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Heavy Fleet and Facilities Optimization

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16. Abstract

The Indiana Department of Transportation (INDOT) is responsible for timely clearance of snow on state-maintained highways in Indiana as part of its wintertime operations. For this and other maintenance purposes, the state's subdistricts maintain 101 administrative units spread throughout the state. These units are staffed by personnel, including snow truck drivers and house snow removal trucks and other equipment. INDOT indicated a need to carry out value engineering analysis of the replacement timing of the truck fleet. To address these questions, this study carried out analysis to ascertain the appropriate truck replacement age, that is different across each of the state's three weather-based regions to minimize the truck life cycle cost. INDOT also indicated a need for research guidance in possible revisions to the administrative unit locations and optimal routes to be taken by trucks in each unit in order to reduce deadhead miles. For purposes of optimizing the truck snow routes, the study developed two alternative algorithmic approaches. The first uses mathematical programming to select work packets for trucks while ensuring that snow is cleared at all snow routes and allowing the users to identify optimal route and unit location. The second approach uses network routing concepts, such as the rural postman problem, and allows the user to change the analysis inputs, such as the number of available drivers and so on. The first approach developed using opensolver (an open source tool with excel) and the second approach coded as an electronic tool, are submitted as part of this report. Both approaches can be used by INDOT's administrative unit managers for decision support regarding the deployment of resources for snow clearing operations and to minimize the associated costs.

17. Key Words
fleet management, vehicle replacement strategy, snow route network, optimal routing, winter operations, cost reduction, performance improvement

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EXECUTIVE SUMMARY

Introduction

This report focuses on a data-driven analysis of the total cost of truck ownership for the Indiana Department of Transportation (INDOT) and associated decisions regarding replacement, snow routing, and efficiency of operations. The main conclusions of the analysis are (1) a differentiated replacement age across the northern, central, and southern regions of the state can decrease overall costs; (2) analysis of the current snow routes and unit locations across the 101 units suggests opportunities to decrease deadhead miles; (3) the solutions provided can be deployed dynamically to provide implementable results; and (4) AVL data enables detailed truck snow spread and travel speed that can be incorporated to generate realistic estimates.

INDOT operates its 1,100 trucks through 101 units that each have dedicated spatial regions of responsibility. Counties across the state face different levels of snowfall, with the north region facing greater snow than the central or the south and the central region facing greater snow than the south.

Findings

Data from each unit shows the travel miles, snow miles, and deadhead miles and shows significant variation in the ratio of deadhead miles to total travel miles across units. Our regression analysis suggests a positive correlation between the deadhead miles and miles driven per truck, suggesting that the snow miles are constrained by salt capacity in trucks. Our analysis suggests that trucks are used more intensively i.e., greater miles driven per year, for up to 60,000 miles. Beyond that threshold, the trucks see less intensive use. The age to reach this threshold varies between the northern, central, and southern regions. INDOT's snow routes, by unit, were then examined and two algorithmic approaches provided. The first approach used mathematical programming to select work packets for trucks that can be implemented while ensuring all segments of roads have their snow cleared. This model's results are discussed in the report. The second approach framed the problem as a directed Chinese postman network routing problem and provided results that include the optimal number of trucks and optimal routes under specific conditions of the snow removal task. INDOT can consider specific additional features that should be added to implement these algorithms.

Implementation

We proposed a model and fit data to generate the optimal truck replacement age by region. We then applied it to the existing fleet of trucks in these regions with varying ages and demonstrated the benefit of varying replacement age by region. To optimize INDOT's snow routes, the first method, based on mathematical programming, was applied to all 101 units. Results for the mathematical programming show that deadhead miles are reduced significantly, potentially increasing across different approaches for all units. On average, Approach 2 reduced deadhead miles by 23.5%. On average, Approach 3 reduced deadhead miles by 31%. On average, Approach 4 reduced deadhead miles by 45.83%. The Greenfield District observed major reduction in deadhead miles (37%) using Approach 2. LaPorte District observed major reduction in deadhead miles (40%) using Approach 3. LaPorte District observed major reduction in deadhead miles (62%) using Approach 4. While the suggested results need to adjust to location constraints, the magnitude of the potential deadhead miles that can be reduced is a key outcome of this study. The second approach developed in this study for the fleet route optimization was coded using Python computer language and stored on a CD. INDOT's snow removal managers can apply this package to any of the state's 104 administrative units to prescribe (a) the optimal number of trucks and their respective routes, (b) the optimal route for each of an available number of trucks, (c) the optimal location of any additional units that are needed.

In summary, this report used a data driven and algorithmic approach to suggest ways to manage the truck fleet to improve performance—i.e., through managing age threshold at replacement, revised routing, and unit location adjustments—to generate both cost reductions and performance improvement.

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1. INTRODUCTION

Indiana Department of Transportation (INDOT) is the government agency responsible for road transportation and related infrastructure in Indiana. INDOT is responsible for interstates, U.S. routes and state roads. INDOT has six offices for handling day to day operations construction and detours, traffic signal operations, permits, and maintenance operations, including repairing potholes and plowing snow (INDOT, n.d.).

Indiana is located in a region that is referred to as a "wet-freeze zone" for purposes of infrastructure management (FHWA, 2018). During winter, the state encounters significant snow events that typically leave most of the state's 30,000 lane-miles of state roads, U.S. routes, and interstate highways, covered with snow. As such, the state agency responsible for road operations and maintenance INDOT tracks weather predictions regularly. The work is distributed as a subdistrict and "unit" level, and collectively, agency possesses about 1,100 trucks for wintertime operations. The goal is to ensure that all roads are open, passable and do not unduly impair mobility and safety during snowfall events.

The wintertime operations do not involve snow removal only, but also includes pre-snowfall activities such as anti-icing (pre-treatment of pavement with brine) to prevent ice or snow bonding to the highway pavement) and post-snowfall activities such as de-icing (applying chemicals to weaken ice-pavement bonding in order to facilitate ice or snow removal.

Depending on the year and weather, the demands for snow removal, for example, may vary across districts. Therefore, it may be the case that some resources (trucks, personnel) are transferred to other subdistricts in a district or units in a subdistrict. Currently the utilization of trucks varies across districts with a normal plan to have 10%–15% more capacity than required to ensure availability of trucks to execute snow routes in a timely manner. Depending on the nature of storage of the truck, the time to be ready to operate routes may be impacted, thus impacting the number of routes required to be operated to clear snow within a specified period. Truck characteristics may also impact the realized hours of operation for snow removal.

Efficient removal of snow is a reflection of INDOT's mission ("collaboratively plan, build, and maintain safe and innovative transportation infrastructure that enhances quality of life, drives economic growth, and accommodates new modes of transport") and is consistent with the agency's goals, strategic plan, vision, and core values (INDOT, 2021). The study has significant benefits to INDOT. An efficient snow removal routing scheme can significantly reduce costs incurred by INDOT's subdistricts. Even a marginal reduction in costs could accumulate overall district and over an extended period of time to constitute significant savings in the high costs associated with fuel, crew salaries, and vehicle capital and maintenance costs (Omer, 2007). This research is motivated by the realization that analytical routing techniques and models can be used to enhance the economic efficiency of snow removal operations.

1.1 Objective

INDOT has distributed its operations into 6 districts across the state—Fort Wayne, LaPorte, Crawfordsville, Greenfield, Seymour, and Vincennes. Each district is made up of subdistricts. INDOT currently owns about 1,100 heavy trucks in its fleet at several unit locations across the state. These are deployed across a variety of operations that include (1) snow removal, (2) chip seal, (3) dumping, (4) blocking, and other activities. These trucks have different ages, capabilities, equipment rating, maintenance costs, miles, depreciation, etc. Depending on the year and weather, the demand for snow removal, one of the major operations undertaken by INDOT, may vary across districts. Our goals in this project are the following:

- Understand the current mix of equipment, associated data regarding maintenance, equipment condition, age, and replacement plans and provide a plan for optimum age of replacement for trucks through an optimization model.
- Understand the current snow route network for each unit location as well as allocation of trucks and explore whether these facility locations, or snow routes or trucks allocated to each unit need to be changed.

Eventually, the project aims to provide INDOT with an actionable recommendation to improve the financial and service performance of its wintertime operations.

1.2 Project Timeline

Figure 1.1 provides the Gantt chart that was prepared to display the division of work across phases and keep track of project deliverables. In Phase I, the team conducted benchmarking for different DOTs in similar region. The team focused on states like Iowa, Minnesota, Illinois, and Texas. The rationale for choosing the states varied from location bias to standardization bias. The analysis portrays the different replacement methods embraced by different states and formulation of a deterministic model that could help understand the useful life of a fleet.

In Phase II, the team analyzed the data and provided some exploratory data analysis. The analysis is dependent on overall and cumulative data for the existing fleet (updated in 2019) for all types of trucks. Initial analysis suggested that majority of cost is borne by dump trucks, so focus was made on that. In absence of a year-to-year basis data on different trucks, extrapolation and analysis was conducted on the cumulative data.

Phase III was divided into two parts for developing an optimization model. The first part of Phase III focused on developing a model for the truck replacement strategy. The analysis performed for Crawfordsville District was used and a model was created using the fleet vehicle data that was provided by

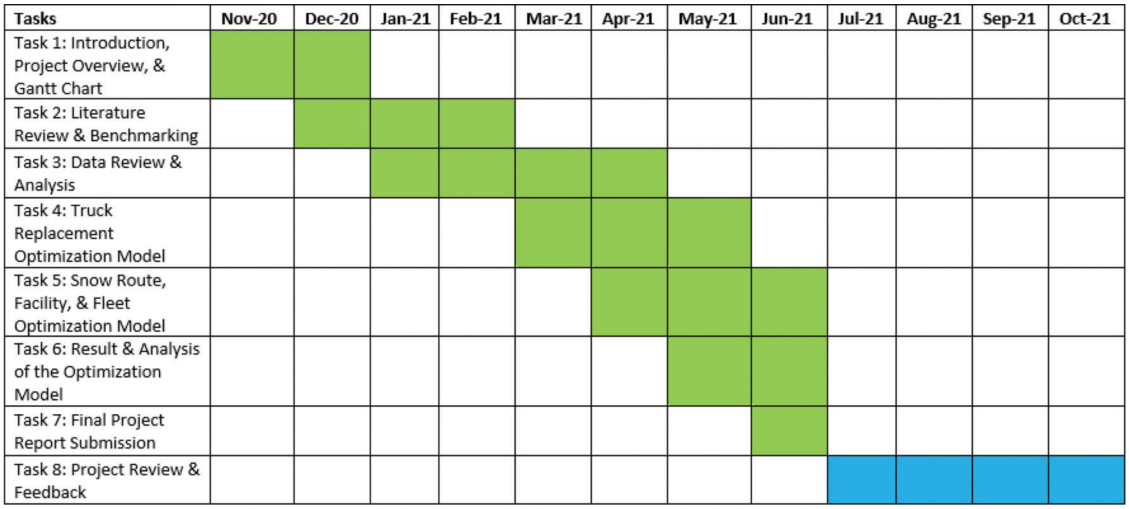


Figure 1.1 Gantt chart.

INDOT as input with the objective of obtaining optimum replacement age for the truck while minimizing the cost per mile and thus the overall owning cost of the truck. This model was expanded to include the analysis for all the districts and prepare a truck replacement strategy for districts in the northern, central, and southern regions individually.

The second part of Phase III and focused on developing an optimization model for snow route, facility, and truck distribution strategy. Two approaches were undertaken to develop a strategy for identifying optimal snow routes, facility locations, and the distribution of trucks in these facilities.

Phase IV focused on generating results from the optimization models and providing INDOT with conclusion and an implementation plan with actionable tasks.

Phase V consisted of preparing a professional document outlining the details of the project and preparing a draft report that was submitted to INDOT.

2. LITERATURE REVIEW

As shown in the Gantt chart (Figure 1.1), the second phase of the project defined the team's literature review and benchmarking approach towards truck replacement and retirement policies and towards snow route, facility, and number of trucks optimization strategy across different DOTs. The team reviewed the existing literature and studied strategies that are outlined or implemented by different institutions. Literature review was performed to understand and provide knowledge of best strategies that INDOT can implement with its operations and thus make its operations more efficient and cost effective.

2.1 Truck Replacement Strategy

The approach for this section was to understand the different policies in place for each DOT and analyze the different scoring methods to evaluate retirement or replacement.

2.1.1 INDOT's Replacement Strategy

The INDOT currently follows a scoring method to represent the replacement decision. The model considers maintenance cost, inspection rating, and age of the vehicle to formulate a total score. A score of 5 is given to the vehicle with highest maintenance cost; the age is considered in absolute value; inspection score represents the condition of vehicle from a scale of 0–5, the lower the better. Summation of all these scores represents the total score, which serves as the key metric. For example, a vehicle with a maintenance cost of $30,000 at age 2 with an inspection score of 960 means that the three score components would be 1 for maintenance, 2 for age, and inspection score of 3. The total score for this vehicle would be (1+2+3) or 6. Figure 2.1 shows the scoring tabulation as adopted by INDOT. A vehicle with higher score is considered more prone to replacement, although the retirement is only formalized once the total score is at or more than 25. For the dataset presented in Figure 2.1, the average age at which a score of 25 is reached is 17. This means that at age 17 a vehicle is extremely likely to be replaced. Our analysis will focus on how replacement can be modified to reduce cost or cost per mile.

2.1.2 Selection of State DOTs

The benchmarking process was expanded to consider a deterministic model with Life Cycle Cost Analysis (LCAA) for each fleet. An initial understanding was made for several DOTs to understand the parameters chosen for replacement decisions. Figure 2.2 (Kriett et al., 2010) shows the list of state DOTs and how they consider each parameter for the scoring process. Our analysis of DOTs was first taken for Ohio, South Dakota, and Pennsylvania. The decision to choose these two states was regional bias, as all have similar weather pattern as Indiana. Texas and Minnesota were chosen for the standardized approach.

Total Maintenance $	TOTAL COM $	TOTAL LABOR $	TOTAL PART $	TOTAL $	Maint $ Score	Age	Age Score	Current Fall Inspection	Inspection Score	Total Snow Fleet Score
	Total	Total	Total	Total Cost Ownership						
$9,195,316	$ 1,046,031	$ 3,623,144	$ 4,526,141	$37,543,110	0-5	2020 Current	>/=0	Results	0-5	Maint Score+Age Score+Insp Score
$97,889	$3,022	$52,705	$42,162	$236,667	3	22	22	934	4	29
$106,781	$1,997	$54,386	$50,398	$249,916	4	20	20	935	4	28
$144,310	$1,430	$69,194	$73,686	$305,987	4	19	19	954	4	27
$88,143	$4,491	$43,869	$39,784	$255,199	3	19	19	955	4	26
$79,502	$1,197	$39,155	$39,150	$213,968	3	18	18	956	4	25
$101,443	$18,147	$44,910	$38,386	$257,404	4	17	17	949	4	25
$107,090	$7,414	$50,240	$49,436	$293,986	4	17	17	955	4	25
$91,198	$5,521	$44,116	$41,561	$230,219	3	20	20	971	2	25
$98,846	$3,664	$45,370	$49,812	$258,996	3	20	20	973	2	25
$123,093	$5,032	$64,544	$53,517	$272,052	4	19	19	973	2	25
$113,920	$70	$54,103	$59,747	$275,142	4	18	18	964	3	25
$125,882	$790	$61,176	$63,915	$282,061	4	18	18	963	3	25
$92,547	$20,516	$39,336	$32,695	$222,400	3	18	18	958	4	25
$80,514	$3,189	$39,730	$37,595	$250,524	3	17	17	947	4	24
$86,029	$6,495	$39,242	$40,292	$230,306	3	17	17	954	4	24
$70,805	$5,165	$34,923	$30,717	$199,541	3	19	19	975	2	24

Figure 2.1 INDOT's snow truck replacement scoring tabulation.

Department of Transportation	Managed Fleet	Data Category: Mileage/ Hours	Time in Service	Operating Cost	Repair Cost	Acquisition Cost	Physical Assessment	Ranking Measure Based on Experience	Plan to Apply LCCA in Near Future
Alabama	All equipment	x	x					x	
California	All equipment	x	x		x				
Florida	All equipment	x	x				x	x	x
Illinois	Heavy trucks	x			x		x	x	
Michigan	Heavy trucks		x				x	x	
Oregon	All equipment	x	x	x	x	x		x	
Texas	All equipment	x	x		x	x		x	
Virginia	All equipment	x	x		x			x	x
Washington State	All equipment	x	x					x	
Portion of DOTs Using Criteria (%)		89	89	11	56	22	33	89	22

Figure 2.2 Prioritization ranking measures across different DOTs.

2.1.3 Benchmarking

Based on the analysis, the following states and their respective DOTs were selected for benchmarking.

- Minnesota: Minnesota Department of Transportation (MnDOT)
- Ohio: Ohio Department of Transportation (ODOT)
- Texas: Texas Department of Transportation (TxDOT)
- South Dakota: South Dakota Department of Transportation (SDDOT)
- Pennsylvania: South Dakota Department of Transportation (PennDOT)

2.1.3.1 Ohio Department of Transportation (ODOT). Ohio has a fleet replacement budget of $50 million which is split evenly between snow and ice equipment and passenger/heavy equipment. The DOT owns several trucks and loaders and integrates to build trucks in order to fulfill the requirement. Currently the DOT builds 130 trucks annually and plans to revamp to 153 in 3 years.

Due to state equipment contracts, ODOT purchases equipment at a deep discount. ODOT purchases pieces of equipment, operates them for a few years, and trades them in a new model at a minimal cost. ODOT's goal is to move remaining fleet to set lifecycles. Districts are given $500K to fund equipment not funded in other areas. Items are scored and ranked based on age, utilization, maintenance cost and district priority. Items with higher scores are funded (ODOT, 2018).

2.1.3.2 South Dakota Department of Transportation (SD DOT). South Dakota falls under same or even severe weather condition as Indiana, and the DOT maintains a huge volume of fleet across the year. SDDOT has relied extensively on technology platforms like Iteris to support the operational side and inform about any road maintenance. Maintenance process for its fleet is observed and taken care by 25 dedicated teams for varied applications. The fleet is comprised of 428 tandem axle trucks and 21 tow-plows. SDDOT also faces similar challenges with respect to higher service level expectations and rising cost of equipment and fuel.

To tackle these challenges, SDDOT has been expanding its Maintenance Decision Support System, using weather forecast, real time feedback and predictive modeling (Xie, n.d.).

2.1.3.3 Pennsylvania Department of Transportation (PennDOT). Pennsylvania falls under similar weather pattern as does Indiana, and thus we chose to consider this state. The DOT follows rigorous process to classify different equipment and process each class differently. The DOT operates with 11 equipment managers and a representative from each district, creating a fleet optimization task force. The mix of equipment contains at least 50% tandem axle dump truck and 50% of single axle dump truck. The expected life for each type of equipment is provided in Figure 2.3 (Fleet Management Division, 2019).

2.1.3.4 Texas Department of Transportation (TxDOT). Texas does not follow the same weather pattern as Indiana, but the team still pursued a benchmarking for Texas since it has a well-defined and broadly adopted equipment replacement model. TERM (Texas Equipment Replacement Model) was developed to classify replacement model depending on age, usage, and repair costs. TERM is defined as follows.

"The logic is that each equipment item reaches a point when there are significant increases in repair costs. Replacement should occur prior to this point. Ad hoc reports were developed and are monitored annually to display historical cost information on usage and repairs to identify vehicles for replacement consideration. From his historical information, standards/benchmarks for each criterion are established for each class of equipment and modified periodically as the need arises." (TxDOT, 2008).

The model uses three criteria: equipment age, life usage, and life repair costs with respect to original purchase cost. This roughly provides a deterministic model to understand and evaluate the replacement decisions.

2.1.3.5 Minnesota Department of Transportation (MnDOT). Minnesota DOT, as of 2012, operated 11,000 fleet of varied size and application. The DOT spends over $14 million in maintenance and repair and $14 million in investment for new purchases. In terms of fleet management, a formal body within the institution oversees the fleet decisions. MnDOT uses M5, an equipment management system that tracks every aspect of fleet. MnDOT represents a centralization process in fleet management, which helps in maintaining a lower but more optimal fleet size. In addition, MnDOT observes and monitors different operational standard in terms of out-of-life-cycle fleet, maintenance requirement, etc.

Besides, MnDOT applies an LCCA model based on the following.

- Ownership costs
- Operating costs
- Depreciation
- Fuel
- License and registration
- Vendor repairs
- Insurance
- Replacement parts
- Remarketing
- Shop labor
- Operator training
- Field labor
- Value of money
- Downtime
- Storage
- Parts inventory
- Obsolescence

2.1.4 Stochastic Model (LCAA)

The LCCA model (Gransberg & O'Connor, 2015) is derived from benchmarking of MnDOT and provides insight of how different cost component may affect the replacement decision. LCCA consists of life-cycle costs, equipment overhaul decisions, replacement analysis and replacement models. There are two components to life cycle costs: ownership and operating costs. Each cost component can be broken down into the following.

- Ownership costs include the following.
  - Initial costs
  - Depreciation

	Expected Life	Industry Usage Hours
Single Axle Dump Trucks	14 Years	14,000 Hours
Tandem Axle Dump Trucks	14 Years	14,000 Hours
Tri-Axle Dump Trucks	14 Years	14,000 Hours
Loaders	17 Years	10,000 Hours
Backhoes	15 Years	10,000 Hours
Crew Cabs	8 Years	N/A

Figure 2.3 Expected life span for different equipment in Pennsylvania.

- Taxes
- Insurance
- Storage and investment costs

- Operating costs include the following.
  - Repair and maintenance, which includes fixed costs and variable costs
  - Fuel costs
  - Operator cost
  - Other consumable equipment costs

The model assumes different factors for repairing, fuel price, historical fuel cost. The formulation is derived by adding each component to reflect the total life cycle cost. The rationale is that as time goes by, the ownership cost would go down, due to depreciation, and the operating cost would go up. The theoretical optimal service life is where the EUAC (estimated uniform annual cost) is minimum, as shown in Figure 2.4. The EUAC is calculated over the entire lifespan of the equipment, and the lowest EUAC each year would be the optimal life. In this case, EUAC is equal to LCC (life cycle cost).

This analysis is extended to INDOT's existing dataset and the EUAC model is implemented for the trucks currently in INDOT's fleet in Section 4.1.

2.2 Snow Removal Optimization Strategy

The approach for this section was to understand the different strategies employed by other institutes to optimize the snow removal operation across its jurisdiction. This included (a) understanding the strategy of employing optimal snow routes, (b) understanding the strategy employed to optimally locate the facility for the operations, and (c) understand how the trucks can be distributed across the facilities based on demand. The study, Efficient routing of snow removal vehicles (Omer, 2007) presented a review of literature on link routing problems in general contexts and also in the snow removal context.

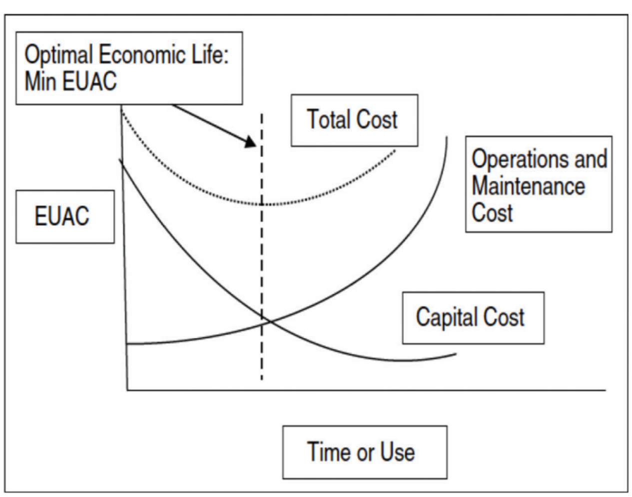


Figure 2.4 EUAC vs. time.

2.2.1 Generic Link Routing Problems

In link routing problems (LRPs) the decision-maker seeks to identify the path or cycle in a network that yields the least impedance (cost, distance, time, etc.) (Eiselt et al., 1995a, 1995b). Variations of LRP include: the scope of the tour (all links in the network vs. only a part thereof); undirected vs. directed vs. mixed; capacity constraints, and so on. Traditionally, in the literature, LRPs have been placed into two classes: the Rural Postman Problem (RPP) and the Chinese Postman Problem (CPP) which is also referred to as the Route Inspection Problem (RIP).

2.2.1.1 The Chinese postman problem (CPP). The CPP tours the network in a manner that visits every link at least once at the least total cost, in a network where the links may be directed, undirected, or both (mixed). A variant is the Capacitated CPP where each link is associated with some quantity being served (collected from or supplied to) and the routing vehicles that serve them have a finite load (weight or volume) capacity for the item being collected or supplied. As such, the vehicle may need to return to the base the depot to replenish or to deposit its stock before setting out again, if needed, to continue operations. Another variant is the Hierarchical CPP where certain links must be served before others (link prioritization).

2.2.1.2 The rural postman problem (RPP). The RPP (Orloff, 1974) is similar to the CPP; the only difference is that only a subset (not all) of the links must be served. Therefore, there are two classes of links: those that must be served and those that are not served. Those that are not served may be used for traveling to the links to be served. The distance traveled in the former class of links are referred to as "deadhead miles," which is the primary performance parameter of concern in the current INDOT study. Eiselt et al. (1995b) argued that most problems in real life applications require that only some not all links need to be served, for example, in contexts of urban waste collection, postal delivery, salt spreading during icy conditions, and snow removal. For example, in snow removal, amount of snow to be "served" at certain links could be zero: a highway jurisdiction that is responsible for serving roads of a certain classification may travel on roads belonging to other jurisdictions to reach their roads. Also, the capacitated variant of this problem is more common than the incapacitated variant, because in most real-world contexts, capacity restrictions are imposed by what the truck can carry (Eiselt et al., 1995b). In other words, in deicing operations, due to limitations on truck load capacities, a deicing truck may be unable to serve all the designated service links and may need to return to the depot or unit to restock the deicer.

2.2.2 Link Routing for Snow Removal

Snow removal is a specific application of network routing problems, and a number of researchers have carried out studies that have thrown light on this context of application. Minsk (1979), Russell and Sorenson (1979) carried out similar studies in this context. Tucker and Clohan (1979) developed a model to simulate snow removal operations on urban street networks; their program allows the decision maker to vary the input data (snowfall attributes and the resources for snow removal operations) in order to assess the impact on some measure of network performance of the operations. Liebling (1970, 1973) used network concepts to analyze snow removal and street cleaning in Zurich. Cook and Alprin (1976) developed a heuristic for routing salt-spreader vehicles, to minimize the time taken to carry out this operation. Lemieux and Campagna (1984) established an algorithm that traced Eulerian circuits on a street network considering link (street) priorities and direction. Gilbert (1989) also considered prioritization of links in street plowing operations.

In the nineties, research continued in this area of urban management. Gelinas (1992) solved the single-vehicle routing problem for snow removal using a combination of concepts including link precedence constraints, Eulerian subnetworks, and dynamic programming, and tested it using data from a jurisdiction in Montreal. Evans and Weant (1990) developed a decision support system to help city agencies to route snow control vehicles in a manner that maximized service, equipment utilization, and reduced the costs of capital and operations. Researchers at Purdue University and the Indiana Department of Transportation (INDOT) developed a system (Computer Aided System for Planning Efficient Routes or CASPER) for snow and ice control in rural areas (Haslam & Wright, 1991), Wang and Wright (1994), Wang et al. (1995), and Wright (1994). The CASPER program combines multi-objective optimization (cost minimization) and spatial variations in the weather data and seeks to limit the number of routes traveled and to reduce the deadhead miles of travel without jeopardizing service levels and established service priorities. It is estimated that using CASPER, INDOT earned savings of $2.2 million in the initial year of deployment and $4.8 million over the following 10 years. Eglese (1994) analyzed sought to maximize the cost efficiency of winter gritting by developing a heuristic algorithm for routing the gritters. The researcher considered time constraints associated with the road treatments, the multiplicity of depot locations, and the capacity limitations of the vehicles. Lotan et al. (1996) studied the combination of depot location determination and vehicle routing regarding winter gritting operations in the city of Antwerp, Belgium, assuming that all the trucks had the same capacity, and all roads have the same priority level. They partitioned the region into smaller jurisdictions and determined the optimal location of primary depots in order to minimize the deadhead miles. Then, they determined the optimal locations of secondary depots and the optimal routes of trucks within subnetworks assigned to them. An important finding from their study was that there are significant benefits of locating units or storage facilities close to borders between the jurisdictions.

