221	N.JCT.U69/K52	KS-MO STATE LINE	423	Mound City	20	39.6	15.9	75.5	120	29%
418A	JCT.U69/K239	South Jct US-69/K-52	423	Mound City	0	0.0	52.5	52.5	60	
860	JCT.U69/K239	KS-MO STATE LINE	423	Mound City	40	0.0	27.4	67.4	120	100%

SNICE ID	SNICE Route Start Point	SNICE Route End Point	Sub-Area	Responsible Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	LOS Req. Time (min)	Route Efficiency
1637	JCT.K3/K65	JCT.K3/K31	423	Mound City	20	16.1	28.9	65.0	120	64%
1288	JCT.K3/K31	JCT.K31/K65	423	Mound City	20	4.1	84.3	108.4	120	95%
418B	South Jct US-69/K-52	North Jct US-69/K-52	423	Mound City	0	0.0	43.4	43.4	60	
1223	N.JCT.K7/K52	S.JCT.U69/K52	423	Mound City	20	0.5	30.5	51.0	90	98%
1225	JCT.K31/K52	S.JCT.K7/K52	423	Mound City	20	0.5	21.1	41.6	90	97%
1562	E.JCT.K7/K31	JCT.U169/K7	423	Mound City	20	0.8	173.8	194.6	120	100%
1806	JCT.I35/U59	MIAMI-JOHNSON CO. LINE	424	Ottawa	20	2.6	129.0	151.6	60	98%
1811	JCT.I35/K273	JCT.I35/U59	424	Ottawa	20	19.5	88.4	127.9	60	82%
1276	JCT.K33/K68	JCT.U56/K33	424	Ottawa	20	12.0	50.0	82.0	90	81%
1158	JCT.I35/U59/K68	JCT.K33/K68	424	Ottawa	20	0.5	38.5	59.0	90	99%
1161	JCT.K68/K268	OSAGE-FRANKLIN CO. LINE	424	Ottawa	20	0.0	3.5	23.5	60	100%
1906	OSAGE-FRANKLIN CO. LINE	JCT.K68/MAIN ST.	424	Ottawa	20	10.6	46.4	77.0	60	81%
2019	JCT.I35/U59	JCT.U56/U59	424	Ottawa	20	7.5	53.1	80.6	60	88%
1813	E. Jct K-31 (Exit 162)	Williamsburg (Exit 170)	425	Waverly	20	16.7	51.8	88.5	60	76%
1819	K-130 (Exit 141)	E. Jct K-31 (Exit 162)	425	Waverly	20	7.0	147.0	174.0	60	95%
1005	JCT.I35/K131	NCL LEBO	425	Waverly	20	38.9	2.5	61.4	90	6%
1295	ECL Waverly/K31	NCL WAVERLY/8TH	425	Waverly	20	1.0	18.0	39.0	120	95%
359	N.JCT.U75/K58	JCT.I35/U75	425	Waverly	40	0.0	79.3	119.3	60	100%

SNICE ID	SNICE Route Start Point	SNICE Route End Point	Sub-Area	Responsible Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	LOS Req. Time (min)	Route Efficiency
1259	E.JCT.U75/K39	JCT.U169/K39	431	Altoona	20	15.7	50.6	86.3	90	76%
1261	JCT.U400/K39	W.JCT.U75/K39	431	Altoona	20	0.0	66.3	86.3	90	100%
1962	ECL FREDONIA	JCT.U75/K47	431	Altoona	20	1.4	40.0	61.4	90	97%
1963	JCT.U75/K47	JCT.U169/K47	431	Altoona	20	1.4	45.4	66.8	90	97%
1903	11 MI.E.E.JCT.U400/K99 (FALL RIVER)	JCT.U400/K47	431	Altoona	40	0.0	54.1	94.1	60	100%
1982	JCT.U400/K47	N.JCT.U400/U75	431	Altoona	20	32.5	37.6	90.2	60	54%
365	N.JCT.U75/U400	JCT.U75/K47	431	Altoona	20	1.6	36.1	57.7	60	96%
385	S.JCT.U75B/U75	N.JCT.U75B/U75	431	Altoona	20	0.8	4.1	24.9	60	84%
2021	JCT.U75/K47	W.JCT.U75/K39	431	Altoona	20	0.5	39.1	59.6	60	99%
174	ECL INDEPENDENCE	S.JCT.U169/U160	432	Independence	20	12.6	23.7	56.3	60	65%
178	ECL LONGTON	W.JCT.U75/U160	432	Independence	20	4.8	119.2	143.9	90	96%
149	S.JCT.U75/U166	WCL COFFEYVILLE	432	Independence	20	17.1	48.8	85.9	60	74%
375	KS-OK STATE LINE	WCL INDEPENDENCE	432	Independence	20	0.0	74.7	94.7	60	100%
2025	ECL COFFEYVILLE	E.JCT.U166/U169	432	Independence	40	17.1	2.5	59.6	60	13%
2026	SCL COFFEYVILLE	W.JCT.U166/U169	432	Independence	20	13.4	8.6	42.0	120	39%
130	E.JCT.U166/U169	S.JCT.U160/U169	432	Independence	20	3.4	35.9	59.3	60	91%
137	KS-OK STATE LINE	SCL COFFEYVILLE	432	Independence	20	24.0	2.0	46.0	60	8%
1960	N.JCT.U160/U169	JCT.U169/U400	432	Independence	20	0.0	32.4	52.4	60	100%
1961	S.JCT.U75/U400	JCT.U169/U400	432	Independence	20	3.4	31.6	55.0	60	90%
1984	NCL INDEPENDENCE	S.JCT.U75/U400	432	Independence	20	15.1	24.6	59.7	60	62%

SNICE ID	SNICE Route Start Point	SNICE Route End Point	Sub-Area	Responsible Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	LOS Req. Time (min)	Route Efficiency
2022	S.JCT.U75/U400	N.JCT.U75/U400	432	Independence	20	46.3	26.2	92.5	60	36%
1070	E.JCT.U160/K99	W.JCT.U400/K99	433	Sedan	40	3.4	77.3	120.7	90	96%
1861	KS-OK STATE LINE	S.JCT.U166/U166B/K99	433	Sedan	20	16.9	28.1	65.0	120	62%
1862	N.JCT.U166BUS/K99	W.JCT.U160/K99	433	Sedan	20	4.0	87.7	111.7	120	96%
180	W.JCT.U160/K99	ECL LONGTON	433	Sedan	20	3.4	62.7	86.1	90	95%
182	WCL GRENOLA	W.JCT.U160/K99	433	Sedan	40	3.4	45.1	88.5	120	93%
1864	W.JCT.U166/U166BUS	WCL SEDAN	433	Sedan	20	2.7	17.8	40.6	90	87%
1865	COWLEY-CHAUTAUQUA CO. LINE	JCT.U166/K99	433	Sedan	20	12.9	95.5	128.3	90	88%
1985	JCT.U166/K99	N.JCT.U75/U166	433	Sedan	20	0.0	68.1	88.1	90	100%
2027	WCL SEDAN	SCL SEDAN	433	Sedan	20	1.2	3.0	24.2	120	72%
2028	SCL SEDAN	E.JCT.U166BUS/U166/K 99	433	Sedan	20	0.5	14.2	34.8	90	97%
1044	JCT.U166/K101	JCT.U160/K101	441	Altamont	20	4.1	47.7	71.8	120	92%
1085	S.JCT.U169/U160	W.JCT.U59/U160	441	Altamont	20	0.5	88.6	109.1	90	99%
147	E.JCT.U166/U169	W.JCT.U59/U166	441	Altamont	40	0.0	128.5	168.5	90	100%
169	JCT.U59/U400	JCT.U400/K126	441	Altamont	20	0.0	39.2	59.2	60	100%
173	JCT.U169/U400	JCT.U59/U400	441	Altamont	40	7.9	53.2	101.1	60	87%
1994	KS-OK STATE LINE	W.JCT.U59/U160	441	Altamont	40	0.0	75.6	115.6	60	100%
1995	W.JCT.U59/U160	JCT.U59/U400	441	Altamont	20	0.0	38.1	58.1	60	100%
1043	ECL WEST MINERAL	JCT.K7/K102	442	Columbus	20	31.2	24.0	75.3	120	43%

SNICE ID	SNICE Route Start Point	SNICE Route End Point	Sub-Area	Responsible Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	LOS Req. Time (min)	Route Efficiency
1042	JCT.K7/K103	JCT.U69/K103	442	Columbus	20	38.9	33.6	92.5	120	46%
1572	JCT.U69/U160/K7	JCT.U400/K7	442	Columbus	20	1.2	38.1	59.3	60	97%
1189	JCT.U69/K171	KS-MO STATE LINE	442	Columbus	20	22.1	16.8	58.9	60	43%
166	JCT.U400/K7	JCT.U69/U400/K171	442	Columbus	20	56.2	23.9	100.1	60	30%
1329	JCT.U166/K26	JCT.K26/K66	442	Columbus	20	12.7	17.3	50.0	90	58%
1164	JCT.U400/K66	KS-MO STATE LINE	442	Columbus	20	0.0	28.8	48.8	60	100%
1080	E.JCT.U59/U160	JCT.U69/K7/U160	442	Columbus	20	0.0	69.5	89.5	90	100%
142	E.JCT.U59/U166	JCT.U69/U166	442	Columbus	20	44.9	48.1	113.1	60	52%
1998	JCT.U69/U166	KS-MO STATE LINE(BAXTER SPRINGS)	442	Columbus	20	0.0	39.5	59.5	60	100%
1997	JCT.U69/U160/K7 (Columbus)	JCT.U69/U400/K171	442	Columbus	20	0.5	62.1	82.6	60	99%
1999	KS-OK STATE LINE	JCT.U400/U69ALT	442	Columbus	20	8.7	13.7	42.4	60	61%
2000	S. Jct US-69/US-400 (Crestline)	JCT.U400/U166	442	Columbus	20	1.5	38.0	59.6	60	96%
1996	KS-OK STATE LINE	JCT.U69/U160/K7	442	Columbus	20	0.0	39.1	59.1	60	100%
990	JCT.U59/K146	JCT.K146/K3	443	Erie	20	8.5	74.4	102.8	120	90%
1909	ECL Chanute	W. Jct US-59	443	Erie	20	4.0	61.4	85.4	90	94%
4	JCT.U169/K47	N.JCT.U59/K47	443	Erie	20	13.0	53.1	86.0	90	80%
2001	JCT.U59/K47	JCT.K3/K47	443	Erie	20	0.0	67.5	87.5	90	100%
124	JCT.U169/K47	JCT.U169/K39	443	Erie	20	27.1	38.2	85.4	60	59%

SNICE ID	SNICE Route Start Point	SNICE Route End Point	Sub-Area	Responsible Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	LOS Req. Time (min)	Route Efficiency
127	JCT.U169/U400	JCT.U169/K47	443	Erie	20	0.0	38.6	58.6	60	100%
475	N.JCT.U59/K47	E.JCT.U59/K39	443	Erie	40	0.0	86.2	126.2	90	100%
483	JCT.U59/U400	N.JCT.U59/K47	443	Erie	20	11.3	54.8	86.2	90	83%
1016	JCT.K7/K126	JCT.U69/K126	444	Pittsburg	20	0.4	20.5	40.9	60	98%
1017	JCT.U400/K126	JCT.K7/K126	444	Pittsburg	40	0.0	72.3	112.3	120	100%
1014	JCT.U69BUS/K126	KS-MO STATE LINE	444	Pittsburg	20	6.7	16.7	43.4	60	71%
167	JCT.U400/K126	JCT.U400/K7	444	Pittsburg	20	0.0	34.2	54.2	60	100%
164	JCT.U160/U69	KS-MO STATE LINE	444	Pittsburg	20	24.9	23.2	68.1	90	48%
430	JCT.U69/U160	S.JCT.U69/U69B2/K47	444	Pittsburg	20	18.3	20.8	59.1	60	53%
441	S.JCT.U69/U69BUS2	N.JCT.U69/U69BUS2	444	Pittsburg	20	29.0	10.2	59.3	60	26%
2003	JCT.U69/U400/K171	JCT.U69/K126	444	Pittsburg	20	3.1	18.3	41.4	60	86%
2004	JCT.U69/K126	JCT.U69/U160	444	Pittsburg	20	2.3	14.9	37.2	60	86%
2005	S.JCT.U69/U69B2/K47	JCT.U69/K7	444	Pittsburg	40	0.0	89.1	129.1	60	100%
1191	JCT.K3/K47	JCT.K7/K47	444	Pittsburg	20	31.8	30.9	82.7	90	49%
1190	JCT.K7/K47	JCT.U69/K47/U69B2	444	Pittsburg	20	12.7	26.0	58.6	60	67%
1570	JCT.K7/K126	JCT.K7/K47	444	Pittsburg	20	23.2	34.4	77.6	90	60%
1571	JCT.U400/K7	JCT.K7/K126	444	Pittsburg	20	23.5	23.9	67.4	90	50%
1643	JCT.K3/K47	E.JCT. K3/K39	444	Pittsburg	20	20.7	69.6	110.3	120	77%
2002	JCT.K7/K47	JCT.K7/K39	444	Pittsburg	20	5.0	70.2	95.2	120	93%

Table 5.3 lists all 16 truck garages with their assigned snow and ice routes, remote sites, truck inventory, and total lane miles. Facilities with the most total lane miles include Ft. Scott (292.4 miles), Pittsburg (281.5 miles), Mound City (265.9 miles), and Columbus (263.3 miles), with an associated fleet size of 6, 7, 5, and 7 snowplow trucks, respectively. The treating cycle times of these areas are 610.2, 575.3, 582.6, and 492.6 minutes, respectively. The three treatment areas with the highest deadhead time include Columbus, Pittsburg, and Independence, with the total ineffective time spent of 218.0, 201.6, and 157.3 minutes, respectively. This is potentially due to the refill station locations and the distances from the truck facility to the treating areas. Consequently, the total travel times of snowplow trucks within these four treating areas were Pittsburg at 1,136.9 minutes, Ft. Scott at 1,063.4 minutes, Columbus at 990.7 minutes, and Mound City at 844.3 minutes. The four treatment areas with the lowest deadhead time also had the highest route efficiency: Iola (98%), Altamont (97%), Yates Center (93%), and Ottawa (90%).

Table 5.3: Baseline Outcomes of Model Parameters in District 4

Sub-area ID	Truck Garage	Responsible Routes (count)	Responsible Length (mile)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	Average Route Efficiency (%)
411	Eureka	5	198.9	7.3	388.8	556.1	89
412	Ft. Scott	12	292.4	113.2	610.2	1,063.4	85
413	Iola	6	169.4	9.6	324.6	454.2	98
414	Yates Ctr	8	198.5	52.0	417.2	689.1	93
421	Garnett	9	209.4	78.6	421.2	699.8	81
422	Louisburg	7	232.5	46.3	423.8	610.0	80
423	Mound City	11	265.9	61.7	582.6	844.3	85
424	Ottawa	7	223.8	52.7	408.9	601.5	90
425	Waverly	5	170.8	63.6	298.7	482.3	74
431	Altoona	9	184.1	53.9	373.3	627.2	89
432	Independence	12	229.6	157.3	430.1	847.4	65
433	Sedan	10	208.2	48.5	499.6	788.1	89
441	Altamont	7	230.6	12.5	470.9	683.4	97
442	Columbus	14	263.3	218.0	492.6	990.7	73
443	Erie	8	210.4	63.9	474.2	718.1	88
444	Pittsburg	16	281.5	201.6	575.3	1,136.9	73

5.4 Model Verification

This section discusses a verification plan to determine variations between collected travel times and times calculated by the optimization model. The model verification process involved a series of meetings with KDOT experts and input from winter maintenance personnel to verify the outcomes of the snow and ice model. The model analyzed two sets of data: the current route operated during winter maintenance operations and the initial optimized routes that must be driven at the typical treating speed. The verification process also included three rounds of checking and verifying the input and outcomes of the model: routing networks, baseline for optimization, and model outcomes.

After conducting data collection and generating comprehensive snow and ice routing networks based on handwritten and GIS maps provided by KDOT, the research team performed several checking rounds with KDOT experts and winter maintenance professionals to ensure the accuracy of the base map used for subsequent optimization steps. The routing information of 144 snow and ice routes in District 4 (i.e., route IDs, route classifications, route start and end points, center-lane miles, number of lanes, fleet size, truck facility locations, route priorities, plowing speed, and responsible areas and associated sub-areas) was examined in detail and confirmed by KDOT personnel. Missing highway segments from the online GIS database were re-entered during this first round of verification, and several city-maintained snow and ice routes were identified and excluded from the base map.

Following initial optimization to establish the baseline for subsequent optimization steps, the research team met with KDOT experts to verify result feasibilities. Specifically, five time-related parameters (reload time, deadhead time, plowing time, total travel time, and LOS time requirements), route efficiency, and LOS satisfaction were verified by KDOT experts and winter maintenance personnel. KDOT field staff recommended the deadhead speed should remain at 35 mph, so the research team conservatively calculated the deadhead time to account for severe snow and ice events, which prevent operational trucks from driving at a normal speed.

KDOT experts and winter maintenance professionals also assessed the optimization results regarding LOS satisfaction percentage and required fleet size in correlation with current snowplow practices and fleet allocation plans. They also assessed optimization outcomes of the model within Areas 2 and 4 of District 4. Although results showed that a majority of the routes in these areas matched optimized outcomes, distribution differences of snowplow trucks on multi-lane highways such as I-35 and US-69, which may require two trucks to cover those lane miles for current KDOT practice, were recognized. For example, snow and ice routes IDs 1806 and 1811 in sub-area 424 are both sections of I-35, which is a four-lane highway with interchanges and ramps; therefore, in practice, both sections are assigned two trucks based on the number of lane miles covered instead of only one truck as shown in the model outcomes. In addition, the model outcomes included imbalanced lane miles among the snowplow trucks. For example, the model assigned only one truck to treat 7.51 lane miles of the snow and ice route ID 1295 in sub-area 425, while the combined snow and ice routes IDs 1819 and 1005, totaling 86.81 lane miles, require two trucks. To optimize the snow and ice route removal in District 4, the optimization model recommended route groupings based on route priority, route efficiency, refill locations, total salt application, deadhead time, and sub-area boundary, as described in Chapter 3. Table 5.4 shows the optimization summary in terms of total travel time, LOS satisfaction, total salt application, and route efficiency.

Table 5.4: Snow and Ice Route Optimization Summary in Area 4

Sub-area		Number of Trucks	Total Travel Time (minute)		Total Salt Application (lbs)		Route Efficiency (%)	
ID	Name		Model Outcome	Potential Saving	Model Outcome	Potential Saving	Model Outcome	Potential Increase
441	Altamont	5	623	30	57,639	1,611	98	0
442	Columbus	7	726	110	65,828	2,422	84	5
443	Erie	5	607	124	52,602	1,273	89	3
444	Pittsburg	7	846	42	70,380	2,870	87	14
Total		24	2,802	306	246,449	8,176		

The optimization outcomes showed a savings of approximately 5.1 hours for the total travel time from all four sub-areas. Sub-area 443 demonstrated the most time savings, approximately 2.1 hours, while the least time savings, 0.5 hours, was in sub-area 441. The optimized routes satisfied LOS requirements for treating cycle times within all four sub-areas. Using the optimized routing plan for the total salt application, KDOT could save up to 8,176 lbs (approximately 4 tons) per treating cycle, and the average route efficiency could increase by 5.5% by implementing the optimization model outcomes.

Chapter 6: Snowplow Fleet Optimization

6.1 Introduction

The objectives of the proposed fleet optimization model were to remove the least efficient trucks from the optimized routes, determine the minimum number of trucks required to maintain LOS satisfaction for each snow and ice route, maintain the LOS satisfaction and minimize the number of trucks, and reallocate/add trucks to maximize LOS satisfaction. The model outcomes included recommendations of a minimum number of trucks needed to maintain and maximize current LOS satisfaction. Six criteria were used for the optimization model: route priority, route efficiency, refill locations, a total salt application used, deadhead time, and sub-area boundary. This chapter presents the results related to optimizing and justifying the fleet size from the model applied for District 4.

6.2 Optimization Approaches

The goal of snow and ice route optimization is to meet a set of service requirements by minimizing an objective function. Figure 6.1 shows an overview of the snow and ice route optimization process in District 4, including three main phases: input, Network Analyst, and analysis of output.

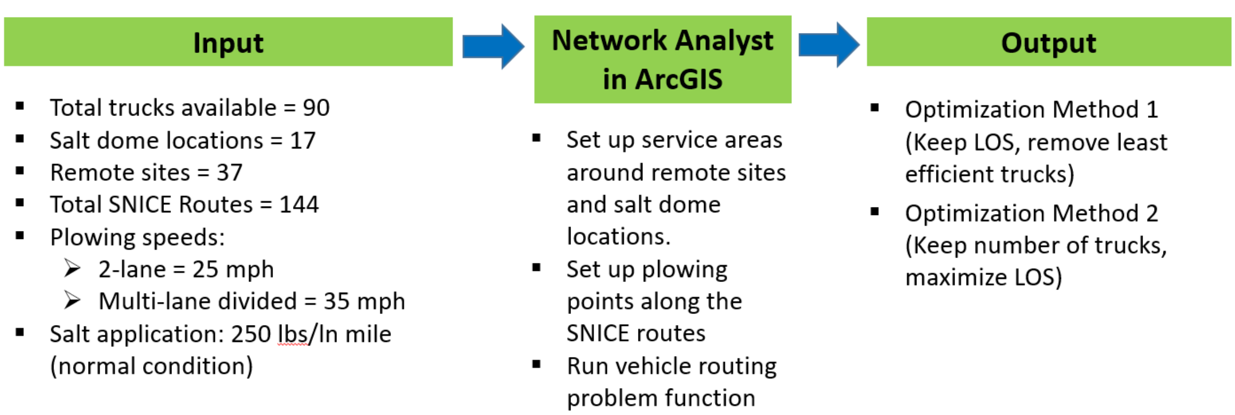

Figure 6.1: Snow and Ice Removal Route Optimization Process

In the input phase, a set of variables was added to the snow and ice optimization model, including the total number of available trucks in District 4 (n = 90), salt dome locations and remote sites (n = 54), total snow and ice routes to plow (n = 144), plowing speeds (two-lane with 25 mph and multi-lane with 35 mph), and salt applications (250 lbs/ln mile for normal conditions and 400 lbs/ln mile for the worst condition). In the second phase, the Network Analyst function in the ArcGIS software package was used to set up service areas around salt dome locations and remote sites, and then plowing points for running vehicle routing problems were created and/or updated with the snow and ice routes. The third phase included a two-step optimization procedure in which Optimization Method 1 aimed to maintain the current LOS setting and minimize the total number of trucks needed in District 4, and Optimization Method 2 aimed to maintain the number of available trucks in the district and maximize the LOS. During the optimization analysis, the researchers removed the least efficient truck and reran the model with a new number of available trucks; new snow and ice routes were created to accommodate the removed truck. The process of removing the least efficient truck and rerunning the model was repeated until the threshold of the maximum number of trucks that could be removed within the LOS requirements for each route in District 4 was removed. Trucks assigned to the second- and third-priority routes were removed before the trucks assigned to the first-priority routes.

6.3 Optimization Results

After multiple iterations that removed the least efficient trucks and recreated new base maps of snow and ice routes, the fleet optimization model ended up with a maximum of nine trucks that could be removed from the current fleet in District 4 while maintaining the satisfied LOS (71%). Four performance metrics were used to determine the efficiency of the optimization model: the fleet size of operational plow trucks, total travel time for one treating iteration, LOS satisfaction percentage, and average truck efficiency based on the 90 snowplow trucks in District 4.

Table 6.1 summarizes the optimization outcome for snow and ice routes based on Optimization Method 1. Results showed that use of this method allowed up to nine snowplow trucks to be removed, while the total travel times remained at 11,760 minutes per treating cycle. Additionally, the current LOS satisfaction percentage and the average snow and ice removal efficiency per 144 routes in District 4 were reserved (71% and 82%, respectively). These results provide insights regarding the potential reduction of trucks for treating all snow and ice routes. Optimization Method 1 may also help KDOT reallocate and develop a more flexible snow and ice removal plan with minimum fleet size while maintaining LOS satisfaction.

Table 6.1: Optimization Outcomes for Snow and Ice Routes in District 4 (Optimization Method 1)

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	Total Salt Needed Per Truck (lbs)	LOS Requirement Time (min)	Operational Trucks	Number of Trucks Removed	LOS Satisfaction?
850	411	40	3.4	3.6	47.1	11,028	90	5	1	Yes
1065	411	40	0.0	102.2	102.2		90			No
1067	411	20	3.4	61.9	85.4	6,451	90			Yes
11	411	40	0.0	95.2	135.2	13,882	60			No
570	411	20	0.4	125.8	146.2	18,351	60			No
1638	412	20	26.3	33.6	79.9	22,257	120	6	0	Yes
1640	412	20	20.7	50.6	50.6		120			Yes
557	412	20	17.6	92.4	92.4		60			No
1284	412	20	19.1	33.5	72.6	5,162	120			Yes
1286	412	40	1.7	16.0	16.0		120			Yes
1252	412	40	0.0	39.7	79.7	9,096	120			Yes
1255	412	40	8.4	47.7	56.1		120			Yes
1166	412	40	0.0	52.4	92.4	12,881	120			Yes
1564	412	20	14.7	71.3	86.0		120			Yes
1566	412	20	4.3	36.4	60.7	3,791	120			Yes
422	412	40	0.0	100.9	140.9	19,915	60			No
425	412	20	0.4	35.7	36.1		60			Yes
123	413	20	8.3	63.0	91.2	9,183	60	5	0	No
2016	413	20	0.0	38.2	58.2	15,312	60			Yes
2013	413	20	0.0	37.1	57.1		60			Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	Total Salt Needed Per Truck (lbs)	LOS Requirement Time (min)	Operational Trucks	Number of Trucks Removed	LOS Satisfaction?
2014	413	20	0.0	66.8	86.8	5,416	60			No
2015	413	20	1.4	52.8	74.2	5,499	90			Yes
474	413	20	0.0	66.7	86.7	6,943	90			Yes
1196	414	40	0.0	96.7	136.7	10,073	90	5	1	No
1198	414	20	3.4	63.0	66.5	12,741	90			Yes
1199	414	20	0.0	54.0	54.0		90			Yes
2501	414	40	0.0	5.2	45.2		90			Yes
567	414	20	0.0	48.0	68.0	12,211	60			No
1040	414	20	48.6	50.1	98.6		120			Yes
364	414	20	0.0	48.7	68.7	14,598	60			No
2017	414	40	0.0	51.4	51.4		60			No
1291	421	40	0.0	28.9	68.9	9,053	120	5	1	Yes
468	421	20	10.4	58.0	68.4		90			Yes
1294	421	20	0.5	124.3	144.8	12,950	120			No
114	421	20	0.0	76.5	96.5	11,849	60			No
136	421	20	2.9	6.7	9.6		90			Yes
460	421	20	32.2	44.9	97.1	11,100	60			No
464	421	20	0.5	31.2	31.7		60			Yes
1957	421	20	9.2	14.3	43.4	7,391	60			Yes
467	421	20	22.9	36.4	36.4		60			No
818	422	20	20.5	2.4	42.9	20,458	120	8	2	Yes
108	422	20	3.4	138.6	138.6		60			No
1154	422	20	13.9	21.6	55.6	2,253	90			Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	Total Salt Needed Per Truck (lbs)	LOS Requirement Time (min)	Operational Trucks	Number of Trucks Removed	LOS Satisfaction?
1155	422	20	0.4	26.2	26.2	3,824	60			Yes
1157	422	20	4.5	64.4	88.9	6,707	90			Yes
415	422	20	0.0	39.0	59.0	5,691	60			Yes
417	422	20	3.4	131.5	155.0	19,181	60			No
973	423	40	0.0	61.7	101.7	14,375	120	**5**	**0**	Yes
418C	423	0	0.0	43.2	43.2					
1221	423	20	39.6	15.9	55.5		120			Yes
418A	423	0	0.0	52.5	52.5	10,514	120			Yes
860	423	40	0.0	27.4	67.4		120			Yes
1637	423	20	16.1	28.9	65.0	11,788	120			Yes
1288	423	20	4.1	84.3	108.4		120			Yes
418B	423	0	0.0	43.4	43.4	11,700	90			Yes
1223	423	20	0.5	30.5	30.5		90			Yes
1225	423	20	0.5	21.1	21.6		90			Yes
1562	423	20	0.8	173.8	194.6	18,107	120			No
1806	424	20	2.6	129.0	151.6	18,815	60	**7**	**2**	No
1811	424	20	19.5	88.4	127.9	12,892	60			No
1276	424	20	12.0	50.0	82.0	5,205	90			Yes
1158	424	20	0.5	38.5	38.5	4,015	90			Yes
1161	424	20	0.0	3.5	23.5	7,271	60			Yes
1906	424	20	10.6	46.4	57.0		60			No
2019	424	20	7.5	53.1	80.6	7,742	60			No
1813	425	20	16.7	51.8	88.5	7,554	60	**5**	**1**	No

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	Total Salt Needed Per Truck (lbs)	LOS Requirement Time (min)	Operational Trucks	Number of Trucks Removed	LOS Satisfaction?
1819	425	20	7.0	147.0	147.0	21,702	60			No
1005	425	20	38.9	2.5	61.4		90			Yes
1295	425	20	1.0	18.0	39.0	1,877	120			Yes
359	425	40	0.0	79.3	119.3	11,565	60			No
1259	431	20	15.7	50.6	86.3	12,172	90	**5**	**0**	Yes
1261	431	20	0.0	66.3	66.3		90			Yes
1962	431	20	1.4	40.0	61.4	8,897	90			Yes
1963	431	20	1.4	45.4	45.4		90			Yes
1903	431	40	0.0	54.1	54.1	13,378	60			No
1982	431	20	32.5	37.6	90.2		60			No
365	431	20	1.6	36.1	57.7	5,866	60			Yes
385	431	20	0.8	4.1	4.1		60			Yes
2021	431	20	0.5	39.1	59.6	5,700	60			Yes
174	432	20	12.6	23.7	56.3	15,868	60	**6**	**0**	Yes
178	432	20	4.8	119.2	119.2		90			No
149	432	20	17.1	48.8	65.9	18,006	60			No
375	432	20	0.0	74.7	94.7		60			No
2025	432	40	17.1	2.5	59.6	6,784	60			Yes
2026	432	20	13.4	8.6	8.6		120			Yes
130	432	20	3.4	35.9	35.9		60			Yes
137	432	20	24.0	2.0	2.0		60			Yes
1960	432	20	0.0	32.4	52.4	9,326	60			Yes
1961	432	20	3.4	31.6	35.0		60			Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	Total Salt Needed Per Truck (lbs)	LOS Requirement Time (min)	Operational Trucks	Number of Trucks Removed	LOS Satisfaction?
1984	432	20	15.1	24.6	59.7	3,593	60			Yes
2022	432	20	46.3	26.2	92.5	3,817	60			No
1070	433	40	3.4	77.3	120.7	8,049	90	**4**	**0**	No
1861	433	20	16.9	28.1	65.0	12,067	120			Yes
1862	433	20	4.0	87.7	87.7		120			Yes
180	433	20	3.4	62.7	86.1	11,232	90			Yes
182	433	40	3.4	45.1	45.1		120			Yes
1864	433	20	2.7	17.8	17.8	20,697	90			Yes
1865	433	20	12.9	95.5	108.3		90			No
1985	433	20	0.0	68.1	68.1		90			Yes
2027	433	20	1.2	3.0	3.0		120			Yes
2028	433	20	0.5	14.2	14.2		90			Yes
1044	441	20	4.1	47.7	71.8	14,201	120	**5**	**0**	Yes
1085	441	20	0.5	88.6	88.6		90			No
147	441	40	0.0	128.5	168.5	13,381	90			No
169	441	20	0.0	39.2	59.2	13,477	60			Yes
173	441	40	7.9	53.2	61.1		60			No
1994	441	40	0.0	75.6	115.6	11,025	60			No
1995	441	20	0.0	38.1	58.1	5,555	60			Yes
1043	442	20	31.2	24.0	75.3	11,557	120	**7**	**0**	Yes
1042	442	20	38.9	33.6	33.6		120			Yes
1572	442	20	1.2	38.1	38.1		60			Yes
1189	442	20	22.1	16.8	16.8	5,935	60			Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	Total Salt Needed Per Truck (lbs)	LOS Requirement Time (min)	Operational Trucks	Number of Trucks Removed	LOS Satisfaction?
166	442	20	56.2	23.9	80.1		60			No
1329	442	20	12.7	17.3	50.0	6,007	90			Yes
1164	442	20	0.0	28.8	28.8		60			Yes
1080	442	20	0.0	69.5	69.5	7,239	90			Yes
142	442	20	44.9	48.1	113.1	12,784	60			No
1998	442	20	0.0	39.5	39.5		60			Yes
1997	442	20	0.5	62.1	62.1	16,601	60			No
1999	442	20	8.7	13.7	22.4		60			Yes
2000	442	20	1.5	38.0	38.0		60			Yes
1996	442	20	0.0	39.1	59.1	5,706	60			Yes
990	443	20	8.5	74.4	102.8	14,146	120	**5**	**1**	Yes
1909	443	20	4.0	61.4	61.4		90			Yes
4	443	20	13.0	53.1	86.0	12,557	90			Yes
2001	443	20	0.0	67.5	67.5		90			Yes
124	443	20	27.1	38.2	58.2	11,209	60			Yes
127	443	20	0.0	38.6	38.6		60			Yes
475	443	40	0.0	86.2	126.2	14,690	90			No
483	443	20	11.3	54.8	66.2		90			Yes
1016	444	20	0.4	20.5	40.9	17,947	60	**7**	**0**	Yes
1017	444	40	0.0	72.3	72.3		120			Yes
1014	444	20	6.7	16.7	23.4		60			Yes
167	444	20	0.0	34.2	34.2		60			Yes
164	444	20	24.9	23.2	68.1	6,953	90			Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	Total Salt Needed Per Truck (lbs)	LOS Requirement Time (min)	Operational Trucks	Number of Trucks Removed	LOS Satisfaction?
430	444	20	18.3	20.8	20.8		60			Yes
441	444	20	29.0	10.2	10.2		60			Yes
2003	444	20	3.1	18.3	41.4	4,845	60			Yes
2004	444	20	2.3	14.9	14.9		60			Yes
2005	444	40	0.0	89.1	129.1	12,992	60			No
1191	444	20	31.8	30.9	82.7	7,009	90			Yes
1190	444	20	12.7	26.0	26.0		60			Yes
1570	444	20	23.2	34.4	77.6	6,077	90			Yes
1571	444	20	23.5	23.9	23.9		90			Yes
1643	444	20	20.7	69.6	110.3	14,556	120			Yes
2002	444	20	5.0	70.2	70.2		120			Yes

Table 6.2 summarizes the results after utilizing Optimization Method 2 to group relevant snow and ice routes for simultaneous treatment and reallocates the trucks in District 4. Although no new trucks were added to the current fleet size of 90 snowplow trucks, the proposed model can help reduce approximately 29 hours of total travel time required to treat all 144 snow and ice routes in District 4 and increase the LOS satisfaction percentage to 81%. In addition, the average removal efficiency for all 144 snow and ice routes increased to 86%, indicating that snowplow trucks could treat routes with higher efficiency compared to current practices. These results could help KDOT develop an improved operational plan with potential reallocations of available trucks in District 4 to increase LOS satisfaction.

Table 6.2: Results of Optimization for Maximizing LOS (Optimization Method 2)

Variable	Current Snow and Ice Route Removal Practices	Optimization Method 2	Difference (Method 2 vs. Current)
Fleet Size	90	90	0
Total Travel Time (minute/cycle)	11,760	10,012	-1,748
LOS Maintained (%)	71	81	+10
Average Route Efficiency (%)	82	86	+4

The following sections describe two snow and ice routes optimized for sub-area 414 at Yates Center and sub-area 443 at Erie in District 4. Before optimization, this sub-area was responsible for eight snow and ice routes (R 364, 567, 1040, 1196, 1998, 1199, 2017, and 2501) with five snowplow trucks, shown in Figure 6.2. The total travel time to simultaneously treat all eight routes was 523.6 minutes (approximately 8.7 hours). The fleet optimization model created an optimized base map that combined snow and ice routes based on their distance to truck facilities, treating time, total travel time, and salt applications needed for a treating cycle (250 lbs/ln mile under a normal condition). The optimized base map consisted of four snow and ice routes combined from the previous eight routes (Figure 6.3) that consequently decreased the fleet size to four snowplow trucks. The total travel time to simultaneously treat all four routes was 383.6 minutes (approximately 6.4 hours). The optimization model also saved approximately 2.3 hours with one snowplow truck that could be reallocated to other sub-areas to improve the overall LOS satisfaction percentage of 16 sub-areas in District 4.

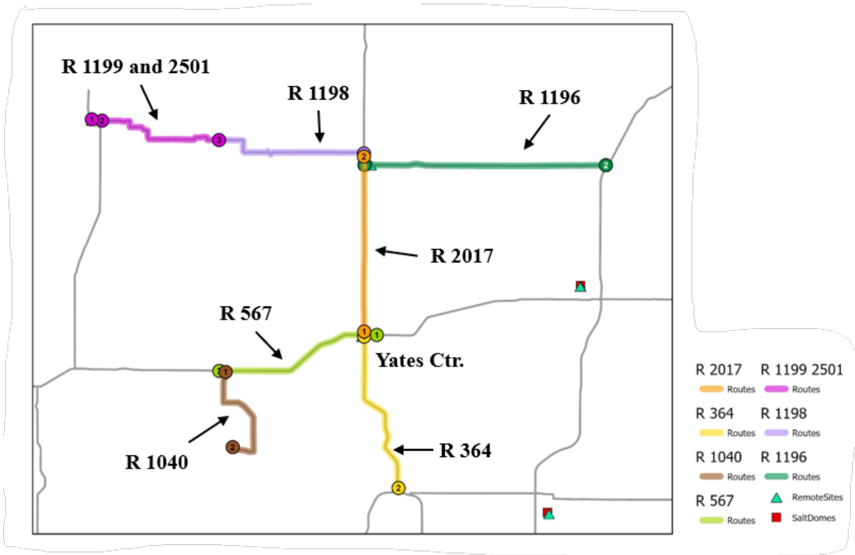

Figure 6.2: Sub-Area 414 at Yates Center (Before Optimization)

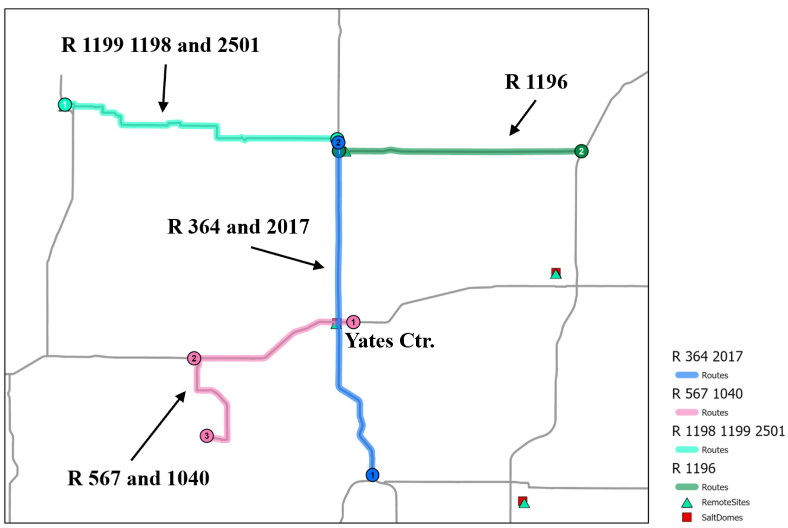

Figure 6.3: Sub-Area 414 at Yates Center (After Optimization)

Tables 6.3 and 6.4 show detailed statistics before and after optimization of snow and ice routes in sub-area 414 at Yates Center. Three possible groupings of snow and ice routes within this sub-area reduced the number of needed trucks and the total travel time from 11 hours to 9 hours. The first group consisted of routes ID# 1198, 1199, and 2501 from the county borderline to the junction between highways K-58 and K-249, resulting in a total treatment length of 50.96 miles. The second group consisted of routes ID# 567 and 1040 from the junction of highways US- 54 of K-58 to junction US-54 of K-105, resulting in a total treatment length of 48.84 miles.

The third group consisted of routes ID# 364 and 2017 from junction US-75 of K-39 to junction US-75 of K-58, resulting in a total treatment length of 58.39 miles. Route ID #1196 from junction US-75 of K-58 to junction US-169 of K-58 was not grouped with others because of its distance from the truck facility or remote sites in Yates Center, thereby requiring more travel time for treatment trucks. Table 6.5 summarizes outcomes for all routes in District 4 using Optimization Method 2.

Table 6.3: Snow and Ice Optimization of Sub-Area 414 at Yates Center (Before Optimization)

Snow and Ice ID	Route Begin	Route End	Route	Lane Mile	Grouped
1196	S.JCT.U75/K58	JCT.U169/K58	K-58	40.29	No
1198	GREENWOOD-COFFEY CO. LINE	N.JCT.U75/K58	K-58	26.27	Yes
1199	JCT.K58/K249/SOUTHWEST RD	GREENWOOD-COFFEY CO. LINE	K-58	22.51	Yes
2501	JCT.K58/K99	JCT.K58/K249	K-58	2.18	Yes
567	JCT.U54/K105	ECL YATES CENTER	US-54	27.98	Yes
1040	JCT.K105.FALL RIVER RD	JCT.U54/K105	K-105	20.86	Yes
364	W.JCT.U75/K39	JCT.U54/U75	US-75	28.42	Yes
2017	JCT.U54/U75	N.JCT.U75/K58	US-75	29.97	Yes
Total Travel Time = 689.1 (min)					

Table 6.4: Snow and Ice Optimization of Sub-Area 414 at Yates Center (After Optimization)

Snow and Ice ID	Route Begin	Route End	Route	Lane Mile	Grouped
1196	S.JCT.U75/K58	JCT.U169/K58	K-58	40.29	No
1198	GREENWOOD-COFFEY CO. LINE	N.JCT.U75/K58	K-58	50.96	Group 1
1199	JCT.K58/K249/SOUTHWEST RD	GREENWOOD-COFFEY CO. LINE	K-58		Group 1
2501	JCT.K58/K99	JCT.K58/K249	K-58		Group 1
567	JCT.U54/K105	ECL YATES CENTER	US-54	48.84	Group 2
1040	JCT.K105.FALL RIVER RD	JCT.U54/K105	K-105		Group 2
364	W.JCT.U75/K39	JCT.U54/U75	US-75	58.39	Group 3
2017	JCT.U54/U75	N.JCT.U75/K58	US-75		Group 3
Total Travel Time = 589.1 (min)					

Table 6.5: Outcomes for Snow and Ice Routes in District 4 (Optimization Method 2)

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	No. of Cycles Before Refilling	Amount of Salt Remaining	Operational Trucks	Route Efficiency	LOS Satisfaction?
850	411	40	3.4	3.6	47.1	1	2,972	**5**	52%	Yes
1065	411		0.0	102.2	102.2				100%	No
1067	411	20	3.4	61.9	85.4	2	7,549		95%	Yes
11(*)	411	40	0.0	95.2	135.2	1	118		100%	Yes
570	411	20	0.4	125.8	146.2	1	-4,351		100%	No
1638	412	20	26.3	33.6	79.9	1	-8,257	**6**	56%	Yes
1640	412		0.0	50.6	50.6				100%	Yes
557	412		0.0	92.4	92.4				100%	No
1284	412	20	19.1	33.5	72.6	3	8,838		64%	Yes
1286	412		0.0	16.0	16.0				100%	Yes
1252	412	40	0.0	39.7	79.7	2	4,904		100%	Yes
1255	412		8.4	47.7	56.1				85%	Yes
1166	412	40	0.0	52.4	92.4	1	1,119		100%	Yes
1564	412		14.7	71.3	86.0				83%	Yes
1566	412	20	4.3	36.4	60.7	4	10,209		89%	Yes
422	412	40	0.0	100.9	140.9	1	-5,915		100%	No
425	412		0.4	35.7	36.1				99%	Yes
123	413	20	8.3	63.0	91.2	2	4,817	**5**	88%	No
2016	413	20	0.0	38.2	58.2	1	-1,312		100%	Yes
2013	413		0.0	57.1	57.1				100%	Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	No. of Cycles Before Refilling	Amount of Salt Remaining	Operational Trucks	Route Efficiency	LOS Satisfaction?
2014	413	20	0.0	66.8	86.8	3	8,584		100%	No
2015	413	40	1.4	52.8	74.2	3	8,501		97%	Yes
474	413	40	0.0	66.7	86.7	2	7,057		100%	Yes
1196(*)	414	40	0.0	96.7	136.7	1	3,927	**5**	100%	Yes
1198	414	40	3.4	63.0	66.5	1	1,259		95%	Yes
1199	414		0.0	54.0	54.0				100%	Yes
2501	414		0.0	5.2	45.2				100%	Yes
567	414	20	0.0	48.0	68.0	1	1,789		100%	No
1040	414		48.6	50.1	98.6				51%	Yes
364	414	20	0.0	48.7	68.7	1	-598		100%	No
2017	414		0.0	51.4	51.4				100%	Yes
1291	421	40	0.0	28.9	68.9	2	4,947	**5**	100%	Yes
468	421		10.4	58.0	68.4				85%	Yes
1294(*)	421	20	0.5	124.3	144.8	1	1,050		100%	Yes
114	421	20	0.0	76.5	96.5	1	2,151		100%	No
136	421		2.9	6.7	9.6				69%	Yes
460	421	20	32.2	44.9	97.1	1	2,900		58%	No
464	421		0.5	31.2	31.7				98%	Yes
1957	421	20	9.2	14.3	43.4	2	6,609		61%	Yes
467	421		0.0	36.4	36.4				100%	Yes
818	422	20	20.5	2.4	42.9	1	-6,458	**8**	10%	Yes
108(*)	422		0.0	138.6	138.6				100%	Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	No. of Cycles Before Refilling	Amount of Salt Remaining	Operational Trucks	Route Efficiency	LOS Satisfaction?
1154	422	20	13.9	21.6	55.6	6	11,747		61%	Yes
1155	422		0.4	26.2	26.2	4	10,176		98%	Yes
1157	422	20	4.5	64.4	88.9	2	7,293		93%	Yes
415	422	20	0.0	39.0	59.0	2	8,309		100%	Yes
417(*)	422	20	3.4	131.5	155.0	1	-5,181		97%	Yes
973	423	40	0.0	61.7	101.7	1	-375	**5**	100%	Yes
418C	423		0.0	43.2	43.2					
1221	423		39.6	15.9	55.5				29%	Yes
418A	423	40	0.0	52.5	52.5	1	3,486			Yes
860	423		0.0	27.4	67.4				100%	Yes
1637	423	20	16.1	28.9	65.0	1	2,212		64%	Yes
1288	423		4.1	84.3	108.4				95%	Yes
418B	423	20	0.0	43.4	43.4	1	2,300			
1223	423		0.0	30.5	30.5				100%	Yes
1225	423		0.5	21.1	21.6				97%	Yes
1562	423	20	0.8	173.8	194.6	1	-4,107		100%	No
1806(*)	424	20	2.6	129.0	151.6	1	-4,815	**7**	98%	Yes
1811	424	20	19.5	88.4	127.9	1	1,108		82%	No
1276	424	20	12.0	50.0	82.0	2	4,780		81%	Yes
1158	424		0.0	38.5	38.5				100%	Yes
1161	424	20	0.0	3.5	23.5	2	6,729		100%	Yes
1906	424		10.6	46.4	57.0				81%	Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	No. of Cycles Before Refilling	Amount of Salt Remaining	Operational Trucks	Route Efficiency	LOS Satisfaction?
2019(*)	424	20	7.5	53.1	80.6	2	6,258		88%	Yes
1813	425	20	16.7	51.8	88.5	2	6,446	**5**	76%	No
1819(*)	425	20	0.0	147.0	147.0	1	-7,702		100%	Yes
1005	425		38.9	2.5	61.4				6%	Yes
1295	425	20	1.0	18.0	39.0	7	12,123		95%	Yes
359	425	40	0.0	79.3	119.3	1	2,435		100%	No
1259	431	20	15.7	50.6	86.3	1	1,828	**5**	76%	Yes
1261	431		0.0	66.3	66.3				100%	Yes
1962	431	20	1.4	40.0	61.4	2	5,103		97%	Yes
1963	431		0.0	45.4	45.4				100%	Yes
1903	431	20	0.0	54.1	54.1	1	622		100%	Yes
1982	431		32.5	37.6	90.2				54%	No
365	431	20	1.6	36.1	57.7	2	8,134		96%	Yes
385	431		0.0	4.1	4.1				100%	Yes
2021	431	20	0.5	39.1	59.6	2	8,300		99%	Yes
174	432	20	12.6	23.7	56.3	1	-1,868	**6**	65%	Yes
178	432		0.0	119.2	119.2				100%	No
149	432	20	17.1	48.8	65.9	1	-4,006		74%	No
375	432		0.0	74.7	94.7				100%	No
2025	432	40	17.1	2.5	59.6	2	7,216		13%	Yes
2026	432		0.0	8.6	8.6				100%	Yes
130	432		0.0	35.9	35.9				100%	Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	No. of Cycles Before Refilling	Amount of Salt Remaining	Operational Trucks	Route Efficiency	LOS Satisfaction?
137	432		0.0	2.0	2.0				100%	Yes
1960	432	20	0.0	32.4	52.4	2	4,674		100%	Yes
1961	432		3.4	31.6	35.0				90%	Yes
1984	432	20	15.1	24.6	59.7	4	10,407		62%	Yes
2022	432	20	46.3	26.2	92.5	4	10,183		36%	No
1070	433	40	3.4	77.3	120.7	2	5,951	4	96%	No
1861	433	20	16.9	28.1	65.0	1	1,933		62%	Yes
1862	433		0.0	87.7	87.7				100%	Yes
180	433	20	3.4	62.7	86.1	1	2,768		95%	Yes
182	433		0.0	45.1	45.1				100%	Yes
1864	433	20	0.0	17.8	17.8	1	-6,697		100%	Yes
1865	433		12.9	95.5	108.3				88%	No
1985	433		0.0	68.1	68.1				100%	Yes
2027	433		0.0	3.0	3.0				100%	Yes
2028	433		0.0	14.2	14.2				100%	Yes
1044	441	20	4.1	47.7	71.8	1	-201	5	92%	Yes
1085	441		0.0	88.6	88.6				100%	Yes
147	441	40	0.0	128.5	168.5	1	619		100%	No
169	441	20	0.0	39.2	59.2	1	523		100%	Yes
173	441		7.9	53.2	61.1				87%	No
1994	441	40	0.0	75.6	115.6	1	2,975		100%	No
1995	441	20	0.0	38.1	58.1	3	8,445		100%	Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	No. of Cycles Before Refilling	Amount of Salt Remaining	Operational Trucks	Route Efficiency	LOS Satisfaction?
1043	442	20	31.2	24.0	75.3	1	2,443	7	43%	Yes
1042	442		0.0	33.6	33.6				100%	Yes
1572	442		0.0	38.1	38.1				100%	Yes
1189	442	20	0.0	16.8	16.8	2	8,065		100%	Yes
166	442		56.2	23.9	80.1				30%	No
1329	442	20	12.7	17.3	50.0	2	7,993		58%	Yes
1164	442		0.0	28.8	28.8				100%	Yes
1080	442	20	0.0	69.5	69.5	2	6,761		100%	Yes
142	442	20	44.9	48.1	113.1	1	1,216		52%	No
1998	442		0.0	39.5	39.5				100%	Yes
1997	442	20	0.0	62.1	62.1	1	-2,601		100%	No
1999	442		8.7	13.7	22.4				61%	Yes
2000	442		0.0	38.0	38.0				100%	Yes
1996	442	20	0.0	39.1	59.1	2	8,294		100%	Yes
990	443	20	8.5	74.4	102.8	1	-146	5	90%	Yes
1909	443		0.0	61.4	61.4				100%	Yes
4	443	20	13.0	53.1	86.0	1	1,443		80%	Yes
2001	443		0.0	67.5	67.5				100%	Yes
124	443	20	27.1	38.2	58.2	1	2,791		59%	Yes
127	443		0.0	38.6	38.6				100%	Yes
475(*)	443	40	0.0	86.2	126.2	1	-690		100%	Yes
483	443		11.3	54.8	66.2				83%	Yes

SNICE ID	Sub-Area	Reload Time (min)	Deadhead Time (min)	Treating Cycle Time (min)	Total Travel Time (min)	No. of Cycles Before Refilling	Amount of Salt Remaining	Operational Trucks	Route Efficiency	LOS Satisfaction?
1016	444	20	0.4	20.5	40.9	1	-3,947	**7**	98%	Yes
1017	444		0.0	72.3	72.3				100%	Yes
1014	444		6.7	16.7	23.4				71%	Yes
167	444		0.0	34.2	34.2				100%	Yes
164	444	20	24.9	23.2	68.1	2	7,047		48%	Yes
430	444		0.0	20.8	20.8				100%	Yes
441	444		0.0	10.2	10.2				100%	Yes
2003	444	20	3.1	18.3	41.4	3	9,155		86%	Yes
2004	444		0.0	14.9	14.9				100%	Yes
2005	444	40	0.0	89.1	129.1	1	1,008		100%	No
1191	444	20	31.8	30.9	82.7	2	6,991		49%	Yes
1190	444		0.0	26.0	26.0				100%	Yes
1570	444	20	23.2	34.4	77.6	2	7,923		60%	Yes
1571	444		0.0	23.9	23.9				100%	Yes
1643	444	20	20.7	69.6	110.3	1	-556		77%	Yes
2002	444		5.0	70.2	70.2				93%	Yes

(*) One truck should be reallocated in this route.