Campbell and Langevin (2000) reviewed past work on link routing for roadway snow and ice control. Also, for Calvert County in Maryland, Haghani and Qiao (2001) developed a decision support system (DSS) to assist agency personnel to decide on snow emergency routes. They formulated the problem as a mathematical program that considers the time windows for the operations and determined that the solution yields significant reductions in deadhead distance and reduced truck inventory needed for the operations. It was estimated that the DSS helped reduce the total route length by 10%–38% and 15%–54% of the deadhead distance. In a subsequent follow-up study, Haghani and Qiao (2002) accounted for a wider gamut of practical constraints and sought to minimize not only the required truck inventory, but also the total deadhead miles associated with a given truck inventory. They assumed that all the roads to be served are bi-directional, and they constructed a capacitated Minimum Spanning Tree to solve the problem. They estimated that at optimal level of operations, the following savings could be earned: 15% reduction in truck inventory and 4% reduction in overall deadhead miles.

3. EXPLORATORY DATA ANALYSIS

The first part of the analysis focused on classifying the fleet according to region. Instead of classifying the regions by district, an approach was taken to classify according to subdistrict or by parking location. To derive the locations according to parking region, zip codes for each location or region was obtained. Since parking location provided more data points to be placed and segregated, the team chose this classification to divide the region according to parking location. Figure 3.1 shows the classification in which each dot represents a parking location and different colors to represent the region to which each location is classified.

3.1 Truck Data

Figure 3.2 shows the distribution of costs for each region across different fleet types. Column three provides information about the average annual maintenance cost and column four provides information about the average annual fuel cost for each fleet type. Column five provides the total operating cost that is the cumulative cost of fuel and maintenance incurred in each region for each fleet type. As can be seen, most cost is incurred for the four types of dump trucks (single axle dump trucks, multi-purpose single axle dump trucks, tandem axle dump trucks, multi-purpose tandem axle dump trucks) and do-all. However, the number of do-all type fleet is much less than dump trucks across all regions. This compelled the team to

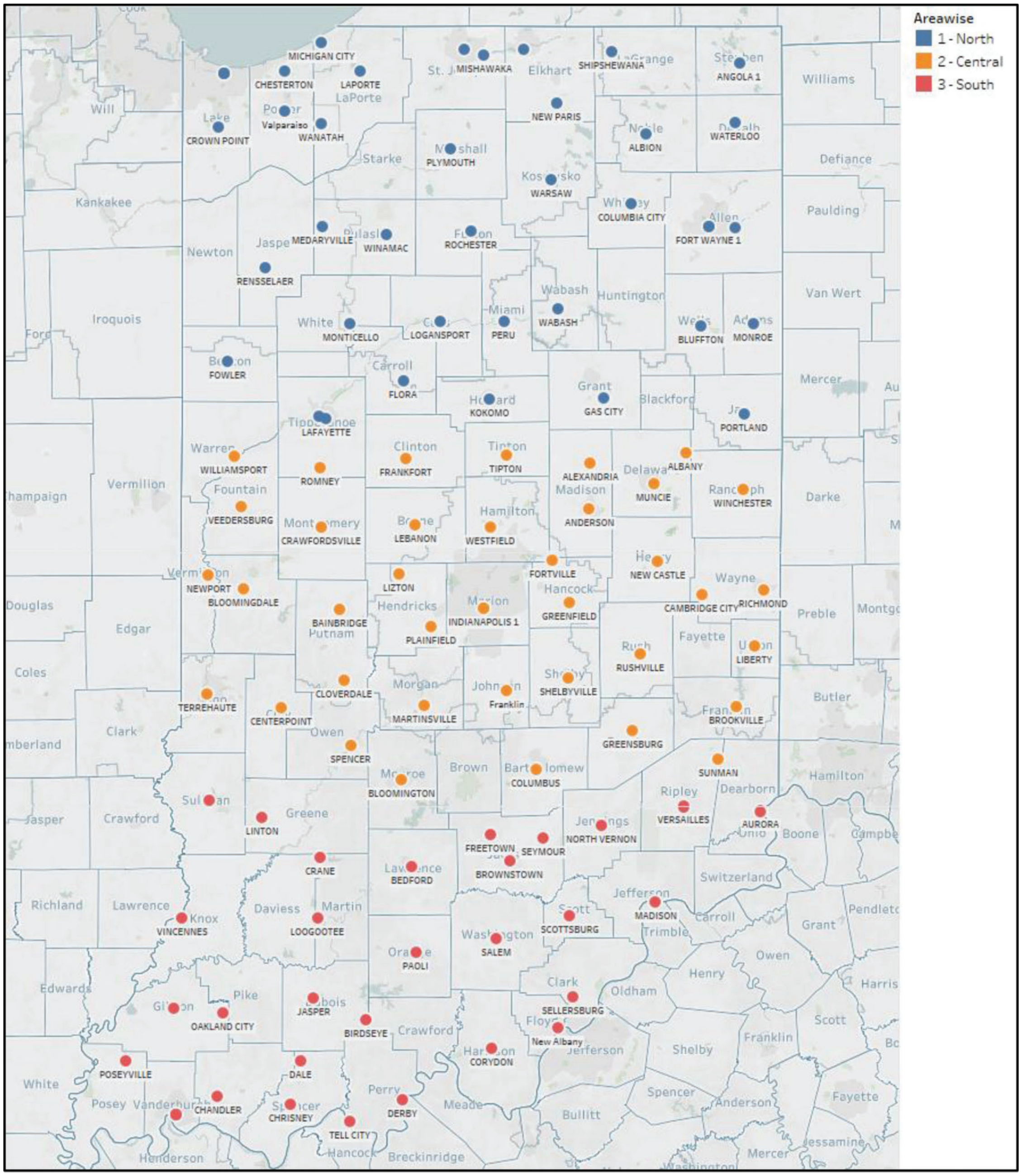


Figure 3.1 Distribution of location and classification according to parking location.

analyze dump trucks, so the team can provide useful insights and valid recommendation to INDOT.

3.1.1 Data Processing

For dump trucks in INDOT's fleet, there are few factors that the report circumscribes—mileage, age, operating cost, and make. INDOT currently operates dump trucks across all the regions, consisting of a huge array across age and mileage. The data set provided required processing and editing to ensure accurate data and remove and discrepancies. The changes made to the data set were as mentioned below.

The following revisions made on fleet data.

- HYUAN, HYUN, and HYUA all converted to HYUNDAI. This was in adherence to the model number which in all cases suggested they are Hyundai make.
- NEWHO and NWHO all converted to NEW HOLLAND. The same logic follows.
- VIKIN converted to VIKING.
- HL740XTD-3 and HL-740XTD-3 all made HL-740X TD-3.

Also, several outliers that were separated by huge margin from the mean were not considered in the analysis. Some examples of outliers are unit number

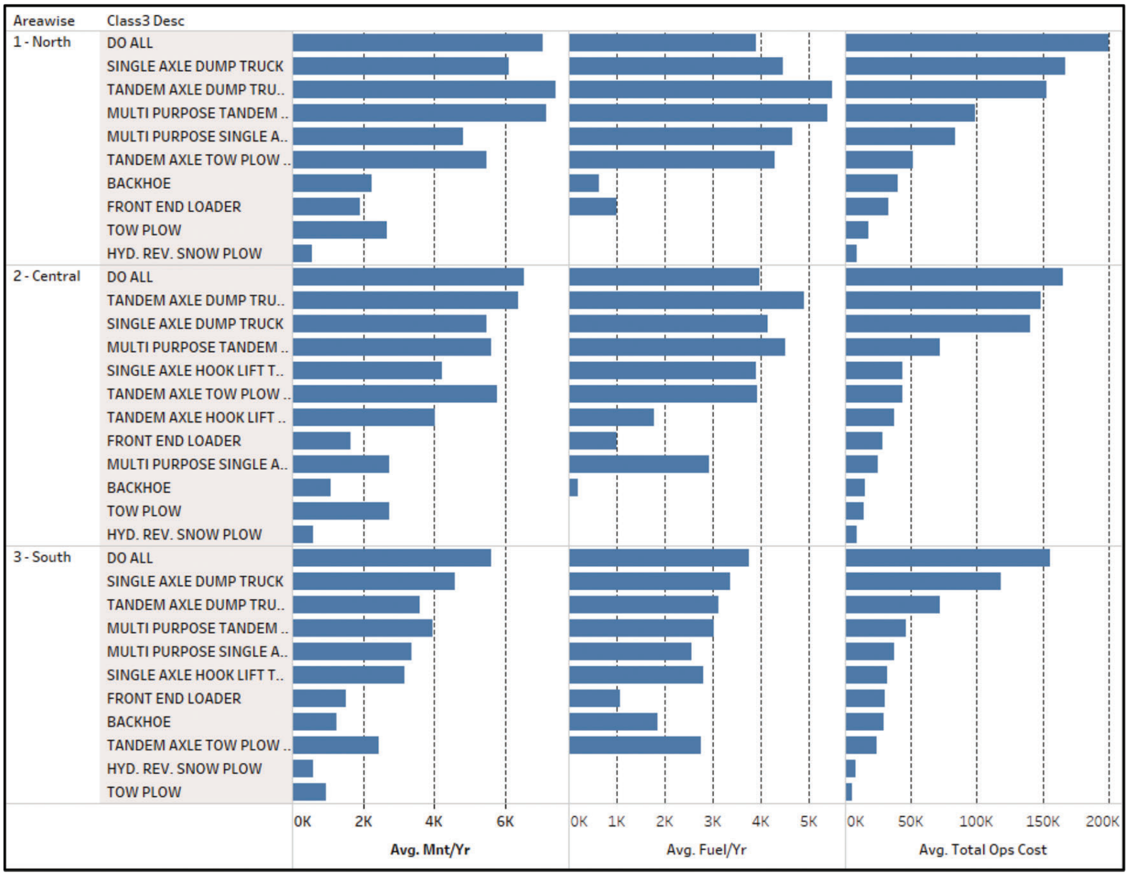


Figure 3.2 Cost components for each region by class.

61058 (maintenance cost of $60,000/year) and unit number 63364 (maintenance cost over $4,000,000 per year). Data has also been converted to reflect the true nature of mileage according to the following formula.

Mileage is calculated as follows.

IF [Class3 Desc] =‘BACKHOE’
OR [Class3 Desc] =‘FRONT END LOADER’
OR [Class3 Desc] =‘HYD. REV. SNOW PLOW’
OR [Class3 Desc] =‘TOW PLOW’
THEN 0
ELSE [Meter]
END

Hours is calculated as follows.

IF [Class3 Desc] =‘BACKHOE’
OR [Class3 Desc] =‘FRONT END LOADER’
OR [Class3 Desc] =‘HYD. REV. SNOW PLOW’
OR [Class3 Desc] =‘TOW PLOW’
THEN [Meter]
ELSE [Meter2]
END

Since INDOT has a large fleet of varying age and mileage, the team chose to divide the data set with a threshold for either age or mileage. The focus of our analysis was on total operating cost, which included both the fuel cost and maintenance cost. The next sections would explore how each factor affects the total operating cost. In absence of sufficient data, all dump trucks are considered in the same category for the analysis.

3.1.2 Total Operating Cost

The total operational cost is considered the focus for our analysis, and thus is defined as summation of fuel and maintenance cost. The major challenge to this analysis is that even though the data are to be interpreted on a year-to-year basis, the data set has only cumulative values. To adjust this, we considered the relation between mileage and operational cost.

Figure 3.3 shows the change in total operational cost across three different regions—northern, central, and southern. Each dot in the figure represents a vehicle. The graph represents how vehicles at different mileage incurs different operational cost. Foregoing the effect of make and types of dump truck, we see that the operational cost in the northern region increases significantly for vehicles that have reached 60,000 miles. The same increase, albeit much smaller, is also found to be consistent across other two regions—central and south. The graphical representation allowed us to classify further the fleet into two groups—vehicles above 60,000 miles and below 60,000 miles.

The above figure allows us to explore in depth the two different categories: 60k+ miles and 60k- miles. However, the analysis of same figure without any categorization provides the following statistics. Figure 3.4 shows the trend lines for each region across all vehicle categories. All the regression models in each region are statistically significant. The statistics of regression model thus obtained are presented in Table 3.1.

The above data shows that change in operational cost for each change in mileage is highest in the northern area, defined by the mileage coefficient. This is quite intuitive as we understand the harsh weather in the northern region might result in higher cost for each increase in mileage. The question at this point is whether similar trends can be observed if we segregate the fleet according to mileage. Figure 3.5 and Table 3.2 show the same trend line observed for vehicles with less than 60,000 mileage.

From Table 3.2, we see that the results for the northern region in case of vehicles with less than 60,000 mileage are different from what found in Table 3.3. The regression statistics suggests that the northern region has less slope (increase in operational cost for each increase in mileage) than the central and southern. This stands in stark contrast. However, a regression model generated for vehicles with more than 60,000 mileage

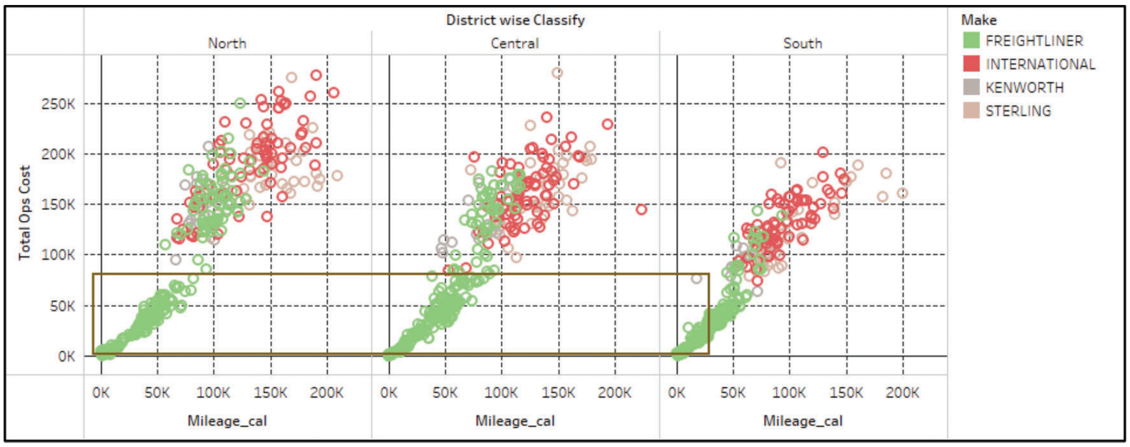


Figure 3.3 Total operational cost vs. mileage.

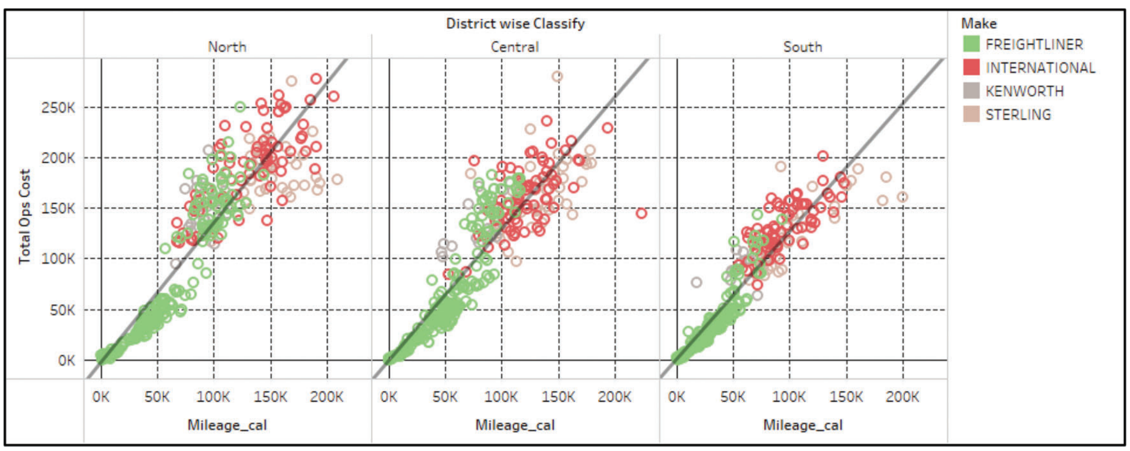


Figure 3.4 Trend lines for total operational cost across all regions and types of dump trucks.

TABLE 3.1
Regression model data for total operational cost vs. mileage by district

Statistical Value	North	Central	South
P-value	<0.001	<0.001	<0.001
R^2 value	0.952	0.947	0.953
Mileage Coeff	1.353	1.289	1.2626
Mileage P-value	<0.001	<0.001	<0.001

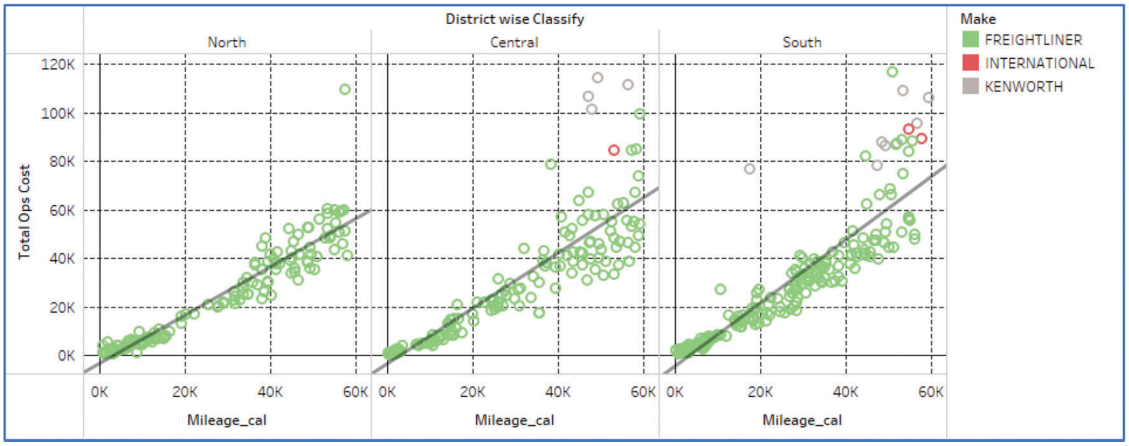


Figure 3.5 Trendlines for total operating cost of vehicles with <60k mileage.

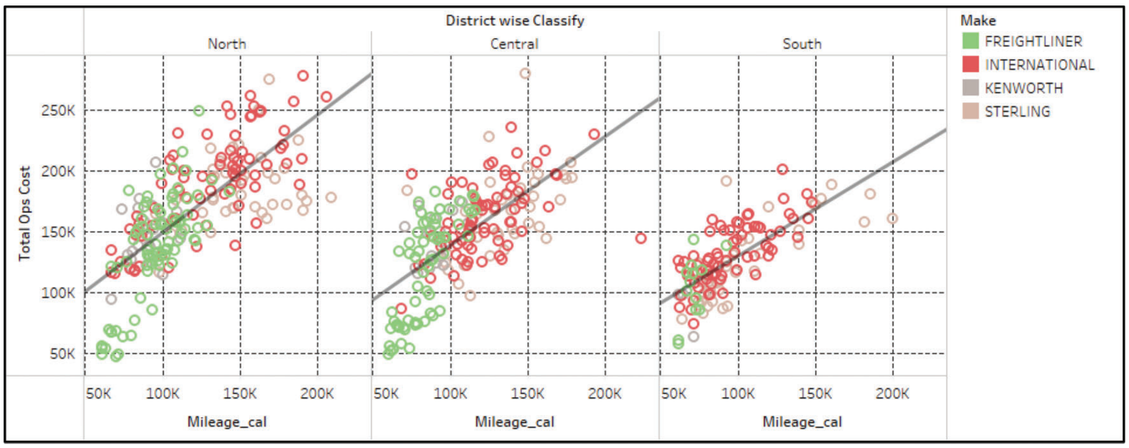


Figure 3.6 Trend lines for vehicles across three regions of mileage > 60k.

TABLE 3.2
Regression model data for total operational cost vs. mileage by district (mileage < 60k)

Statistical Value	North	Central	South
P-value	<0.001	<0.001	<0.001
R^2 value	0.939	0.878	0.9021
Mileage Coeff	0.912	1.057	1.183
Mileage P-value	<0.001	<0.001	<0.001

TABLE 3.3
Regression model data for total operational cost vs. mileage by district (mileage > 60k)

Statistical Value	North	Central	South
P-value	<0.001	<0.001	<0.001
R^2 value	0.537	0.457	0.542
Intercept Coeff	52,043	48,817	52,326
Intercept P-value	<0.001	<0.001	<0.001
Mileage Coeff	0.964	0.892	0.77
Mileage P-value	<0.001	<0.001	<0.001

suggests higher operating cost in the northern region for each increase in mileage. This result is presented in Figure 3.6 and Table 3.3.

Table 3.3 shows strong alignment with the trend we obtained from overall analysis of fleet. One factor we considered consistent for our analysis so far was age.

TABLE 3.4
Regression model data for mileage vs. age by district (mileage < 60k)

Statistical Value	North	Central	South
P-value	<0.001	<0.001	<0.001
R^2 value	0.957	0.906	0.93
Age Coeff	9,850	8,123	6,071
Age P-value	<0.001	<0.001	<0.001

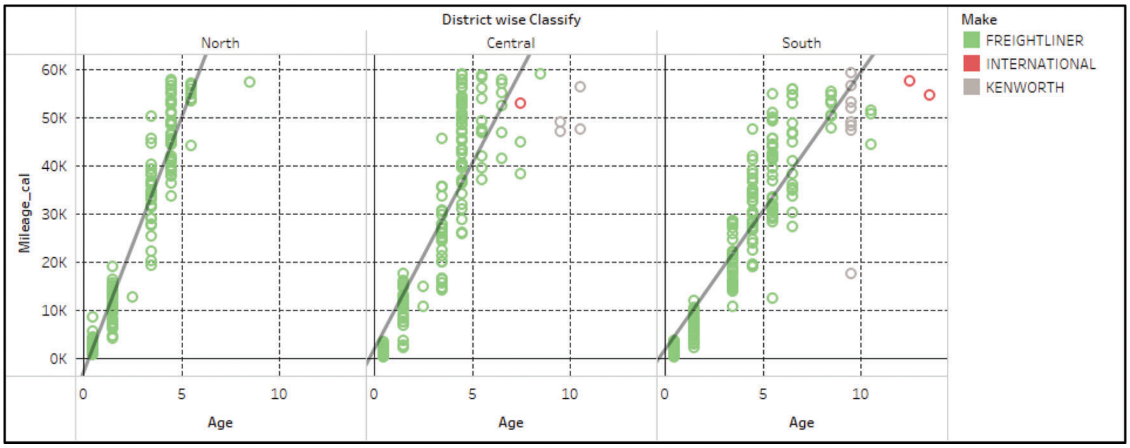


Figure 3.7 Vehicle trend lines for mileage vs. age in different regions (<60k mileage).

To understand how this change can be explained, the next section elaborates the different relation of total operational cost with respect to age and the relation between age and mileage for different regions across the two mileage categories.

3.1.3 Mileage and Age

Figure 3.7 and Table 3.4 shows the trend line for each region's dump trucks of age with respect to mileage. As can be seen, the vehicles in the northern region "ages" less than those in the central and southern regions. The increasing slope means that for each increasing age a vehicle in a particular region is running more than other regions. In the northern region, for each increase in age the mileage increases the most among all the regions and thus is run more. For any given mileage below 60,000 in northern region, a vehicle has less age and thus provides better performance and less operational cost. This helps resolve the paradox we had in Section 3.1.2. The results clearly point out two things—vehicle in a particular age runs the most in the northern, followed by the central and southern, and the operational cost depends both on mileage and age.

The above analysis shows that not just mileage or age, but both together play a role in understanding whether a vehicle is performing efficiently. Since the northern region has so much affinity towards aging of fleet so as to reverse the nature of trend with respect to mileage, the region requires more attention in terms of the two parameters.

Figure 3.8 and Table 3.5 show similar analysis for vehicle with more than 60,000 mileage. The results emphasize general intuition that with age the miles driven increases for every region. However, the mileage increases in the northern region more rapidly than any other region for vehicles with more than 60,000 mileage. The statistical data for this regression model are presented in Table 3.5. This part of our analysis complements our finding in the previous section in that increase in age results in increase in mileage, consequently increasing the total operating cost.

3.1.4 Total Operation Cost and Age

Since it has been proven that the total operational cost across different regions varies by mileage and age, this section explores the relation, if any, between total operation cost and age. The goal of this analysis is to see if the counterintuitive finding in the northern region can be emphasized with another parameter.

Figure 3.9 and Table 3.6 present the analysis for total operation cost and age across all regions for vehicles with mileage less than 60,000. As can be seen from a mileage of 60,000, the northern region has a much younger fleet on average than the central or southern regions. However, the statistical data suggest that with age the slope is steeper in the north followed by the central and south. In the northern region the operating cost increases more steeply with age, and thus age could be a better metric to choose for operating cost in the northern region when mileage is less than 60,000. This seems to be a

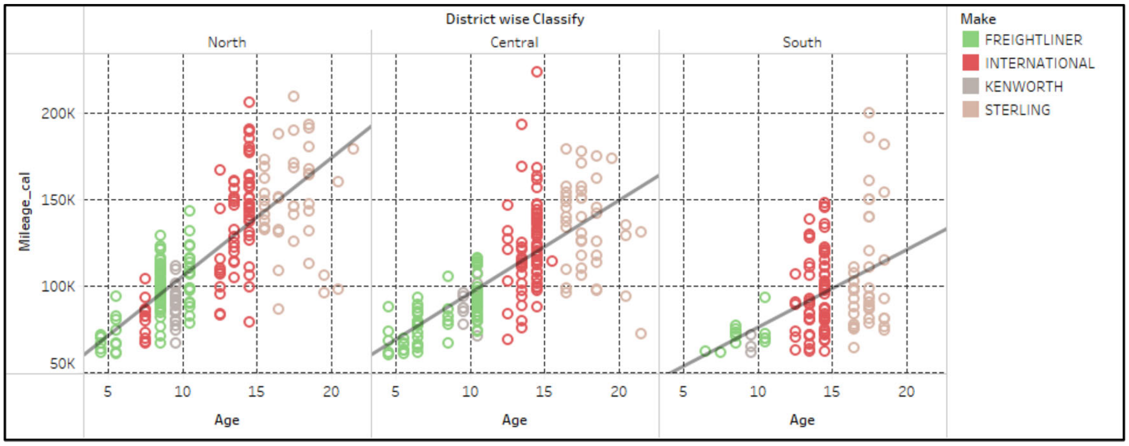


Figure 3.8 Trend lines for mileage and age (mileage > 60k).