Table 6.6 summarizes the optimization results for 144 snow and ice routes in District 4. Accordingly, the optimization model could help KDOT save approximately 29 hours of travel time per treating cycle for all 144 routes and decrease the deadhead time by 5 hours per treating cycle. Before optimization, the number of snow and ice routes that satisfy the LOS requirements included 102 of 144 routes, indicating an LOS satisfaction rate of 71%. After optimization, the LOS satisfaction rate increased to 81%, with 116 of 144 routes satisfying LOS requirements. The average removal efficiency of the 144 snow and ice routes also increased to 86%. These results could help KDOT implement a more efficient and effective snow and ice removal operational plan with fewer resources and a decreased fleet size.

Table 6.6: Summary of Snow and Ice Route Optimization Results

Performance Metric	Before Optimized	After Optimized	Result
Total travel time (minute/cycle)	11,760	10,012	29 hours saved
Deadhead times (minute/cycle)	1,209	920	5 hours saved
Number of routes satisfied LOS requirements (n= 144)	102	116	14 routes increased
LOS satisfaction (%)	71	81	10% increased
Average Route Efficiency (%)	82	86	4% increased

Figure 6.4 compares the LOS satisfaction percentage and fleet size required for snow and ice removal operations to the current practice, Optimization Method 1, Optimization Method 2, and an ideal situation in which the LOS satisfaction reaches 100%. Use of Optimization Method 1 would allow KDOT to remove up to nine snowplow trucks from their current practices while maintaining the LOS satisfaction percentage at 71%. With the current fleet size of 90 snowplow trucks, the optimization model could increase the LOS satisfaction to 81%. To reach the maximum LOS satisfaction rate, the optimization model recommends the addition of 28 trucks.

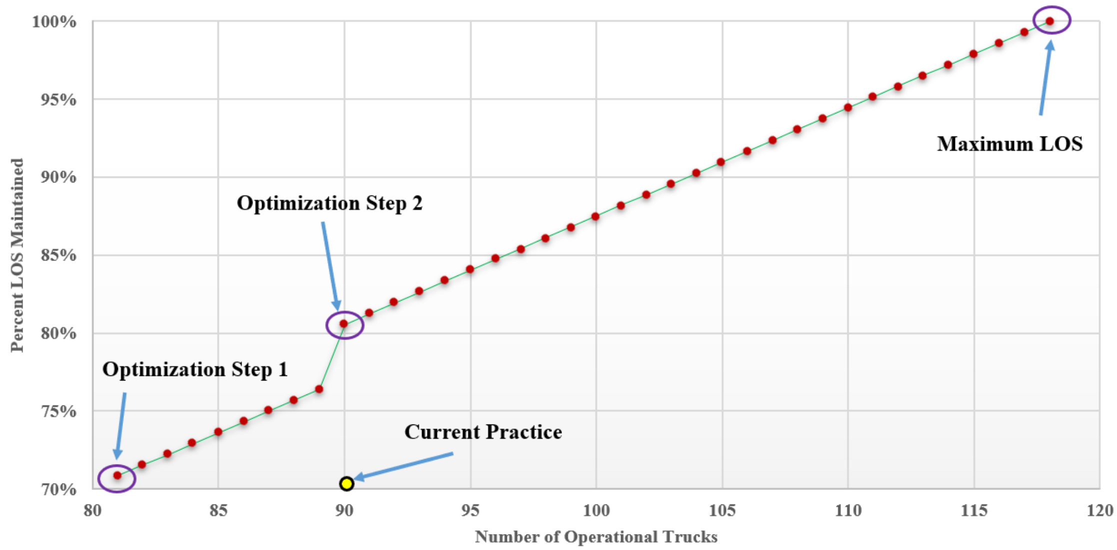

Figure 6.4: LOS versus Number of Operational Trucks Needed in District 4

The LOS satisfaction percentage of current practices of snow and ice removal operation in District 4 is 71%, but the application of the optimization model without adding trucks increased the LOS satisfaction percentage to 81%. To achieve an LOS satisfaction percentage of 85%, meaning 122 of 144 snow and ice routes satisfy LOS requirements, KDOT should add at least six trucks to their current fleet, and to achieve an LOS satisfaction percentage of 90%, meaning 129 of 144 snow and ice routes satisfy LOS requirements, KDOT should add at least 13 trucks to their current fleet. Similarly, to achieve an LOS satisfaction percentage of 95%, meaning 137 of 144 snow and ice routes satisfy LOS requirements, KDOT should add at least 21 trucks to their current fleet. Finally, to reach 100% LOS satisfaction, KDOT should add at least 28 trucks to their current fleet. However, reallocation of additional trucks within the 16 sub-areas will require a detailed implementation plan.

Chapter 7: Conclusions

7.1 Summary

Although management of winter maintenance operations is critical to ensure safe travel routes, it is a complex process with a wide range of operational objectives and constraints. State DOTs spend substantial resources on snow and ice control activities and operations. For example, KDOT spends from $7 million to $22 million annually, and KDOT winter maintenance operations currently deploy a fleet of 591 snowplow trucks, including 1,182 drivers and approximately 200 engineering technicians, to maintain more than 25,000 lane miles. The deployment of so many trucks over a vast maintenance area makes it operationally difficult to determine optimal maintenance routes and fleet size.

The objective of this project was to develop a snowplow route optimization plan using modern technologies and modeling techniques to cost-effectively support KDOT's winter maintenance operations. This optimization plan could help KDOT efficiently allocate limited resources to maintain all snow and ice routes in an economical, safe, and reliable manner. Model development included digitizing all snow and ice base routes and available truck facilities in District 4, identifying optimized routes and fleet size for current snow and ice route removal operations, and determining the total number of operational trucks needed for District 4 to maintain current LOS requirements. A GIS-based software platform was utilized to develop a fleet optimization model for snow and ice route removal operations for the 144 snow and ice routes in the district.

The model results provided a detailed set of district route maps, including individual route descriptions with time-related parameters (total travel time, treating cycle time, and deadhead time), route efficiency, and percent of LOS satisfaction of route removal operations. The three model outcomes were model baseline, Optimization Method 1, and Optimization Method 2. The model baseline outcome showed digitized snow and ice base routes and available truck facilities based on current practice. Optimization Method 1 removed the least efficient trucks from the optimized routes and determined the minimum number of trucks required to maintain the LOS satisfaction for each route in District 4. The current LOS satisfaction percentage of 71% was maintained when a maximum of nine trucks were removed from the current fleet. Results of

Optimization Method 2 indicated that the proposed model could reduce approximately 29 hours of total travel time required to treat all 144 snow and ice routes and increase the LOS satisfaction percentage to 81% using the current fleet size of 90 snowplow trucks.

Expected benefits from implementing the optimized routes include cost savings from increased LOS satisfaction and decreased total travel time required to plow all snow roads in District 4. Implementation of the proposed model could reduce snow removal costs and enhance the safety of drivers who travel during snow and ice events, as well as decrease risks of accidents related to extreme weather conditions. Specifically, the shortened total treatment time for all snow and ice roads per cycle due to the proposed optimization model could increase traffic safety and decrease accident risks while allowing KDOT to have a flexible fleet size that could be allocated during heavy snow events. This report also highlights the applicability of GIS technology for assisting transportation management with operational considerations. The study results facilitate the automation of snowplow optimization processes using ArcGIS software packages and its extensions to provide satisfactory services during snow and ice events. Overall, the proposed optimization model could increase the total LOS satisfaction in District 4, thereby enabling KDOT to secure its outstanding maintenance service during snow and ice events.

7.2 Key Findings and Recommendations

Several state DOTs have considered computerized tools to facilitate the snowplow optimization process to improve the efficiency of snow and ice removal operations by minimizing total service times or total cycle time (Appendix A). These study findings illustrate the potential benefits of the route optimization model in District 4 by justifying the fleet size and determining where to allocate limited resources while maintaining roadway safety and reliability. Consequently, an optimization strategy was recommended for KDOT snow and ice route removal operations regarding the number of plowing cycles that could be conducted before a refill is required. The recommendations were based on the assumptions of 14,000 lbs of salt applications per snowplow truck and 250 lbs/ln mile. For example, route #570 requires a total of 18,351 lbs of salt, but a truck can handle only 14,000 lbs. Therefore, the truck treating route #1067 with the remaining 7,549 lbs of salt could take over the rest of route #570, which requires 4,351 lbs to reduce another treating cycle. This study used a fleet of 90 snowplow trucks for optimization with the assumption that no mechanical errors or lack of staff were present in District 4. To achieve the results shown in the optimization method, a safety factor of 10% of the fleet should be considered in the model.

If one sub-area has a shortage of one truck, recommendations based on the optimization results are summarized as follows:

- In sub-area 411 – Eureka: With five snowplow trucks available, the truck shortage could be covered by allocating the truck treating route #1076 to plow the remaining part of route #570.
- In sub-area 412 – Ft. Scott: With six snowplow trucks available, the truck shortage could be covered by allocating the truck treating route #1566 to plow the remaining part of routes #1252 and #1255.
- In sub-area 413 – Iola: With five snowplow trucks available, the truck shortage could be covered by allocating the truck treating route #2014 to plow the remaining part of route #2015.
- In sub-area 414 – Yates Center: With five snowplow trucks available, the truck shortage could be covered by the optimization results.
- In sub-area 421 – Garnett: With five snowplow trucks available, the truck shortage could be covered by allocating the truck treating routes #467 and #1957 to plow the remaining part of routes #468 and #1291.
- In sub-area 422 – Louisburg: With eight snowplow trucks available, the truck shortage could be covered by allocating the truck treating route #1154 to plow the remaining part of route #1155.
- In sub-area 423 – Mound City: With five snowplow trucks available, a full fleet size is required for this sub-area.
- In sub-area 424 – Ottawa: With seven snowplow trucks available, the truck shortage could be covered by allocating the truck treating routes #1158 and #1276 to plow the remaining part of routes #1161 and #1906.

- In sub-area 425 – Waverly: With five snowplow trucks available, the truck shortage could be covered by allocating the truck treating route #1295 to plow the remaining part of route #359.
- In sub-area 431 – Altoona: With five snowplow trucks available, the truck shortage could be covered by allocating the truck treating routes #365 and #385 to plow the remaining part of route #2021.
- In sub-area 432 – Independence: With six snowplow trucks available, the truck shortage could be covered by allocating the truck treating route #1984 to plow the remaining part of route #2022.
- In sub-area 433 – Sedan: With four snowplow trucks available, the truck shortage could be covered by allocating the truck treating route #1070 to plow the remaining part of routes #180 and #182.
- In sub-area 441 – Altamont: With five snowplow trucks available, the truck shortage could be covered by allocating the truck treating route #1995 to plow the remaining part of route #1994.
- In sub-area 442 – Columbus: With seven snowplow trucks available, the truck shortage could be covered by allocating the truck treating route #1080 to plow the remaining part of route #1996.
- In sub-area 443 – Erie: With five snowplow trucks available, the truck shortage could be covered by the optimization results.
- In sub-area 444 – Pittsburg: With seven snowplow trucks available, the truck shortage could be covered by allocating the truck treating routes #2003 and #2004 to plow the remaining part of routes #1190 and #1191.

However, implementation of the proposed optimization model has several challenges. First, the current snow removal plan of District 4 substantially relies on the balance between the snow route length and the number of trucks allocated in each sub-area. Implementing the proposed optimization model will result in an unbalanced snow route length and many trucks that may create challenges to KDOT snow and ice removal operation professionals. Nevertheless, researchers (Dowds et al., 2016) found that "route balance is a less effective indicator of route efficiency when the service territory is highly asymmetric relative to the location of the maintenance garage." Second, implementation of the proposed optimization model in this study may create confusion or reduce plowing efficiency because of route changes with potentially different operating procedures. Finally, assumptions such as vehicle travel speed, turn penalties, and deadhead times required to develop the model may not accurately reflect actual truck speeds. It is important to note that coordination between optimization modelers and operations personnel plays a vital role in successfully implementing the proposed optimization model.

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Appendix A: Key State-of-Practice of Snowplow Optimization

State DOTs have begun to consider using GIS-based applications for optimizing winter maintenance operations. From a pool of collected documents and current snowplow practices, eight DOTs, including Colorado, Delaware, Iowa, Kentucky, Minnesota, Missouri, Ohio, and Vermont, were selected for review. This appendix provided key findings related to the optimization of snow and ice routes and fleet sizes using innovative algorithms and GIS-based technologies.

A.1 Colorado Department of Transportation

In 2016, the Colorado Department of Transportation (CDOT) contracted with Vaisala Inc. to assess their winter service practices within Region 4 in Colorado and provide operational recommendations as needed to increase snow removal efficiency in terms of cost and time manners and reduce snow-related incidents in the CDOT's road network. The objective of their project was to identify an alternative for route reduction via the snow route optimization process without compromising the level of service (LOS) satisfaction. Accordingly, CDOT wanted to make the best use of the available snowplowing time and range and maximize their resource deployment for winter operations within Region 4. Other snow route removal optimization options, such as establishing new facilities, reallocating depots, or requirements to meet specific treatment times, were not included in the study. The project only conducted a set of desk-based activities without actual route design exercising at that time. Although CDOT set no time limit for the snowplowing treatment of the roads, the optimization process must consider the LOS requirements.

Data for the snow route optimization process, including snow operation maps and LOS requirements, were collected from meetings and e-mail exchanges of headline information between CDOT and Vaisala's staff in terms of hand-written and GIS-based maps. The data referred to the road network that lies within the Maintenance Supervisory Area of Boulder, which is responsible for approximately 9,699 center lane miles, including ramps. There were six facilities or depots with a fleet of 29 trucks along with the Maintenance Supervisory Area of Boulder that service all snow and ice routes in Region 4. Most trucks can only treat one lane at a time; however, since CDOT employs the Tow-Plow system on their large highways and/or interstates, they can clear and/or plow two lanes at once. The salt applications were calculated in pounds per lane mile, ranging from 120 to 250 depending on the severity of the snow events. CDOT considers five LOS categories in their winter operations:

- A represents the highest LOS to maintain wet pavement throughout a storm on highly traveled highways and snowpack or icy but passable conditions on low-volume roads.
- B represents a high LOS to maintain wet pavement as much as possible on highly traveled highways to snowpack/icy conditions on low-volume roads.
- C represents a moderate LOS to maintain wet pavement as much as possible to patches of snow or slush on highly traveled highways and keep patches of snow or ice to predominately snowpack/icy conditions on low-volume roads.
- D represents a marginal LOS to maintain patches of "oatmeal" snow, packed snow/ice on highly traveled highways to predominately snowpack/icy conditions on low-volume roads.
- F represents poor LOS satisfaction since clearing, plowing, and de-icing solution applications are conducted on a very limited basis, impairing mobility on all roadways. Therefore, patches of snow/ice exist on the highest-standard roads, which may degenerate to snowpack/icy conditions accompanying slowdowns and/or delays.

CDOT utilized the snow route optimization, built upon GIS-provided maps and snowplow requirements, to meet a set of targets, including LOS improvements, efficiency in resource allocation, and accommodation of constraints via "what-if" scenario modeling. The optimization process considered the fleet size, the required spread rate of salt applications (pounds per lane mile), and the size and capacity of the trucks as CDOT requires their trucks to plow and spread the salt concurrently. The average traveling speed of the fleet was set at 30 mph during the daytime and 35 mph during the nighttime, while the average plowing speed was set at 15 mph for urban roadways and 25 mph for rural roadways. After the optimization process, CDOT enhanced its fleet of snowplow trucks to cover all wide main highways and small roads successfully. The report also recommended CDOT replace old trucks with tandems as they show sufficient employment of available resources. The location of facilities was used as one of the factors to reduce the number of snow and ice routes within CDOT's winter maintenance plan. The route optimization suggested that facilities should be able to consider treatment continuity, resulting in a reduction of 5% in the total distance that their fleet was responsible for. The report also recommended the establishment of some refill stations across the snow road network to reduce the total traveling time of the fleet and maximize the satisfaction percent of LOS required times.

A.2 Delaware Department of Transportation

The Delaware Department of Transportation (DelDOT) prioritizes the removal of snow and ice routes in winter road maintenance operations as its importance for the safety and mobility of road users. During winter maintenance operations, DelDOT is responsible for more than 13,450 lane miles with 575 snow-fighting personnel and 450 pieces of equipment. DelDOT utilizes standard performance standards for snow and ice route removal depending on the severity of the snow events. For instance, with snowfall less than 4 inches, DelDOT aims to provide a clear and passable roadway within 24 hours after the end of the snowfall, within 48 hours with snowfall between 4 and 8 inches, and within 72 hours with snowfall over 8 inches. The operational problem that DelDOT experienced included snowplow routing and allocation of available resources (e.g., equipment, supplies, and personnel) during a snow event. In 2018, DelDOT contracted Delaware Center for Transportation to evaluate their existing snow and ice control operations and develop a snowplow route optimization model to derive appropriate snowplow routing strategies for resource allocations in winter maintenance activities. The goal of the project was to support DelDOT in minimizing the total travel distance and travel times for snowplow trucks in three counties in Delaware using a GIS-based platform that can be easily incorporated with the existing transportation system of DelDOT. Additionally, the results were expected to ensure the accessibility of snowplow trucks to all primary road segments and minimize the total operational costs. Figure A.1 shows an overview of the snowplow operating process at DelDOT.

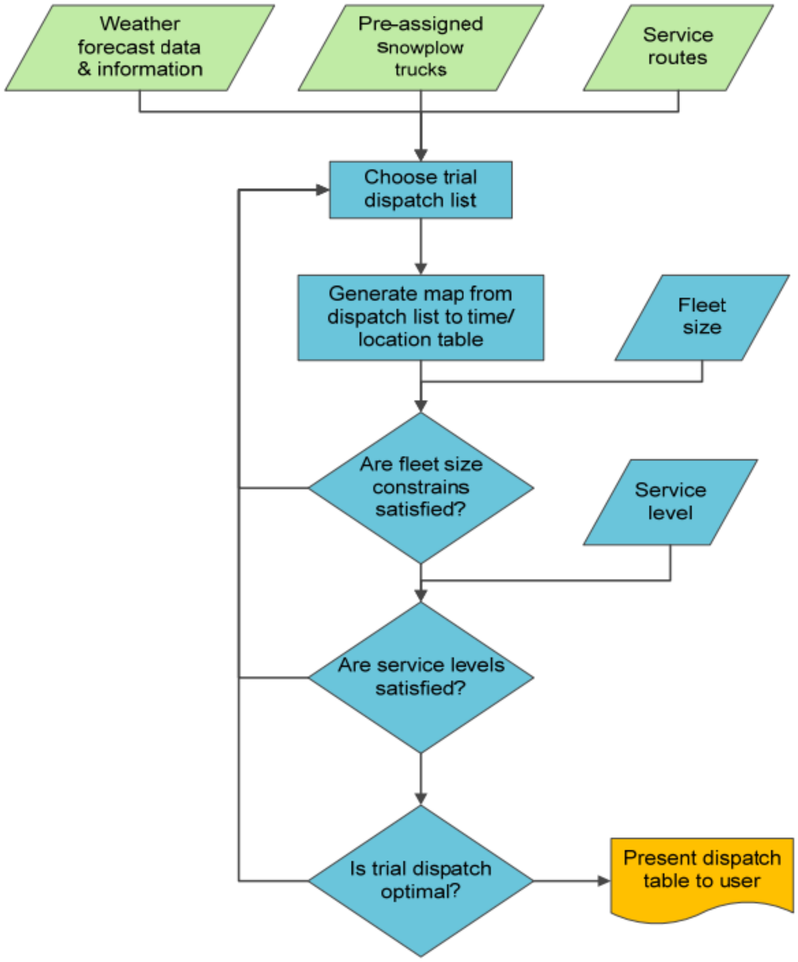

Figure A.1: Standard Snow-Plow Operating Process at DelDOT (Li et al., 2018)

The route optimization model was established using the commercial software package ArcGIS, and its extension Network Analyst with the vehicle routing problem toolset. The GIS-based snowplow route optimization included seven steps:

1. Create the base map with ArcGIS and input all necessary reference maps,
2. Establish layers of roadways and target areas,
3. Review the layers of roadways,
4. Update the network of roadways,
5. Create plowing nodes for the routing problem,
6. Build the network dataset using Network Analyst, and
7. Develop optimized snow routes using vehicle routing problems.

Prior to the model development process, relevant inputs were considered, including road classification (Interstates, primaries, secondaries, locals, and subdivisions), number of lanes, and intersection modifications. Then, model parameters were defined, including length measurement (using ArcGIS to measure the length of each segment), travel time calculation (travel time = length/speed limit), and direction information (one-way or two-way) to determine an optimal fleet size for snowplow operations.

The route optimization model was conducted for two scenarios of snow removal truck capacities: 6-wheelers and 10-wheelers. In the first scenario, the 10-wheelers can access lower-class roadways; however, in the second scenario, the 10-wheelers only provide service for primary and secondary roadways. The route optimization results showed that the limitation in the 10-wheelers' service areas led to an increase in the total travel time of 10%. The report also provided optimized routes in five service areas within Delaware's South District and compared two scenarios in detail. As a result, the optimization model helped reduce the total cycle times for completing each snowplow route and provided different scenarios for performing snow and ice control activities.

A.3 Iowa Department of Transportation

The Iowa Department of Transportation (Iowa DOT) operates its annual winter road maintenance operations by servicing 24,000 lane miles, including interstates, US highways, and Iowa roadways. Specifically, they send a fleet of snowplow trucks to clear and remove snow and ice on roadways in accordance with spreading materials (e.g., sand and/or salt applications) for de-icing, anti-icing, and increasing friction to ensure the safety of the road travelers. In 2020, they conducted a snow route optimization project focusing on improving the efficiency of winter maintenance activities in District 3, located in northwest Iowa, which was performed based on staff knowledge and past experience. The objective of the project was to increase cost savings, enhance safety and mobility, and reduce impacts on the environment. The optimization process included 20 truck facilities responsible for servicing 4,000 lane miles during snow events. Two types of maintenance trucks available at the facilities in Iowa include medium-duty single trucks and heavy-duty tandem trucks. Iowa DOT performs snow and ice route removal operations according to their LOS requirements for each route priority. Road segments with a higher priority should be treated more frequently than those with a lower priority.