TABLE 3.5
Regression model data for mileage vs. age by district (mileage > 60k)

Statistical Value	North	Central	South
P-value	<0.001	<0.001	<0.001
R^2 value	0.537	0.457	0.542
Intercept Coeff	37,653.1	42,614.4	31,392
Intercept P-value	<0.001	<0.001	0.0135
Age Coeff	6,835.17	5,356.85	4,485
Age P-value	<0.001	<0.001	<0.001

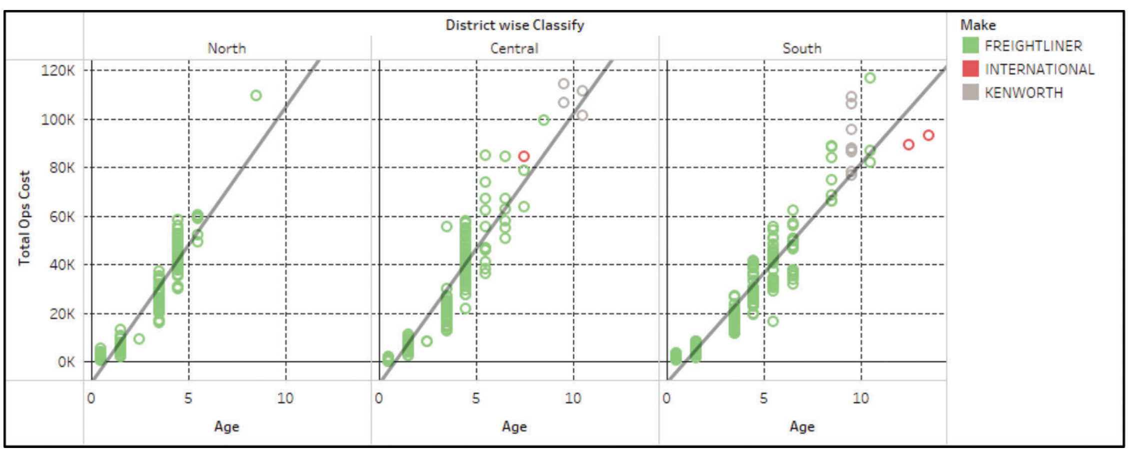


Figure 3.9 Trend line for vehicle operational cost and age (mileage < 60k).

TABLE 3.6
Regression model data for total operational cost vs. age by district (mileage < 60k)

Statistical Value	North	Central	South
P-value	<0.001	<0.001	<0.001
R^2 value	0.934	0.923	0.889
Age Coeff	9,120	9,209	7,558
Age P-value	<0.001	<0.001	<0.001

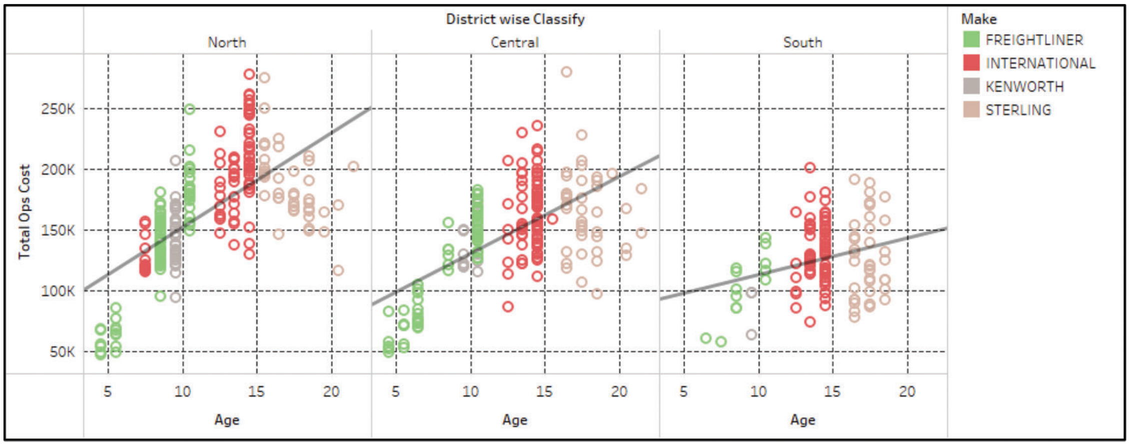


Figure 3.10 Trend line for vehicle operational cost and age (mileage > 60k).

TABLE 3.7
Regression model data for total operational cost vs. age by district (mileage > 60k)

Statistical Value	North	Central	South
P-value	<0.001	<0.001	<0.001
R^2 value	0.894	0.883	0.889
Intercept Coeff	-6,593.9	-7,087	-7,034
Intercept P-value	<0.001	<0.001	0.0135
Age Coeff	11,362.4	11,138	9,047.4
Age P-value	<0.001	<0.001	<0.001

more justified approach to understand how aging and wear and tear can reduce performance of a fleet.

Figure 3.10 and Table 3.7 shows similar analysis for vehicles with mileage greater than 60,000. The result suggests that operational cost increases fastest with respect to age for the northern region followed by the central and southern regions. As a vehicle ages over 60,000 mileage, it causes higher incremental change in operational cost in the northern region than it does in the central and southern regions.

In this section we tried to decide and define the different parameters that most affect the performance of a fleet and aid in replacement decisions. We see that the vehicles below 60,000 mileage are more influenced by age in the northern region than in other regions, and thus it might be advisable to pursue a replacement strategy for northern region once a vehicle crosses 60,000 mileage. Also, we see that incremental change in operational cost is highest for the northern region followed by the central and southern regions when the mileage category is more than 60,000. The shift or jump in operational cost is not as significant in other regions as it is in the northern. One important assumption we made in our analysis so far is that the make of a vehicle plays consistent role across any category or region. The following section will consider how make might or might not affect the operational cost. This is important because most of the vehicles below 60,000 mileage are of Freightliner make, which might stand up as a reason for the lower cost in this segment.

3.1.5 Make

In the data set we received, there are four different makes of dump trucks—Freightliner, Kenworth, International, and Sterling. Freightliner has majority of the new fleet, fleet with less than 60,000 mileage. Since most of the fleet below 60,000 is Freightliner make, it is not possible to analyze the effect of make on this category. However, for fleet above 60,000, the make is more diversified and thus provides an opportunity to understand whether make has any effect on the performance of fleet. The objective of the analysis is to see whether the Freightliner make, which through our analysis of fleet below 60,000 mileage shows lower operational cost, is more efficient than other makes. To understand this, an analysis is conducted on make for different fleet above 60,000.

Figure 3.11 shows the segregation of data for fleet above 60,000 defined by different regions. It shows that there are not always sufficient data to analyze each region and make in one regression. We conducted a holistic analysis for all regions across different make, wherever possible.

Figure 3.12 and Table 3.8 shows the regression model and statistics for the northern region across different makes. For Kenworth make, there are not sufficient data

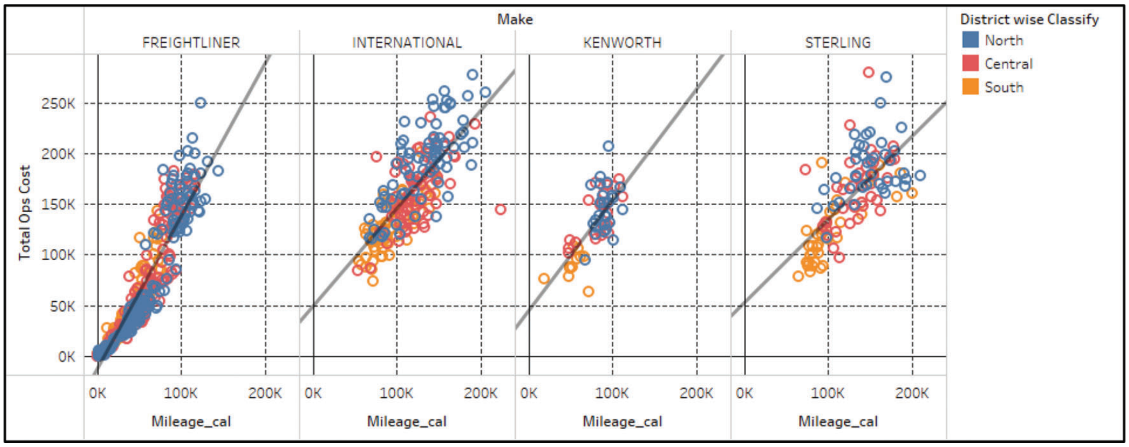


Figure 3.11 Total operational cost vs. mileage by make.

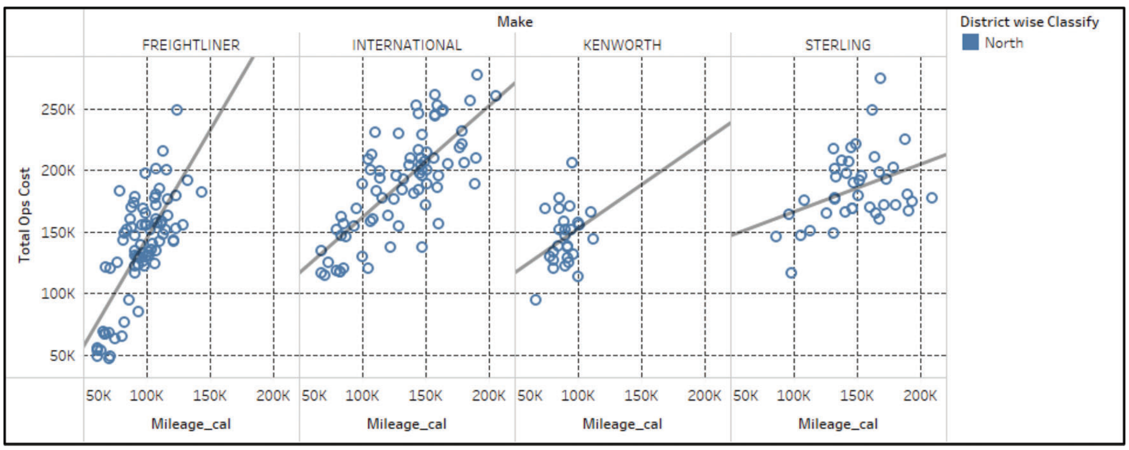


Figure 3.12 Relation between vehicle cost and mileage by make in northern region.

TABLE 3.8
Regression model data for total operational cost vs. mileage by make (northern region)

Statistical Value	Freightliner	International	Sterling
P-value	<0.001	<0.001	0.00449
Intercept Coeff	-28,920	71,381	130,598
Intercept P-value	0.0153	<0.001	<0.001
Mileage Coeff	1.74	0.90	0.36
Mileage P-value	<0.001	<0.001	0.0135

to conduct a regression model, or rather, the data are not sufficiently sparse. We see that Freightliner model has a higher incremental change in operational cost than its counterparts. Also, Sterling has the least incremental change, which might be because Sterling models are all old and close to the end of the life cycle.

The above regression shows that Freightliner has a negative intercept in the northern region, but the slope is higher than any other. This might lead to an eventual higher operating cost for this make than with others.

Figure 3.13 and Table 3.9 represent the regression for each make in central region. Kenworth is not considered in regression model as there are not much data to analyze for this make.

The statistics show similar results to those we obtained for the northern region. The models are significant. However, the incremental change in operational cost is highest for Freightliner, which shows that it tends to incur higher cost eventually. We also see all the slopes are less than those in similar category for the northern region.

Figure 3.14 and Table 3.10 represent the regression for each make in the southern region. Kenworth is not considered in regression model as there are not much data to analyze for this make.

The regression model for Freightliner has an intercept which is not significant. This is mostly because most of the data points are within a narrow range.

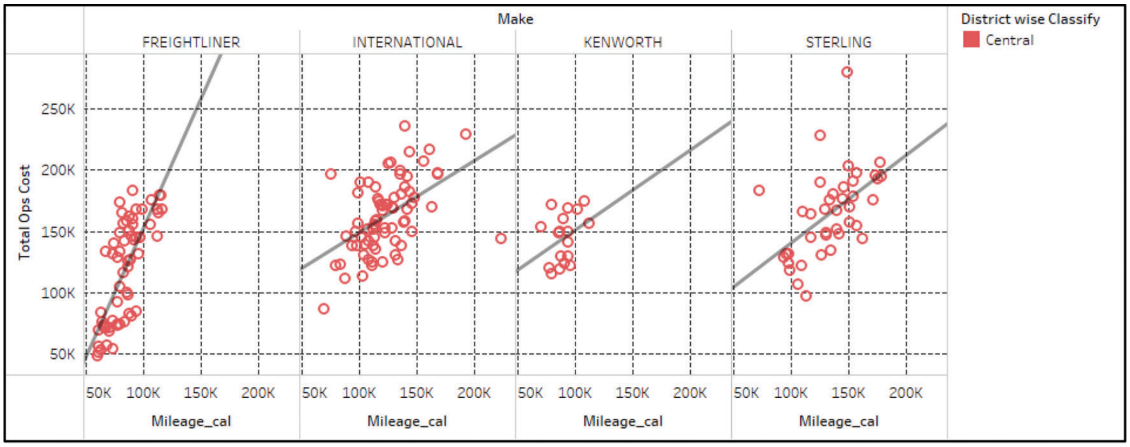


Figure 3.13 Relation between vehicle cost and mileage by make in central region.

TABLE 3.9
Regression model data for total operational cost vs. mileage by make (central region)

Statistical Value	Freightliner	International	Sterling
P-value	<0.001	<0.001	0.00449
Intercept Coeff	-32,674	84,040	68,810
Intercept P-value	0.0033	<0.001	0.009
Mileage Coeff	1.81	0.63	0.71
Mileage P-value	0.0004	<0.001	<0.001

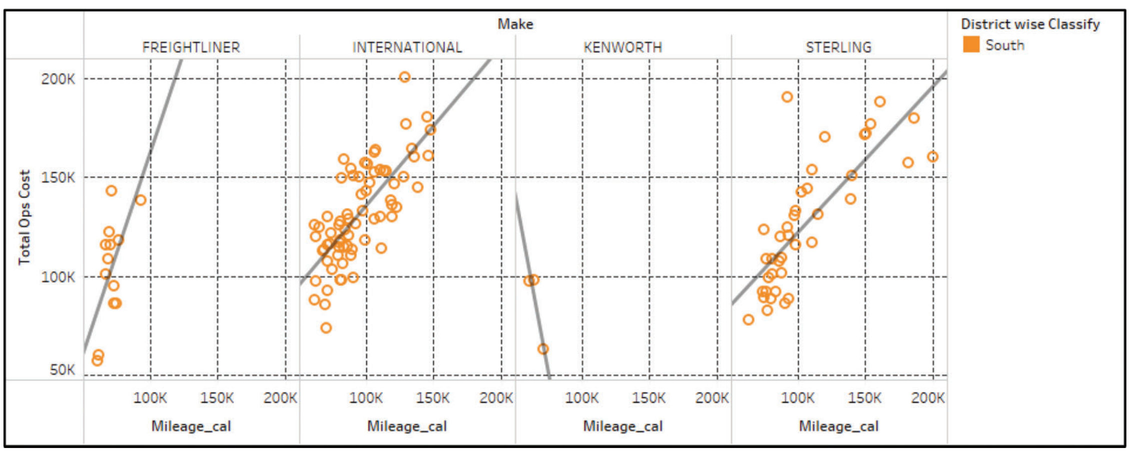


Figure 3.14 Relation between vehicle cost and mileage by make in southern region.

TABLE 3.10
Regression model data for total operational cost vs. mileage by make (southern region)

Statistical Value	Freightliner	International	Sterling
P-value	0.0010	<0.001	<0.001
Intercept Coeff	3,413.55	52,599	61,799
Intercept P-value	0.886	<0.001	<0.001
Mileage Coeff	1.43	0.825	0.63
Mileage P-value	0.001	<0.001	<0.001

However, for the other two makes, the same notion holds that incremental change in cost is higher for International than Sterling.

With the overall analysis, it can be suggested that Freightliner does provide low cost in the short to medium run, but the high slope in the regression model shows that Freightliner will result in high operation cost in the long run. also, sterling has a lower incremental change in cost for the north and south but higher for the central. In order to fully understand the nature of change in incremental cost for each make, an analysis was done for each make above 60,000 mileage. Figure 3.15 and Table 3.11 show the regression model and statistics for each make. Also, Figure 3.16 shows the result of the regression model plotted for a range of mileage, providing an estimate of the eventual change in operational cost with gradual increase in mileage.

The above analysis shows that international, averaged across all regions, incurs the highest operational cost, followed by Sterling. Freightliner has a higher slope which results it to incur more operational cost eventually. Given that Freightliner has a very low intercept, it is advisable to use Freightliner for conditions in which a vehicle can be retired before it crosses 88–90 thousand miles, beyond which the operational cost is lower for other makes.

So far, the analysis provides a basis for understanding how regions, mileage, and age can play a factor in determining the different replacement or retirement policies to be embraced by INDOT. It also provides an understanding of how make can be chosen to ensure lower operational cost for different regions. The analysis however has some assumptions. It assumed that the trends observed on make with mileage above 60,000 are to be held true for mileage below 60,000. For example, the steep slope of Freightliner above 60,000 will also be true for Freightliner below 60,000.

3.2 Snow Route Data

INDOT has an aggregate of 929 snow routes in its network to clear the snow during winter season. These snow routes are associated with the 101 unit locations across the state. INDOT shared, from its database, a list of all the snow routes and the corresponding segments associated with each unit location. This dataset also contained information describing the snow route along the highway routes, the total miles traveled by the truck on a single snow route (travel miles), the miles traveled by a truck to remove snow from the roads (snow lane miles), and the associated deadhead miles on the snow route. The snow lane miles are considered to be the productive miles driven by the truck, whereas the deadhead miles are the non-productive miles traveled by the truck where the truck is traversing from point A to point B without clearing snow on the road or where the snow has been already cleared. The team performed exploratory analysis on this data to understand the data at the region level and at the district level before performing detailed analysis at the unit level.

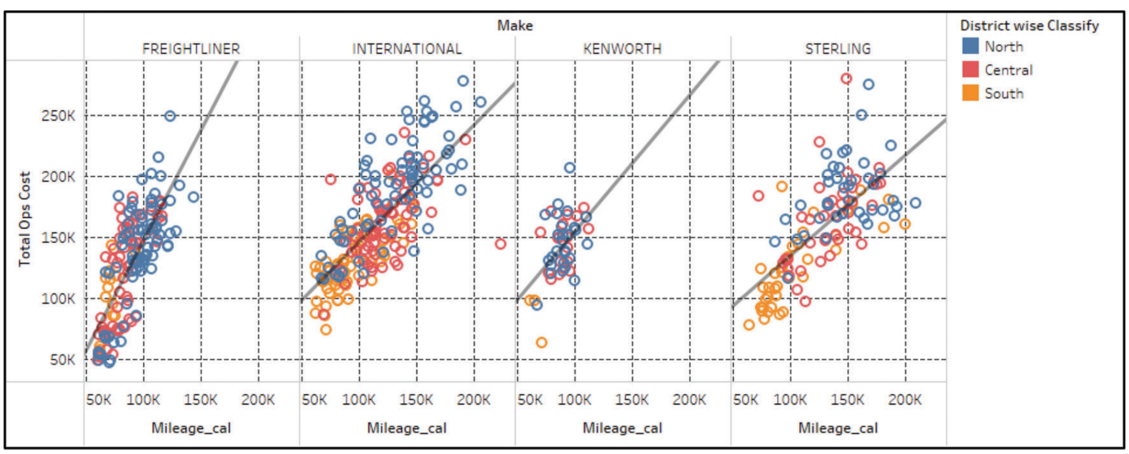


Figure 3.15 Regression lines for each make (mileage > 60k).

TABLE 3.11
Regression model data for total operational cost vs. mileage by make

Statistical Value	Freightliner	International	Sterling
P-value	0.0010	<0.001	<0.001
Intercept Coeff	3,413.55	52,599	61,799
Intercept P-value	0.886	<0.001	<0.001
Mileage Coeff	1.43	0.825	0.63
Mileage P-value	0.001	<0.001	<0.001

3.2.1 Region-Wise Analysis

This section provides details about the snow routes at the regional level. Table 3.12 provides the count of units and snow routes present in each region. The central region, comprising of Marion County, consists of maximum number of units and snow routes, followed by the northern region and subsequently the southern region. Figure 3.17 shows the information in Table 3.12 in a graphical representation. Table 3.13 and

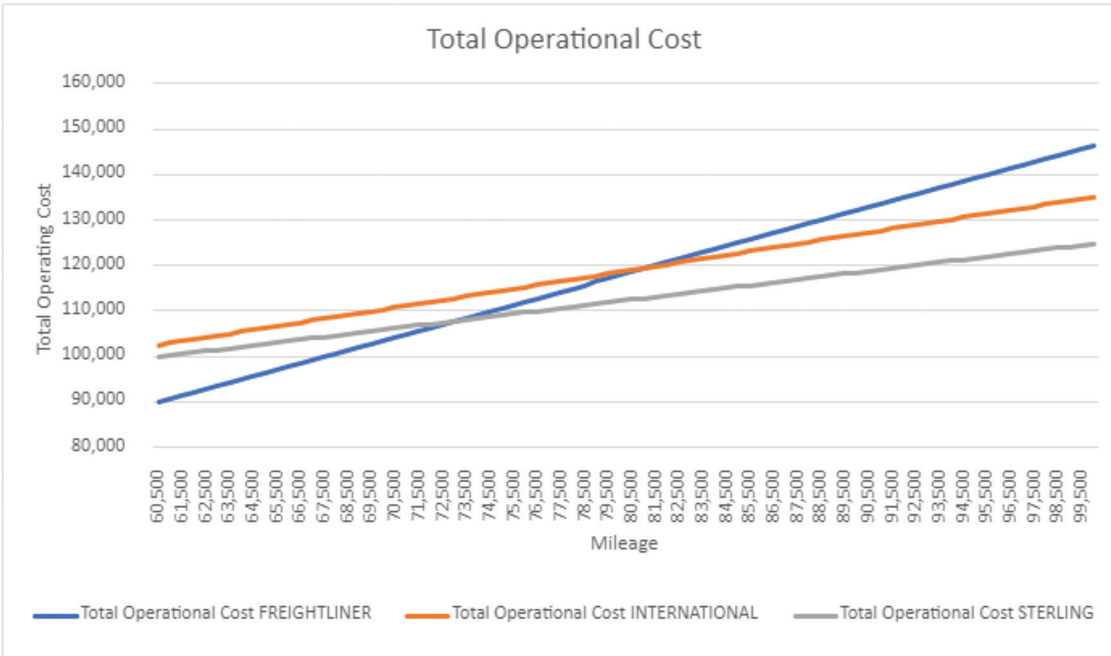


Figure 3.16 Extrapolation of regression equation for each make.

TABLE 3.12
Region-wise count of snow routes and units

Region	Count of Units	Count of Snow Routes
Northern	31	315
Central	37	321
Southern	33	293
Grand Total	*101*	*929*

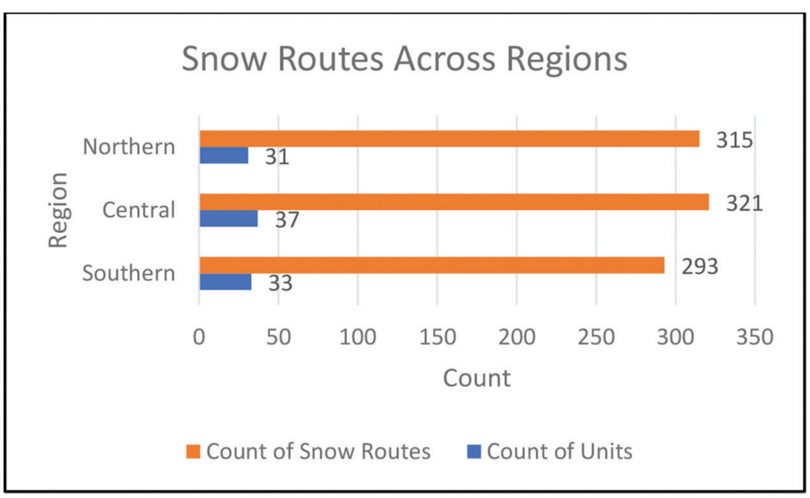


Figure 3.17 District-wise count of snow routes vs. units.

TABLE 3.13
Region-wise travel miles, snow lane miles, and deadhead miles

Region	Sum of Travel Miles	Sum of Snow Lane Miles	Sum of Deadhead Miles	% of Deadhead Miles
Northern	12,522	10,128	2,394	19
Central	13,351	10,327	3,024	23
Southern	11,271	9,900	1,371	12
Grand Total	*37,144*	*30,355*	*6,789*	—

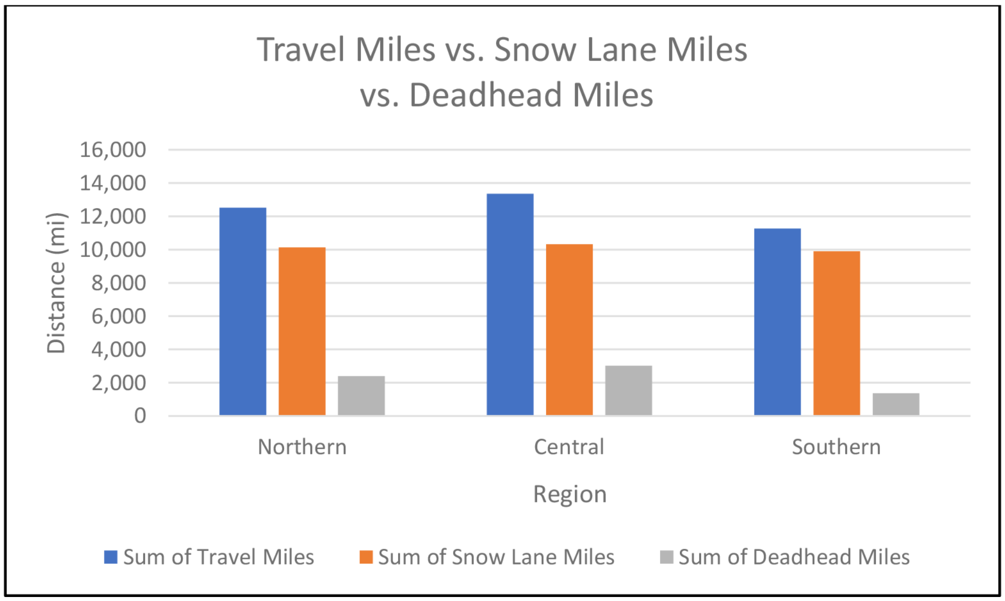


Figure 3.18 Region-wise travel miles, snow lane miles, and deadhead miles.

Figure 3.18 represent the total travel miles, total snow lane miles, and total deadhead miles across the three regions. The total travel miles is the aggregate of total snow lane miles and total deadhead miles. Travel miles are the total miles traveled by the truck. Snow lane miles are the miles traveled by the truck to clear the snow. Deadhead miles are the miles traveled by trucks where the truck does not clear the snow but travels only to reach the starting point of the next snow route segment. The central region has the maximum amount of travel miles, snow lane miles, and deadhead miles.

3.2.2 District-Wise Analysis

This section provides data about the snow routes at the district level. As mentioned in Section 1, there are six districts in Indiana. Table 3.14 and Figure 3.19 provides the count of units and snow routes at the district level. Greenfield District in the central region has the maximum number of units. Greenfield District in the central region and LaPorte District in the northern region, each have maximum number of snow routes. Table 3.15 and Figure 3.20 represent the total travel miles, total snow lane miles, and total deadhead miles across the districts in the state. Greenfield District in the central region, has the maximum number of travel miles, snow lane miles, and the deadhead miles.

TABLE 3.14
District-wise count of snow routes and units

District	Count of Units	Count of Snow Routes
Crawfordsville District	17	145
Fort Wayne District	14	139
Greenfield District	20	176
LaPorte District	17	176
Seymour District	16	150
Vincennes District	17	143
Grand Total	*101*	*929*

The team performed exploratory data analysis on the truck data and the snow route data combined. The major attribute considered was % of deadhead miles (% of DH). We calculated % of deadhead miles as the ratio of deadhead miles is to travel miles (sum of snow lane miles and deadhead miles). We explored whether % of deadhead miles depended on any parameters. We generated correlation matrix at region and district level as shown in Figure 3.21 and Figure 3.22, respectively.

The exploratory analysis for % of deadhead miles did not fetch very insightful results. There was very little

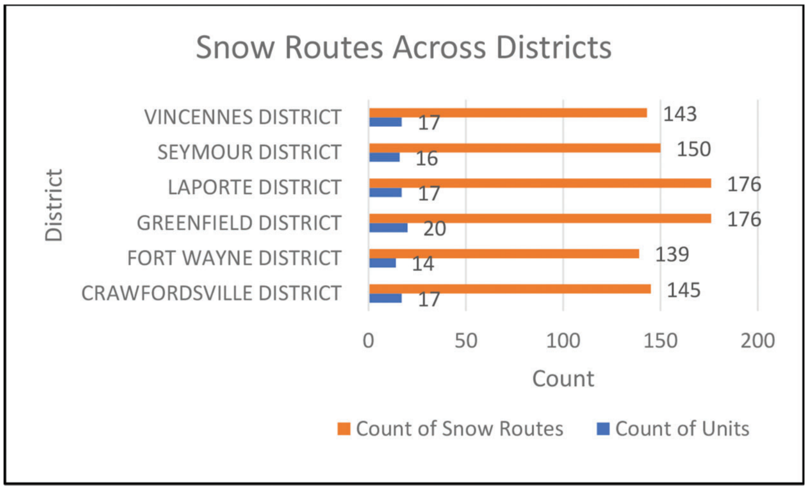


Figure 3.19 District-wise count of snow routes vs. units.

TABLE 3.15
District-wise travel miles, snow lane miles, and deadhead miles

District	Sum of Travel Miles	Sum of Snow Lane Miles	Sum of Deadhead Miles	% of Deadhead Miles
Crawfordsville District	6,252	4,910	1,342	2
Fort Wayne District	6,407	4,982	1,425	22
Greenfield District	7,099	5,417	1,682	24
LaPorte District	6,115	5,146	969	16
Seymour District	4,937	4,933	4	0
Vincennes District	6,334	4,967	1,367	22
Grand Total	*37,146*	*30,357*	*6,789*	

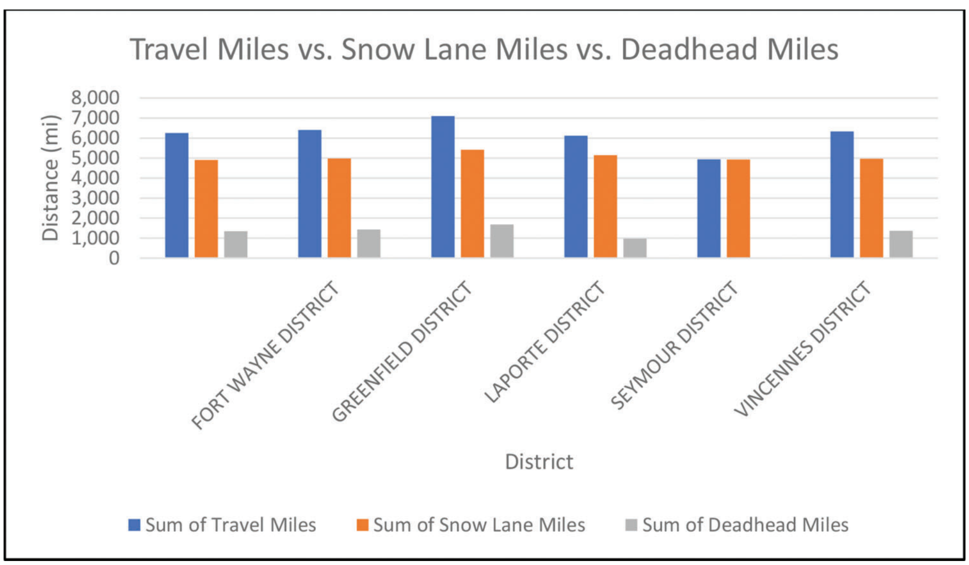


Figure 3.20 District-wise travel miles, snow lane miles, and deadhead miles.

correlation between % of deadhead miles and other parameters. Even though certain region or district showed higher correlation, the results were not consistent. Consistent positive correlation was observed between % of deadhead miles and sum of deadhead miles and sum of travel miles which was expected as % of deadhead miles is derived from those two parameters. Hence, no conclusions could be made about these positive correlations and from overall correlation analysis between these parameters.

	North	Central	South
	% of DH	*% of DH*	*% of DH*
% of DH	1	1	1
Total no. of trucks	0.080420976	0.338022538	-0.197443634
Sum of Travel Miles	0.599571542	0.430928269	0.38193453
Average of Age	0.020274577	-0.061196496	0.364606515
Sum of Deadhead miles	0.886440796	0.815639126	0.967922784
Average of Mile/Yr	-0.18184207	-0.161272795	-0.503740954
Average of Miles/Gallon	0.148204543	0.256659193	0.430862796
Average of Fuel/Yr	-0.269619585	-0.250363599	-0.540752978
Average of Fuel Do	-0.029780115	-0.160669809	-0.090692728
Average of Hrs/Yr	-0.421498656	-0.312660285	-0.649586088
Average of Maint Do	0.025732884	-0.087829032	0.16518405
Average of PURCHASE DO	-0.03092399	-0.128844993	-0.174116691
Average of Mnt/Yr	-0.174145244	-0.088151727	-0.345497837
Average of Total Ops Cost	0.004757811	-0.091450636	0.061280456
Count of Snow Route	0.013350337	0.411766494	-0.168778353
Sum of Snow Lane Miles	0.322726773	0.1474249	-0.14698169

Figure 3.21 Correlation analysis of % of deadhead miles at region level.

	Fort Wayne	La Porte	Crawfordsville	Greenfield	Seymour	Vincennes
	% of DH	*% of DH*	*% of DH*	*% of DH*	*% of DH*	*% of DH*
% of DH	1	1	1	1	1	1
Total no. of trucks	0.44679618	0.041788039	-0.116779411	0.517235121	0.343264365	-0.162443909
Sum of Travel Miles	0.34096613	0.673113294	0.046034007	0.548055363	0.338401041	0.365997442
Average of Age	0.174095474	0.196251154	0.141251241	-0.171065085	-0.192942341	-0.052309394
Sum of Deadhead miles	0.724967534	0.926416667	0.744002547	0.848921728	1	0.913311823
Average of Mile/Yr	0.107467391	0.039168327	-0.15959613	-0.194969667	-0.165303037	0.038691997
Average of Miles/Gallon	-0.337075149	0.309042937	-0.016643607	0.329396612	-0.373865147	0.418357603
Average of Fuel/Yr	0.341349749	-0.098921988	-0.08378882	-0.407958119	-0.070968188	-0.17517304
Average of Fuel Do	0.358922005	0.067040898	0.107826611	-0.324968377	0.192809917	-0.293378435
Average of Hrs/Yr	0.09085051	-0.34820914	0.025190338	-0.644786413	-0.329114826	-0.570174073
Average of Maint Do	0.336995814	0.288777279	0.311179065	-0.104159149	0.221717295	-0.310523131
Average of PURCHASE DO	-0.225226229	0.042371753	0.014383304	-0.226695533	-0.419889458	0.219051401
Average of Mnt/Yr	0.241715691	0.055789941	0.334347165	-0.105288238	-0.184825831	-0.336462138
Average of Total Ops Cost	0.37995848	0.221174688	0.242852947	-0.109521472	0.214029736	-0.307043685
Count of Snow Route	0.476754553	-0.114431929	-0.161654194	0.60133224	0.202471668	0.027921665
Sum of Snow Lane Miles	0.144680766	0.318672931	-0.282692409	0.299915293	0.329831151	-0.173263722

Figure 3.22 Correlation analysis of % of deadhead miles at district level.

We then calculated miles/snow route by taking the ratio of travel miles is to count of snow route. We calculated the correlation between these two metrics and found that correlation between % of deadhead miles and miles/snow route is 0.32. Figure 3.23 shows the scatter plot of % of deadhead miles vs miles/snow route. Here, the data was considered at the unit level and only non-zero % of deadhead miles values were considered.

From this analysis, we observed slight positive correlation. This shows that the higher the miles per snow route, higher the % of deadhead miles. Thus, it was inferred that the truck travel length had an effect on deadhead miles. In other words, when a truck has a longer route, higher deadhead miles are recorded. The truck can be believed to travel longer to utilize the salt for snow removal operation and incur higher deadhead miles.

3.3 Automated Vehicle Location (AVL) System Data

Last winter season, 2020, INDOT installed AVL system sensors on the trucks in the fleet. These sensors are used to record data while the truck is performing operations, for instance, snow removal operations. These sensors have recorded data for the following various attributes.

- Coordinates (latitude and longitude)
- Solid rate
- Actual solid rate
- Direct liquid rate
- Prewet rate
- Liquid rate
- Granular loop mode
- Direct loop mode
- Prewet loop mode

This data has been recorded for every truck that has been used for snow removal operation during the winter season. The data is distinguished by unique vehicle ID, vehicle's commission number (vehicle name), and timestamp.

As this was the first instance of recording this data, some inconsistencies have been observed with the data but the GPS (coordinates) data of when and where the

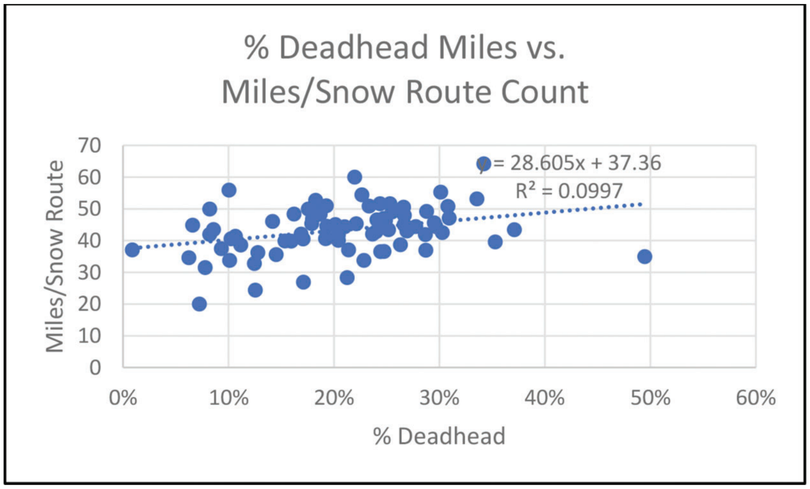


Figure 3.23 Correlation between % of deadhead miles and miles/snow route.

vehicle_id	vehicle_name	time_stamp	latitude	longitude	prev_latitude	prev_longitude	distance_feet	time	speed_ft_per_sec
179	63703	2020-11-05 00:24:30	39.74656	-86.04047	39.746517	-86.04044	34848	8 mins	72.60
179	63703	2020-11-05 00:25:30	39.746395	-86.04186	39.74656	-86.04047	26928	8 mins	56.10
179	63703	2020-11-05 00:26:30	39.752533	-86.043304	39.746395	-86.04186	2112	1 min	35.20
179	63703	2020-11-05 00:27:30	39.752087	-86.03688	39.752533	-86.043304	2112	1 min	35.20
179	63703	2020-11-05 00:28:30	39.75183	-86.035805	39.752087	-86.03688	315	1 min	5.25
179	63703	2020-11-05 00:29:30	39.750305	-86.02954	39.75183	-86.035805	2640	2 mins	22.00
179	63703	2020-11-05 00:30:30	39.750195	-86.02992	39.750305	-86.02954	144	1 min	2.40
179	63703	2020-11-05 00:31:30	39.750195	-86.02992	39.750195	-86.02992	1	1 min	0.02
179	63703	2020-11-05 00:32:30	39.750206	-86.029976	39.750195	-86.02992	3	1 min	0.05
179	63703	2020-11-05 00:33:30	39.750237	-86.02995	39.750206	-86.029976	13	1 min	0.22
179	63703	2020-11-05 00:34:30	39.750237	-86.02995	39.750237	-86.02995	1	1 min	0.02
179	63703	2020-11-05 00:35:30	39.750237	-86.02995	39.750237	-86.02995	1	1 min	0.02
179	63703	2020-11-05 00:36:30	39.750237	-86.02995	39.750237	-86.02995	1	1 min	0.02

Figure 3.24 GPS data.

truck is situated on the route while performing snow removal operation has been very valuable.

3.3.1 Analysis

The team, upon receiving more than 11 million records of data, recorded by AVL system sensors, from INDOT performed exploratory data analysis on it. The data was imported to MySQL database and cleaned to have correct data type. The team analyzed two sets of data: GPS data and the spread rate data recorded every 100 seconds.

3.3.1.1 GPS data. As the dataset consisted of 11 million+ records, the team sorted the data based on the vehicle name and the timestamp to considered the data for one particular truck on a particular day. The coordinate location data was used to calculate the distance covered by a truck between the times at which the sensors recorded the geo location. Using window function on MySQL each row was updated with the previous geo_location that is the location at which the truck was present at the time right before. With the help of Google Distance MatrixAPI, distance (ft) between two consecutive locations was calculated. The aggregate of this distance provides the length of the route taken by the truck while performing the operation. Using the distance calculated from the coordinates and the time between sensor recordings, the team was also able to calculate the speed of the truck (ft/s). Figure 3.24 shows the sample calculation from the dataset for vehicle name "61073" on November 5, 2020.

3.3.1.2 Spread Rate Data

Actual Solid Rate

Next, the team analyzed the spread rate data. A plot of the actual solid rate for vehicle name "61073" was plotted on a time series graph as shown in Figure 3.25.

A spike in the actual solid rate values was observed during the month of January 2021. Upon preliminary inspection, it was concluded that this spike was due to the weather conditions—high amount of snow fall—during that time and could be corresponding to the amount of snow in the Terre Haute subdistrict.

Upon closer inspection of the data for the month of January, more spikes were observed in the value of actual solid rate as shown in Figure 3.26.

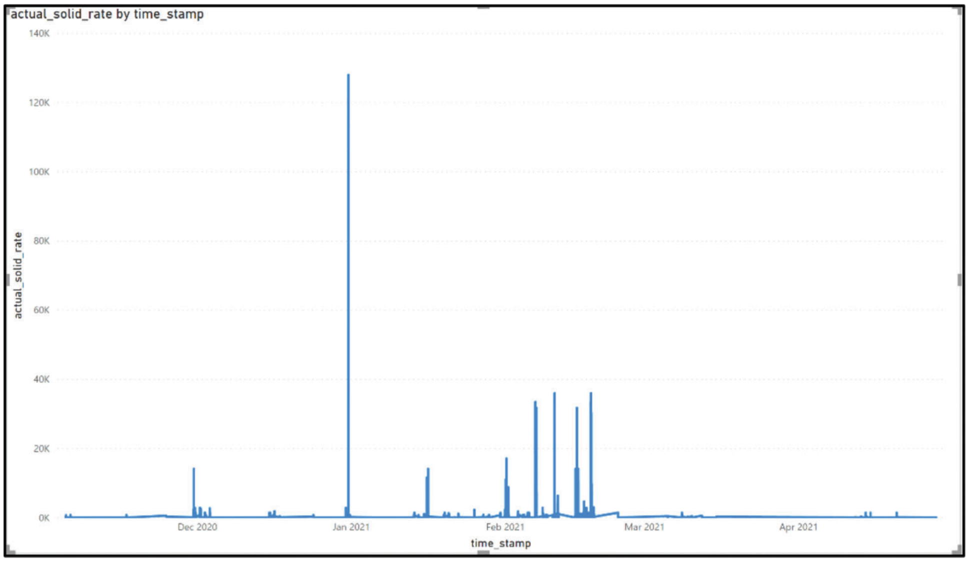


Figure 3.25 Actual solid rate for a truck.

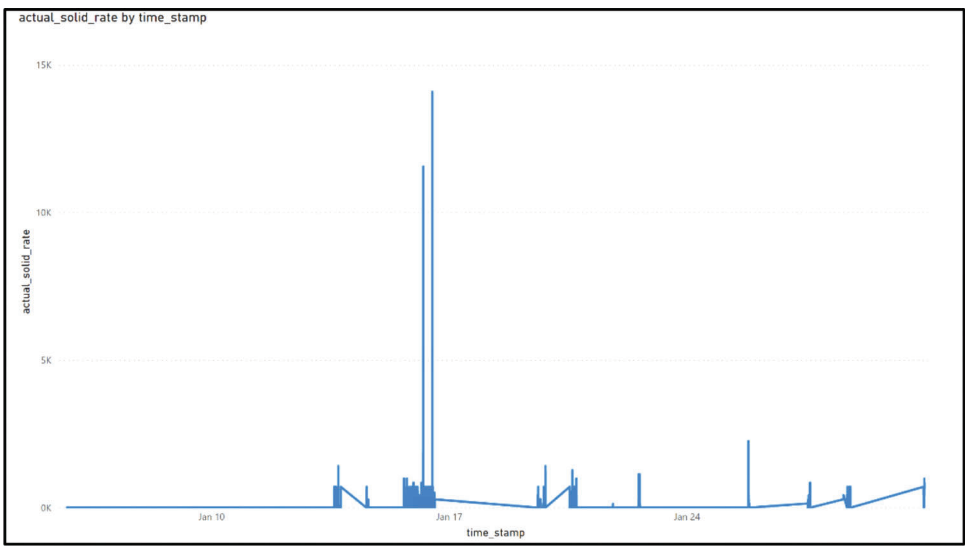


Figure 3.26 Actual solid rate in January.

Using the GPS location data, the spread rate values, for vehicle name "61073" during January, were plotted on a map using Microsoft PowerBI as shown in Figure 3.27. Plotting the data on the map generates the route taken by the truck during that time. The circles present in the figure indicate the sensor recorded GPS data and the size of the circles represent the value of spread rate. Higher the rate, greater is the diameter of the circle.

Upon closer inspection of the route generated by the GPS data, high volume of overlapping circles was observed at a particular location as shown in Figure 3.28. This means that multiple readings were recorded in proximity over a long time. This led to generation of a greater circle in Figure 3.27. Further inspection revealed that the truck spent significantly more time at this location as shown in Figure 3.28. This location was found to be a unit location—Terre Haute. Thus, the truck had a high actual solid rate of dispense at this location to clear the snow around the facility so other trucks and operations can be performed smoothly and more efficiently.

Direct Liquid Rate

The team performed a similar analysis on direct liquid rate data for the same vehicle. A spike in the direct liquid rate values was observed during the month of December 2020 as shown in Figure 3.29. Upon closer inspection of the data for the month of December, multiple spikes were observed in the value of direct liquid rate on December 30 and December 31 as shown in Figure 3.30.

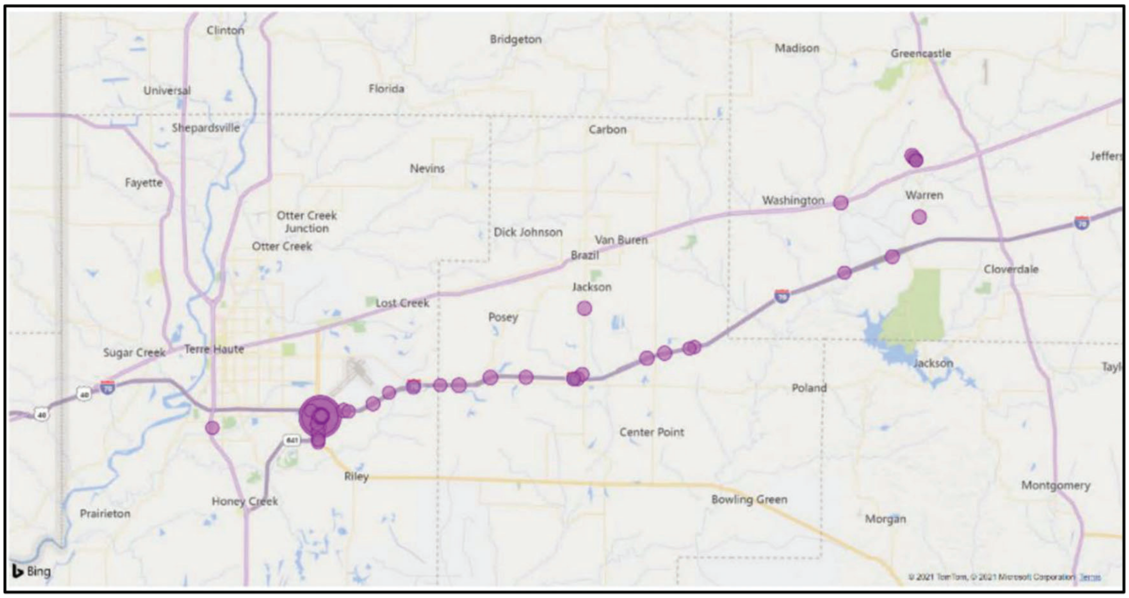


Figure 3.27 Actual solid rate visualization on map.

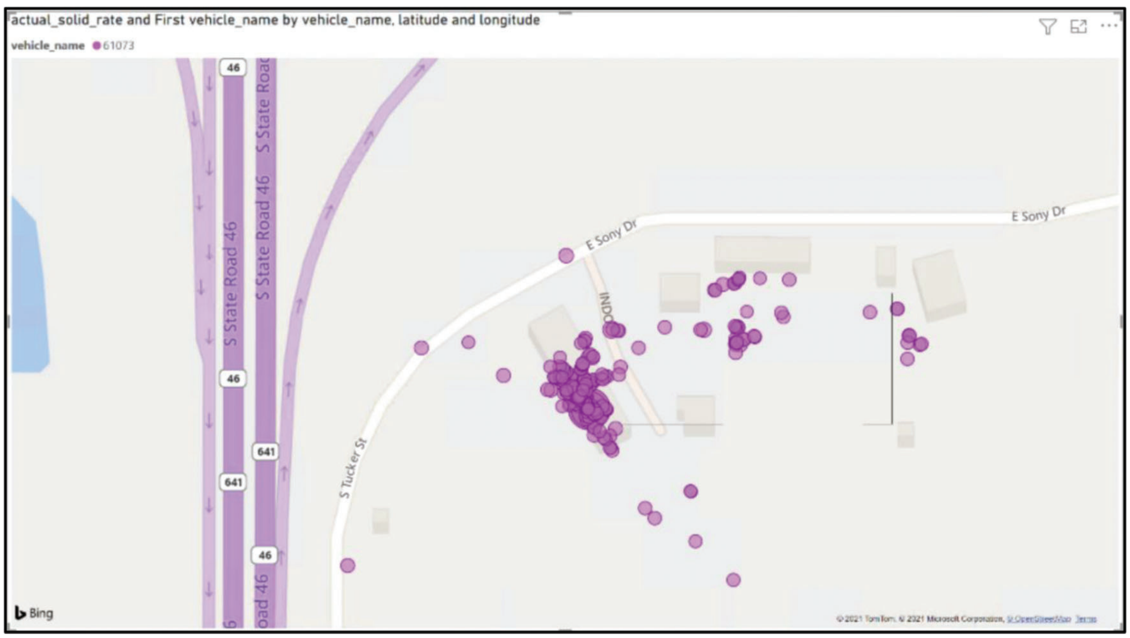


Figure 3.28 High volume of actual solid rate data points recorded.

Plotting the data on the map generated the route taken by the truck during that time. The circles present in the figure indicate the sensor recorded GPS data and the size of the circles represent the value of spread rate. The higher the rate, the greater is the diameter of the circle. Figure 3.31 represents the direct liquid rate data on a map using the corresponding GPS location data for vehicle name "61073."

Upon further inspection of the GPS location data where the data points are bigger, it was observed that the bigger circles are situated at junctions/intersections, as shown in Figure 3.32, and the truck spent significantly more time at the location, as shown in Figure 3.33. This location was found to be a unit location—Terre Haute. Thus, the truck had a high direct liquid rate of dispense at these locations.

Pre-Wet Rate

The team also performed a similar analysis on pre-wet rate data for the same vehicle. A spike in the pre-wet rate values was observed during the several months as shown in Figure 3.34. Upon closer inspec-

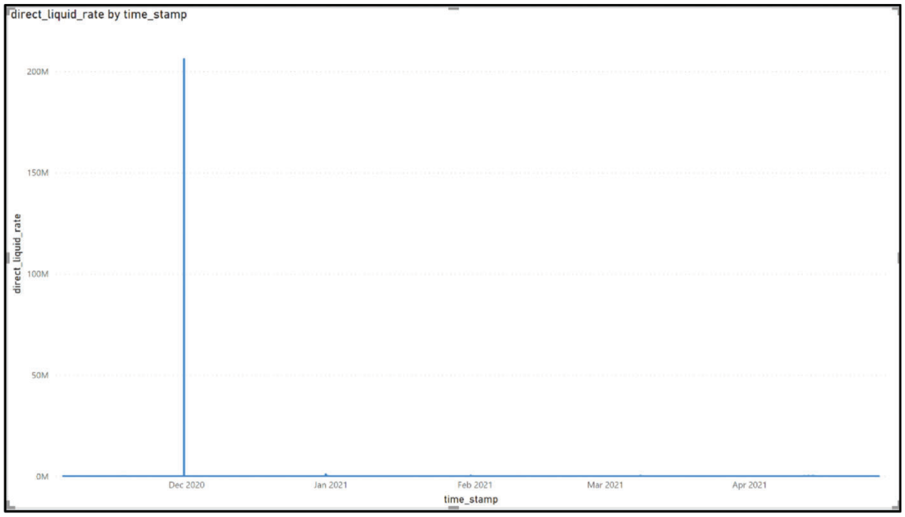


Figure 3.29 Direct liquid rate for a truck.

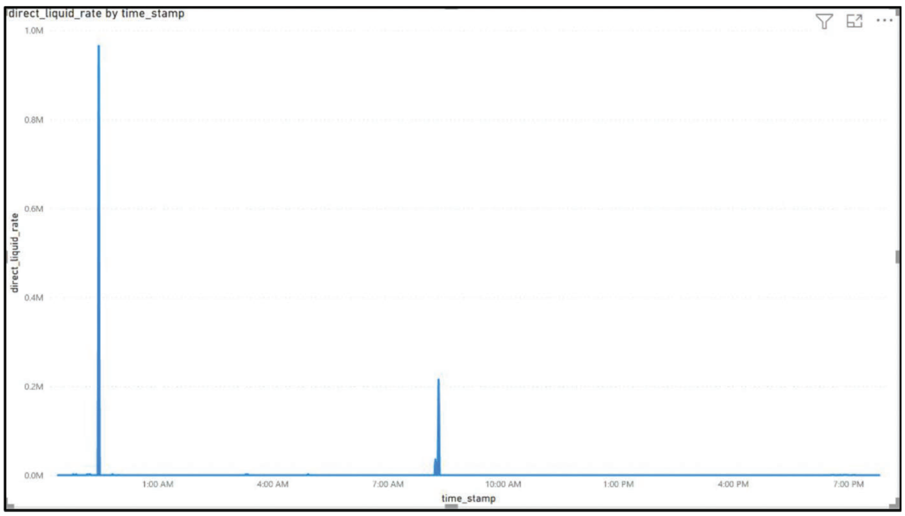


Figure 3.30 Direct liquid rate in December.

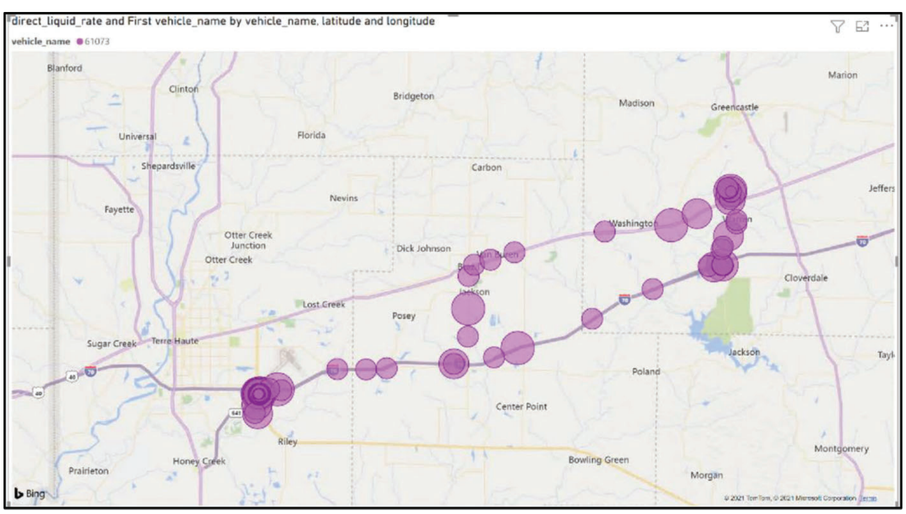


Figure 3.31 Direct liquid rate visualization on map.