The route optimization plan of Iowa DOT was to address two snowplow routing problems in District 3. The first problem referred to optimizing the winter maintenance truck routes for single truck facilities within the district's responsible service maps of snowplow routes. The second problem referred to optimizing the winter maintenance routes for multiple truck facilities, given the possible adjustments of the service boundaries between the facilities. To solve both routing problems, the optimization methodology was built upon the capacitated arc routing problems (CARPs), which uses a memetic algorithm to perform optimization with constraints of treatment cycle time, heterogeneous truck capacities, fleet size, road conditions, and work-shift duration. The optimization process included two tasks: (1) determine optimal snow routes with the same LOS requirements and the fleet size remained unchanged and (2) identify a combination of optimal snow routes and service areas simultaneously with the adjustment that a truck could be refilled at another facility or refill station rather than their own (Dong et al., 2020). The dataset used in the optimization process included:

- Weather data (e.g., snow dates and storm severities) from 2016 to 2018,
- Maintenance truck operation data (e.g., GPS location, treating locations, truck capacity, truck speed and direction, spreading rate and type, and timestamp), and
- Traffic network data (e.g., roadway information, reference posts, facility type, and LOS requirements).

The route optimization process considered four practical constraints, including:

- Capacity of maintenance trucks (e.g., 12,000 pounds for single-axle trucks and 16,000 pounds for tandem-axle trucks),
- Fleet size (e.g., variation in the number of trucks at each facility),
- Road-truck dependency (e.g., locations to plow and clear the snow and with two examples as shown in Figure A.2 – undivided multilane road, and Figure A.3 – divided multilane road), and
- Treating cycle time (e.g., the frequency of services provided on roadways).

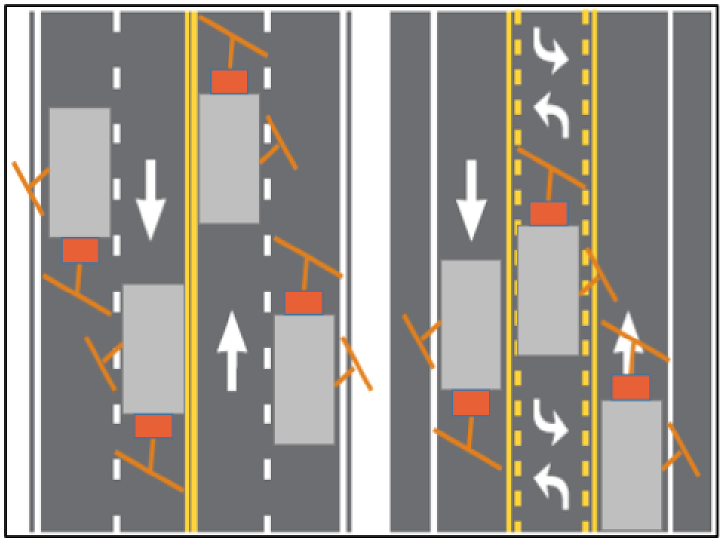

Figure A.2: Road-Truck Dependency with Undivided Multilane Roads (adapted from Dong et al., 2020)

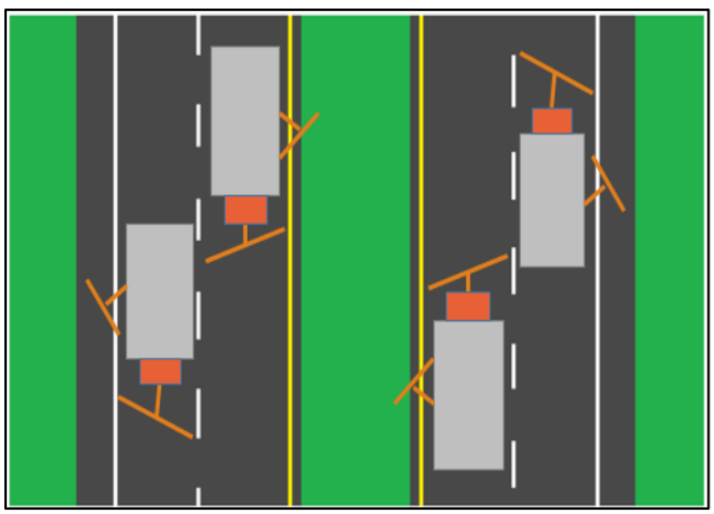

Figure A.3: Road-Truck Dependency with Divided Multilane Roads (adapted from Dong et al., 2020)

The optimization model recommended modifications and truck allocations between 18 facilities, as shown in Table A.1. The optimization results from addressing the first routing problem showed that Iowa DOT could save 13.2% of the deadhead distance between the truck facility and the service area compared with the current snowplow operations. Additionally, the deadhead time savings could be more when the optimized snow routes strictly satisfy all the aforementioned constraints. Iowa DOT also performed a sensitivity analysis to determine the travel distance under different spreading rates of sand and/or salt applications, ranging from 150 pounds per lane mile to 300 pounds per lane mile. As a result, with the spreading rates, less than 300 pounds per lane mile, the Correctionville and Pocahontas facilities in District 3 could considerably reduce their deadhead times, resulting in a treating cycle time of 2.5 hours. The optimization results from addressing the second routing problem showed that there was an insignificant difference between the optimized routes with the adjustments of multiple facilities and those with the adjustment of single facilities. Accordingly, the total optimized travel distance for all trucks in the multi-facility adjustment scenario was 4,860 miles, slightly lower than the total optimized travel distance (4,919) for all trucks in the single-facility adjustment scenario. One possible reason was due to the routing network structure and locations of facilities under the current Iowa DOT's responsibility maps.

Table A.1: Optimization Results from Iowa DOT (adapted from Dong et al., 2020)

Facility Name	Current # of snow routes	Optimized # of snow routes	Recommendation
Ashton	10	10	Change boundary, Change route due to time constraint
Carroll	5	4	Saving deadhead and truck
Cherokee	6	6	Saving deadhead
Correctionville	4	6	Add # of lanes, Change route due to capacity constraint
Denison	6	6	Change boundary
Emmetsburg	5	4	Saving deadhead
Ida Grove	4	3	Saving truck
Le Mars	8	7	Saving deadhead
Onawa	7	10	Saving deadhead, Change route due to time constraint
Pocahontas	6	6	Saving deadhead
Rockwell City	6	6	Change route due to time constraints
Sac City	5	7	Add # of lanes
Sioux City Hamilton	9	10	Change route due to time constraints
Sioux City Leeds	7	8	Change route due to time constraints
Sloan	6	5	Currently efficient
Spencer	6	5	Currently efficient
Spirit Lake	8	5	Saving deadhead and truck
Storm Lake	6	5	Saving deadhead and truck

A.4 Kentucky Department of Transportation

The Kentucky Transportation Cabinet (KYTC) spends $40 to $80 million annually for clearing and removing snow and ice from the state's roadways across twelve highway districts. For instance, KYTC spent a total of over 75$ million on snow and ice removal operations in 2014 with:

- $29 million for materials,
- $20 million went toward contract equipment,
- $17 million for labor costs, and
- $9 million for purchasing state equipment.

The annual maintenance cost is affected by various factors, including the location of facilities, number of trucks, materials, and roadways. The practices of KYTC's snow removal plan largely involved county-based routing networks where each county attained a certain number of facilities and trucks available to treat the roadways during a snow event. Snow and ice routes were cleared and plowed within a given timeframe based on their categorization and priority derived from AADT. In addition, snowfall in Kentucky usually happens in two- or three-day bursts that require a snow removal treatment as an emergency rather than a maintenance activity. Therefore, KYTC wanted to optimize the routing system to increase snow removal efficiency, improve safety, and reduce the total time and resources needed in their winter maintenance operations. KYTC contracted the Kentucky Transportation Center (KTC) to perform a thorough data-driven analysis of KYTC's snow route removal operations and develop a GIS-based optimization model to improve their snow and ice treatment system. The measurements of the optimization outcomes were based on time, locations of facilities (truck garages and refill stations), availability of the salt application, and fleet size.

Researchers from KTC developed a snow route optimization model for four counties located in Districts 6 and 7 of the State of Kentucky. The route optimization process is aimed at improving the efficiency of Kentucky's snow and ice removal program through strategies derived from a combination of optimization tools, including ArcGIS and its extension, Network Analyst, and vehicle routing problem toolset. Routing data were compiled in terms of books, digital maps, and other notes for incorporating into Network Analyst. The typical route length for snow plowing is 20 to 25 miles. KYTC used their current traveling and treating times of their control routes (routes currently used for the KYTC's snow and ice program) as a baseline for the subsequent optimization process. The model was initially developed based on a county-based optimization process where snowplow trucks were assigned within particular counties based on their fleet availability and route priorities. New routing alternatives were created for each county. Then, they combined these routes to present a county-level route with the district. However, the results of the initially developed model raised some limitations, such as overly complex routing groupings and unrealistic snowplowing paths. Therefore, they developed the subsequent optimization model at a district level where the fleet of snowplow trucks and salt storage were shared among neighboring counties within the same district.

The vehicle routing problem toolset was used to determine the optimal solution for the fleet of snowplow trucks to service the spread of salt applications as an order in Network Analyst with consideration of detailed settings of directions for multilane highways as shown in Figure A.4. Outcomes were expected to include various county-level route maps focusing on the district-wide optimization process. The optimization process conducted a series of tasks, including:

- Identifying route overlay with roadway attributes: number of lanes, traffic volume, one-way/two-way, route type, the speed limit,
- Determining the directions for one-way and divided highways,
- Simplifying the route network,
- Determining multiple-lane roadways, and
- Finalizing the network

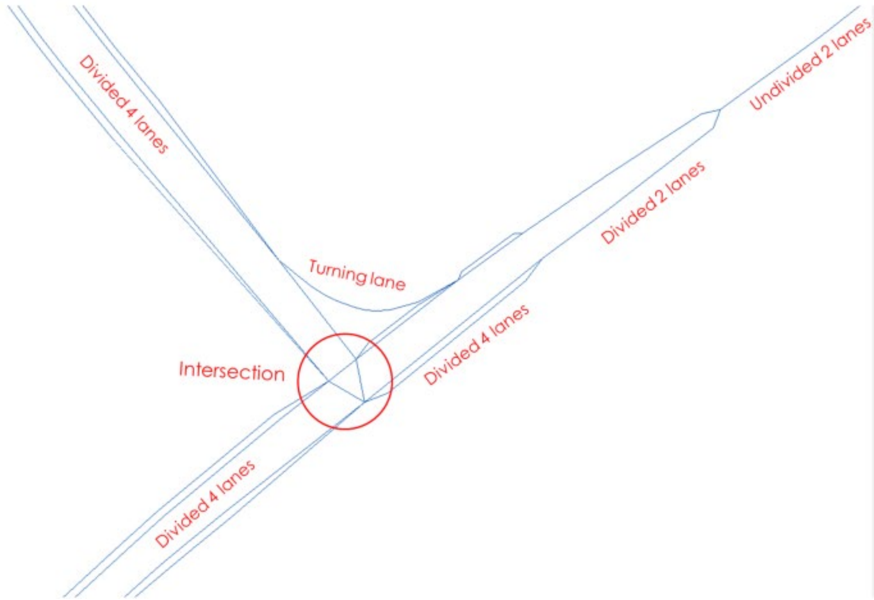

Figure A.4: Setting Up Directions for Multiple Lanes (Blandford et al., 2017)

By implementing new optimized snow and ice routes, KYTC was able to increase their LOS satisfaction with on-schedule treating times and fewer used trucks, resulting in considerable savings in cost and resources. Specifically, in two counties, Grant and Pendleton, in District 6, the optimization model helped KYTC with a potential reduction of six trucks, leading to a cost-saving of $25,000 per truck annually. Similarly, in Clark and Montgomery Counties in District 7, the optimization model showed a possible saving of $75,000 per year when they could remove three trucks from the district's fleet. As a result, a total of $225,000 in operational costs could be reduced annually for KYTC. Additionally, by conducting route optimization at a district level so that the trucks can cross the county lines, the model also provided KYTC with a set of new routes in Clark and Montgomery counties to reduce the total travel time during a snow event. A summary of improvements in total travel time in snow route removal operations in District 7, Kentucky, is shown in Table A.2. Through the lessons learned from the GIS-based route optimization project, KYTC stated the utilization of Network Analyst and vehicle routing problem was considered the most appropriate approach to optimize snow and ice removal operations in Kentucky.

Table A.2: Improvements of Total Travel Times in District 7, Kentucky, with GIS-Based Route Optimization (adapted from Blandford et al., 2017)

County	Current Routes	Optimized Routes	Improvement Percent (%)
Anderson	1,358	1,296	4.6
Bourbon	1,529	1,287	15.8
Boyle	926	892	3.7
Clark	2,651	2,394	9.7
Fayette	2,004	1,376	31.3
Garrard	997	961	3.6
Jessamine	1,050	925	11.9
Madison	957	824	13.9
Mercer	1,114	1,114	0
Montgomery	1,210	1,210	0
Scott	3,177	3,177	0
Woodford	1,089	1,089	0
Total	18,062	16,545	8.4

A.5 Minnesota Department of Transportation

The Minnesota Department of Transportation (MnDOT) conducts its annual winter maintenance operations through 137 truck stations and 18 headquarters sites. MnDOT aims to provide a well-designed winter maintenance routing network for snow and ice removal services that can effectively increase route clearance and reduce deadheading, route overlaps, and cost overruns. MnDOT prioritizes the safety of the traveling public and emergency service response times which are all relied on the efficiency of winter maintenance operations. To achieve this objective, in 2016, MnDOT contracted with researchers in the Transportation Research Center at the University of Vermont to review and identify best practices for snow and ice route removal optimization. Their focus was on computerized route optimization tools and processes that aim to generate new routes based on mathematical algorithms to complement the snow route removal improvement efforts. Specifically, they reviewed nine studies from seven DOTs, including Iowa, Pennsylvania, Indiana, Vermont, Wisconsin, Kentucky, and Utah, and two municipal Departments of Public Works, including Centennial, Colorado, and Niles, Illinois, and synthesized results with regard to implementations of computerized routing tools in the snowplow route optimization process. Common route optimization tools include off-the-shelf software packages, such as:

- Fleet Route software produced by C2Logix,
- ArcGIS developed by ESRI, and
- TransCAD created by Caliper Corporation.

These GIS-based applications can address the data needs in the snow route optimization process by digitally incorporating the data into a master database, tracking relevant winter maintenance data, and generating new route maps. In addition, these tools can enhance the applicability of GIS-generated results by providing a clear visualization of the optimized routes with color-coding routes by length. The results showed that using GIS-based applications can optimize the snow and ice route removal operation by reducing the snowplow route length, ranging from 5% up to 50%. In addition, although GIS-based route optimization is a powerful tool, MnDOT recommends that there is always the need for expert judgments in the snowplow routing design process. Accordingly, to successfully conduct snow route optimization projects, practitioners need to consider the close cooperation between experienced winter maintenance professionals and the individuals performing the snow route optimization and take time to review and revise the route optimization to determine the feasibility of the optimized routes prior to implementations. Shortcomings of computer-generated results may include missing possible turnarounds and unrealistic vehicle travel speeds. Therefore, the report recommended that GIS-based route optimization models need to incorporate essential highway features, such as highway crossovers, safe turnaround locations at the edge of service territory boundaries, and directions of one-way and divided highways in order to provide a highly accurate base map of the routing network used in winter maintenance operations. In their other study in 2019, MnDOT also recommended the use of a GIS-based model to investigate and optimize their truck stations for winter maintenance operations with a focus on cost analysis (Holik & Anderson, 2019). The GIS-optimization process could help MnDOT with operational strategies to rebuild 123 truck stations, relocate 24 truck stations, and combine two truck stations so that they can eventually obtain a total cost saving of $23,362,000 over a 50-year period. Another study of MnDOT in 2020 suggested the utilization of multiple advanced equipment and tools to collect, store, and analyze snow and ice road data, as shown in Figure A.5, to support the GIS-based route optimization processes in winter maintenance operations (Minge et al. 2020). Accordingly, the GIS-based optimization model can be incorporated with mobile sensor systems, driver assistance systems, connected and autonomous vehicle (CAV) systems, and video analytics.

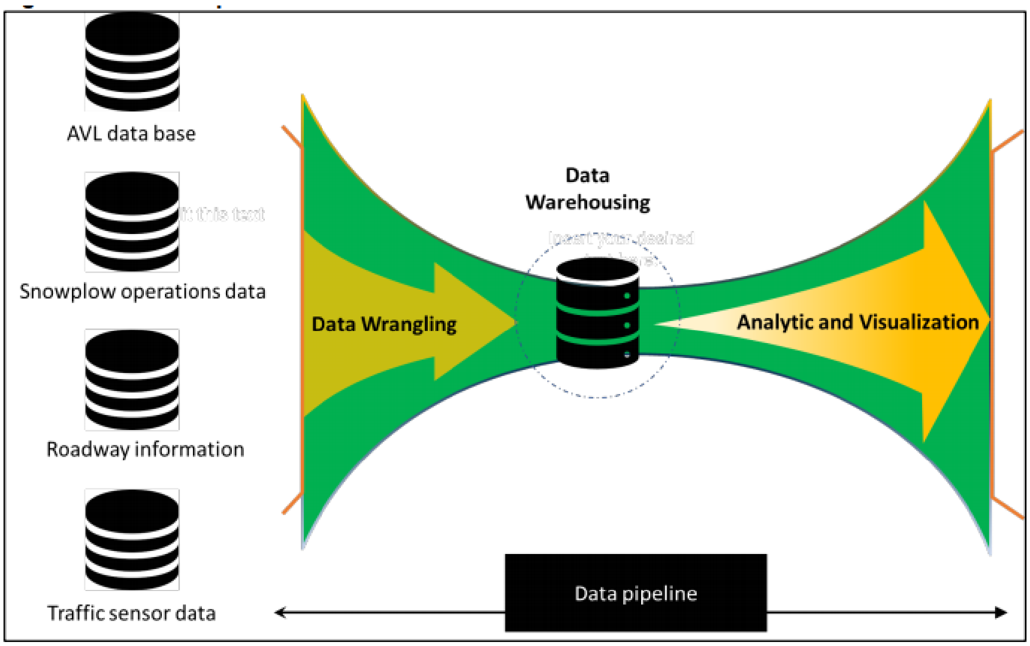

Figure A.5: Snow and Ice Road Data Collection and Analysis at MnDOT
(Minge et al., 2020)

A.6 Missouri Department of Transportation

In 2011, the Missouri Department of Transportation (MoDOT) contracted with researchers at the University of Missouri to develop a snow route optimization model considering a series of critical tasks, such as identifying fleet locations, making routing decisions, selecting appropriate materials, and determining treatment procedures for MoDOT's winter maintenance operations. The objectives of the project were to:

1. Develop a protocol for evaluating the LOS requirements and constraints in their snow and ice route removal operation;
2. Establish integrated algorithms to generate optimal snow routing and fleet allocations; and
3. Assess impacts of different material treatments and equipment in winter maintenance operations.

The project concentrated on the transportation network of the St. Louis District in Missouri to solve snow routing problems in an integrated manner. The project outcomes were expected to allow MoDOT to increase the efficiency in their snow removal service, determine the optimal snow routing network that trucks can follow, and sufficiently allocate snowplow trucks in different scenarios when resources are limited. Additionally, the route optimization model focused on minimizing treating cycle times and deadhead distance in the snow route network. The route optimization methodology was built upon a systematic, heuristic-based approach that could integrate the winter road maintenance planning decisions into snow and ice route removal activities. Some routing parameters were considered, including:

- Length of serviced routes (up to 40 lane miles per route),
- Treating time (around 80 minutes),
- Treating speed (around 30 miles per hour),
- Salt application rate (approximately 5,000 pounds per usage), and
- Average cycle time (around 90 to 120 minutes).

The average cycle time also included the deadhead time plus 30 minutes of refilling time. The optimization process consisted of an initial route construction and the nested iterations of snow routing network improvement procedures until the best routing solution was reached. The initial route construction was conducted with the route-first, cluster-second method, where the optimal routing solutions were identified based on operational constraints, including the capacity of snowplow trucks and the frequency of the treatment. Then, the optimization model attempted to iteratively combine some snow routes together to reduce the total number of snow routes in the network. The snow routing network improvement procedures utilized two heuristics: one arc-position movement and one arc-position exchange for increasing the accuracy of the route groupings. While the arc-position movement heuristic attempted to remove a series of arcs in the same area and then move them to other positions, the arc-position exchange heuristic provided configurations among multiple snow routes so that one arc position was removed from each route and then moved to the optimal area within the other respective snow route. All the algorithms were coded using the Java program.

The route optimization results assisted MoDOT in providing the best efficient snow removal services and maintaining a high LOS satisfaction within the available resources. Specifically, the model determined the optimal snow routing solutions for St. Charles County with ten optimized routes, North St. Louis County with six optimized routes, West St. Louis County with nine optimized routes, St. Louis City with four optimized routes, Franklin County with 11 optimized routes, South St. Louis County with 10 optimized routes, and Jefferson County with 10 optimized routes. The optimized snow routes could help minimize the deadhead time and distance and make the tour more reasonable. The optimization outcomes also suggested closing several maintenance facilities in Weldon Spring (St. Charles County), Page (West St. Louis County), Eureka (West St. Louis County), Shreve (St. Louis City), and Barnhart (South St. Louis County) to provide some cost savings opportunities.

A.7 Ohio Department of Transportation

During winter maintenance operations, the Ohio Department of Transportation (ODOT) is responsible for servicing 43,000 lane miles of roadways by using a fleet of 1,600 trucks located in 200 garages, yards, and outposts to spread approximately 650,000 tons of salt applications. The deployment of a large number of trucks over a vast service area causes various operational problems related to routing directions, cost overruns, and resource limitations. In their snow and ice route removal operations, ODOT has set the county borders as the maintenance boundaries for relevant truck facilities, which might limit potential opportunities for route optimizations related to allocations of snowplow trucks in the winter maintenance activities. In 2016, ODOT conducted a snowplow fleet optimization project for three districts in Ohio (Districts 1, 2, and 10) to enhance the efficiency of snowplowing practices and increase the LOS satisfaction of the snow and ice route removal operation. The objectives of their project were to:

- Digitalize a base map with snow routes and locations of truck facilities across the three districts;
- Configure the maintenance boundaries by removing the county borders;
- Verify the developed base map in terms of total travel times, treating cycle times, and deadhead times using GPS recorders attached in their snowplow trucks; and
- Determine the optimal fleet size for each facility by removing the least efficient trucks and adding more trucks as needed.

To achieve their objectives, ODOT utilized a GIS-based route optimization model, established by using a combination of ArcGIS software package, ERSI's Network Analyst, vehicle routing problem toolsets, and Qtravel, a computer program that can analyze data collected from GPS recorders. Figure A.6 shows an example of plowing locations in District 10's route network.

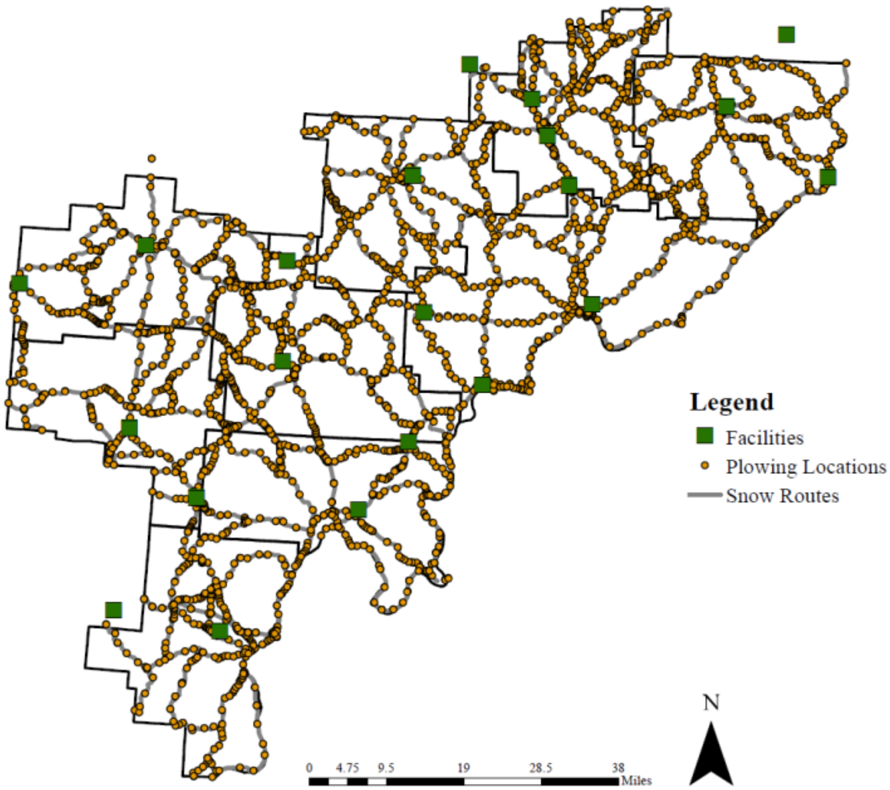

Figure A.6: Snowplowing Locations in District 10's Route Network, Ohio
(adapted from Schneider et al., 2016)

The methodology of the route optimization model included five steps:

1. Data collection,
2. Route optimization model development,
3. Initial optimization,
4. Model verification, and
5. Fleet optimization.