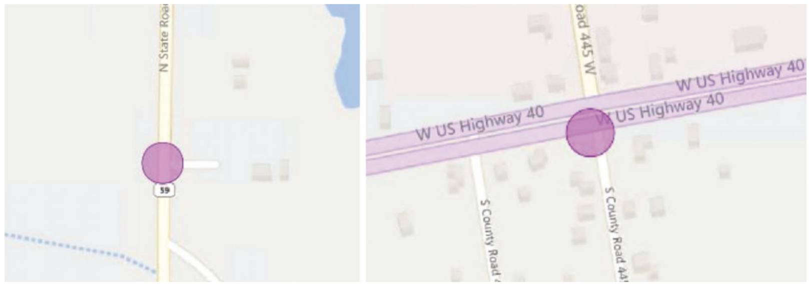


Figure 3.32 High value of direct liquid rate data (a) and (b).

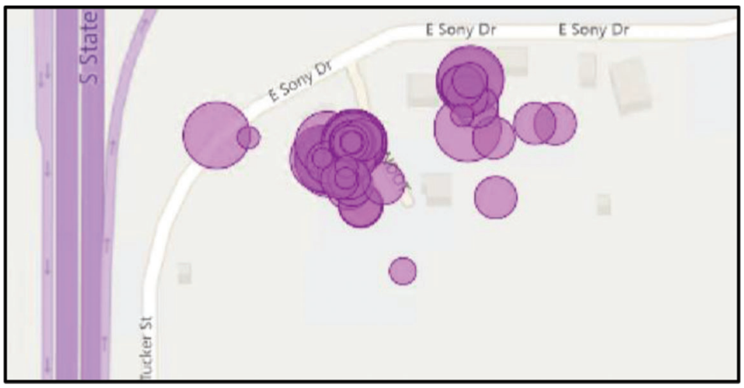


Figure 3.33 High volume of direct liquid rate data points recorded.

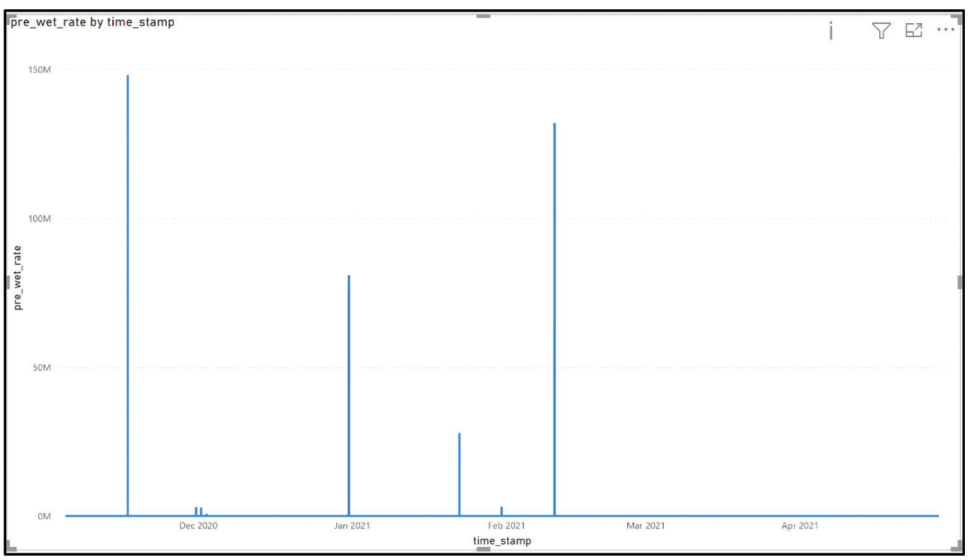


Figure 3.34 Pre-wet rate for a truck.

tion of the data, distinct spike was observed in the value of pre-wet rate in the month of January as shown in Figure 3.35.

Plotting the pre-wet data on the map, using the GPS data, generated the route taken by the truck during that time. The circles present in the figure indicate the sensor recorded GPS data and the size of the circles represent the value of spread rate. Higher the rate, greater is the diameter of the circle. Figure 3.36 represents the pre-wet rate data on a map using the corresponding GPS location data for vehicle name "61073."

Upon further inspection of the GPS location data where the data points are bigger, it was observed that the bigger circles are situated at a location where the truck spent significantly more time, as shown in Figure 3.37. This location was found to be a unit location—Terre Haute. Thus, the truck had a high pre-wet rate of dispense at this location.

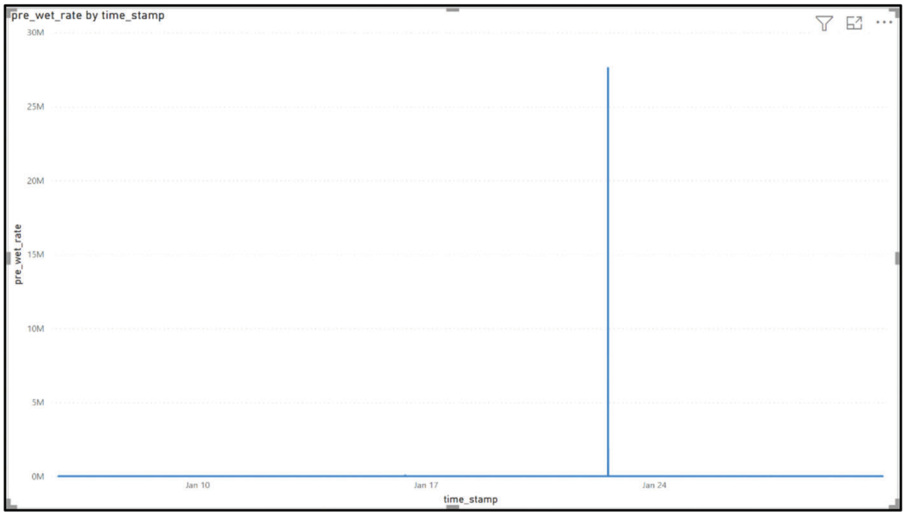


Figure 3.35 Pre-wet rate in January.

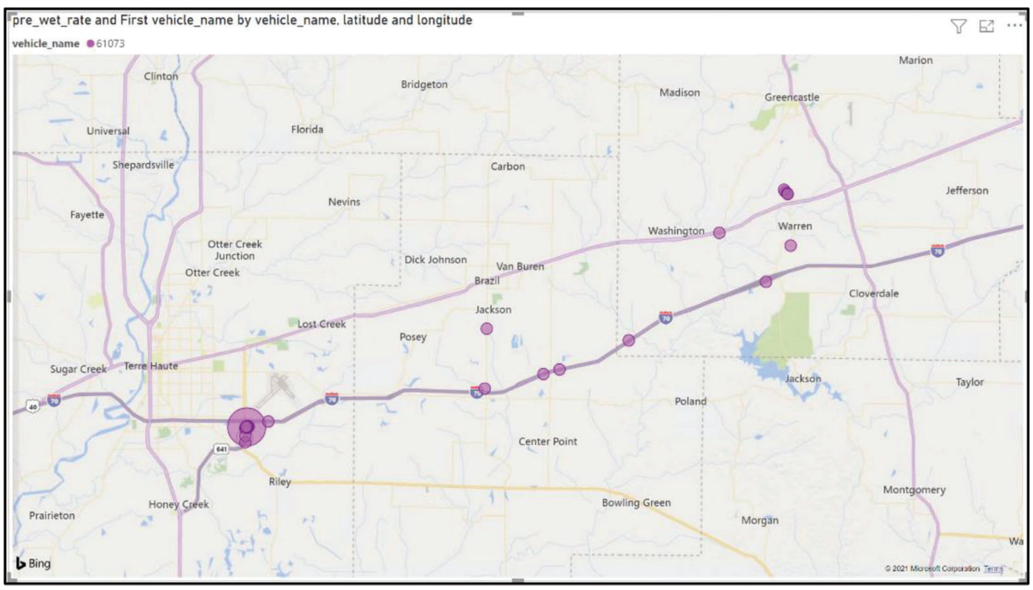


Figure 3.36 Pre-wet rate visualization on map.

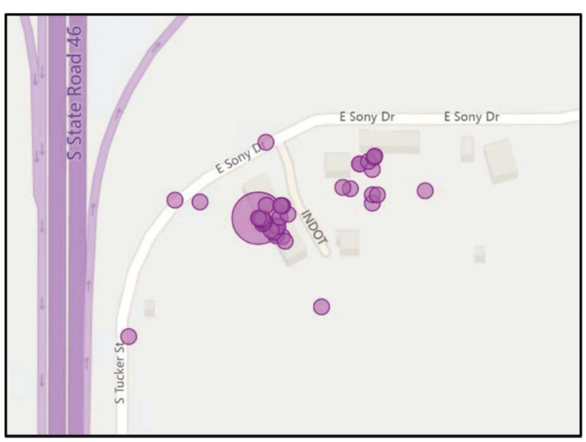


Figure 3.37 High volume of recorded pre-wet rate data points.

3.3.2 Conclusion

Thus, based on the observations, it was concluded that the root cause for high volume of solid or liquid spread rate could be one of the following.

- The truck is located at a unit location.
- The truck is operating in a blast mode at a junction/intersection or a bridge.
- The truck was operated in a manual override mode.

Further analysis can be performed on this data as this data seems promising and is very valuable. The GPS location data can be analyzed to keep track of the truck's location on the snow route based on its GPS location being recorded by the AVL system sensor. Being aware of the truck's location at all times can help in case of emergencies and also provide insight into the amount of time spent by the truck at different locations and the distance covered by the truck between intervals. Useful insights can also be provided about the speed of the truck and the mileage of the truck.

The spread rate data helps understand the resource utilization of salt, deicers, and other agents. This can help make insightful decisions about the amount of salt the truck needs to carry or the route a truck with higher salt carrying capacity can be assigned with.

4. OPTIMIZATION MODELS

The team worked on developing optimization models for the main deliverables of the project—truck replacement strategy and snow route, facility location, and truck distribution planning for minimization of deadhead miles. The optimization models are based on the data shared by INDOT of their current fleet composition and their snow route network.

4.1 Truck Replacement Optimization Model

From the truck data set, consider the Sterling L7500 dump truck that was purchased in 2005. Upon applying the EUAC model, the results are obtained as shown in Figure 4.1.

Even though the change in cost does not seem explicit in Figure 4.1, we can see the intersection of operational and ownership cost, which means that the expected retirement age for this model is close to 9.5 years. Beyond this point, the cost of repair and maintenance exceeds the ownership cost for the model. The team expanded the analysis to include an average of all vehicles in the northern, central, and southern regions. Figure 4.2, Figure 4.3, and Figure 4.4 represent the EUAC analysis in the northern, central, and southern regions, respectively. The area classification is consistent to what has been presented in Section 3. The average values are considered as shown in Table 4.1.

The above analysis shows that the expected retirement age for vehicles in the northern region is significantly less than that in the central or southern region. The concern here is that in absence of year-on-year values of depreciation and other cost components, it is difficult to analyze the exact model defined in the literature review. But based on certain assumptions, the team developed a model that reflects the model from the literature review and provides INDOT with actionable recommendations.

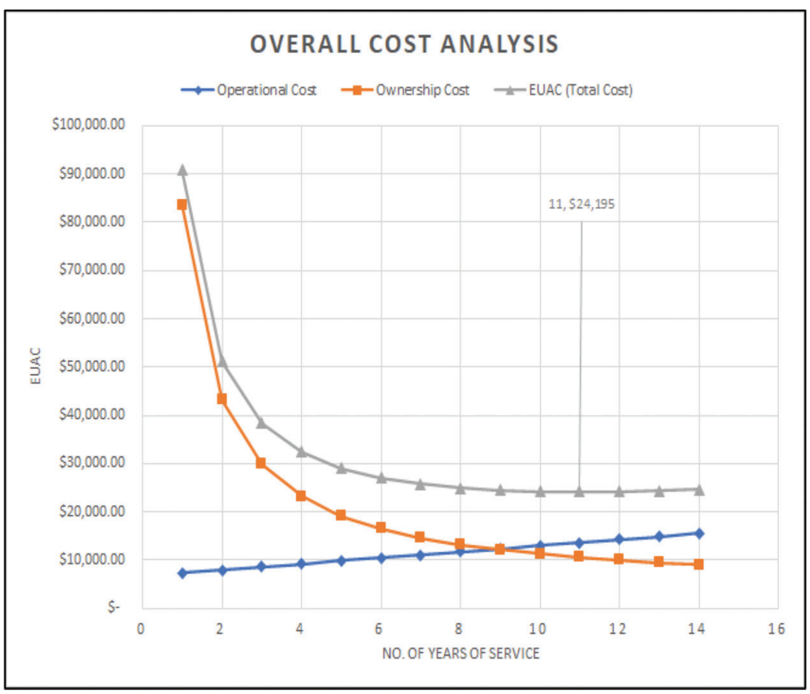


Figure 4.1 EUAC analysis for 2005 L7500 model.

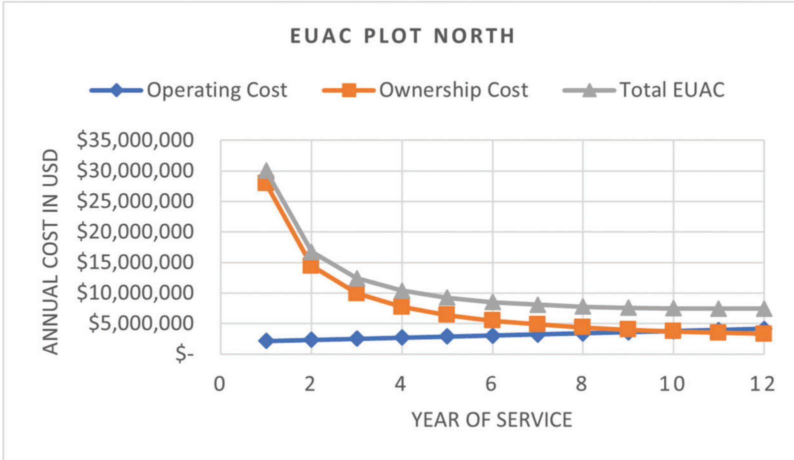


Figure 4.2 EUAC in northern region.

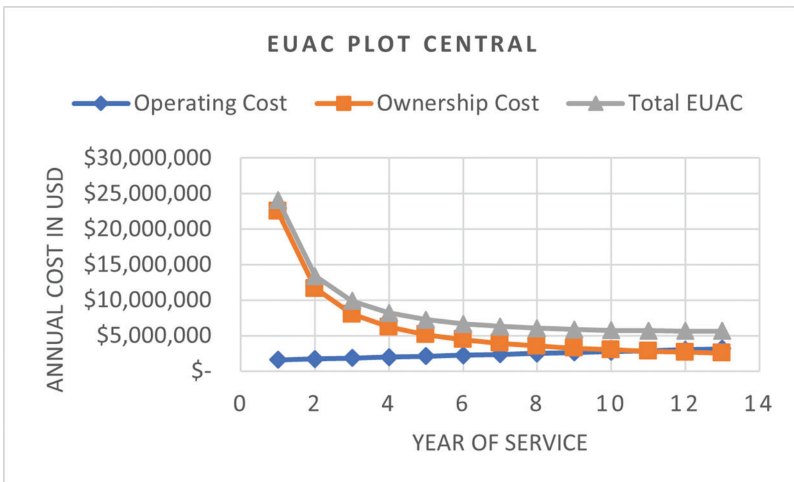


Figure 4.3 EUAC in central region.

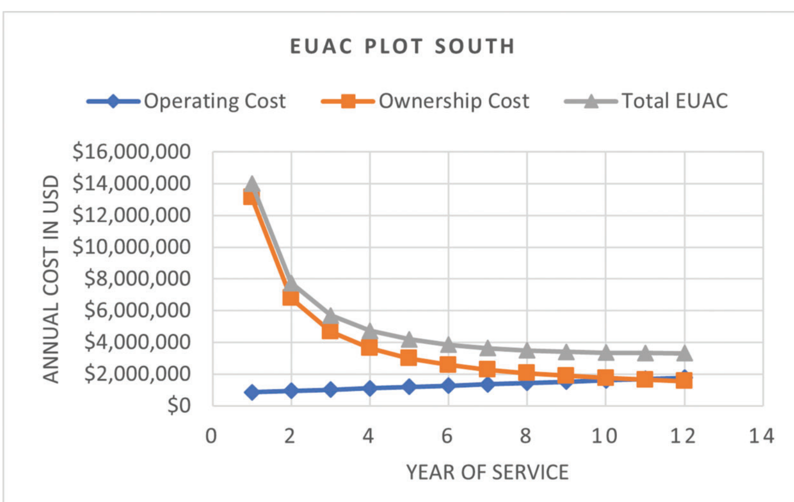


Figure 4.4 EUAC in southern region.

TABLE 4.1
Average costs in each region

Region	Sum of Total Main Cost	Average of Average Fuel Price	Average Age	Sum of Total Fuel Cost	Sum of Purchase Cost
Northern	$16,614,223.51	$2.72	12.50	$11,696,478.72	$23,907,767.30
Central	$22,054,354.28	$2.70	11.59	$14,243,374.88	$29,638,318.58
Southern	$9,249,095.78	$2.76	14.31	$6,504,517.67	$13,953,069.34
Grand Total	*$47,917,673.57*	*$2.72*	*12.55*	*$32,444,371.27*	*$67,499,155.22*

4.2 Optimization Model for Replacement Strategy

The replacement strategy for fleet under INDOT has been one of the most focused point of this project. To devise the optimal age, an optimization model and piecewise regression was used for each specific region, northern, central, and southern. The model used can be broken down into three segments.

- The first segment deals with the piecewise regression, and the goal of this section is to find the annual mileage as it changes once the vehicle crosses 60k miles. Also, the regression tries to see how the cost and mileage change with time.
- The second segment is based on fitting a model for total operational cost to the available dataset. This model provides annual operational cost for each year a vehicle is in operation.
- The third segment is based on EUAC model as obtained from benchmarking and literature review, and this section combines the finding from Sections 1 and 2 to derive the miles driven and cost accumulated over age.

4.2.1 Section 1: Piecewise Regression

As presented in the earlier section of the report, the data can be divided into two broad sections based on the total mileage. However, to do a quantitative analysis, the data was further broken down to see how the mileage and cost change with time. This was done by classifying the data for every 5 years from 0 to 15 years. This required two piecewise-regression for three regions—one for mileage and one for cost. The intuition behind was that a vehicle beyond age 10 or 15 years, depending on the age, does not travel extensively and might serve as stand-by. The result helps in determining the cut-off age required for the next sections. The model is defined as follows.

$M_i^{/} = \beta_{i0} t_i + \sum_j \beta_{ij}(t_i - 5k) d_j$ where β_{ij} is the incremental slope for each section defined by k.

k = integer and depends on the range of age in dataset; in this study k = 1, 2, 3.

d_j is a dummy variable to define each section of the dataset, such that, for example, d_1 is zero for below 5 years age and 1 otherwise; d_2 is zero below 10 years and 1 otherwise; d_3 is zero below 15 years age and 1 otherwise. $M_i^{/}$ is the total mileage that a vehicle with t_i years in operation has travelled in region i.

Similar model is also created for total cost analysis across each region.

$C_i^{/} = \alpha_{i0} t_i + \sum_j \alpha_{ij}(t_i - 5k) d_j$ where α_{ij} is the incremental slope for each section defined by k.

$C_i^{/}$ is the total mileage that a vehicle with t_i years in operation has travelled in region i. As presented in the earlier section of the report, the data can be divided into two broad sections based on the total mileage

The goal of this analysis is to see how the slope for mileage and cost changes with age across the three regions. According to the analysis in this section, a determination of cut-off age is made. Cut-off age (t_i^*) is the time beyond which the slope for cost changes, which will be discussed in Section 2. The piecewise regression provides different results for the three regions.

The analysis of the northern region shows an increase in cost and mileage up to 10 years in operation. Cost declines beyond 10 years, but mileage increases at previous rate, indicating that the trucks beyond 10 years may not provide a correct indication of the trends. Beyond 10 years of age, the current fleet has vehicles which have either travelled more in their past and are stand-by now or may have experienced less fuel and maintenance cost. This allows us to consider vehicles below 10 years of age so that the nature of increase in cost can be reflected. Figure 4.5 and Table 4.2 show the analysis of cost in the northern region. In both cases the regressions had over 96% R^2 value.

For mileage, Figure 4.6 and Table 4.3 show the results.

Similar analysis is performed for the central and southern regions. The central region follows a similar trend as in the northern region, which means that vehicles beyond 10 years of age are not to be considered if we are to obtain the trends in the region. Figure 4.7 and Figure 4.8 show the trend and regression line for cost and mileage in the central region. Also, Table 4.4 and Table 4.5 provide the statistical data.

It is difficult to get a prominent conclusion for the southern region, as both cost and mileage seem to be increasing with time. Figure 4.9 and Figure 4.10 show the regression in the southern region. However, Section 2 attempts to restrict the data use to 10 years for a better fit. This will be discussed in detail in the next section.

From this regression, we also get the mileages for different age bands. Figures 4.9 and Figure 4.10 show the regression in the southern region. Table 4.6 and

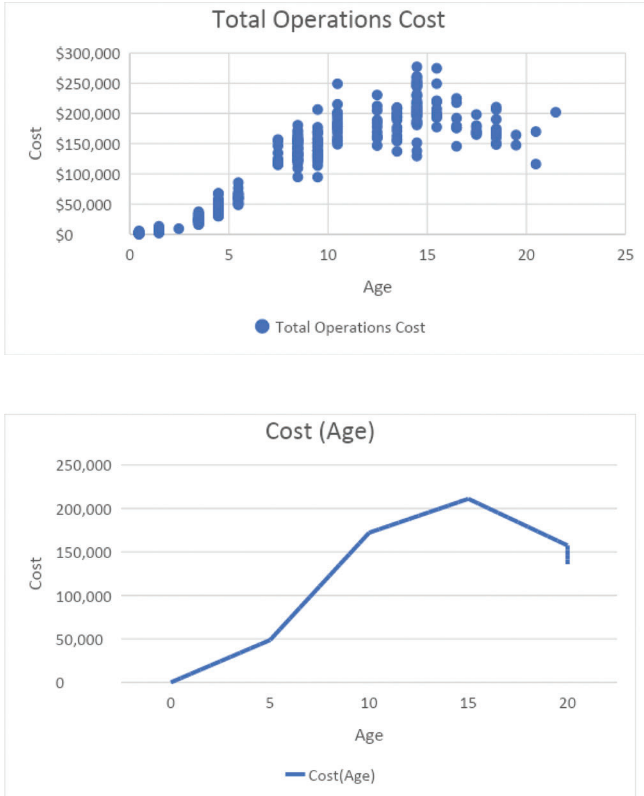


Figure 4.5 Trend and scatterplot for cost in northern region.

TABLE 4.2
Statistical data for regression of cost in northern region

α_{i0}	α_{i1}	α_{i2}	α_{i3}
Slope	**Increment in Slope Beyond 5 Years**	**Increment in Slope Beyond 10 Years**	**Increment in Slope Beyond 15 Years**
9,726	14,979	-16,911	-18,522
Slope Below 5 Years	**Slope Between 5 and 10 Years**	**Slope Between 10 and 15 Years**	**Slope Beyond 15 Years**
9,726	24,704	7,793	-10,728

Table 4.7 provide the statistical analysis results for the regression performed on the trucks from the southern region. For each region, the mileage is obtained from the above analysis. These slopes will be used to calculate the mileage for each region.

4.2.2 Section 2: Fitting the Cost Parameters

This section deals with the cost factors. The model is devised to construct a cost structure across vehicles of different age. The goal is to fit the model to the existing dataset. The model is structured to have three parameters—two linear parameters (S_{i1}, S_{i2}) that would be used depending on the cut-off age and one exponential parameter to consider the gradual increase in cost over time. As mentioned in Section 1, a cut-off age is the age at which the slope of cost takes a shift in the parameters. Table 4.8 provides some key definitions that are required for this section and beyond.

The model can now be defined as follows.

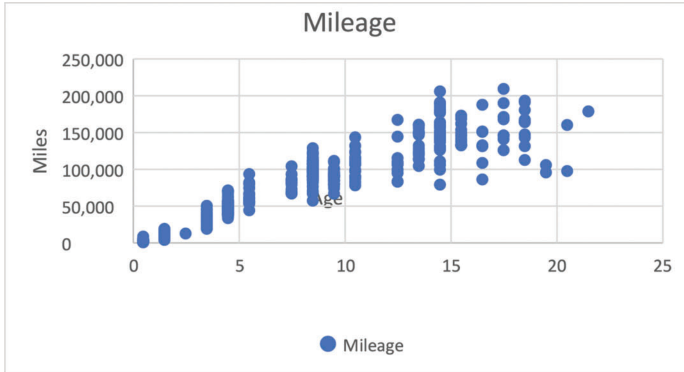
The cost from the linear function for any year t is: $(S_{i1}\alpha_1 + S_{i2}\alpha_2)$

Where, $\alpha_1 = 1$ and $\alpha_2 = 0$ for $t \leq t_i^*$

And $\alpha_1 = 0$ and $\alpha_2 = 1$ for $t > t_i^*$

Therefore, the total cost contributed by the linear components (CL_i^t) at any year t is as follows.

$CL_i^t = \sum_{t=1}^{N}(S_{i1}\alpha_1 + S_{i2}\alpha_2)$ where, N is the number of years for which the calculation is done. Figure 4.11 shows a snip of the Excel model used for this part. Cell



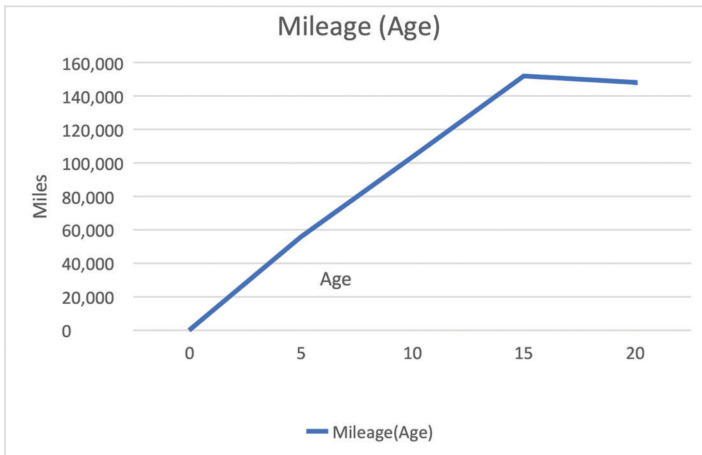


Figure 4.6 Mileage for northern region across time.

TABLE 4.3
Statistical data of mileage in northern region

β_{i0}	β_{i1}	β_{i2}	β_{i3}
Slope	**Increment in Slope Beyond 5 Years**	**Increment in Slope Beyond 10 Years**	**Increment in Slope Beyond 15 Year**
11,138	-1,577	119	-10,442
Slope Below 5 Years	**Slope Between 5 and 10 Years**	**Slope Between 10 and 15 Years**	**Slope Beyond 15 Year**
11,138	9,562	9,681	-761

M6 to M12 shows the linear components used, and Cell O6 to O12 provides the calculation for cost contributed by these linear sections.

In other words, the linear slopes are the increase in cost each year depending on whether the vehicle is above or below cut-off age. Thus, each year's cost needs to be summed up to get the total cost in a given period of time (N).

Next step is to have the model incorporate the exponential component to define the modeled cost for each region. This would mean that the data required to be fitted into the dataset is as follows.

$C^*_{it} = CL^t_i(e^{t*P_i})$ where, C^*_{it} is the total modeled cost at time t for region i.

Thus, we can now fit this model to obtain the RSS, which is defined as follows.