First, the optimization model utilized data collected from three districts, including snow and ice route information and locations of truck facilities (e.g., garages, outposts, refill stations) in terms of handwritten and digital maps. Second, the route optimization model was created using vehicle routing problem toolsets to load all plowing locations across the snow routes (), limit trucks from traveling on county and township roadways, and assign treating cycle times based on the LOS requirements for each route priority. The project used three route priorities, with the treating cycle times ranging from 60 minutes (Priority 1) to 150 minutes (Priority 3).

Third, after creating a base map of all necessary layers of road network information, an initial optimization was performed to analyze the current state of practice in the snow and ice route removal operations in three districts and set up a baseline for the subsequent fleet optimization. A salt application rate of 250 pounds per lane mile was used in the initial optimization. This process was also used to determine the minimum number of snowplow trucks needed in the worst-case scenario of winter maintenance operations. Accordingly, the results included district overview maps, individual snow and ice route maps, and individual snow and ice route descriptions for all three districts. Fourth, the verification process was accomplished by identifying differences in the results between each district's initial optimization and current practices. Finally, the fleet optimization was conducted by iteratively removing the least efficient trucks until the maximum LOS satisfaction was maintained. Then, the minimum number of trucks for each facility during a snow event was determined. The fleet optimization removed the trucks responsible for lower priority routes before removing the trucks responsible for the higher priority routes, as shown in Figure A.7.

The fleet optimization results showed that:

- In District 1, a total of five snowplow trucks could be removed from the fleet, while the total travel time could be reduced up to approximately 3.5 hours per treating cycle.
- In District 2, a total of eight trucks could be removed while the total travel time could be reduced up to 6 hours per treating cycle.
- In District 10, seven snowplow trucks could be removed from the fleet while the total travel time could be reduced up to 14 hours per treating cycle.

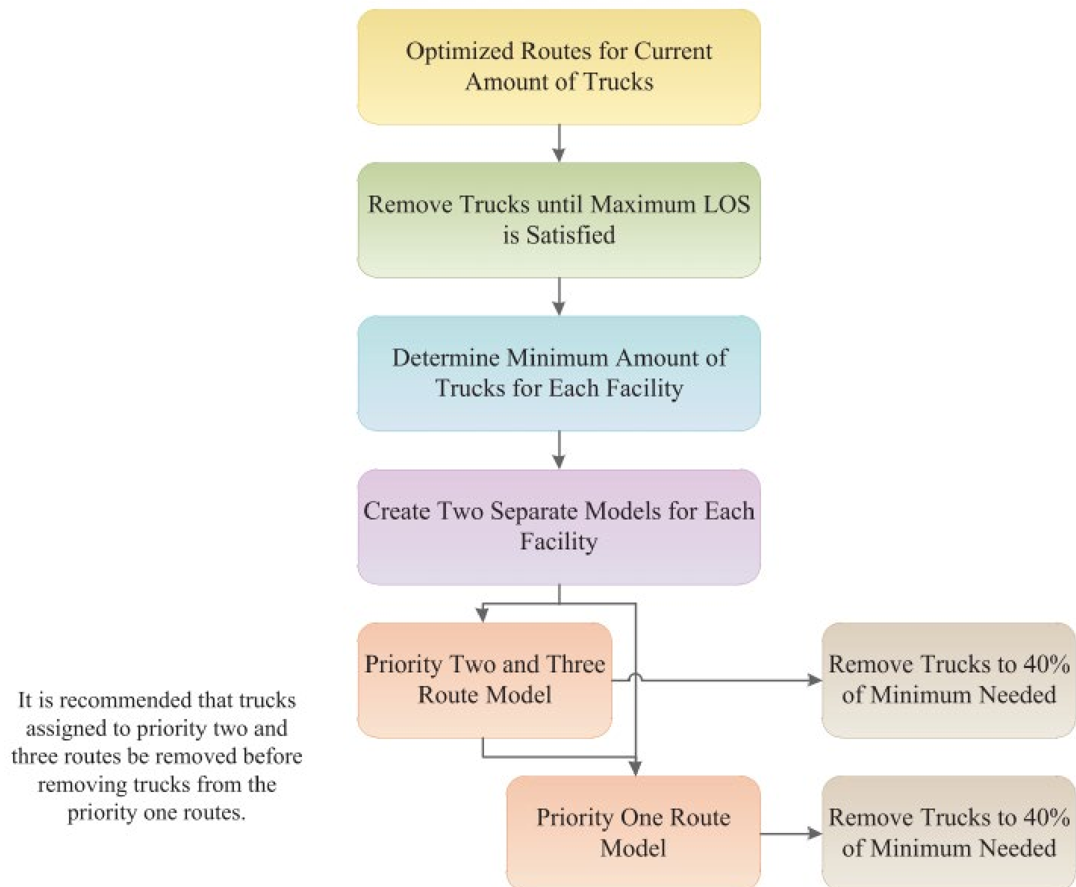

Figure A.7: Fleet Optimization Methodology
(adapted from Schneider et al., 2016)

The LOS satisfaction was maintained in each district. The route optimization model also recommended the addition of four trucks in District 1 to increase the LOS satisfaction to 65% and an addition of nine trucks in District 2 to increase the LOS satisfaction to 50%. Additionally, the route optimization model showed some demanding areas where the trucks could not treat the snow routes within the LOS required times. Therefore, the report suggested ODOT build additional facilities across the service areas to reduce the deadhead times and improve LOS.

A.8 Vermont Department of Transportation

The Vermont Agency of Transportation (VTrans) operates 61 truck garages to provide winter maintenance operations across the State of Vermont. In their report in 2013, they attempted to increase the efficiency of the snow and ice control operations in their annual winter maintenance activities by tackling two challenges: (a) the total amount of time needed to treat all prioritized routes and (b) cost efficiency of cost and resources. The first challenge refers to the ability to provide rapid treatments for prioritized routes, such as highway corridors, that are considered critical to the route network's functioning in Vermont. The second challenge is achieving cost efficiency by clearing and plowing the snow and ice routes with the lowest possible labor hours, materials, and fuel in winter maintenance operations. VTrans attempted to optimize the snow route treatments by considering a number of short-term and long-term performance measures. Short-term performance measures can provide immediate feedback on the effectiveness of the snow and ice removal activities so that speedy adjustments can be made, while long-term performance measures can provide a rating system for the effectiveness of the entire network so that strategical adjustments can be made. The objective of VTrans was to address:

- Network clustering problem,
- Truck allocation problem, and
- Vehicle routing problem.

First, VTrans needed to determine snowplow service areas to know each truck facility's responsible roadway segments. Then, an appropriate number of snowplow trucks needed to be assigned to the relevant truck facility based on the characteristics of the service area. Finally, optimal roadways needed to be developed to minimize the total travel time of the fleet on the network. To solve these routing problems, a complex balancing of route groupings throughout the network was required. Therefore, VTrans established a route optimization plan based on priorities for the roadway network to maximize the LOS satisfaction of snowplowing operations in terms of labor hours and fuel.

To develop the route optimization plan, VTrans introduced the measurement of roadway criticality using the network robustness index (NRI), which was calculated based on the AADT of the road network and the snow levels. Snow-intensity levels dictated the amount of salt application needed, ranging from low salt (200 pounds mile per lane mile), medium salt (500 pounds mile per lane mile), and high salt (800 pounds mile per lane mile), which was also considered as one of the constraints for the route optimization process. There was a four-task process in VTrans' route optimization plan. First, they conducted optimization for the service areas that the truck facilities were responsible for in terms of the total travel time and the treatment time. Second, they developed allocation plans for alternatively assigning a different number of snowplow trucks to a particular truck facility based on the need of the service area. Third, they optimized the routing network where the truck needed to travel and treat the required snow routes based on the treatment time and the fuel consumption metrics, as shown in Figure A.8. Finally, they evaluated the outcomes of the truck allocations based on the efficiency of treating high prioritized routes, as measured by NRI. They utilized the TransCAD toolset produced by Caliper Corporation, a GIS-based platform to help transportation professionals store, display, manage, and analyze transportation data to develop the road network for solving the vehicle routing problem.

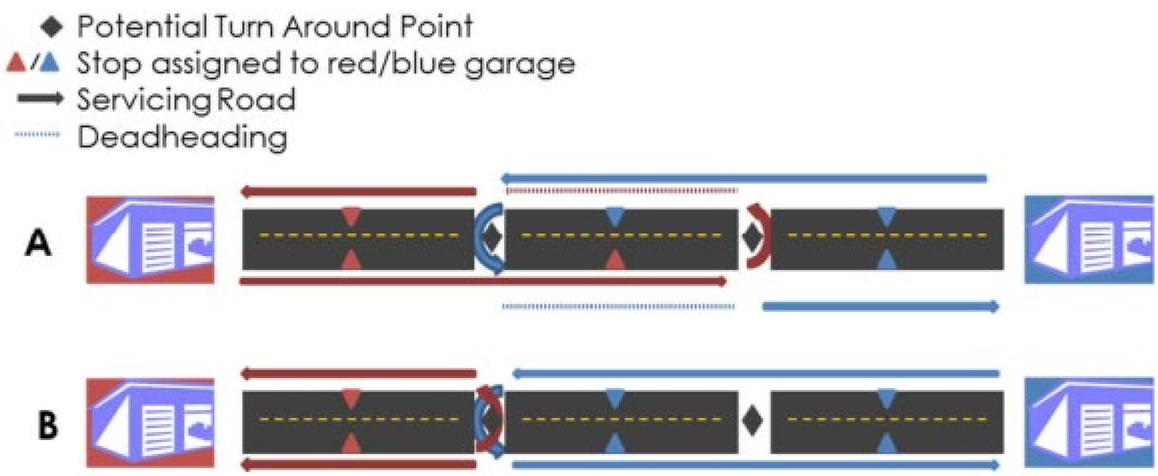

Figure A.8: Optimized Snowplow Truck Allocations
(Dowds et al., 2013)

The results of the route optimization process were assessed based on the longest round-trip travel time, total road length, the first priority total road length, and NRI across 61 maintenance garages with the ignorance of the county boundaries within the same district. Accordingly, there was a high variation in the distribution of the service areas between the maintenance garages that required vehicle allocations. A total of 317 trucks were reallocated to saturate 61 garages. The maximum allocation of snowplow trucks happened for the Colchester garage with 10 trucks. Following the truck allocations, optimized snow routes were generated for each garage based on the three levels of a snow event (low salt, medium salt, and high salt). The route optimization process generated a total of 2,490 new routes for VTrans. The results showed that the deadhead time was minimized when the closest garage treated the snow routes. For instance, in the Morrisville garage, they only needed four out of the six trucks located in the garage to treat six surrounding snow routes that the garage was responsible for. VTrans reached the most optimal balance between snow route removal service and fuel efficiency by implementing the developed route optimization process.

Appendix B: Snow and Ice Route Optimization in District 4

B.1 Sub-Area 411 at Eureka

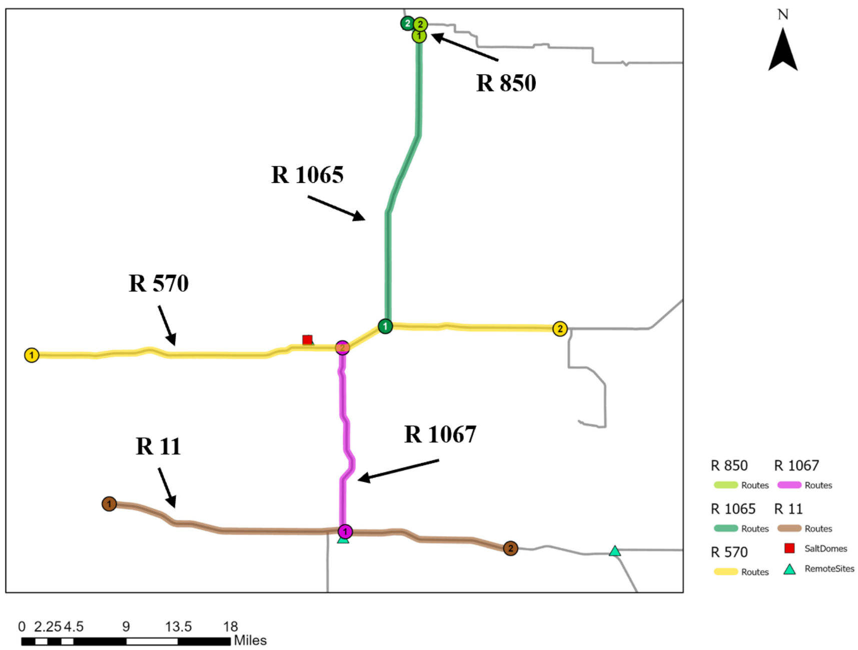

Figure B.1: Before Optimization (5 routes per treating cycle)

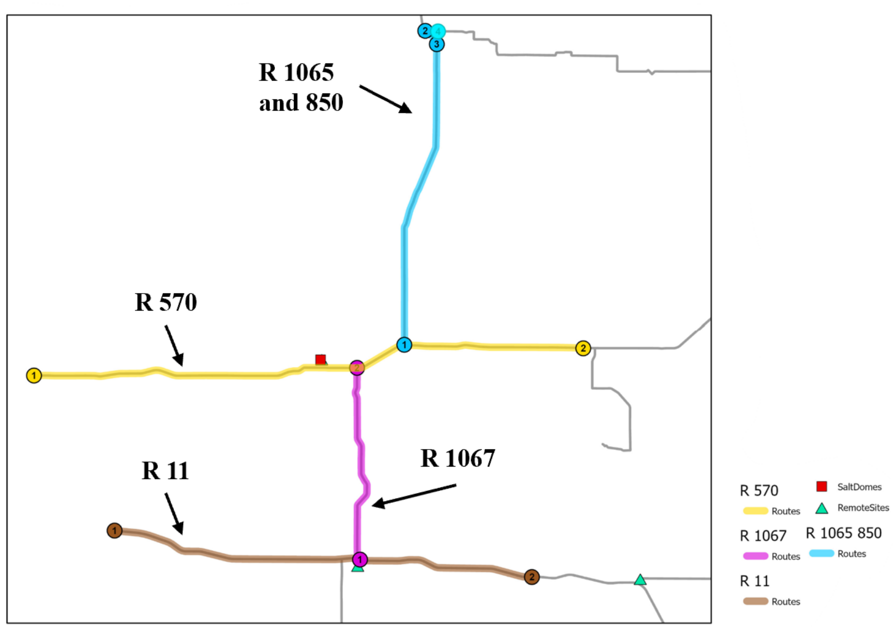

Figure B.2: After Optimization (4 routes per treating cycle)

Table B.1: Before Optimization (5 routes per treating cycle)

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
850	JCT.K99/K249	JCT.K58/K249	K-249	1.52
1065	E.JCT.U54/K99	JCT.K58/K99	K-99	42.60
1067	JCT.U400/K99	JCT.U54/K99	K-99	25.80
11	BUTLER-GREENWOOD CO. LINE	11 MI.E.E.JCT.U400/K99 (FALL RIVER)	US-400	55.53
570	WCL ROSALIA	JCT.U54/K105	US-54	73.41
Total Travel Time = 556.1 (min)				

Table B.2: After Optimization (4 routes per treating cycle)

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
850	JCT.K99/K249	JCT.K58/K249	K-249	44.12	Yes (1)
1065	E.JCT.U54/K99	JCT.K58/K99	K-99		Yes (1)
1067	JCT.U400/K99	JCT.U54/K99	K-99	25.80	No
11	BUTLER-GREENWOOD CO. LINE	11 MI.E.E.JCT.U400/K99 (FALL RIVER)	US-400	55.53	No
570	WCL ROSALIA	JCT.U54/K105	US-54	73.41	No
Total Travel Time = 516.1 (min)					

B.2 Sub-Area 412 at Ft. Scott

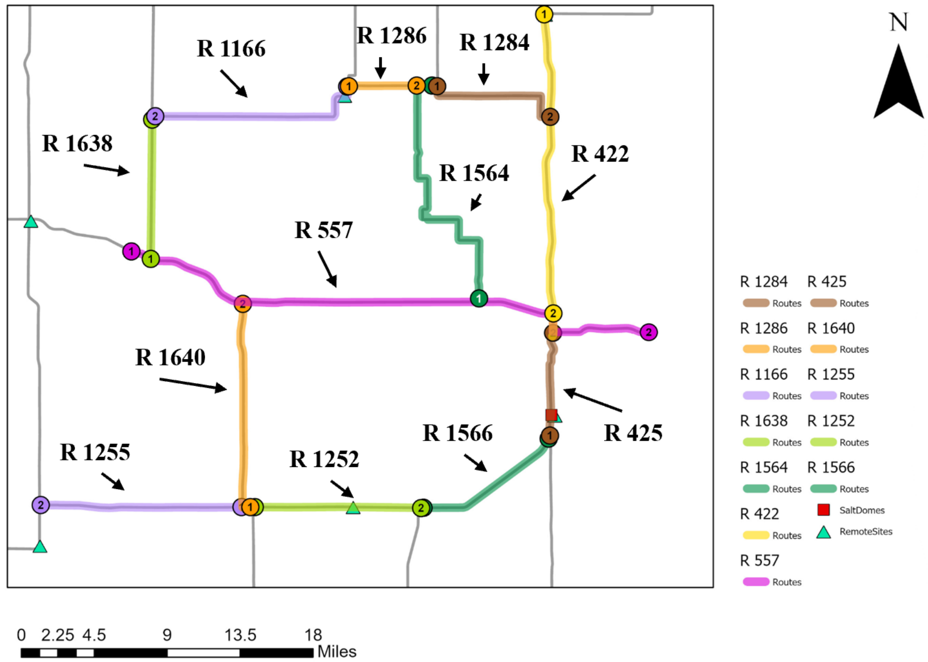

Figure B.3: Before Optimization (12 routes per treating cycle)

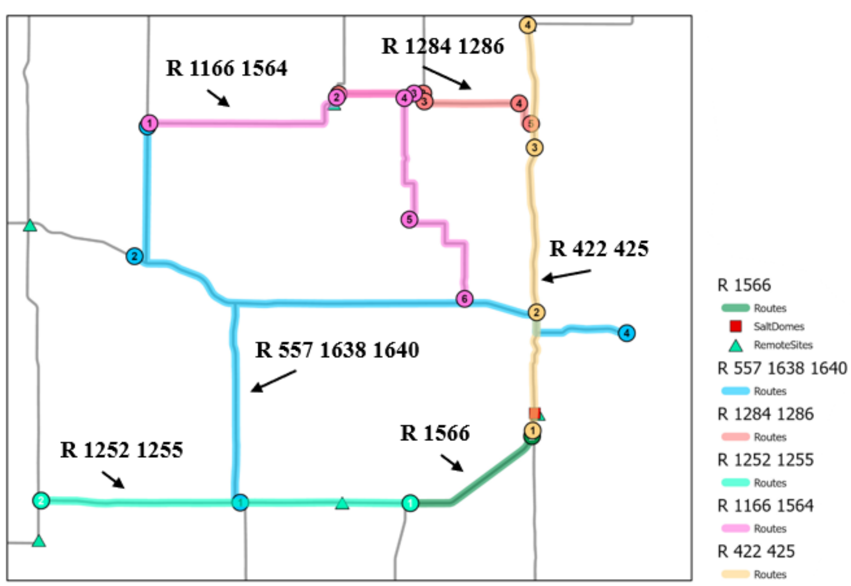

Figure B.4: After Optimization (6 routes per treating cycle)

Table B.3: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
1638	W.JCT.U54/K3	JCT.K3/K65	K-3	14.00
1640	JCT.K3/K39	E.JCT.U54/K3	K-3	21.10
557	ECL Bronson	KS-MO STATE LINE	US-54	53.92
1284	E.JCT.K7/K31	JCT.U69/K31	K-31	13.96
1286	JCT.K31/K65	W.JCT.K7/K31	K-31	6.69
1252	E.JCT.K3/K39	JCT.K7/K39	K-39	16.53
1255	E.JCT.U59/K39	W.JCT.K3/K39	K-39	19.86
1166	JCT.K3/K65	JCT.K31/K65	K-65	21.82
1564	JCT.U54/K7	E.JCT.K7/K31	K-7	29.70
1566	JCT.K7/K39	JCT.U69/K7	K-7	15.16
422	JCT.U54/U69	JCT.U69/K239	US-69	58.85
425	JCT.U69/K7	JCT.U54/U69	US-69	20.81
Total Travel Time = 1,063.4 (min)				

Table B.4: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1638	W.JCT.U54/K3	JCT.K3/K65	K-3	89.02	Yes (1)
1640	JCT.K3/K39	E.JCT.U54/K3	K-3		Yes (1)
557	ECL Bronson	KS-MO STATE LINE	US-54		Yes (1)
1284	E.JCT.K7/K31	JCT.U69/K31	K-31	20.65	Yes (2)
1286	JCT.K31/K65	W.JCT.K7/K31	K-31		Yes (2)
1252	E.JCT.K3/K39	JCT.K7/K39	K-39	36.39	Yes (3)
1255	E.JCT.U59/K39	W.JCT.K3/K39	K-39		Yes (3)
1166	JCT.K3/K65	JCT.K31/K65	K-65	51.52	Yes (4)
1564	JCT.U54/K7	E.JCT.K7/K31	K-7		Yes (4)
1566	JCT.K7/K39	JCT.U69/K7	K-7	15.16	No
422	JCT.U54/U69	JCT.U69/K239	US-69	79.66	Yes (5)
425	JCT.U69/K7	JCT.U54/U69	US-69		Yes (5)
Total Travel Time = 863.4 (min)					

B.3 Sub-Area 413 at Iola

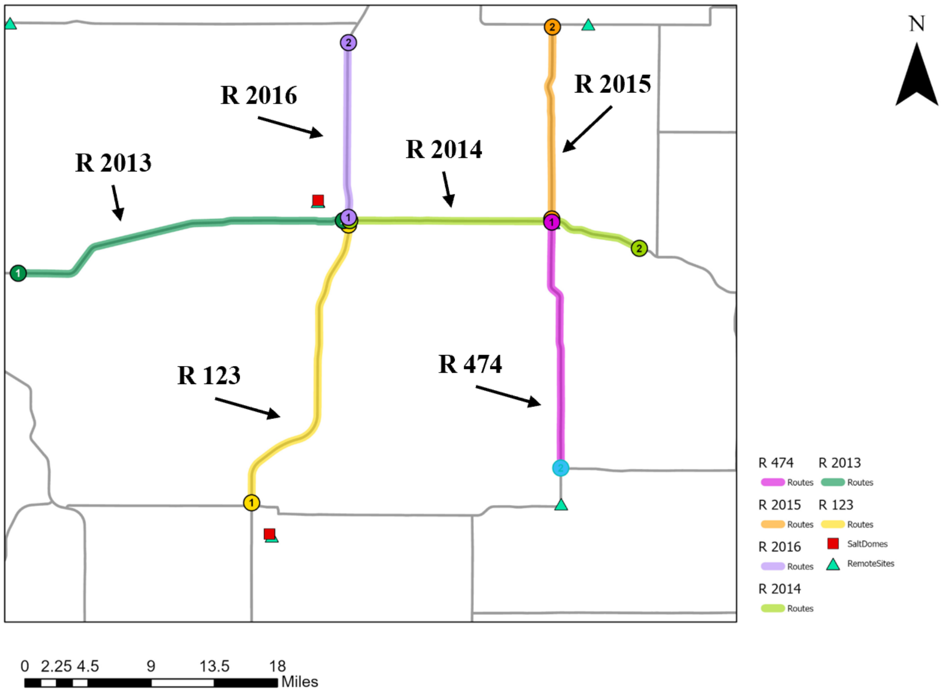

Figure B.5: Before Optimization (6 routes per treating cycle)

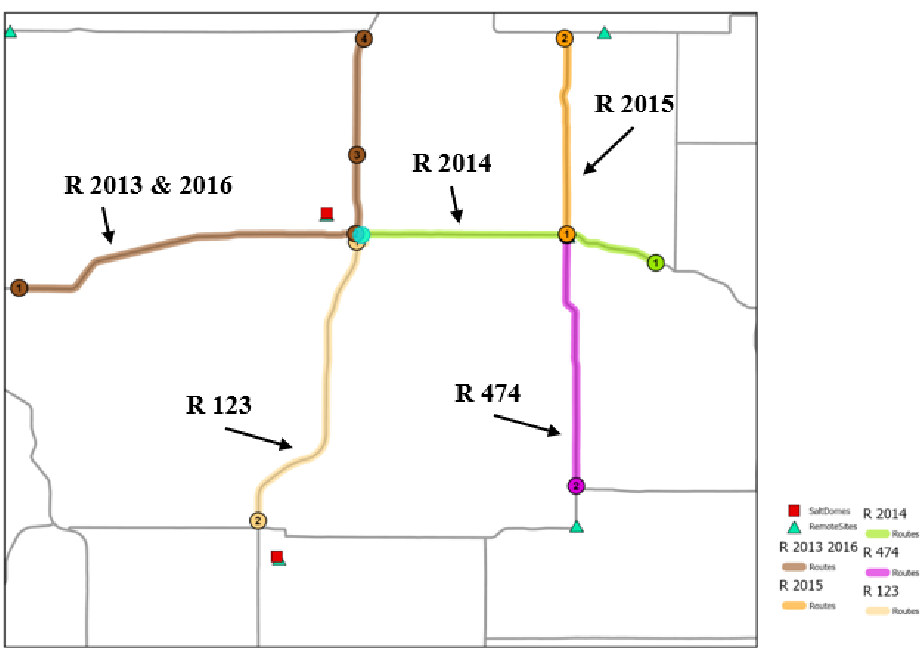

Figure B.6: After Optimization (5 routes per treating cycle)

Table B.5: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
123	JCT.U169/K39	JCT.U54/U169	US-169	36.73
2016	JCT.U54/U169	JCT.U58/U169	US-169	22.28
2014	LA HARPE	ALLEN-BOURBON CO. LINE	US-54	21.66
2013	ECL YATES CENTER	JCT.U54/U169	US-54	38.97
2015	NCL Moran (JCT.U54)/U59	JCT.U59/K31	US-59	22.00
474	E.JCT.U59/K39	SCL Moran	US-59	27.77
Total Travel Time = 454.2 (min)				

Table B.6: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
123	JCT.U169/K39	JCT.U54/U169	US-169	36.73	No
2014	LA HARPE	ALLEN-BOURBON CO. LINE	US-54	38.97	No
2016	JCT.U54/U169	JCT.U58/U169	US-169	43.94	Yes (1)
2013	ECL YATES CENTER	JCT.U54/U169	US-54		Yes (1)
2015	NCL Moran (JCT.U54)/U59	JCT.U59/K31	US-59	22.00	No
474	E.JCT.U59/K39	SCL Moran	US-59	27.77	No
Total Travel Time = 434.2 (min)					

B.4 Sub-Area 414 at Yates Center

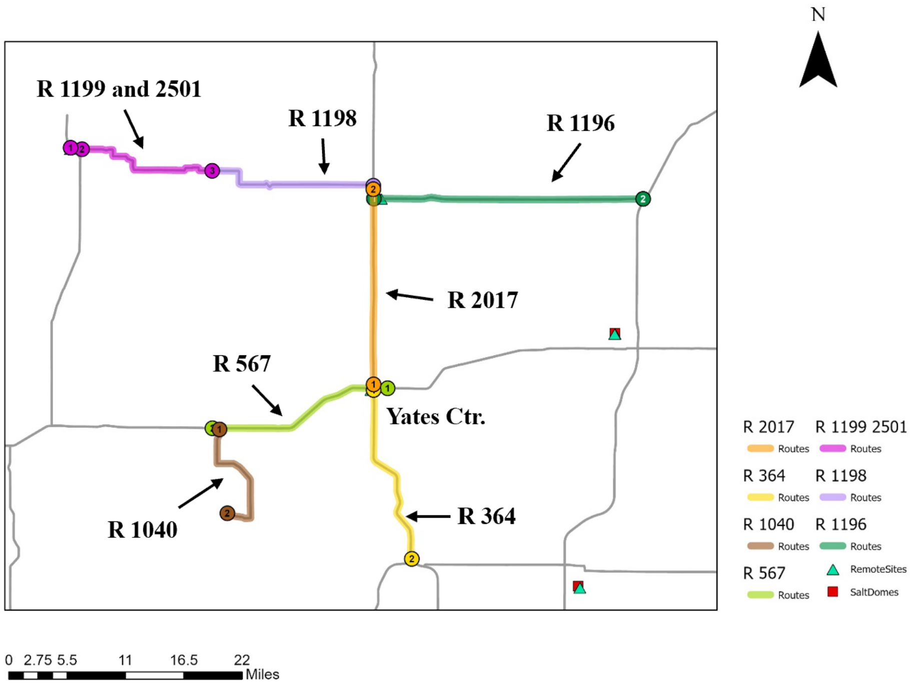

Figure B.7: Before Optimization (8 routes per treating cycle)

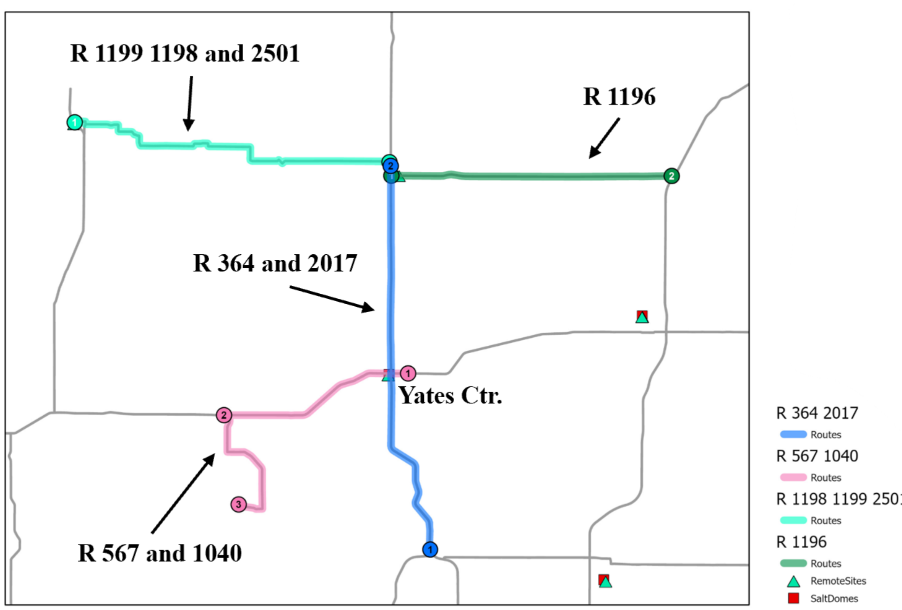

Figure B.8: After Optimization (4 routes per treating cycle)

Table B.7: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
1196	S.JCT.U75/K58	JCT.U169/K58	K-58	40.29
1198	GREENWOOD-COFFEY CO. LINE	N.JCT.U75/K58	K-58	26.27
1199	JCT.K58/K249/SOUTHWEST RD	GREENWOOD-COFFEY CO. LINE	K-58	22.51
2501	JCT.K58/K99	JCT.K58/K249	K-58	2.18
567	JCT.U54/K105	ECL YATES CENTER	US-54	27.98
1040	JCT.K105.FALL RIVER RD	JCT.U54/K105	K-105	20.86
364	W.JCT.U75/K39	JCT.U54/U75	US-75	28.42
2017	JCT.U54/U75	N.JCT.U75/K58	US-75	29.97
Total Travel Time = 689.1 (min)				

Table B.8: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1196	S.JCT.U75/K58	JCT.U169/K58	K-58	40.29	No
1198	GREENWOOD-COFFEY CO. LINE	N.JCT.U75/K58	K-58	50.96	Yes (1)
1199	JCT.K58/K249/SOUTHWEST RD	GREENWOOD-COFFEY CO. LINE	K-58		Yes (1)
2501	JCT.K58/K99	JCT.K58/K249	K-58		Yes (1)
567	JCT.U54/K105	ECL YATES CENTER	US-54	48.84	Yes (2)
1040	JCT.K105.FALL RIVER RD	JCT.U54/K105	K-105		Yes (2)
364	W.JCT.U75/K39	JCT.U54/U75	US-75	58.93	Yes (3)
2017	JCT.U54/U75	N.JCT.U75/K58	US-75		Yes (3)
Total Travel Time = 589.1 (min)					

B.5 Sub-Area 421 at Garnett

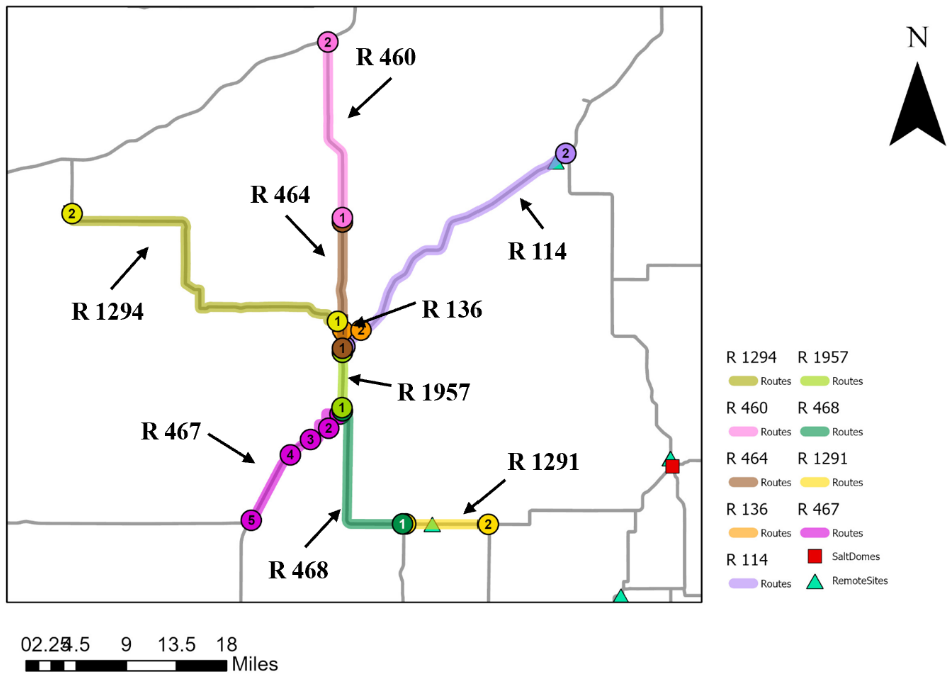

Figure B.9: Before Optimization (9 routes per treating cycle)

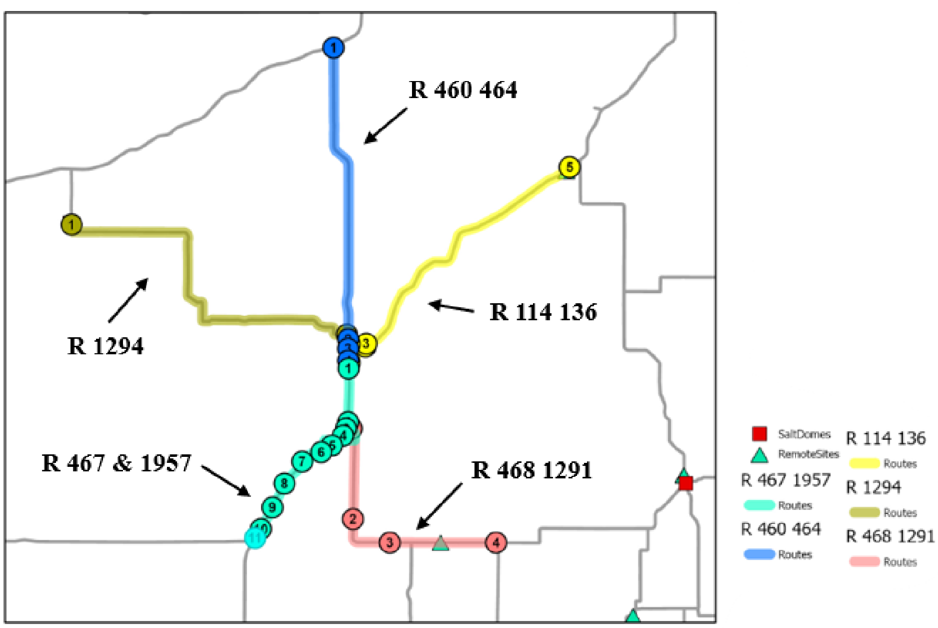

Figure B.10: After Optimization (5 routes per treating cycle)

Table B.9: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
1291	S.JCT.U59/K31	JCT.K3/K31	K-31	12.03
468	S.JCT.U59/K31	S.JCT.U59/U169	US-59	24.18
1294	ECL Waverly	N.JCT.U59/K31	K-31	51.80
114	N.JCT.U59/U169	JCT.U169/K7	US-169	44.61
136	JCT.U59/U169BUS	JCT.U169/U169BUS	US-169B	2.78
460	ANDERSON-FRANKLIN CO. LINE	JCT.U59/I35	US-59	26.18
464	N.JCT.U59/U169	ANDERSON-FRANKLIN CO. LINE	US-59	18.22
1957	S.JCT.U59/U169	N.JCT.U59/U169	US-59	8.32
467	JCT.U169/K58	S.JCT.U59/U169	US-169	21.25
Total Travel Time = 702.8 (min)				

Table B.10: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1291	S.JCT.U59/K31	JCT.K3/K31	K-31	36.21	Yes (1)
468	S.JCT.U59/K31	S.JCT.U59/U169	US-59		Yes (1)
1294	ECL Waverly	N.JCT.U59/K31	K-31	51.80	No
114	N.JCT.U59/U169	JCT.U169/K7	US-169	47.39	Yes (2)
136	JCT.U59/U169BUS	JCT.U169/U169BUS	US-169B		Yes (2)
460	ANDERSON-FRANKLIN CO. LINE	JCT.U59/I35	US-59	44.4	Yes (3)
464	N.JCT.U59/U169	ANDERSON-FRANKLIN CO. LINE	US-59		Yes (3)
1957	S.JCT.U59/U169	N.JCT.U59/U169	US-59	29.57	Yes (4)
467	JCT.U169/K58	S.JCT.U59/U169	US-169		Yes (4)
Total Travel Time = 596.9 (min)					

B.6 Sub-Area 422 at Louisburg

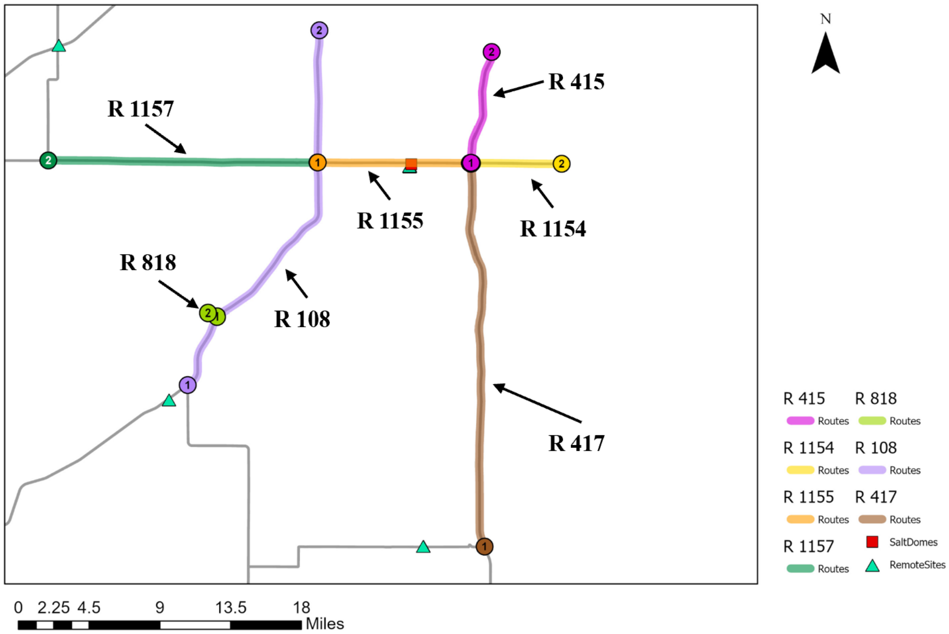

Figure B.11: Before Optimization (7 routes per treating cycle)

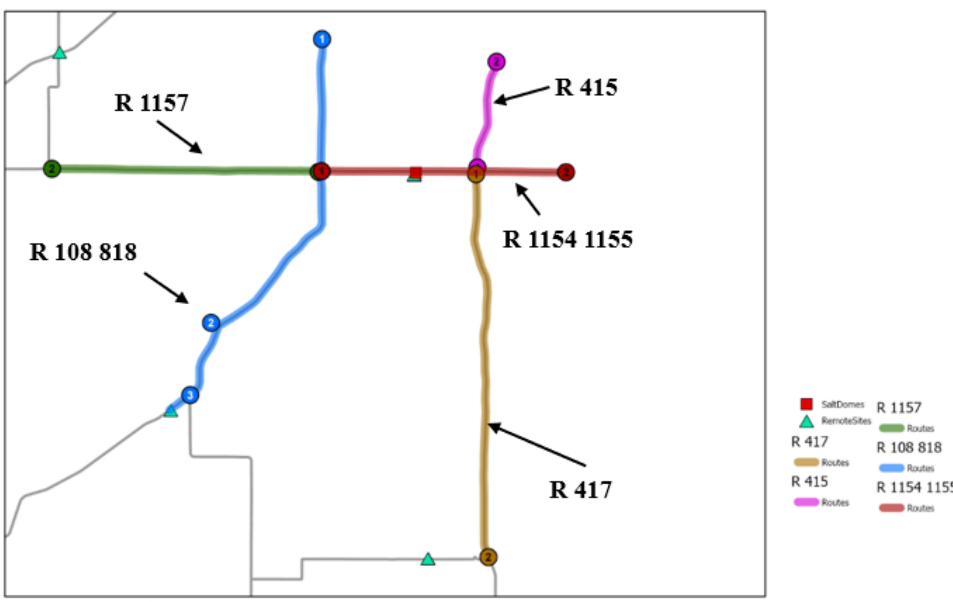

Figure B.12: After Optimization (5 routes per treating cycle)

Table B.11: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
818	JCT.U169/K279	STATE HOSPITAL	K-279	1.00	No
108	JCT.U169/K7	MI.S.MIAMI-JOHNSON CO. LINE	US-169	80.83	No
1154	JCT.U69/K68	KS-MO STATE LINE	K-68	9.01	No
1155	JCT.U169/K68	JCT.U69/K68	K-68	15.29	No
1157	JCT.K33/K68	JCT.U169/K68	K-68	26.83	No
415	JCT.U69/K68	0.5 MI.S.MIAMI-JOHNSON CO. LINE	US-69	22.77	No
417	JCT.U69/K152	JCT.U69/K68	US-69	76.72	No
Total Travel Time = 610.0 (min)					

Table B.12: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
818	JCT.U169/K279	STATE HOSPITAL	K-279	81.83	Yes (1)
108	JCT.U169/K7	MI.S.MIAMI-JOHNSON CO. LINE	US-169		Yes (1)
1154	JCT.U69/K68	KS-MO STATE LINE	K-68	24.3	Yes (2)
1155	JCT.U169/K68	JCT.U69/K68	K-68		Yes (2)
1157	JCT.K33/K68	JCT.U169/K68	K-68	26.83	No
415	JCT.U69/K68	0.5 MI.S.MIAMI-JOHNSON CO. LINE	US-69	22.77	No
417	JCT.U69/K152	JCT.U69/K68	US-69	76.72	No
Total Travel Time = 566.2 (min)					

B.7 Sub-Area 423 at Mound City

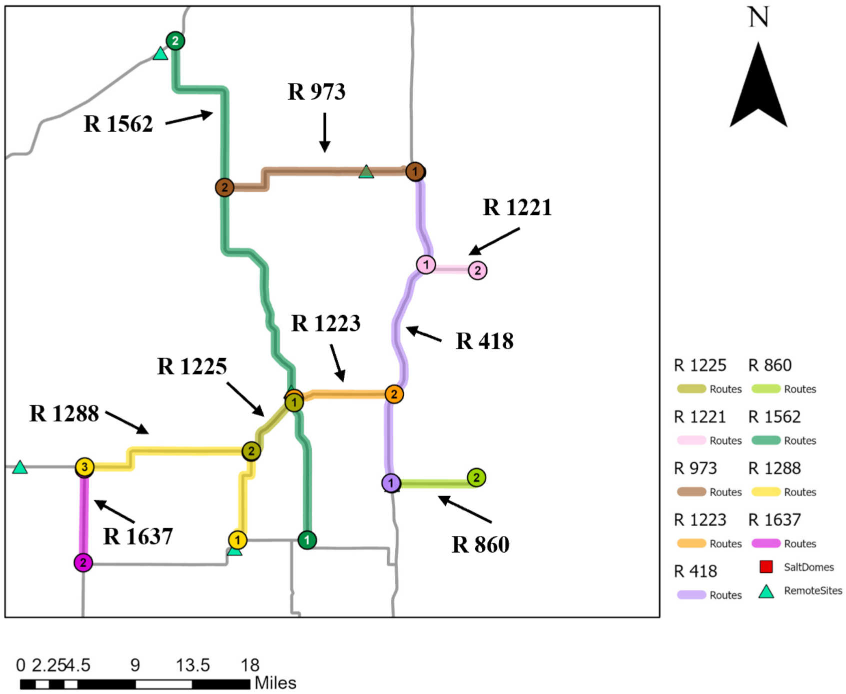

Figure B.13: Before Optimization (9 routes per treating cycle)

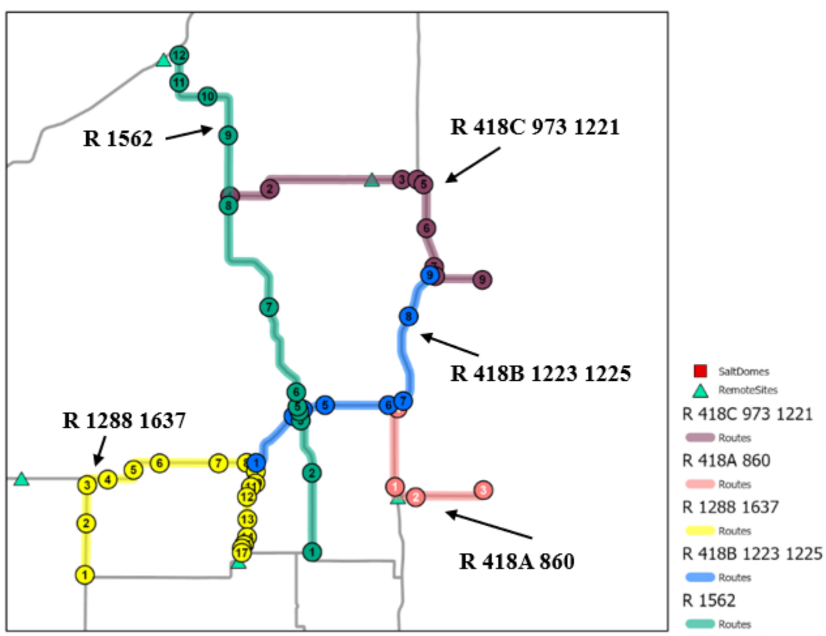

Figure B.14: After Optimization (5 routes per treating cycle)

Table B.13: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
973	JCT.K7/K152	JCT.U69/K152	K-152	25.70
418C	North Jct US-69/K-52	JCT.U69/K152	US-69	25.19
1221	N.JCT.U69/K52	KS-MO STATE LINE	K-52	6.61
418A	JCT.U69/K239	South Jct US-69/K-52	US-69	30.64
860	JCT.U69/K239	KS-MO STATE LINE	K-239	11.42
1637	JCT.K3/K65	JCT.K3/K31	K-3	12.02
1288	JCT.K3/K31	JCT.K31/K65	K-31	35.13
418B	South Jct US-69/K-52	North Jct US-69/K-52	US-69	25.30
1223	N.JCT.K7/K52	S.JCT.U69/K52	K-52	12.72
1225	JCT.K31/K52	S.JCT.K7/K52	K-52	8.78
1562	E.JCT.K7/K31	JCT.U169/K7	K-7	72.43
Total Travel Time = 844.3 (min)				

Table B.14: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
973	JCT.K7/K152	JCT.U69/K152	K-152	57.5	Yes (1)
418C	North Jct US-69/K-52	JCT.U69/K152	US-69		Yes (1)
1221	N.JCT.U69/K52	KS-MO STATE LINE	K-52		Yes (1)
418A	JCT.U69/K239	South Jct US-69/K-52	US-69	42.06	Yes (2)
860	JCT.U69/K239	KS-MO STATE LINE	K-239		Yes (2)
1637	JCT.K3/K65	JCT.K3/K31	K-3	47.15	Yes (3)
1288	JCT.K3/K31	JCT.K31/K65	K-31		Yes (3)
418B	South Jct US-69/K-52	North Jct US-69/K-52	US-69	46.8	Yes (4)
1223	N.JCT.K7/K52	S.JCT.U69/K52	K-52		Yes (4)
1225	JCT.K31/K52	S.JCT.K7/K52	K-52		Yes (4)
1562	E.JCT.K7/K31	JCT.U169/K7	K-7	72.43	No
Total Travel Time = 783.8 (min)					

B.8 Sub-Area 424 at Ottawa

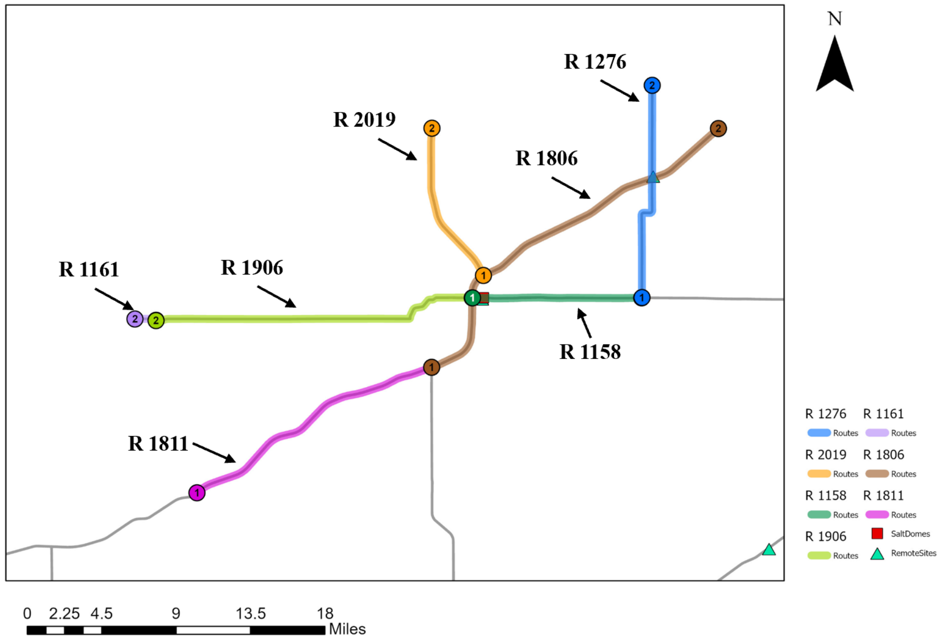

Figure B.15: Before Optimization (7 routes per treating cycle)