$\text{RSS} = \sum_i (C^*_{it} - C^k_i)^2$ where Age (A^i_k = t).

Also, TSS can be defined as $\text{TSS} = \sum_i (\bar{C}_l - C^k_i)^2$ where $\bar{C}_l = C^k_i/(\text{number of data chosen})$.

The fit of this model can be evaluated by calculating $R^2 = (1 - \text{RSS}/\text{TSS})$.

The optimization problem that needs to be solved for a better fit of the model is as follows.

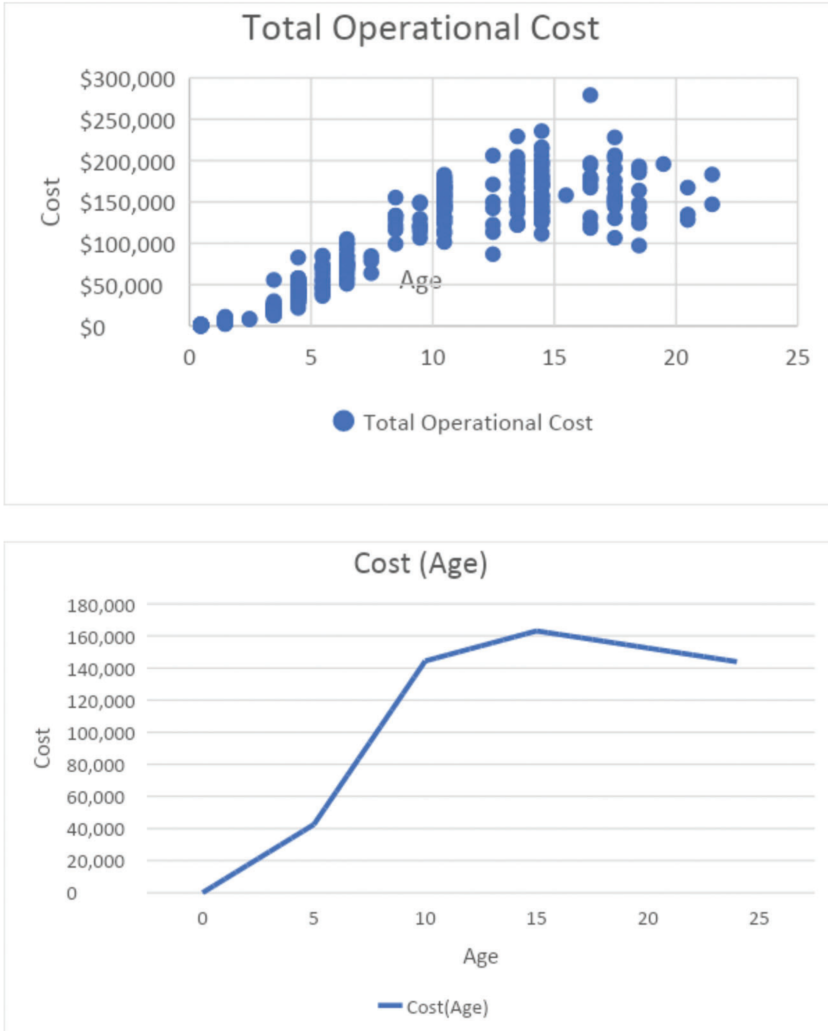


Figure 4.7 Trend and scatterplot for cost in central region.

TABLE 4.4
Statistical data of cost in central region

α_{i0}	α_{i1}	α_{i2}	α_{i3}
Slope	**Increment in Slope Beyond 5 Years**	**Increment in Slope Beyond 10 Years**	**Increment in Slope Beyond 15 Year**
8,830	11,879	-16,640	-5,877
Slope Below 5 Years	**Slope Between 5 and 10 Years**	**Slope Between 10 and 15 Years**	**Slope Beyond 15 Year**
8,830	20,709	4,069	-1,808

Variables: $S_{i1,}$ S_{i2}, and P_i (the parameters are specific to region i)

$Min(RSS)$

s.t

$S_{i1,}$ $S_{i2,}$ and $P_i \geq 0$

At this point, the best way to have a better fit is to see which cut-off age gets our model a good fit. The model was solved on GRG-Non Linear Engine, and Table 4.9 shows the parameter values and the fit of our model alongside the cut-off age that provided best fit. Also,

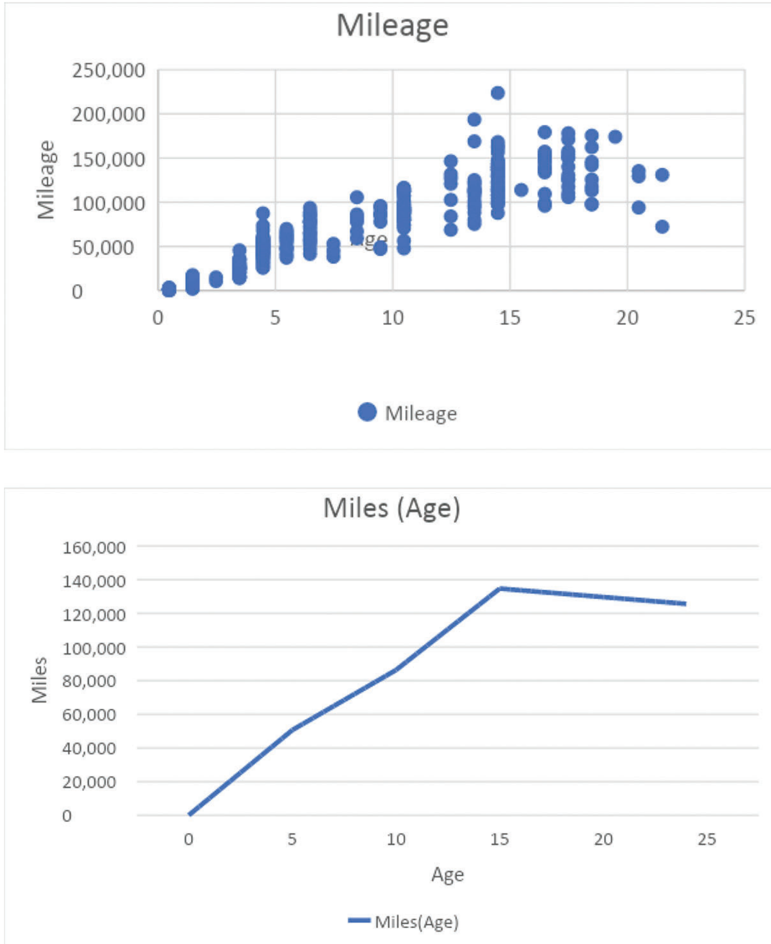


Figure 4.8 Mileage regression with age in central region.

TABLE 4.5
Statistical data of mileage slope in central region

β_{i0}	β_{i1}	β_{i2}	β_{i3}
Slope	**Increment in Slope Beyond 5 Years**	**Increment in Slope Beyond 10 Years**	**Increment in Slope Beyond 15 Year**
10,130	-3,000	2,547	-10,687
Slope Below 5 Years	**Slope Between 5 and 10 Years**	**Slope Between 10 and 15 Years**	**Slope Beyond 15 Year**
10,130	7,126	9,673	-1,055

care was taken to ensure the cut-off age is relatable to change in slope found from piecewise regression in Section 1.

Once these values are obtained, the model provides total cost at different age. With this model, we get the differential cost among subsequent age to find the cost incurred at a particular age. Thus, the operational cost at any year t can be expressed as $OC_{it} = (C^*_{it} - C^*_{i(t-1)})$. A snap of the model for the southern region is provided in Figure 4.12.

It is to be noted that age denomination is for every 6-months. This allowed to have a better fit in the data set which does not have many vehicles with integral age values.

4.2.3 Section 3: Cost and Mileage Modeling Across Age

This segment relies on our literature review for EUAC model and presents an equivalent model to the EUAC (equivalent uniform annual cost). The cost accumulated along time is converted to a uniform

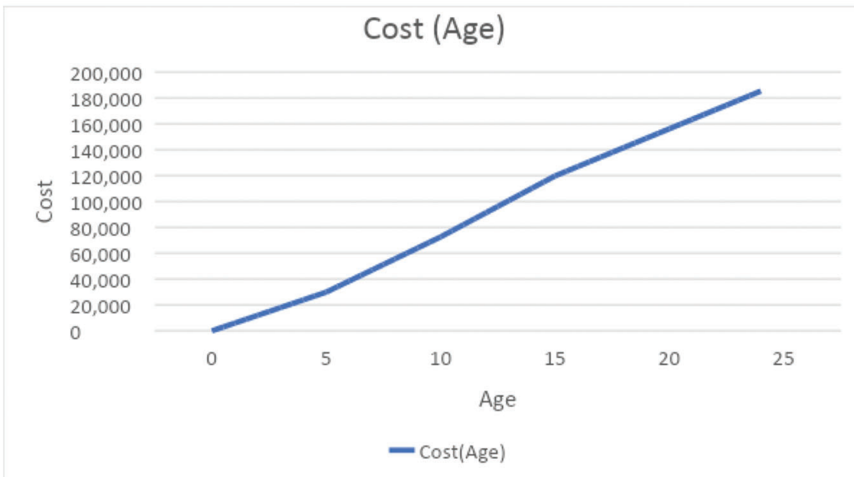


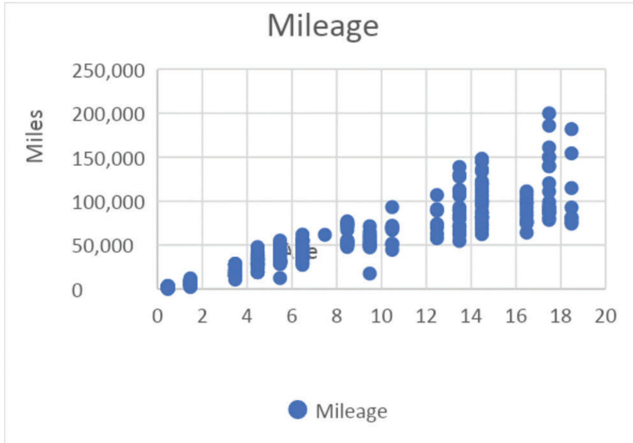
Figure 4.9 Cost regression in southern region.

TABLE 4.6
Statistical data of regression in southern region

α_{i0}	α_{i1}	α_{i2}	α_{i3}
Slope	**Increment in Slope Beyond 5 Years**	**Increment in Slope Beyond 10 Years**	**Increment in Slope Beyond 15 Year**
5,989	2,551	884	-2,127
Slope Below 5 Years	**Slope Between 5 and 10 Years**	**Slope Between 10 and 15 Years**	**Slope Beyond 15 Year**
5,989	8,540	9,424	7,297

annual cost across the same time length by discounting the cost with appropriate interest rate. Table 4.10 provides some definition that are required for this section.

From Sections 1 and 2, we already have the cost for each year that a vehicle accrues over time. The capital cost involved in acquiring a vehicle has a useful worth equal to price minus salvage (P-S). Once a vehicle is purchased, the one-time capital cost at the time of purchase can also be defined as a series of annuity from the year of purchase to the current year of operation. It is a simple discounting process which equals the discounted values of annuity to the present value at the time of purchase. Thus, as a vehicle ages, the ownership cost in terms of EUAC is the annuity that would result in the capital cost. The discounting factor (A_p) is defined as follows.



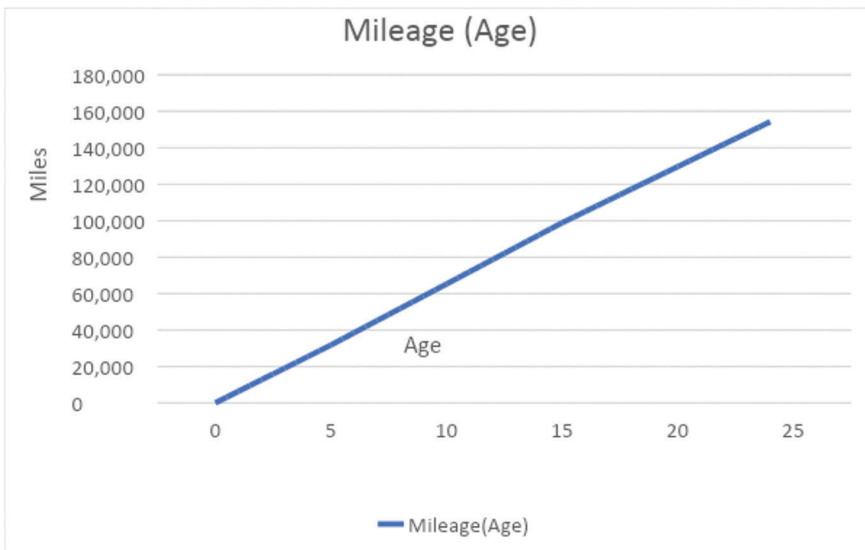


Figure 4.10 Mileage regression in southern region.

TABLE 4.7
Statistical data of southern region

β_{i0}	β_{i1}	β_{i2}	β_{i3}
Slope	**Increment in Slope Beyond 5 Years**	**Increment in Slope Beyond 10 Years**	**Increment in Slope Beyond 15 Year**
6,349	343	25	-561
Slope Below 5 Years	**Slope Between 5 and 10 Years**	**Slope Between 10 and 15 Years**	**Slope Beyond 15 Year**
6,349	6,692	6,717	6,156

$A_p = {(I(1+I)^t)}/{((1+I)^t - 1)}$ where t is the time through which the vehicle has been in operation.

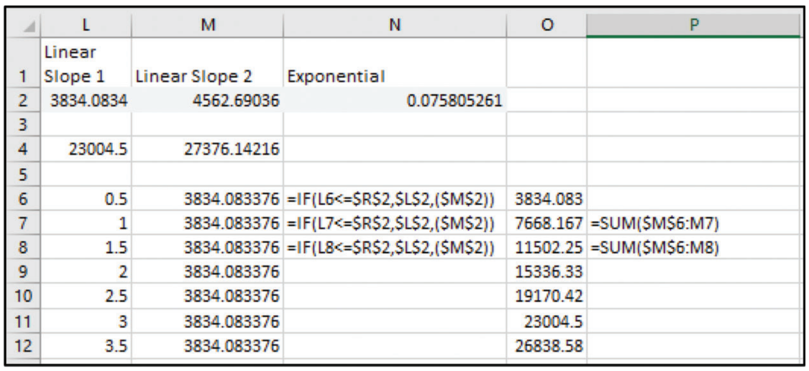
The ownership cost is thus defined as follow.

$C^t_{own} = P * (1 - S) * A_p$

The operational cost for a particular year t in region i is OC_{it}. In order to have the equivalent uniform cost, we need to discount the cost incurred by a vehicle along its service to the current age. This means discounting the series of cash flow in the past to the current year of

TABLE 4.8
Definition of metrics used in Section 2

Parameters	Description
Total Operating Cost	The sum of fuel and R&M cost as obtained from the data set and evaluated in exploratory data analysis section
Age (A^i_k)	The age of vehicle k in region i
Slope Parameter 1 (S_{i1})	The linear component used to fit the cost model to dataset below cut-off age
Slope Parameter 2 (S_{i2})	The linear component used to fit the cost model to dataset beyond cut-off age
Exponential Parameter (P_i)	The exponential cost component for each region i
Model C^*_{it}	The cost obtained from modeling of vehicle of age t in region i
Mean $\bar{C}_i$	The mean total operating cost in region i
RSS_i	The residual square error in region i
t_i*	Cut-off age to switch between linear function



	L	M	N	O	P
1	Linear Slope 1	Linear Slope 2	Exponential		
2	3834.0834	4562.69036	0.075805261		
3					
4	23004.5	27376.14216			
5					
6	0.5	3834.083376	=IF(L6<=$R$2,$L$2,($M$2))	3834.083	
7	1	3834.083376	=IF(L7<=$R$2,$L$2,($M$2))	7668.167	=SUM($M$6:M7)
8	1.5	3834.083376	=IF(L8<=$R$2,$L$2,($M$2))	11502.25	=SUM($M$6:M8)
9	2	3834.083376		15336.33	
10	2.5	3834.083376		19170.42	
11	3	3834.083376		23004.5	
12	3.5	3834.083376		26838.58	

Figure 4.11 Excel formulation of the fitted model.

TABLE 4.9
Values obtained and parameters in fitted model

Region	S_{i1}	S_{i2}	P_i	Cut-off Age (t_i*)	R^2 Value
Northern	4,043.94	6,414	0.05135	5	0.926
Central	2,713.2	1,338.12	0.1158	7	0.9040
Southern	1,504.2	2,044.5	0.4965	7	0.9069

operation. This present value (PV_i) is defined as follows.

$PV_i = \sum_{t=1}^{n} OC_{it} * (1+I)^{n-t}$

The objective of finding this present value is to discount the past cash flows to the current year of operation. Once this value is obtained for a year of operation *t*, the equivalent cost approach can be implemented. To do so, this cumulative present value is to be converted to a series of annuity that started from the year of inception to the current time. This is the equivalent cost approach towards operational cost that has been used for ownership cost. The discount factor (A_f) that is to be used to obtain the annuity for operational cost is thus mentioned below.

$A_f = \frac{I}{((1+I)^t - 1)}$ where t is the year of calculation.

Thus, the operational cost in the EUAC model is $C^t_i = PV_i * A_f$.

These two cost components determine the usability of a truck running at a particular age. The total cost is the summation of these two cost parts for any time t and is simply defined as $T_{it} = C^t_{own} + C^t_i$.

While using the present value of components, this model is more concise about the amount by which the annual cost for a vehicle goes up as it ages. Figure 4.13 shows how the cost changes associated with the use of a vehicle.

To implement this model, the following assumptions were made.

- The interest rate is consistent across time and is maintained at 5%.
- The list price of a vehicle is $110,000.
- The salvage percentage is maintained at 20%.

The intuition is that a vehicle should be replaced at the point where the total cost is at minimum. Going beyond this point, necessarily means that the vehicle is incurring more cost per year. At this point, we also focused on the cost incurred per mile of travel for a vehicle. From our regression model in Section 1, we

L	M	N	O	P	Q
Linear 1	Linear	Exp		Cut-off age	
1504.18	2044.55	0.49651		7	
Age					
0.5	1504.18	1504.18	1066.192876		
1	1504.18	3008.37	3008.369108	3008.37	
1.5	1504.18	4512.55	5518.918788		
2	1504.18	6016.74	8488.412269	5480.04	
2.5	1504.18	7520.92	11853.69019		
3	1504.18	9025.11	15572.17757	7083.77	
3.5	1504.18	10529.3	19612.64185		
4	1504.18	12033.5	23950.89839	8378.72	
4.5	1504.18	13537.7	28567.49962		
5	1504.18	15041.8	33446.36433	9495.47	
5.5	1504.18	16546	38573.90561		
6	1504.18	18050.2	43938.44584	10492.1	
6.5	1504.18	19554.4	49529.8075		
7	1504.18	21058.6	55339.01716	11400.6	
7.5	2044.55	23103.1	62827.56902		
8	2044.55	25147.7	70614.50837	15275.5	
8.5	2044.55	27192.2	78688.89771		
9	2044.55	29236.8	87040.90061	16426.4	

Figure 4.12 Snap of the fitted model for southern region.

TABLE 4.10
Definitions for Section 3

I	Interest rate, considered 5% for all regions
S	Salvage value, considered 20% for all regions
P	Price of a vehicle or the capital cost involved, considered $110,000 for all regions
C^{t}_{own}	Ownership cost for vehicle at age t
C^{t}_{i}	Operational cost associated with vehicle at age t for region i

already have the mileage per year for different ages. This allows us to define the total mileage $(M^{/}_{it})$ for a vehicle at time t. Thus, the average annual mileage can now be determined as $(\overline{M^{/}_{it}})(M^{/}_{it}/t)$. Since we already have the annual cost from the EUAC model, the cost per mile can now be defined as $T_{it}/M^{/}_{it}$.

4.3 Model Findings and Recommendations

All the models are taken together to create the cost distribution for each region. The snaps of the model for the northern, central, and southern regions are shown in Appendix B. The following part of this section details the findings for each region. The model is run for different age ranges for different regions. Since the northern and central regions have higher cost gradient and higher chances of early retirement, the age range is considered for 1 to 15. However, to explore the southern region, a higher age bracket is chosen (1 to 21).

From the analysis, we found different age for minimal cost across the three regions. The finding is very intuitive in that the minimal cost is reached in the northern region at a much early age, followed by the central and southern. Since replacement age has been a major focus point in this project, this model provides an excellent method to ascertain the different ages at which a vehicle needs to be replaced in different regions. The different findings are provided in the section below.

TABLE 4.11
Replacement age for different regions

Region	Minimal Total EUAC Cost	Age	Cost Per Mile
North	$28,865	9	$2.77
Central	$26,388	10	$3.00
South	$22,005	13	$3.35

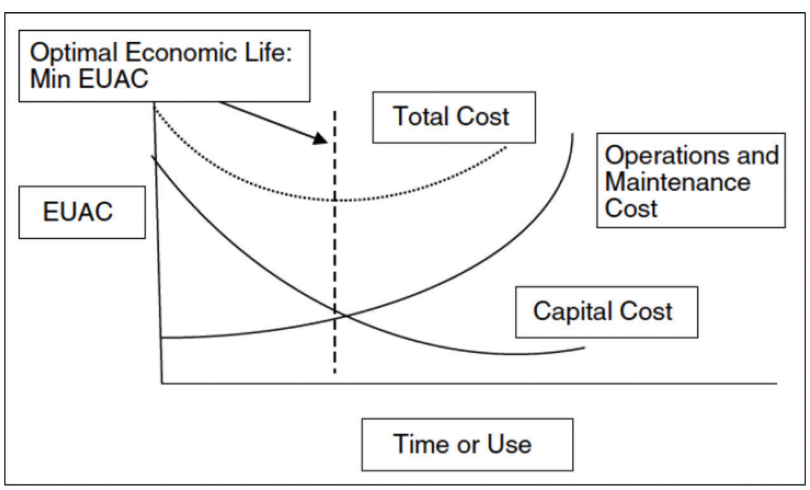


Figure 4.13 Change in the two cost components and total cost.

Table 4.11 shows the age at which the total cost and the cost per mile get minimal.

An interesting finding at this point is that even though the EUAC cost increase as one goes north, the cost per mile goes down. Since each region has its own characteristics, the change in cost per mile can be a result of the higher miles driven in the northern region than in other regions for vehicles within similar age band.

4.3.1 North

From our understanding, the northern region suffers most deterioration of fleet. From our analysis and models in previous sections, we have already seen that cost increases steeply and fast in the northern region. Figure 4.14 shows the EUAC model for northern region. The graph represents similar trend as was observed during our literature review. The graph shows how the EUAC cost would change as the vehicle ages.

It might be noted here that for each increase in use or age, the increase in cost is for each service year and for each vehicle. This allows us to consider some flexibility in terms of the choice of replacement age.

Cost per mile for the northern region is shown in Figure 4.15. This would allow more flexibility in determination of the age at which INDOT might choose to retire a vehicle.

On observing the data and model findings, it may be chosen to retire a vehicle in the northern region after approximately 8–10 years of operation. Increasing the usage would incur higher cost for each year the vehicle has been in operation.

4.3.2 Central

In the central region, similar observations are noted. The analysis also goes with our intuition that in the central region the optimum age will be higher than that

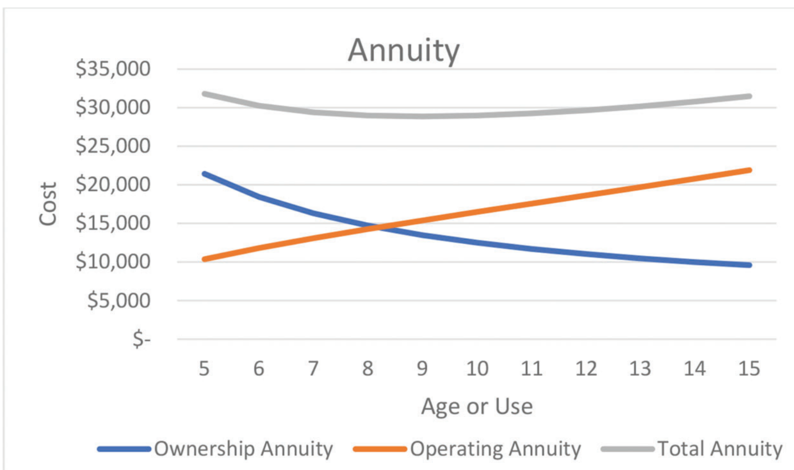


Figure 4.14 EUAC cost model across time for northern region.

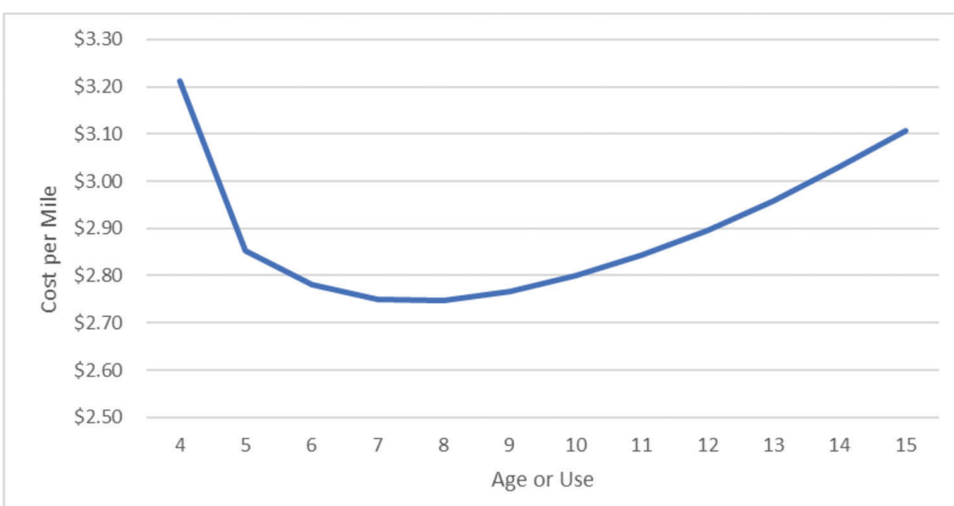


Figure 4.15 Cost per mile change across age in northern region.

in the northern region. Figure 4.16 shows the EUAC curve for vehicle in the central region.

The cost per mile for the central region has been calculated in a similar way, and the results are provided in Figure 4.17. It is to be noted that in the central region even though the minimal cost is at around 10 years, the increase in cost is not as steep as in the northern region. This means that for the central region there is a more flexibility in choosing the replacement age.

The analysis shows that the optimum age to replace a vehicle in the central region is approximately 10–12 years. However, the central region provides more flexibility in terms of the rate of increase in cost.

4.3.3 South

For the southern region, the minimal cost is achieved at approximately 13 years of service. The slope of the curve is, however, much less steep than that in any other regions. This goes with our intuition that the vehicles in the southern region ages at a much slower rate, and the model thus provides maximum flexibility for this region to determine the retirement age. Figure 4.18 and Figure 4.19 show the EUAC model and cost per mile for the southern region, respectively.

Since in the EUAC model the initial phase has much higher cost owing to ownership component, the x-axis has been chosen accordingly to show the change in cost and minimal cost more conveniently.