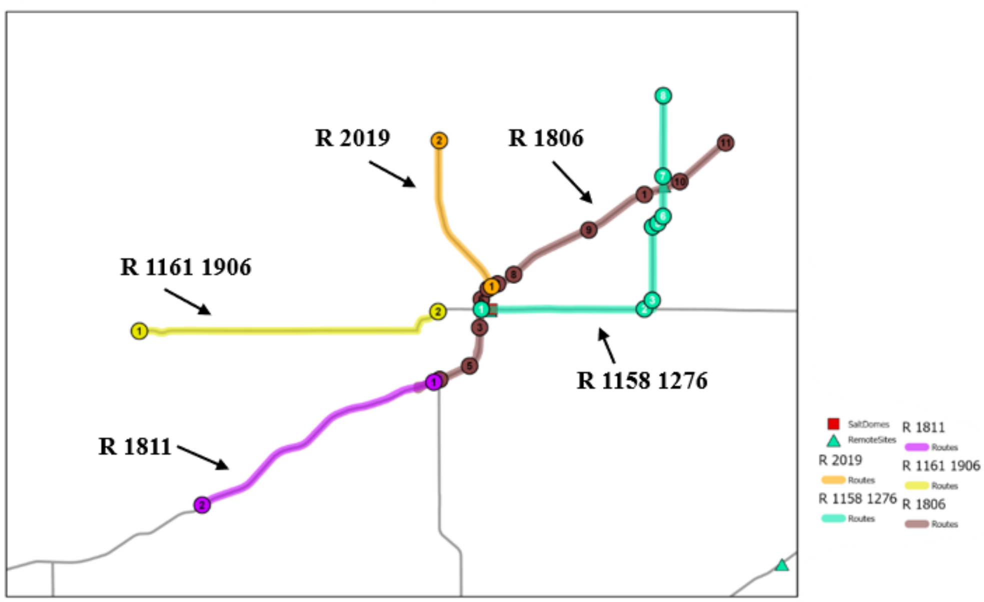

Figure B.16: After Optimization (5 routes per treating cycle)

Table B.15: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1806	JCT.I35/U59	MIAMI-JOHNSON CO. LINE	I-35	75.26	No
1811	JCT.I35/K273	JCT.I35/U59	I-35	51.57	No
1276	JCT.K33/K68	JCT.U56/K33	K-33	20.82	No
1158	JCT.I35/U59/K68	JCT.K33/K68	K-68	16.06	No
1161	JCT.K68/K268	OSAGE-FRANKLIN CO. LINE	K-68	2.01	No
1906	OSAGE-FRANKLIN CO. LINE	JCT.K68/MAIN ST.	K-68	27.07	No
2019	JCT.I35/U59	JCT.U56/U59	US-59	30.97	No
Total Travel Time = 601.5 (min)					

Table B.16: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1806	JCT.I35/U59	MIAMI-JOHNSON CO. LINE	I-35	75.26	No
1811	JCT.I35/K273	JCT.I35/U59	I-35	51.57	No
1276	JCT.K33/K68	JCT.U56/K33	K-33	36.88	Yes (1)
1158	JCT.I35/U59/K68	JCT.K33/K68	K-68		Yes (1)
1161	JCT.K68/K268	OSAGE-FRANKLIN CO. LINE	K-68	29.08	Yes (2)
1906	OSAGE-FRANKLIN CO. LINE	JCT.K68/MAIN ST.	K-68		Yes (2)
2019	JCT.I35/U59	JCT.U56/U59	US-59	30.97	No
Total Travel Time = 561.0 (min)					

B.9 Sub-Area 425 at Waverly

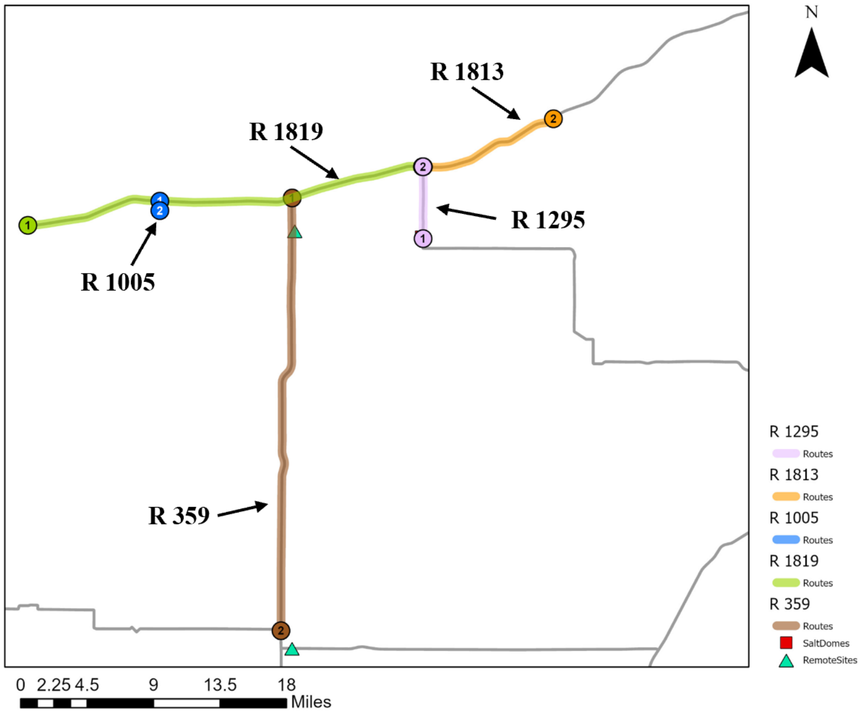

Figure B.17: Before Optimization (5 routes per treating cycle)

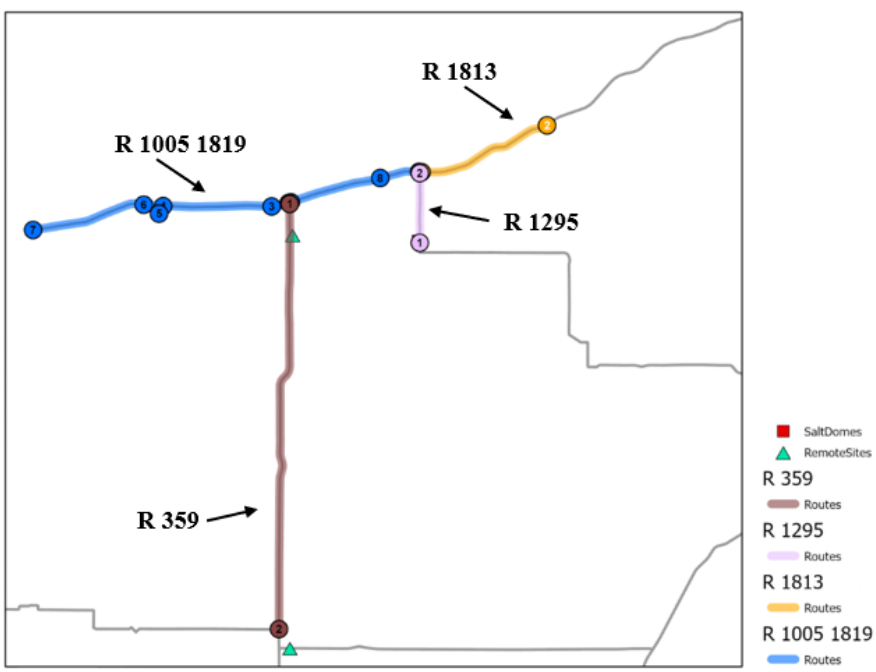

Figure B.18: After Optimization (4 routes per treating cycle)

Table B.17: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1813	E. Jct K-31 (Exit 162)	Williamsburg (Exit 170)	I-35	30.22	No
1819	K-130 (Exit 141)	E. Jct K-31 (Exit 162)	I-35	85.76	No
1005	JCT.I35/K131	NCL LEBO	K-131	1.05	No
1295	ECL Waverly/K31	NCL WAVERLY/8TH	K-31	7.51	No
359	N.JCT.U75/K58	JCT.I35/U75	US-75	46.26	No
Total Travel Time = 482.3 (min)					

Table B.18: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1813	E. Jct K-31 (Exit 162)	Williamsburg (Exit 170)	I-35	30.22	No
1819	K-130 (Exit 141)	E. Jct K-31 (Exit 162)	I-35	86.81	Yes (1)
1005	JCT.I35/K131	NCL LEBO	K-131		Yes (1)
1295	ECL Waverly/K31	NCL WAVERLY/8TH	K-31	7.51	No
359	N.JCT.U75/K58	JCT.I35/U75	US-75	46.26	No
Total Travel Time = 455.3 (min)					

B.10 Sub-Area 431 at Altoona

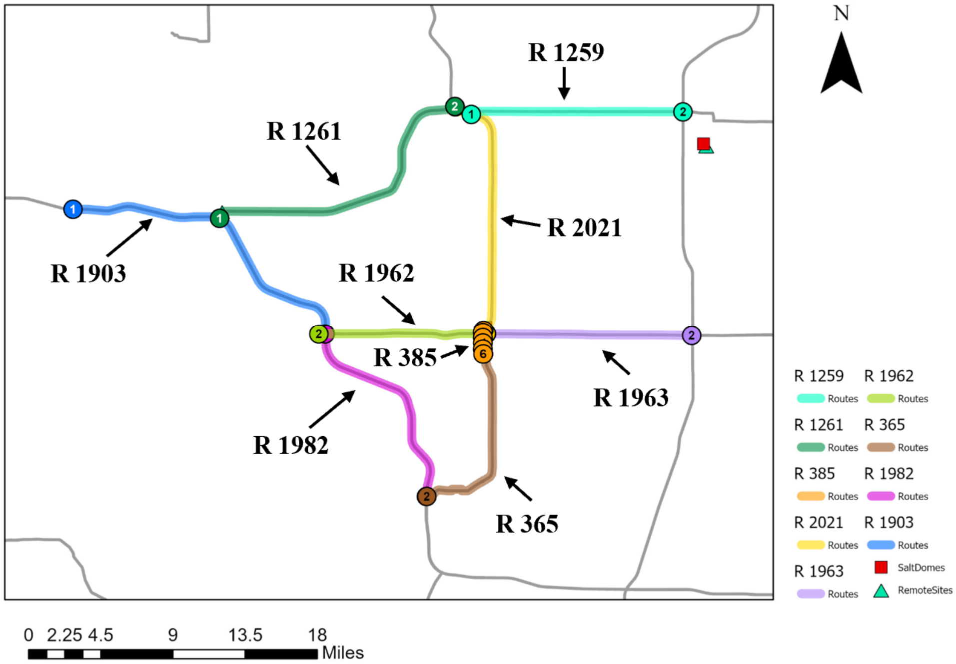

Figure B.19: Before Optimization (9 routes per treating cycle)

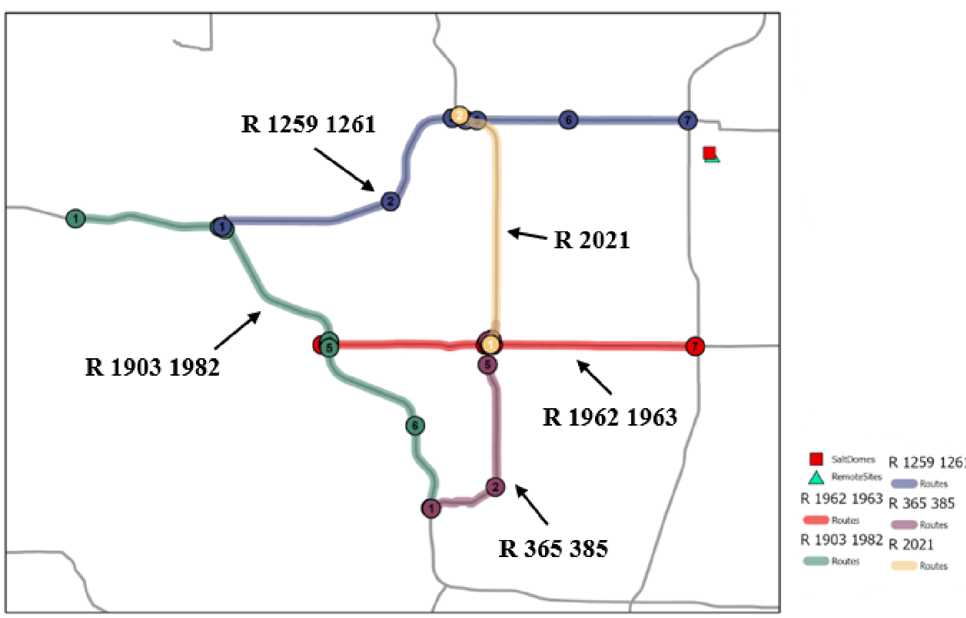

Figure B.20: After Optimization (5 routes per treating cycle)

Table B.19: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
1259	E.JCT.U75/K39	JCT.U169/K39	K-39	21.07
1261	JCT.U400/K39	W.JCT.U75/K39	K-39	27.62
1962	ECL FREDONIA	JCT.U75/K47	K-47	16.66
1963	JCT.U75/K47	JCT.U169/K47	K-47	18.93
1903	11 MI.E.E.JCT.U400/K99 (FALL RIVER)	JCT.U400/K47	US-400	31.55
1982	JCT.U400/K47	N.JCT.U400/U75	US-400	21.96
365	N.JCT.U75/U400	JCT.U75/K47	US-75	21.04
385	S.JCT.U75B/U75	N.JCT.U75B/U75	US-75B	2.42
2021	JCT.U75/K47	W.JCT.U75/K39	US-75	22.80
Total Travel Time = 627.2 (min)				

Table B.20: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1259	E.JCT.U75/K39	JCT.U169/K39	K-39	48.69	Yes (1)
1261	JCT.U400/K39	W.JCT.U75/K39	K-39		Yes (1)
1962	ECL FREDONIA	JCT.U75/K47	K-47	35.59	Yes (2)
1963	JCT.U75/K47	JCT.U169/K47	K-47		Yes (2)
1903	11 MI.E.E.JCT.U400/K99 (FALL RIVER)	JCT.U400/K47	US-400	53.51	Yes (3)
1982	JCT.U400/K47	N.JCT.U400/U75	US-400		Yes (3)
365	N.JCT.U75/U400	JCT.U75/K47	US-75	23.46	Yes (4)
385	S.JCT.U75B/U75	N.JCT.U75B/U75	US-75B		Yes (4)
2021	JCT.U75/K47	W.JCT.U75/K39	US-75	22.80	No
Total Travel Time = 525.1 (min)					

B.11 Sub-Area 432 at Independence

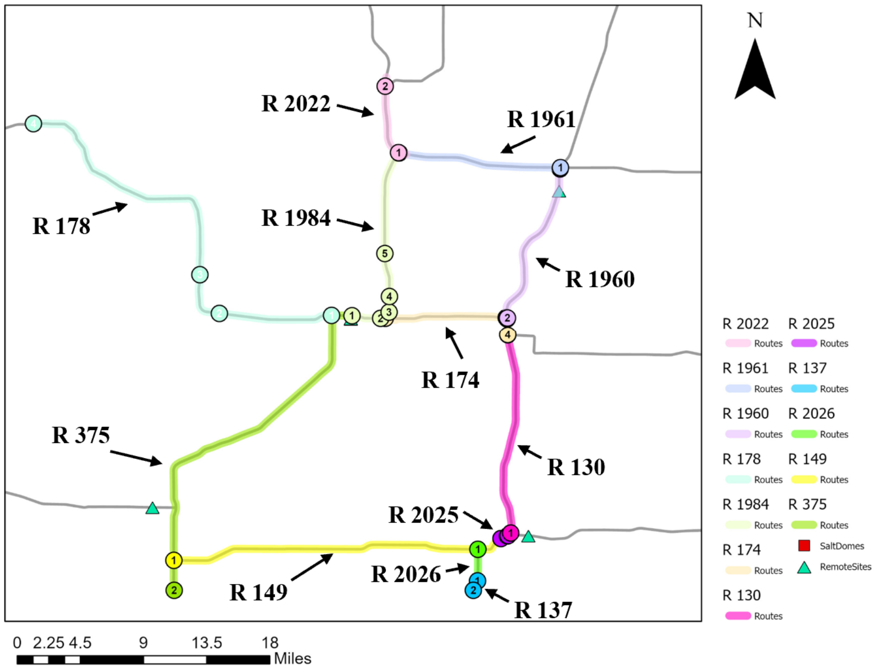

Figure B.21: Before Optimization (12 routes per treating cycle)

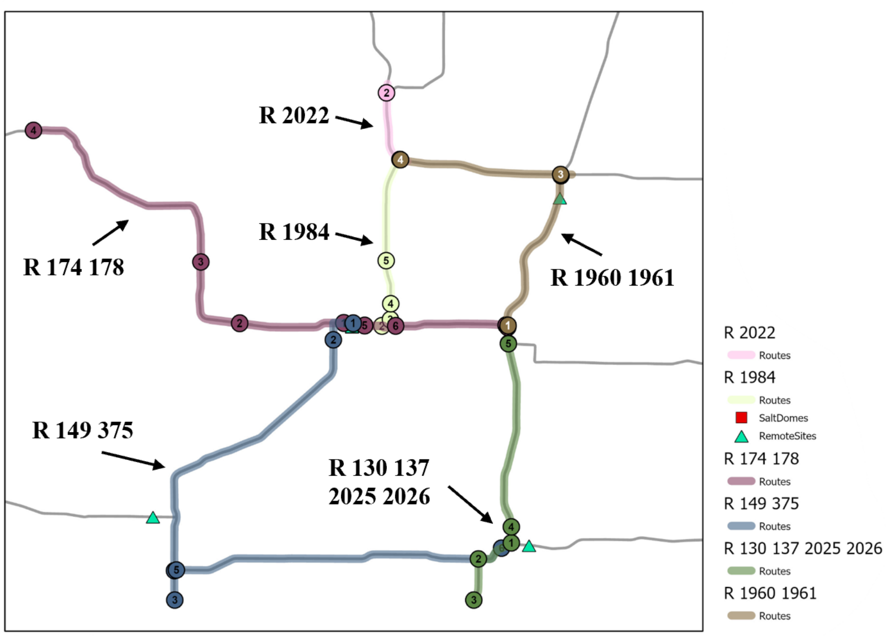

Figure B.22: After Optimization (6 routes per treating cycle)

Table B.21: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
174	ECL INDEPENDENCE	S.JCT.U169/U160	US-160	13.82
178	ECL LONGTON	W.JCT.U75/U160	US-160	49.65
149	S.JCT.U75/U166	WCL COFFEYVILLE	US-166	28.46
375	KS-OK STATE LINE	WCL INDEPENDENCE	US-75	43.56
2025	ECL COFFEYVILLE	E.JCT.U166/U169	US-166	1.45
2026	SCL COFFEYVILLE	W.JCT.U166/U169	US-169	3.59
130	E.JCT.U166/U169	S.JCT.U160/U169	US-169	20.92
137	KS-OK STATE LINE	SCL COFFEYVILLE	US-169	1.17
1960	N.JCT.U160/U169	JCT.U169/U400	US-169	18.88
1961	S.JCT.U75/U400	JCT.U169/U400	US-400	18.42
1984	NCL INDEPENDENCE	S.JCT.U75/U400	US-75	14.37
2022	S.JCT.U75/U400	N.JCT.U75/U400	US-75	15.27
Total Travel Time = 847.4 (min)				

Table B.22: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
174	ECL INDEPENDENCE	S.JCT.U169/U160	US-160	63.47	Yes (1)
178	ECL LONGTON	W.JCT.U75/U160	US-160		Yes (1)
149	S.JCT.U75/U166	WCL COFFEYVILLE	US-166	72.02	Yes (2)
375	KS-OK STATE LINE	WCL INDEPENDENCE	US-75		Yes (2)
2025	ECL COFFEYVILLE	E.JCT.U166/U169	US-166	27.13	Yes (3)
2026	SCL COFFEYVILLE	W.JCT.U166/U169	US-169		Yes (3)
130	E.JCT.U166/U169	S.JCT.U160/U169	US-169		Yes (3)
137	KS-OK STATE LINE	SCL COFFEYVILLE	US-169		Yes (3)
1960	N.JCT.U160/U169	JCT.U169/U400	US-169	37.30	Yes (4)
1961	S.JCT.U75/U400	JCT.U169/U400	US-400		Yes (4)
1984	NCL INDEPENDENCE	S.JCT.U75/U400	US-75	14.37	No
2022	S.JCT.U75/U400	N.JCT.U75/U400	US-75	15.27	No
Total Travel Time = 681.8 (min)					

B.12 Sub-Area 433 at Sedan

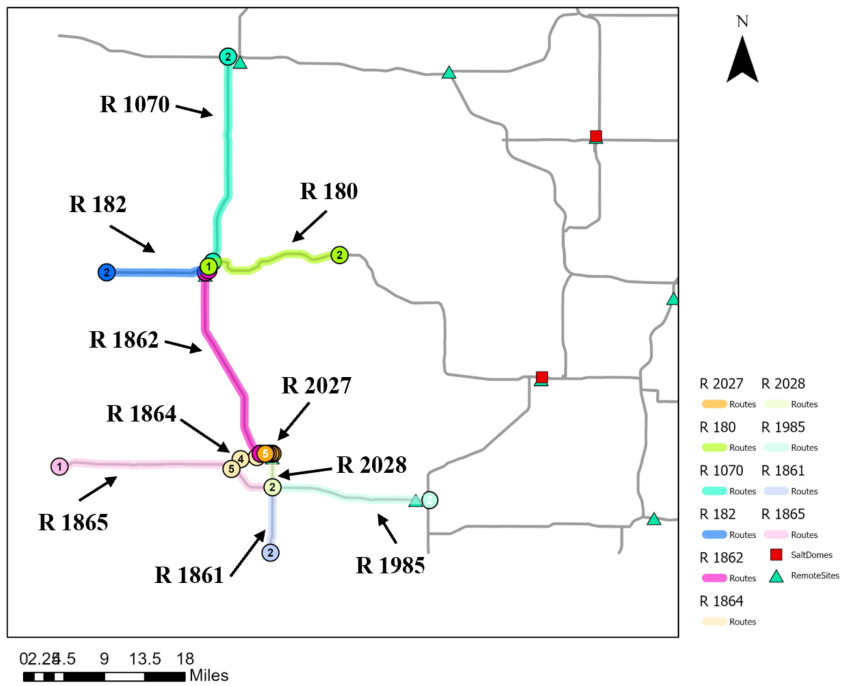

Figure B.23: Before Optimization (10 routes per treating cycle)

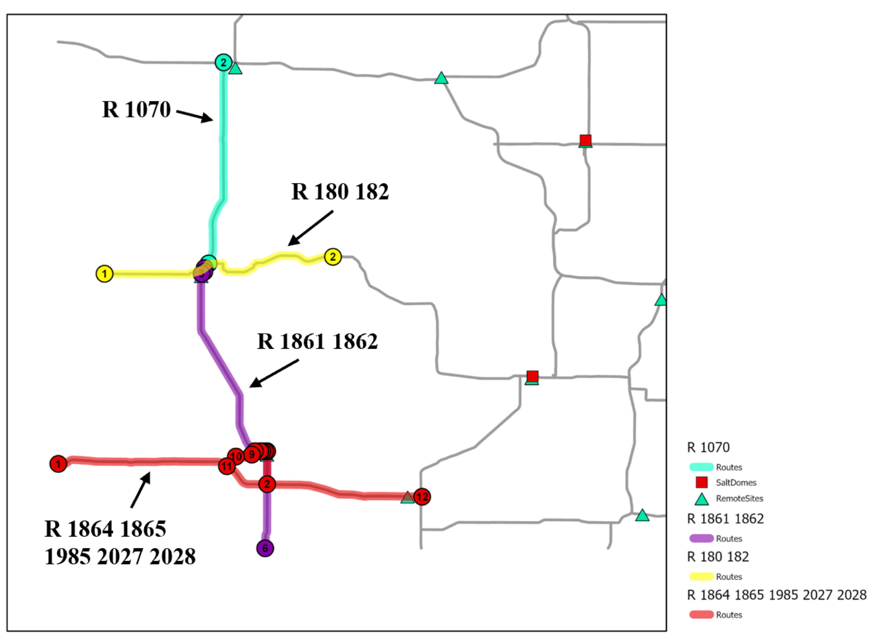

Figure B.24: After Optimization (4 routes per treating cycle)

Table B.23: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
1070	E.JCT.U160/K99	W.JCT.U400/K99	K-99	32.20
1861	KS-OK STATE LINE	S.JCT.U166/U166B/K99	K-99	11.71
1862	N.JCT.U166BUS/K99	W.JCT.U160/K99	K-99	36.55
180	W.JCT.U160/K99	ECL LONGTON	US-160	26.13
182	WCL GRENOLA	W.JCT.U160/K99	US-160	18.80
1864	W.JCT.U166/U166BUS	WCL SEDAN	US-166B	7.43
1865	COWLEY-CHAUTAUQUA CO. LINE	JCT.U166/K99	US-166	39.78
1985	JCT.U166/K99	N.JCT.U75/U166	US-166	28.38
2027	WCL SEDAN	SCL SEDAN	US-166B	1.27
2028	SCL SEDAN	E.JCT.U166BUS/U166/K99	US-166B	5.93
Total Travel Time = 788.1 (min)				

Table B.24: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1070	E.JCT.U160/K99	W.JCT.U400/K99	K-99	32.20	No
1861	KS-OK STATE LINE	S.JCT.U166/U166B/K99	K-99	48.26	Yes (1)
1862	N.JCT.U166BUS/K99	W.JCT.U160/K99	K-99		Yes (1)
180	W.JCT.U160/K99	ECL LONGTON	US-160	44.93	Yes (2)
182	WCL GRENOLA	W.JCT.U160/K99	US-160		Yes (2)
1864	W.JCT.U166/U166BUS	WCL SEDAN	US-166B	82.79	Yes (3)
1865	COWLEY-CHAUTAUQUA CO. LINE	JCT.U166/K99	US-166		Yes (3)
1985	JCT.U166/K99	N.JCT.U75/U166	US-166		Yes (3)
2027	WCL SEDAN	SCL SEDAN	US-166B		Yes (3)
2028	SCL SEDAN	E.JCT.U166BUS/U166/K99	US-166B		Yes (3)
Total Travel Time = 616.3 (min)					

B.13 Sub-Area 441 at Altamont

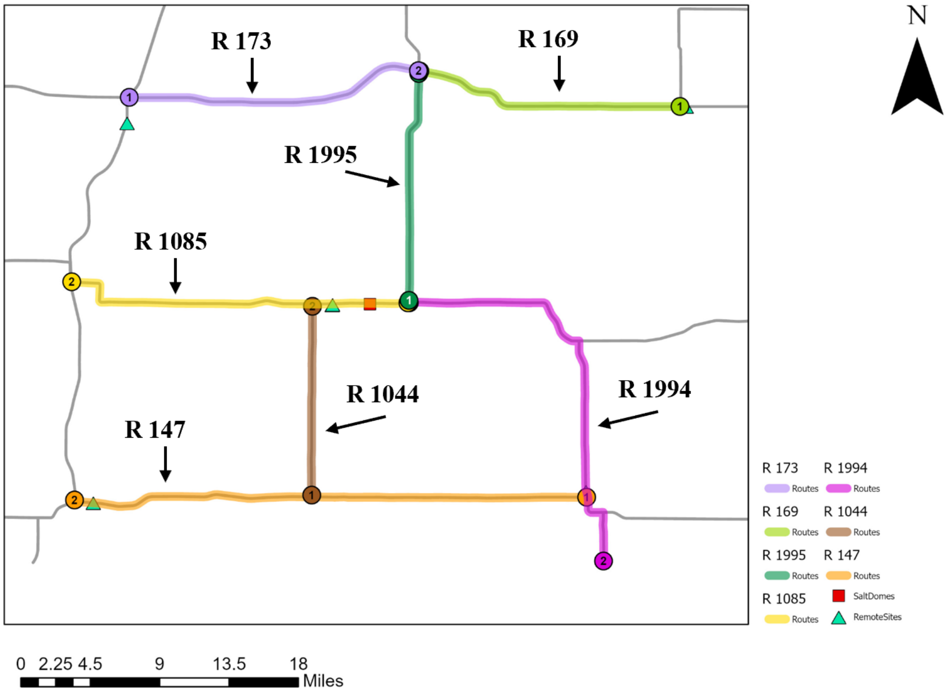

Figure B.25: Before Optimization (7 routes per treating cycle)

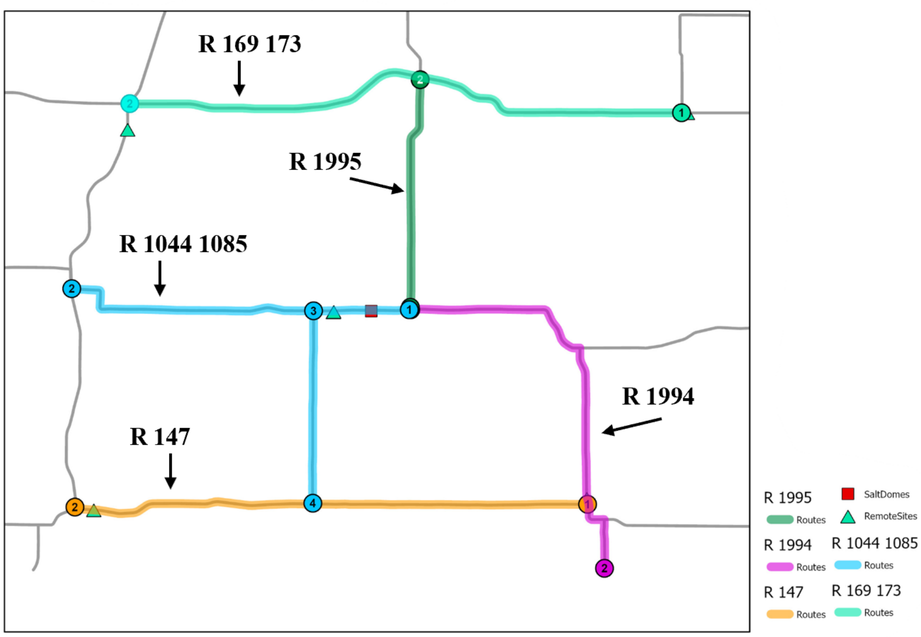

Figure B.26: After Optimization (5 routes per treating cycle)

Table B.25: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
1044	JCT.U166/K101	JCT.U160/K101	K-101	19.89
1085	S.JCT.U169/U160	W.JCT.U59/U160	US-160	36.92
147	E.JCT.U166/U169	W.JCT.U59/U166	US-166	53.52
169	JCT.U59/U400	JCT.U400/K126	US-400	22.85
173	JCT.U169/U400	JCT.U59/U400	US-400	31.05
1994	KS-OK STATE LINE	W.JCT.U59/U160	US-59	44.10
1995	W.JCT.U59/U160	JCT.U59/U400	US-59	22.22
Total Travel Time = 683.4 (min)				

Table B.26: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1044	JCT.U166/K101	JCT.U160/K101	K-101	56.81	Yes (1)
1085	S.JCT.U169/U160	W.JCT.U59/U160	US-160		Yes (1)
147	E.JCT.U166/U169	W.JCT.U59/U166	US-166	53.52	No
169	JCT.U59/U400	JCT.U400/K126	US-400	53.90	Yes (2)
173	JCT.U169/U400	JCT.U59/U400	US-400		Yes (2)
1994	KS-OK STATE LINE	W.JCT.U59/U160	US-59	44.10	No
1995	W.JCT.U59/U160	JCT.U59/U400	US-59	22.22	No
Total Travel Time = 622.9 (min)					

B.14 Sub-Area 442 at Columbus

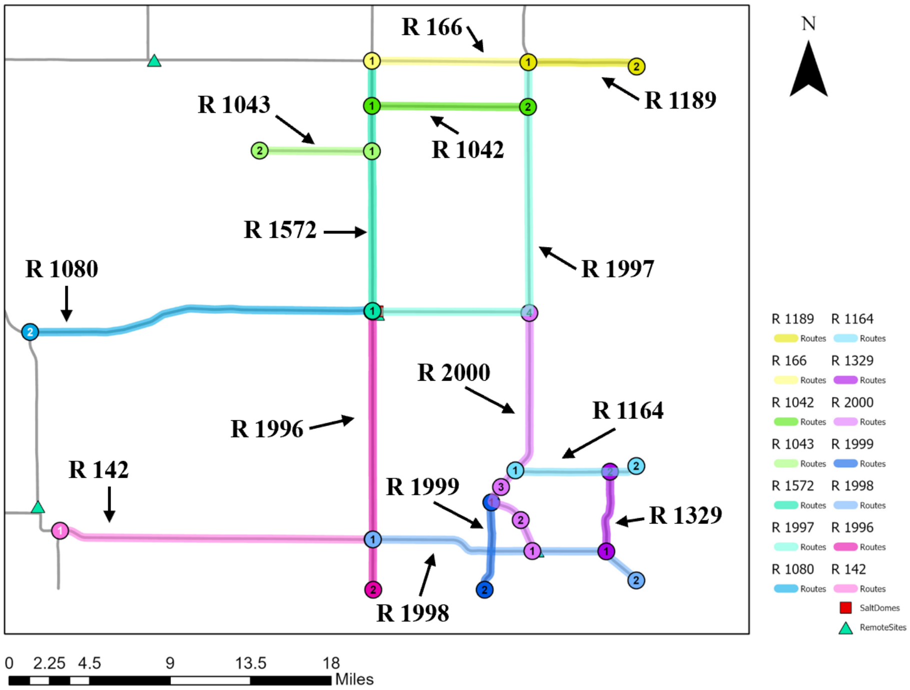

Figure B.27: Before Optimization (14 routes per treating cycle)

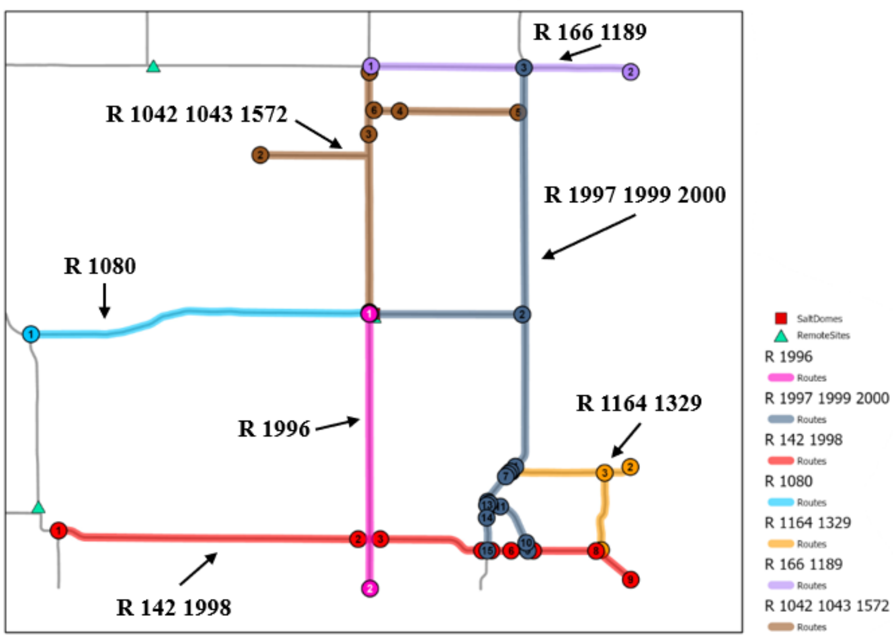

Figure B.28: After Optimization (7 routes per treating cycle)

Table B.27: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
1043	ECL WEST MINERAL	JCT.K7/K102	K-102	10.02
1042	JCT.K7/K103	JCT.U69/K103	K-103	13.98
1189	JCT.U69/K171	KS-MO STATE LINE	K-171	22.23
1329	JCT.U166/K26	JCT.K26/K66	K-26	9.80
1164	JCT.U400/K66	KS-MO STATE LINE	K-66	13.94
1572	JCT.U69/U160/K7	JCT.U400/K7	K-7	7.21
1080	E.JCT.U59/U160	JCT.U69/K7/U160	US-160	16.82
142	E.JCT.U59/U166	JCT.U69/U166	US-166	28.95
1998	JCT.U69/U166	KS-MO STATE LINE (BAXTER SPRINGS)	US-166	28.08
166	JCT.U400/K7	JCT.U69/U400/K171	US-400	23.05
1997	JCT.U69/U160/K7 (Columbus)	JCT.U69/U400/K171	US-69	36.22
1999	KS-OK STATE LINE	JCT.U400/U69ALT	US-69A	8.00
2000	S. Jct US-69/US-400 (Crestline)	JCT.U400/U166	US-69	22.19
1996	KS-OK STATE LINE	JCT.U69/U160/K7	US-69	22.82
Total Travel Time = 990.7 (min)				

Table B.28: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1043	ECL WEST MINERAL	JCT.K7/K102	K-102	46.23	Yes (1)
1042	JCT.K7/K103	JCT.U69/K103	K-103		Yes (1)
1572	JCT.U69/U160/K7	JCT.U400/K7	K-7		Yes (1)
1189	JCT.U69/K171	KS-MO STATE LINE	K-171	23.74	Yes (2)
166	JCT.U400/K7	JCT.U69/U400/K171	US-400		Yes (2)
1329	JCT.U166/K26	JCT.K26/K66	K-26	24.03	Yes (3)
1164	JCT.U400/K66	KS-MO STATE LINE	K-66		Yes (3)
1080	E.JCT.U59/U160	JCT.U69/K7/U160	US-160	28.95	No
142	E.JCT.U59/U166	JCT.U69/U166	US-166	51.13	Yes (4)
1998	JCT.U69/U166	KS-MO STATE LINE (BAXTER SPRINGS)	US-166		Yes (4)
1997	JCT.U69/U160/K7 (Columbus)	JCT.U69/U400/K171	US-69	66.41	Yes (5)
1999	KS-OK STATE LINE	JCT.U400/U69ALT	US-69A		Yes (5)
2000	S. Jct US-69/US-400 (Crestline)	JCT.U400/U166	US-69		Yes (5)
1996	KS-OK STATE LINE	JCT.U69/U160/K7	US-69	22.82	No
Total Travel Time = 726.4 (min)					

B.15 Sub-Area 443 at Erie

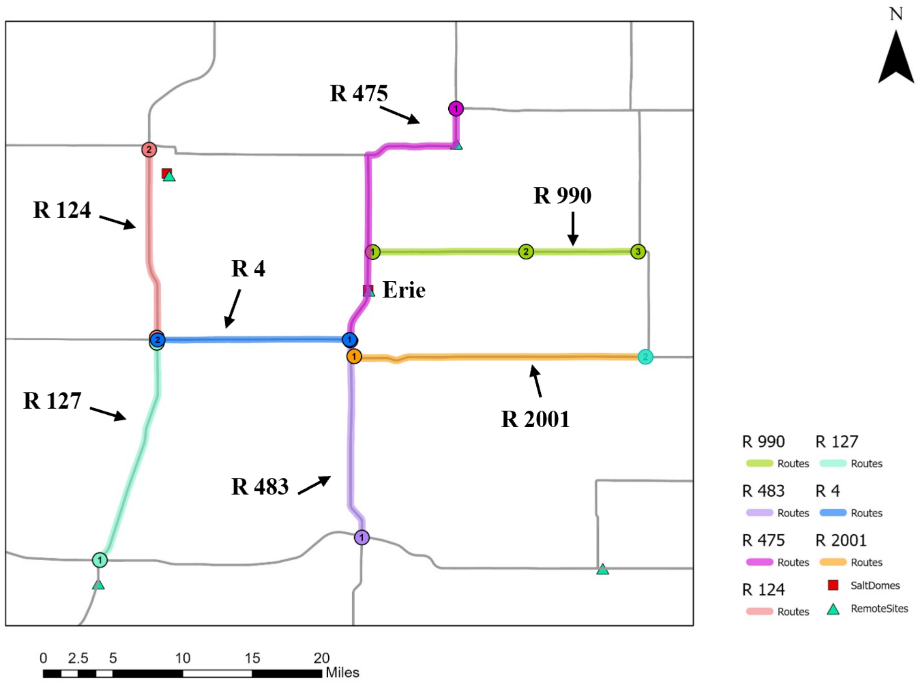

Figure B.29: Before Optimization (7 routes per treating cycle)

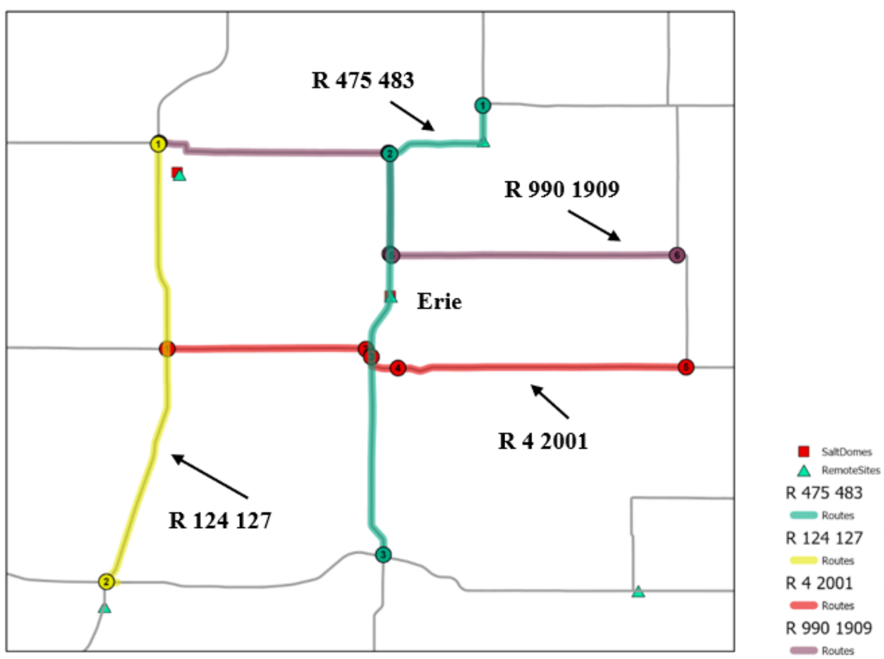

Figure B.30: After Optimization (4 routes per treating cycle)

Table B.29: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
990	JCT.U59/K146	JCT.K146/K3	K-146	30.99
4	JCT.U169/K47	N.JCT.U59/K47	K-47	25.60
2001	JCT.U59/K47	JCT.K3/K47	K-47	22.11
124	JCT.U169/K47	JCT.U169/K39	US-169	28.12
127	JCT.U169/U400	JCT.U169/K47	US-169	22.31
475	N.JCT.U59/K47	E.JCT.U59/K39	US-59	22.53
483	JCT.U59/U400	N.JCT.U59/K47	US-59	35.91
Total Travel Time = 691.0 (min)				

Table B.30: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
990	JCT.U59/K146	JCT.K146/K3	K-146	56.59	Yes (1)
1909	ECL Chanute	W. Jct US-59	K-39		Yes (1)
4	JCT.U169/K47	N.JCT.U59/K47	K-47	50.23	Yes (2)
2001	JCT.U59/K47	JCT.K3/K47	K-47		Yes (2)
124	JCT.U169/K47	JCT.U169/K39	US-169	44.84	Yes (3)
127	JCT.U169/U400	JCT.U169/K47	US-169		Yes (3)
475	N.JCT.U59/K47	E.JCT.U59/K39	US-59	58.76	Yes (4)
483	JCT.U59/U400	N.JCT.U59/K47	US-59		Yes (4)
Total Travel Time = 607.0 (min)					

B.16 Sub-Area 444 at Pittsburg

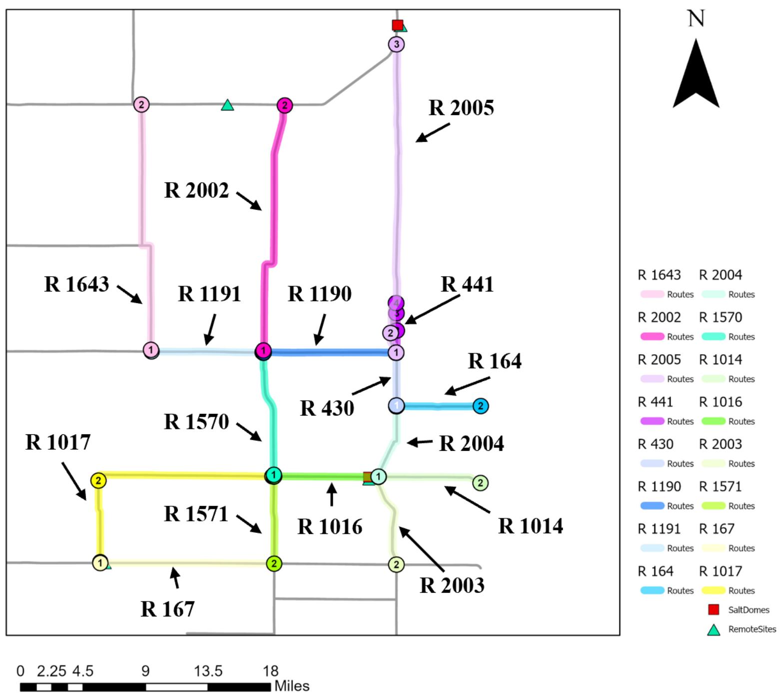

Figure B.31: Before Optimization (16 routes per treating cycle)

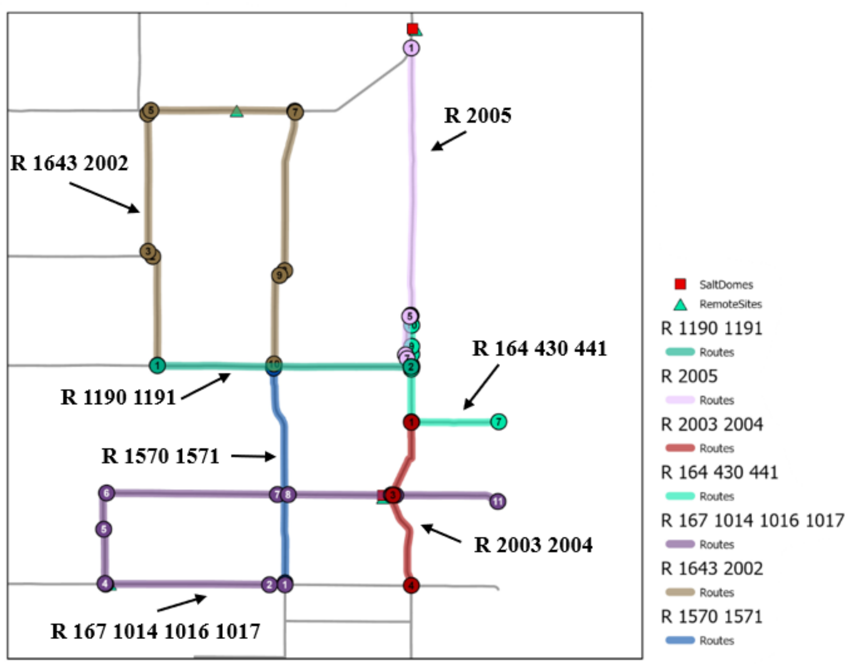

Figure B.32: After Optimization (7 routes per treating cycle)

Table B.31: Before Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile
1016	JCT.K7/K126	JCT.U69/K126	K-126	11.98
1017	JCT.U400/K126	JCT.K7/K126	K-126	30.11
1014	JCT.U69BUS/K126	KS-MO STATE LINE	K-126	9.75
167	JCT.U400/K126	JCT.U400/K7	US-400	19.95
1643	JCT.K3/K47	E.JCT. K3/K39	K-3	9.69
164	JCT.U160/U69	KS-MO STATE LINE	US-160	12.15
430	JCT.U69/U160	S.JCT.U69/U69B2/K47	US-69	5.98
441	S.JCT.U69/U69BUS2	N.JCT.U69/U69BUS2	US-69B2	10.69
2003	JCT.U69/U400/K171	JCT.U69/K126	US-69	8.69
2004	JCT.U69/K126	JCT.U69/U160	US-69	51.97
2005	S.JCT.U69/U69B2/K47	JCT.U69/K7	US-69	12.87
1191	JCT.K3/K47	JCT.K7/K47	K-47	15.16
1190	JCT.K7/K47	JCT.U69/K47/U69B2	K-47	14.35
1570	JCT.K7/K126	JCT.K7/K47	K-7	9.95
1571	JCT.U400/K7	JCT.K7/K126	K-7	28.99
2002	JCT.K7/K47	JCT.K7/K39	K-7	29.24
Total Travel Time = 1,131.9 (min)				

Table B.32: After Optimization

SNOW AND ICE ID	Route Begin	Route End	Route's Name	Lane Mile	Grouped?
1016	JCT.K7/K126	JCT.U69/K126	K-126	71.79	Yes (1)
1017	JCT.U400/K126	JCT.K7/K126	K-126		Yes (1)
1014	JCT.U69BUS/K126	KS-MO STATE LINE	K-126		Yes (1)
167	JCT.U400/K126	JCT.U400/K7	US-400		Yes (1)
164	JCT.U160/U69	KS-MO STATE LINE	US-160	27.82	Yes (2)
430	JCT.U69/U160	S.JCT.U69/U69B2/K47	US-69		Yes (2)
441	S.JCT.U69/U69BUS2	N.JCT.U69/U69BUS2	US-69B2		Yes (2)
2003	JCT.U69/U400/K171	JCT.U69/K126	US-69	19.38	Yes (3)
2004	JCT.U69/K126	JCT.U69/U160	US-69		Yes (3)
2005	S.JCT.U69/U69B2/ K47	JCT.U69/K7	US-69	51.97	No
1191	JCT.K3/K47	JCT.K7/K47	K-47	28.03	Yes (4)
1190	JCT.K7/K47	JCT.U69/K47/U69B2	K-47		Yes (4)
1570	JCT.K7/K126	JCT.K7/K47	K-7	24.3	Yes (5)
1571	JCT.U400/K7	JCT.K7/K126	K-7		Yes (5)
1643	JCT.K3/K47	E.JCT. K3/K39	K-3	58.23	Yes (6)
2002	JCT.K7/K47	JCT.K7/K39	K-7		Yes (6)
Total Travel Time = 846.1 (min)					

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