4.4 Snow Route Optimization Model

The problem of vehicle routing on road networks for purposes including snow removal, has been a longstanding research topic (Campbell & Langevin, 1995; Clarke & Wright, 1964; Dantzig & Ramser, 1959; Gray & Male, 1981; Minsk, 1970). Keseling (1994), Lindsey and Seely (1999), and Cortina and Low (2001)

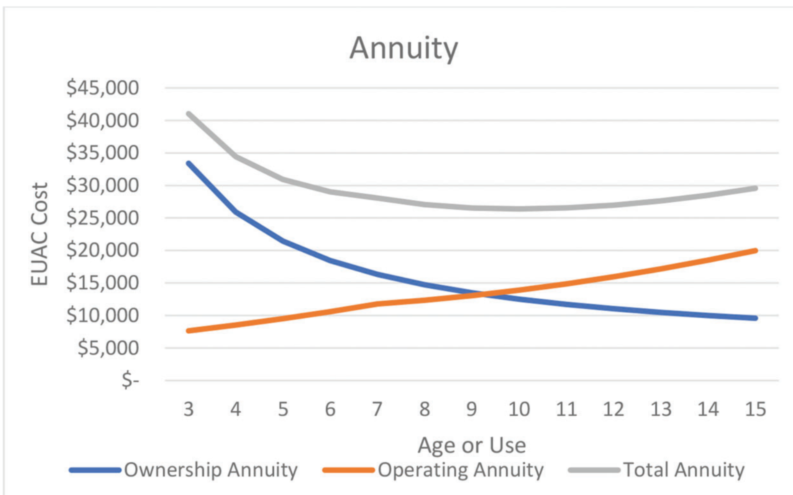


Figure 4.16 EUAC model across time in central region.

Figure 4.17 Cost per mile derived from EUAC for central region.

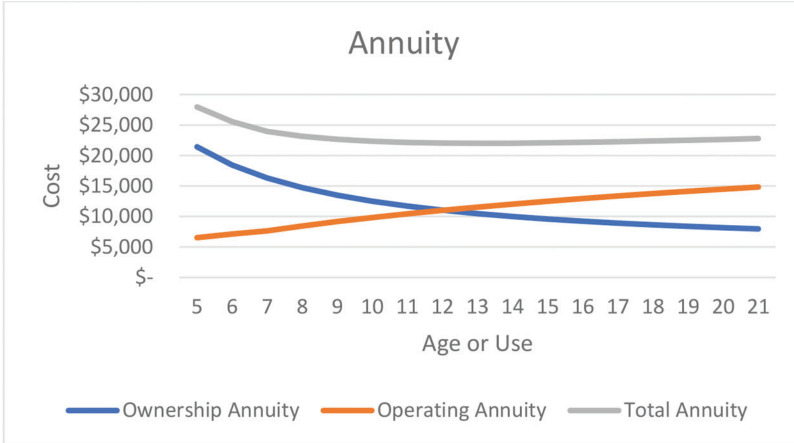


Figure 4.18 EUAC model across time for southern region.

Figure 4.19 Cost per mile for southern region.

discussed procedures for snow removal operations in states including Maryland, New York, and Utah. A broader term of "snow management" could be defined to include the following activities.

- Snow plowing.
- Spreading deicing chemicals and abrasives.
- Snow loading and disposal.

In some areas, only one or two of these three operations are carried out, and in others, all three are carried out.

Assigning trucks to routes for snow removal can be a complex undertaking due to the uncertain and rapidly changing nature of the weather and the variabilities associated with snow removal equipment and personnel, and in some cases, the complexity of the road network (Campbell & Langevin, 2000; Cook & Alprin, 1976). The motivation for snow removal in winter is primarily one of accessibility (the agency seeks to ensure that the road users have access to social and economic destinations). However, mobility and safety are also key motivations. Cook and Alprin (1976) determined that crash rates are high at road sections that are left untreated after experiencing light snow or freezing rain.

4.4.1 Planning-Level Considerations of the Snow Removal Problem

Planning level considerations for the snow removal problem have been studied by Campbell and Langevin (2000) and other researchers. These considerations include the following.

- *Functional classes and road surface types.* Any road network typically includes a varied mix of road classes and surface types. Road classifications schemes include rural vs. urban, interstate vs. non-interstates, state vs. local, single-lane vs. multi-lane, and so on. Depending on the ownership or jurisdiction of the snow removal administrative units, the scope of snow removal may be restricted to specific road classes. As such, it may be the case that certain roads may be available for travel but are not earmarked for snow clearing by a specific administrative unit due to jurisdictional limitations. Also, the pavement surface types may include rigid (concrete), asphalt, chip seal, and gravel, and may influence the type of equipment needed or used for the snow removal. In the present study, only state highways are considered—interstates, US roads, and state roads. All these roads are paved.

- *Unit locations*. The number and geographical distribution of units (depots where vehicles are parked, and chemicals/abrasives are stored) also influences the efficiency of snow removal operations. A greater number of units generally translates into higher efficiency of operations (however, if the number of units is too large, the savings in operations may be offset by the cost of providing and maintaining the units). In addition, for a given number of units, facility location techniques could be used to generate the most optimal locations of the units. Where the deicing trucks need to be refilled, the agency also seeks to optimize the locations of the units such that returns to the units for refilling, is minimal.

4.4.2 Operations-Level Considerations of the Snow Removal Problem

In this chapter, we address considerations at the planning level not the operations level. Planning level solutions are useful for purposes of resource planning and budgeting. At the operational level, however, it is well recognized that vicissitudes in weather and logistical resources may cause variations from the solutions developed at the planning level. As such, for the sake of completeness, we discuss herein, a few issues at the operational level that could be useful as INDOT continues to refine its snow removal operations. These issues have been raised by previous researchers and practitioners, and some were discussed in SPR-4502 SAC meetings with INDOT personnel. Campbell and Langevin (2000) identified some of the following issues.

1. *Weather variations*. Significant temporal and spatial variations in snowfall intensity, and variations in temperature and wind can cause changes in snow removal demand over time for a given location and across a region at a given time. Often, these changes are unexpected and cause problems in snow management.
2. *Variations in resources and the anthropogenic environment*. It is generally more difficult to carry out snow removal operations in built up environments compared to natural environments. At urban areas, snow removal is made more complex due to the need to contend with public transit stops, intersections sidewalks, crosswalks, and fire hydrants. At rural areas, however, snow removal operations are facilitated when there is available space for dumping/piling snow in areas adjacent to the road section.
3. *Resource availability*. Variations in the availability of resources (human drivers and trucks) could impair the implementation of planned snow removal operations. Also, the availability of specific equipment (which includes snowplows, snow loaders and spreaders, and there are several variations of each type, and for specific purposes. The need for specific types of equipment may vary from time to time and from location to location.
4. *Route (link) prioritization*. In certain cases, certain roadways in a network are assigned higher priority for snow removal, due for example, to road class, traffic volume, proximity to specific facilities such as hospitals, and so on. When this happens, the optimal total travel distance (and deadhead miles) covered by the snow vehicles increases significantly compared to a no-prioritization case.

4.4.3 Vehicle Routing Strategies

In operations research, the area of vehicle routing addresses contexts that include postal delivery, infrastructure inspection, snow removal, refuse collection, and so on. Past researchers have determined that efficient routing can lead to significant savings to the organizations in the private and public sector that routinely carry out routing as part of their operations. Continuing advances in operations research, and information technology and computing power has innovations in solution approaches to problems formulations of increasing complexity (Bodin & Golden, 1981).

Omer (2007) established three levels of decision making associated with snow vehicle routing.

1. Strategic (analysis and decisions on the locations of the operations base, depot, or units).
2. Tactical (analysis and decisions on fleet size and mix).
3. Operational (analysis and decisions on vehicle routing and staffing).

4.4.4 Approach 1

This approach aims to do the following.

- Determine optimal routes across the unit.

  - Explore the possibility of reassigning some of the existing snow routes from one unit to another.
  - Identify optimal unit locations.
  - Determine optimal number of trucks required to service the routes at the unit.

These objectives are achieved with the goal of reducing the deadhead miles that a truck needs to travel while performing snow removal operation.

4.4.4.1 Methodology. The first approach to optimizing the deadhead miles associated with the snow routes involved building a mathematical model and used Open Solver in Excel to obtain a solution. The goal of the model is to choose locations for units and snow routes to minimize the deadhead miles given a constraint on the number of units. It is assumed that truck clears snow in every link upon arrival at the start of a route, until it reaches back at the start, then drives back to the unit. There are no deadhead miles within the loop that the truck traverses once it reached the start of a route. The deadhead miles are the miles driven without clearing snow i.e., from the unit to the start of the route and from the end of the route back to the unit.

Let “I” refer to the edges of a network, “j” refers to snow routes that form a loop and involves snow removal along all the edges of the loop, “k” refers to the nodes of the network where units can be located and where edges meet. Let A_{ij} equal 1 if route j removes snow from arc j. Let N refer to the number of units permitted. Let D_{kj} refer to the shortest path to get from unit node k to one of the nodes that are contained in the snow route j. Thus, the deadhead mile for a truck located in k that executes route j is $2 \times D_{kj}$.

Let X_j equal to 1 if snow route j is chosen, 0 otherwise. Let Y_{kj} equal to 1 if unit k is the location for the truck that runs route j, 0 otherwise. Let Z_k equal to 1 if unit k was chosen, 0 otherwise.

Thus, our model is

$$Minimize \sum_k \sum_j D_{kj} Y_{kj} \quad \text{(Equation 4.1)}$$

With constraints shown below.

$$\sum_k Y_k \leq N \quad \text{(Equation 4.2)}$$

$$\sum_j A_{ij} X_j \geq 1 \quad \text{(Equation 4.3)}$$

$$Y_{kj} \leq X_j \quad \text{(Equation 4.4)}$$

$$Y_{kj} \leq X_j \quad \text{(Equation 4.5)}$$

$$\sum_k Y_{kj} \geq X_j \quad \text{(Equation 4.6)}$$

$$X_j, Y_{kj}, Z_k \in 0,1 \quad \text{(Equation 4.7)}$$

For the purpose of testing this model, first, a single unit, 1101 from the Terre Haute subdistrict, Crawfordsville District was chosen. The 10 snow routes assigned to this unit are defined by the Mile Post number and associated route (state route/US highway/interstate route). The mile post numbers (IndianaMap, n.d.) were converted to latitude, longitude pairs (MyGeodata Converter, n.d.) and then imported into Google Maps. Each distinct milepost was assigned a node number and a network was developed with the existing snow route descriptions. A total of 24 distinct nodes (k) were created as part of this network. Using these nodes, the edges (i) associated with each of the 10 routes (j) were listed and the routes created. For the purpose of this model, it is assumed that the node 14 is the current unit location, as it is the nearest node to the address of unit 1101.

To test the robustness of the model further, routes associated with unit 1102 were added to the twenty-four-node network described in the paragraph above. A total of 43 distinct nodes (k) now exist as part of this network with two units. Using these nodes, the edges (i) associated with each of the 16 routes (j) were listed and the routes created. For the purpose of this model, it is assumed that the nodes 14 and 31 are the current unit locations, as they are the nearest nodes to the addresses of units 1101 and 1102.

4.4.4.2 Analysis. The model was tested for the following scenarios.

- Use existing routes and unit location to test model output.
- Optimize existing routes to select best possible location of unit from existing candidate nodes.
- Add additional possible snow routes and optimize possible routes to the current unit with a fixed location.
- Add additional possible snow routes and optimize possible routes along with unit location.

Figure 4.20 provides an example of the four different approaches mentioned above.

We explain in detail the mathematical model and the analysis of one of the units in Crawfordsville District—Unit 1101.

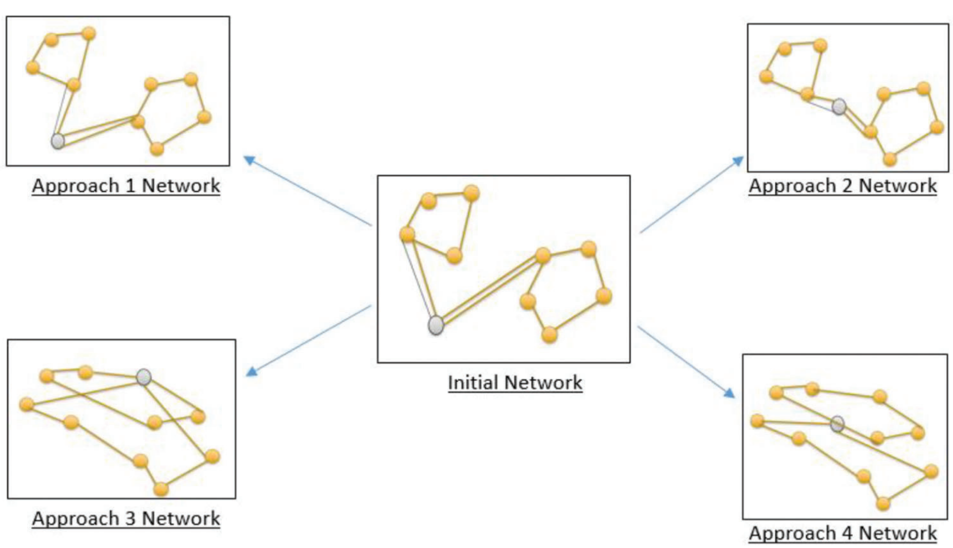


Figure 4.20 Route network.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	X	1	1	1	1	1	1	1	1	1	1	10		N	1	
2	i\j	1	2	3	4	5	6	7	8	9	10	Coverage		bigM	20	
3	1-2	1										1	1			
4	2-1	1										1	1			
5	3-4	1										1	1			
6	4-3	1										1	1			
7	5-6		1									1	1			
8	6-5		1									1	1			
9	6-22									1		1	1			
10	22-23									1		1	1			
11	23-6									1		1	1			
12	7-8			1								1	1			
13	8-7			1								1	1			
14	9-10			1								1	1			
15	9-20							1				1	1			
16	20-9							1				1	1			
17	7-20										1	1	1			
18	20-7										1	1	1			
19	7-24										1	1	1			
20	24-20										1	1	1			
21	11-12				1							1	1			
22	12-11				1							1	1			
23	12-21								1			1	1			
24	21-12								1			1	1			
25	13-14					1						1	1			
26	14-13					1						1	1			
27	13-17					1						1	1			
28	17-15					1						1	1			
29	15-13					1						1	1			
30	17-16					1						1	1			
31	16-17					1						1	1			
32	18-19						1					1	1			
33	19-18						1					1	1			

Figure 4.21 Existing snow route network.

Dkj												
k\j												
1	0	6.7	18.1	17.5	18.6	0.3	20.6	17.5	12.4	17.2		136
2	0	8.8	23.4	7.1	13.6	13.2	25.4	9.7	15.8	22.5		
3	0	10.8	20.7	5.4	15.2	15.2	27	11.3	18.5	24.4		
4	0	16.8	14.7	11.3	14.7	21.2	31.8	16	24.5	30.4		
5	6.7	0	16.9	12.3	13.3	6.7	19.4	12.3	10	16		
6	10	0	6.9	7.6	6.5	3.1	9.3	6.7	0	5.9		
7	18.1	6.9	0	24.9	11.4	27.6	33.8	23	6.9	0		
8	14.7	17.9	0	44.7	29.7	45.6	51.9	41.1	17.9	11		
9	23.9	12.7	0	15.3	11.5	8.1	0	11.7	7.1	7		
10	24.9	13.7	0	14.3	10.5	7.1	1	10.7	6.1	6		
11	5.4	14.8	30.5	0	20.3	20.3	31.5	16.4	23.8	29.5		
12	9.7	7.6	14.3	0	4.1	9.7	15.3	0	7.6	12.9		
13	15.8	8.7	12.8	6.4	0	5.4	13.8	5.5	6.6	10.6		
14	13.6	6.5	10.5	4.1	0	5.6	11.5	2.9	4.5	8.8		
15	14.7	18.3	11.4	14.7	0	17.7	23.3	13.2	16.7	11.4		
16	16.3	11.8	15.9	7.6	0	8.5	16.9	6	9.7	13.9		
17	16.3	10.7	14.7	8.3	0	7.3	15.7	4.9	8.5	12.8		
18	0.3	6.7	19.1	17.8	18.1	0	20.1	17.8	12.9	17.4		
19	13.7	3.1	7.1	9.7	5.4	0	8.1	6.2	3.1	5.5		
20	20.6	9.3	6	16	11.9	8.6	0	4.7	9.1	0		
21	15.8	6.7	10.7	5.5	1.4	6.2	4.7	0	6.6	4.7		
22	12.6	1	7.6	8.3	6.4	3.1	8.6	6.6	0	4.9		
23	13.2	2	6.1	8.7	4.5	1.6	7.1	6.6	0	4.5		
24	17.2	5.9	10	12.9	8.8	5.5	4	10.8	4.5	0		

Figure 4.22 Deadhead miles with current network.

1. Use Existing routes and unit location to test model output.

The existing snow route network was entered into the model as shown in Figure 4.21. The total deadhead for this snow route is 136 miles, as shown in Figure 4.22, and the number of units is capped at 1. The constraint of fixing the unit at node 14 was added, as shown in Figure 4.23, and the model solved. The output, as expected, resulted in the network as it is currently being run, with all routes assigned to unit at node 14 as shown in Figure 4.24.

2. Optimize existing routes to select best possible location of unit from existing candidate nodes.

The same model was solved with the option to reassign the unit location to another node. This resulted in an optimized deadhead value of 108.6 miles as shown in Figure 4.25, with the new unit located at node 23 as shown in Figure 4.26.

The new unit location and routes associated with it are represented in Figure 4.27.

Ykj	0/1											Zk	0/1	
1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
2	0	0	0	0	0	0	0	0	0	0	0	0		0
3	0	0	0	0	0	0	0	0	0	0	0	0		0
4	0	0	0	0	0	0	0	0	0	0	0	0		0
5	0	0	0	0	0	0	0	0	0	0	0	0		0
6	0	0	0	0	0	0	0	0	0	0	0	0		0
7	0	0	0	0	0	0	0	0	0	0	0	0		0
8	0	0	0	0	0	0	0	0	0	0	0	0		0
9	0	0	0	0	0	0	0	0	0	0	0	0		0
10	0	0	0	0	0	0	0	0	0	0	0	0		0
11	0	0	0	0	0	0	0	0	0	0	0	0		0
12	0	0	0	0	0	0	0	0	0	0	0	0		0
13	0	0	0	0	0	0	0	0	0	0	0	0		0
14	1	1	1	1	1	1	1	1	1	1	10	1		20
15	0	0	0	0	0	0	0	0	0	0	0	0		0
16	0	0	0	0	0	0	0	0	0	0	0	0		0
17	0	0	0	0	0	0	0	0	0	0	0	0		0
18	0	0	0	0	0	0	0	0	0	0	0	0		0
19	0	0	0	0	0	0	0	0	0	0	0	0		0
20	0	0	0	0	0	0	0	0	0	0	0	0		0
21	0	0	0	0	0	0	0	0	0	0	0	0		0
22	0	0	0	0	0	0	0	0	0	0	0	0		0
23	0	0	0	0	0	0	0	0	0	0	0	0		0
24	0	0	0	0	0	0	0	0	0	0	0	0		0
	1	1	1	1	1	1	1	1	1	1				

Figure 4.23 Solution for existing snow route with unit at node 14.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	X	1	1	1	1	1	1	1	1	1	1	10		N	1
2	i\j	1	2	3	4	5	6	7	8	9	10	Coverage		bigM	20
3	1-2	1										1	1		
4	2-1	1										1	1		
5	3-4	1										1	1		
6	4-3	1										1	1		
7	5-6		1									1	1		
8	6-5		1									1	1		
9	6-22									1		1	1		
10	22-23									1		1	1		
11	23-6									1		1	1		
12	7-8			1								1	1		
13	8-7			1								1	1		
14	9-10			1								1	1		
15	9-20							1				1	1		
16	20-9							1				1	1		
17	7-20										1	1	1		
18	20-7										1	1	1		
19	7-24										1	1	1		
20	24-20										1	1	1		
21	11-12				1							1	1		
22	12-11				1							1	1		
23	12-21								1			1	1		
24	21-12								1			1	1		
25	13-14					1						1	1		
26	14-13					1						1	1		
27	13-17					1						1	1		
28	17-15					1						1	1		
29	15-13					1						1	1		
30	17-16					1						1	1		
31	16-17					1						1	1		
32	18-19						1					1	1		
33	19-18						1					1	1		
34															

Figure 4.24 Snow route network.

3. Add additional possible snow routes and optimize possible routes to the current unit with a fixed location.

As shown in Figure 4.28, possible snow routes were added based on the existing network. The new routes (X_j) were initially set to 0. With the unit location fixed at node 14 as noted in Figure 4.30, the model was solved. The optimized solution resulted in a deadhead of 109.8 miles as shown in Figure 4.29, and allocation of snow routes with a reduction of total routes from 10 to 8 as displayed in Figure 4.28.

The new routes associated with the current unit location are represented in Figure 4.31 using Google Maps.

4. Add additional possible snow routes and optimize possible routes along with unit location.

As shown in Figure 4.32, additional probable routes with a probable new unit location are considered for scenario 4. The model with additional possible snow routes was solved to also include the possibility of reassigning the unit location to a new node. As shown

35													
36	Dkj												
37	k\j												
38	1	0	6.7	18.1	17.5	18.6	0.3	20.6	17.5	12.4	17.2		108.6
39	2	0	8.8	23.4	7.1	13.6	13.2	25.4	9.7	15.8	22.5		
40	3	0	10.8	20.7	5.4	15.2	15.2	27	11.3	18.5	24.4		
41	4	0	16.8	14.7	11.3	14.7	21.2	31.8	16	24.5	30.4		
42	5	6.7	0	16.9	12.3	13.3	6.7	19.4	12.3	10	16		
43	6	10	0	6.9	7.6	6.5	3.1	9.3	6.7	0	5.9		
44	7	18.1	6.9	0	24.9	11.4	27.6	33.8	23	6.9	0		
45	8	14.7	17.9	0	44.7	29.7	45.6	51.9	41.1	17.9	11		
46	9	23.9	12.7	0	15.3	11.5	8.1	0	11.7	7.1	7		
47	10	24.9	13.7	0	14.3	10.5	7.1	1	10.7	6.1	6		
48	11	5.4	14.8	30.5	0	20.3	20.3	31.5	16.4	23.8	29.5		
49	12	9.7	7.6	14.3	0	4.1	9.7	15.3	0	7.6	12.9		
50	13	15.8	8.7	12.8	6.4	0	5.4	13.8	5.5	6.6	10.6		
51	14	13.6	6.5	10.5	4.1	0	5.6	11.5	2.9	4.5	8.8		
52	15	14.7	18.3	11.4	14.7	0	17.7	23.3	13.2	16.7	11.4		
53	16	16.3	11.8	15.9	7.6	0	8.5	16.9	6	9.7	13.9		
54	17	16.3	10.7	14.7	8.3	0	7.3	15.7	4.9	8.5	12.8		
55	18	0.3	6.7	19.1	17.8	18.1	0	20.1	17.8	12.9	17.4		
56	19	13.7	3.1	7.1	9.7	5.4	0	8.1	6.2	3.1	5.5		
57	20	20.6	9.3	6	16	11.9	8.6	0	4.7	9.1	0		
58	21	15.8	6.7	10.7	5.5	1.4	6.2	4.7	0	6.6	4.7		
59	22	12.6	1	7.6	8.3	6.4	3.1	8.6	6.6	0	4.9		
60	23	13.2	2	6.1	8.7	4.5	1.6	7.1	6.6	0	4.5		
61	24	17.2	5.9	10	12.9	8.8	5.5	4	10.8	4.5	0		
62													

Figure 4.25 Optimized deadhead with new unit location.

70															
71	Ykj	0/1										Zk	0/1		
72	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
73	2	0	0	0	0	0	0	0	0	0	0	0	0		0
74	3	0	0	0	0	0	0	0	0	0	0	0	0		0
75	4	0	0	0	0	0	0	0	0	0	0	0	0		0
76	5	0	0	0	0	0	0	0	0	0	0	0	0		0
77	6	0	0	0	0	0	0	0	0	0	0	0	0		0
78	7	0	0	0	0	0	0	0	0	0	0	0	0		0
79	8	0	0	0	0	0	0	0	0	0	0	0	0		0
80	9	0	0	0	0	0	0	0	0	0	0	0	0		0
81	10	0	0	0	0	0	0	0	0	0	0	0	0		0
82	11	0	0	0	0	0	0	0	0	0	0	0	0		0
83	12	0	0	0	0	0	0	0	0	0	0	0	0		0
84	13	0	0	0	0	0	0	0	0	0	0	0	0		0
85	14	0	0	0	0	0	0	0	0	0	0	0	0		0
86	15	0	0	0	0	0	0	0	0	0	0	0	0		0
87	16	0	0	0	0	0	0	0	0	0	0	0	0		0
88	17	0	0	0	0	0	0	0	0	0	0	0	0		0
89	18	0	0	0	0	0	0	0	0	0	0	0	0		0
90	19	0	0	0	0	0	0	0	0	0	0	0	0		0
91	20	0	0	0	0	0	0	0	0	0	0	0	0		0
92	21	0	0	0	0	0	0	0	0	0	0	0	0		0
93	22	0	0	0	0	0	0	0	0	0	0	0	0		0
94	23	1	1	1	1	1	1	1	1	1	1	10	1		20
95	24	0	0	0	0	0	0	0	0	0	0	0	0		0
96															
97		1	1	1	1	1	1	1	1	1	1				
98															

Figure 4.26 Solution for existing network with new unit location at node 23.

in Figure 4.33, the optimized solution yielded a result of 85.2 deadhead miles and allocation of snow routes with a reduction of total routes from 10 to 8, with the new unit located at node 23 as shown in Figure 4.34.

The new routes associated with the new unit location is represented in Figure 4.35.

The results for the remaining units across six districts are displayed in Appendix C.

4.4.5 Approach 2

In Table 4.12, we present a classification of snow vehicle routing problems based on characteristics that describe the problem.

4.4.5.1 Methodology

4.4.5.1.1 Preliminary discussion. From the study objectives, we developed four analysis options (modules) for the user of our electronic tool: optimal-fleet-size, variable-fleet-size, optimal-fleet-size-multilane, variable-fleet-size-multilane. Optimal-fleet-size module helps the tool's user to make decisions on the optimal number of trucks and their respective snow routes. The variable-fleet-size module gives the flexibility of the tool's user to find the optimal route for their existing trucks.

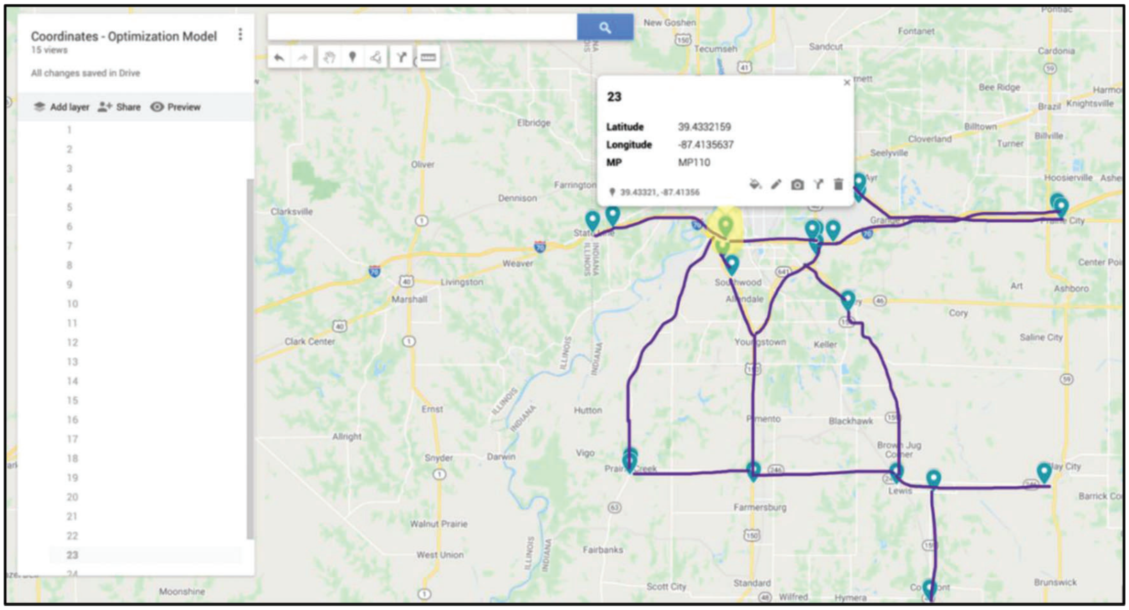


Figure 4.27 New unit location and associated routes—scenario 2.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	X	1	0	1	0	1	1	0	0	0	0	1	1	1	1	0	8		N
2	i\j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Coverage		bigM
3	1-2	1															1	1	
4	2-1	1															1	1	
5	3-4	1															1	1	
6	4-3	1															1	1	
7	5-6		1										1				1	1	
8	6-5		1										1				1	1	
9	6-22									1			1				1	1	
10	22-23									1			1				1	1	
11	23-6									1			1				1	1	
12	7-8			1												1	1	1	
13	8-7			1												1	1	1	
14	9-10			1										1			2	1	
15	9-20							1						1			1	1	
16	20-9							1						1			1	1	
17	7-20										1			1			1	1	
18	20-7										1				1		1	1	
19	7-24										1				1		1	1	
20	24-20										1				1		1	1	
21	11-12				1							1					1	1	
22	12-11				1							1					1	1	
23	12-21								1			1					1	1	
24	21-12								1			1					1	1	
25	13-14					1											1	1	
26	14-13					1											1	1	
27	13-17					1											1	1	
28	17-15					1											1	1	
29	15-13					1											1	1	
30	17-16					1											1	1	
31	16-17					1											1	1	
32	18-19						1										1	1	
33	19-18						1										1	1	
34																			

Figure 4.28 Existing snow routes with probable additional routes.

Optimal-Fleet-Size

- Algorithm provides the optimal number of trucks and the optimal route for each truck.
- Optimal routes consist of snow routes (fixed) and DH routes (variable).
- The identified optimal number of trucks may be less (or more) than the existing number of trucks.
- Snow removal time, cruise speed and snow removal speed can be changed by the user (input).

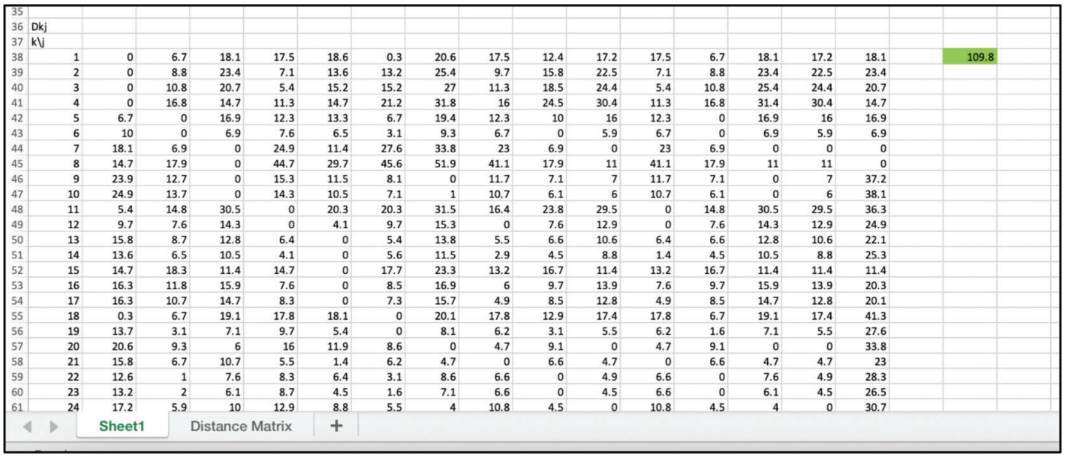
Variable-Fleet-Size

- The number of trucks will be the input of this module.
- The algorithm results will indicate the optimal route for each truck.
- Optimal routes consist of snow routes (fixed) and DH routes (variable).
- The optimal number of routes will be equal to the number of trucks available (one route for each truck).

Certain segments have multiple lanes and therefore need to be served multiple times. Therefore, the tool's modules Optimal-Fleet-Size-MultiLane and Variable-Fleet-Size-MultiLane, are designed to provide solutions for the cases of multiple lanes.

Optimal-Fleet-Size-MultiLane

- Some segments have multiple lanes in which snow needs to be cleared.

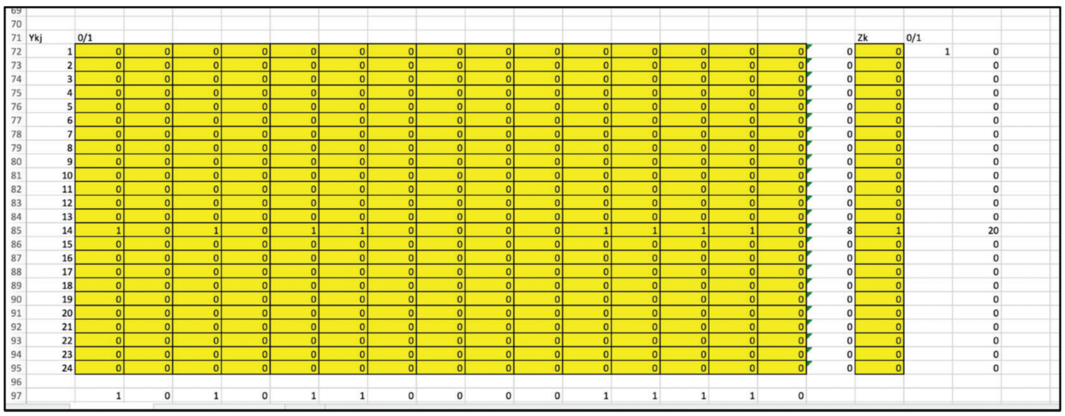


Dkj

k\j																
1	0	6.7	18.1	17.5	18.6	0.3	20.6	17.5	12.4	17.2	17.5	6.7	18.1	17.2	18.1	109.8
2	0	8.8	23.4	7.1	13.6	13.2	25.4	9.7	15.8	22.5	7.1	8.8	23.4	22.5	23.4	
3	0	10.8	20.7	5.4	15.2	15.2	27	11.3	18.5	24.4	5.4	10.8	25.4	24.4	20.7	
4	0	16.8	14.7	11.3	14.7	21.2	31.8	16	24.5	30.4	11.3	16.8	31.4	30.4	14.7	
5	6.7	0	16.9	12.3	13.3	6.7	19.4	12.3	10	16	12.3	0	16.9	16	16.9	
6	10	0	6.9	7.6	6.5	3.1	9.3	6.7	0	5.9	6.7	0	6.9	5.9	6.9	
7	18.1	6.9	0	24.9	11.4	27.6	33.8	23	6.9	0	23	6.9	0	0	0	
8	14.7	17.9	0	44.7	29.7	45.6	51.9	41.1	17.9	11	41.1	17.9	11	11	0	
9	23.9	12.7	0	15.3	11.5	8.1	0	11.7	7.1	7	11.7	7.1	0	7	37.2	
10	24.9	13.7	0	14.3	10.5	7.1	1	10.7	6.1	6	10.7	6.1	0	6	38.1	
11	5.4	14.8	30.5	0	20.3	20.3	31.5	16.4	23.8	29.5	0	14.8	30.5	29.5	36.3	
12	9.7	7.6	14.3	0	4.1	9.7	15.3	0	7.6	12.9	0	7.6	14.3	12.9	24.9	
13	15.8	8.7	12.8	6.4	0	5.4	13.8	5.5	6.6	10.6	6.4	6.6	12.8	10.6	22.1	
14	13.6	6.5	10.5	4.1	0	5.6	11.5	2.9	4.5	8.8	1.4	4.5	10.5	8.8	25.3	
15	14.7	18.3	11.4	14.7	0	17.7	23.3	13.2	16.7	11.4	13.2	16.7	11.4	11.4	11.4	
16	16.3	11.8	15.9	7.6	0	8.5	16.9	6	9.7	13.9	7.6	9.7	15.9	13.9	20.3	
17	16.3	10.7	14.7	8.3	0	7.3	15.7	4.9	8.5	12.8	4.9	8.5	14.7	12.8	20.1	
18	0.3	6.7	19.1	17.8	18.1	0	20.1	17.8	12.9	17.4	17.8	6.7	19.1	17.4	41.3	
19	13.7	3.1	7.1	9.7	5.4	0	8.1	6.2	3.1	5.5	6.2	1.6	7.1	5.5	27.6	
20	20.6	9.3	6	16	11.9	8.6	0	4.7	9.1	0	4.7	9.1	0	0	33.8	
21	15.8	6.7	10.7	5.5	1.4	6.2	4.7	0	6.6	4.7	0	6.6	4.7	4.7	23	
22	12.6	1	7.6	8.3	6.4	3.1	8.6	6.6	0	4.9	6.6	0	7.6	4.9	28.3	
23	13.2	2	6.1	8.7	4.5	1.6	7.1	6.6	0	4.5	6.6	0	6.1	4.5	26.5	
24	17.2	5.9	10	12.9	8.8	5.5	4	10.8	4.5	0	10.8	4.5	4	0	30.7	

Sheet1 | Distance Matrix

Figure 4.29 Optimized deadhead miles for new routes.



Ykj	0/1																Zk	0/1	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
14	1	0	1	0	1	1	0	0	0	0	1	1	1	1	0	8	1		20
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	1	0	1	0	1	1	0	0	0	0	1	1	1	1	0				

Figure 4.30 Routes to be run if unit location is fixed at node 14.

- The algorithm provides the optimal number of trucks and the optimal route for each truck to cover all the service segments (segments to be cleared of snow).
- Optimal routes include both snow routes (fixed) and DH routes (variable).
- Optimal number of trucks may be less (or more) than the existing number of trucks.
- Snow removal time, cruise speed and snow removal speed can be changed by the user (input).

Variable-Fleet-Size-MultiLane

- Some segments have multiple lanes at which snow needs to be cleared.
- Segments with multiple lanes and therefore need multiple iterations of snow removal, are considered.
- The number of trucks is an input for the algorithm.
- The algorithm provides the optimal route for each truck.
- Optimal routes consist of snow routes (fixed) and DH routes (variable).

4.4.5.1.2 Snow route generated algorithms

1. Introduction

In determining the optimal routes for existing trucks, we identify optimal routing for existing trucks in each unit with the goal to minimize the deadhead miles and record the network performance metrics associated with the optimal routing. The two performance metrics are the number of deadhead miles and the total time spent in the snow removal. The number of deadhead miles is calculated as follows.

$$\text{Deadhead miles} = \text{Travel Miles} - \text{Snow Miles} \quad \text{(Equation 4.8)}$$

As shown in Figure 4.36, the deadhead miles are generated in at least one of two ways: (a) the connected segment between the unit and the start of the snow route; or (b) the shared (overlapping) segments traveled by other trucks. According to the units' information and snow routes' data, the second way generates most of the deadhead miles. Therefore, it is necessary to determine the optimal snow route to minimize the incident of shared segments, and therefore, to reduce the deadhead miles. The objective of the algorithms is to minimize deadhead miles, therefore, the first way of deadhead mile generation, is also considered in the analysis.

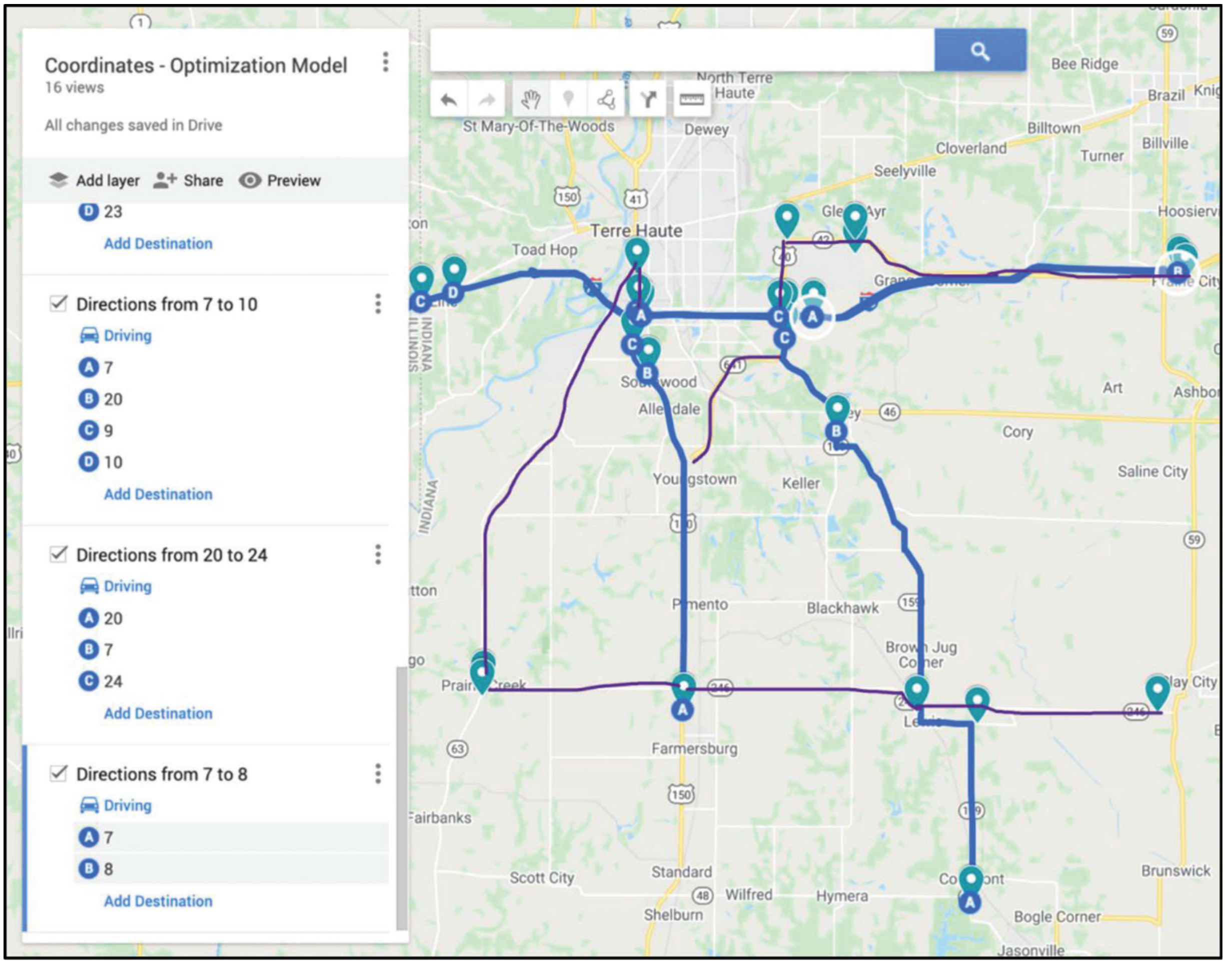
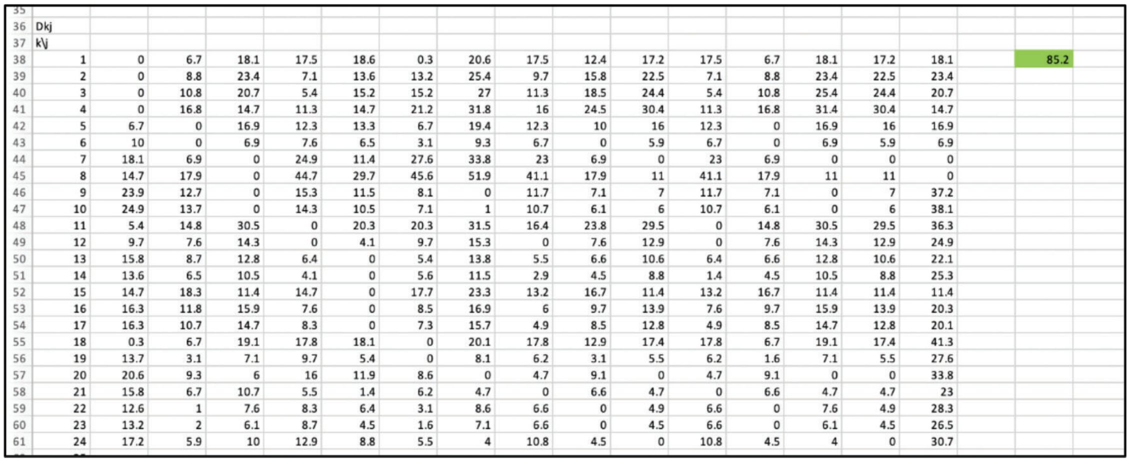


Figure 4.31 New routes to be run with unit location at node 14.

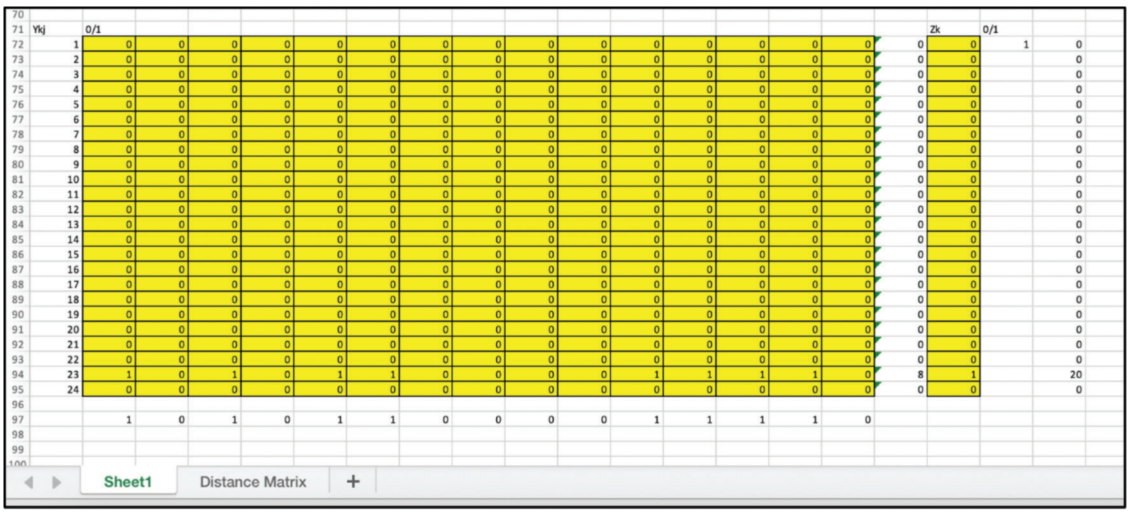
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	X	1	0	1	0	1	1	0	0	0	0	1	1	1	1	0	8		N	1
2	i\j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Coverage		bigM	20
3	1-2	1															1	1		
4	2-1	1															1	1		
5	3-4	1															1	1		
6	4-3	1															1	1		
7	5-6		1										1				1	1		
8	6-5		1										1				1	1		
9	6-22									1			1				1	1		
10	22-23									1			1				1	1		
11	23-6									1			1				1	1		
12	7-8			1												1	1	1		
13	8-7			1												1	1	1		
14	9-10			1										1			2	1		
15	9-20							1						1			1	1		
16	20-9							1						1			1	1		
17	7-20										1			1			1	1		
18	20-7										1				1		1	1		
19	7-24										1				1		1	1		
20	24-20										1				1		1	1		
21	11-12				1							1					1	1		
22	12-11				1							1					1	1		
23	12-21								1			1					1	1		
24	21-12								1			1					1	1		
25	13-14					1											1	1		
26	14-13					1											1	1		
27	13-17					1											1	1		
28	17-15					1											1	1		
29	15-13					1											1	1		
30	17-16					1											1	1		
31	16-17					1											1	1		
32	18-19						1										1	1		
33	19-18						1										1	1		
34																				

Figure 4.32 Additional probable routes with new unit location.



Dkj																	
k\j																	
1	0	6.7	18.1	17.5	18.6	0.3	20.6	17.5	12.4	17.2	17.5	6.7	18.1	17.2	18.1		85.2
2	0	8.8	23.4	7.1	13.6	13.2	25.4	9.7	15.8	22.5	7.1	8.8	23.4	22.5	23.4		
3	0	10.8	20.7	5.4	15.2	15.2	27	11.3	18.5	24.4	5.4	10.8	25.4	24.4	20.7		
4	0	16.8	14.7	11.3	14.7	21.2	31.8	16	24.5	30.4	11.3	16.8	31.4	30.4	14.7		
5	6.7	0	16.9	12.3	13.3	6.7	19.4	12.3	10	16	12.3	0	16.9	16	16.9		
6	10	0	6.9	7.6	6.5	3.1	9.3	6.7	0	5.9	6.7	0	6.9	5.9	6.9		
7	18.1	6.9	0	24.9	11.4	27.6	33.8	23	6.9	0	23	6.9	0	0	0		
8	14.7	17.9	0	44.7	29.7	45.6	51.9	41.1	17.9	11	41.1	17.9	11	11	0		
9	23.9	12.7	0	15.3	11.5	8.1	0	11.7	7.1	7	11.7	7.1	0	7	37.2		
10	24.9	13.7	0	14.3	10.5	7.1	1	10.7	6.1	6	10.7	6.1	0	6	38.1		
11	5.4	14.8	30.5	0	20.3	20.3	31.5	16.4	23.8	29.5	0	14.8	30.5	29.5	36.3		
12	9.7	7.6	14.3	0	4.1	9.7	15.3	0	7.6	12.9	0	7.6	14.3	12.9	24.9		
13	15.8	8.7	12.8	6.4	0	5.4	13.8	5.5	6.6	10.6	6.4	6.6	12.8	10.6	22.1		
14	13.6	6.5	10.5	4.1	0	5.6	11.5	2.9	4.5	8.8	1.4	4.5	10.5	8.8	25.3		
15	14.7	18.3	11.4	14.7	0	17.7	23.3	13.2	16.7	11.4	13.2	16.7	11.4	11.4	11.4		
16	16.3	11.8	15.9	7.6	0	8.5	16.9	6	9.7	13.9	7.6	9.7	15.9	13.9	20.3		
17	16.3	10.7	14.7	8.3	0	7.3	15.7	4.9	8.5	12.8	4.9	8.5	14.7	12.8	20.1		
18	0.3	6.7	19.1	17.8	18.1	0	20.1	17.8	12.9	17.4	17.8	6.7	19.1	17.4	41.3		
19	13.7	3.1	7.1	9.7	5.4	0	8.1	6.2	3.1	5.5	6.2	1.6	7.1	5.5	27.6		
20	20.6	9.3	6	16	11.9	8.6	0	4.7	9.1	0	4.7	9.1	0	0	33.8		
21	15.8	6.7	10.7	5.5	1.4	6.2	4.7	0	6.6	4.7	0	6.6	4.7	4.7	23		
22	12.6	1	7.6	8.3	6.4	3.1	8.6	6.6	0	4.9	6.6	0	7.6	4.9	28.3		
23	13.2	2	6.1	8.7	4.5	1.6	7.1	6.6	0	4.5	6.6	0	6.1	4.5	26.5		
24	17.2	5.9	10	12.9	8.8	5.5	4	10.8	4.5	0	10.8	4.5	4	0	30.7		

Figure 4.33 Optimized deadhead on creating, reassigning new routes, and moving unit to a new location.



Ykj	0/1																Zk	0/1	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
23	1	0	1	0	1	1	0	0	0	0	1	1	1	1	0	8	1		20
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	1	0	1	0	1	1	0	0	0	0	1	1	1	1	0				

Sheet1 | Distance Matrix | +

Figure 4.34 New routes assigned to unit located at node 23.

- Total time spent in clearing the snow=sum of travel times spent on each link.
- Other output: specific snow routes cleared by each truck.

2. Assumptions

The following assumptions, derived based in part from on Omer (2007), are made in formulating the problem.

- The distance between nodes, and service requirement of each link and other requisite data on the road network are available.
- The number of prospective routes is not fixed.
- All snow removal trucks have the same capacity, and this does not change with time.
- As shown in Figure 4.37, any vehicle that starts traveling on a road link with or without service at that link, should complete that link or segment, that is, trucks do not break a route in the middle of a link.
- The truck speed during snow removal may be less than that during traveling on a link without removing the snow.
- There is no priority for the snow removal across the links. However, priority could be incorporated by first carrying out the routing for the highest priority roads, and then repeat for road of successively lower priority.
- Delays or stopping times for traffic signals or poor road conditions are assumed to be negligible.
- The time required to remove snow on a road link depends on the link distance and travel speed.

3. Data Preprocessing

To carry out preprocessing of the data, the steps are the following as shown in Figure 4.38.

- *Snow route location* (start and end MP, road name).
- *Units' location* (match the map and the Excel data).
- *Network structure* from the INDOT District Mile Marker Map.

4. Input Files

The input file contains five different input information as shown in Figure 4.39: Node A, Node Z, Types, Length, and Lanes.

- Node A: the link (segment) start Milepost point.
- Node Z: the link (segment) end Milepost point.
- Types: the type of the segment/link (service or cruise).

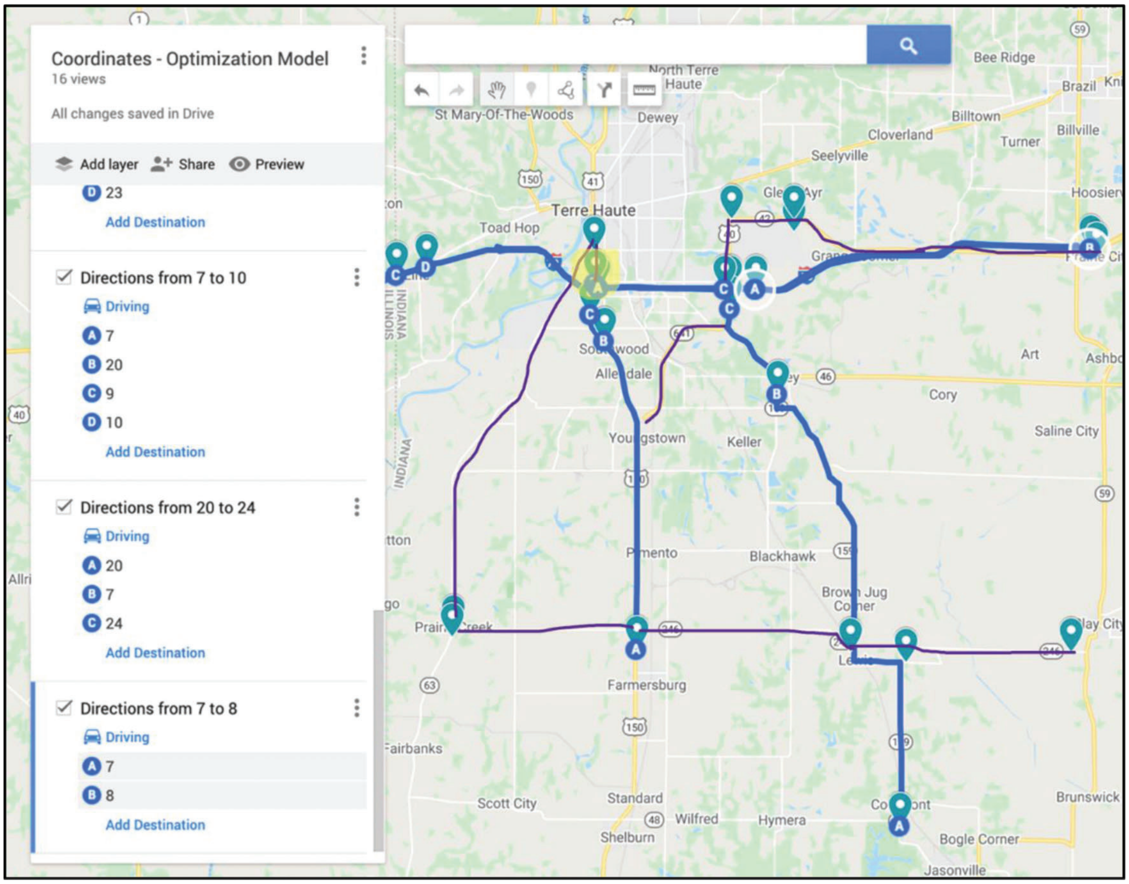


Figure 4.35 New routes and new unit located at node 23.

- Length: the length of the segment/link.
- Lanes: On the link, how many lanes need to have snow removed.

The input files included in the “Input_files” folder, which includes all the given units across Indiana.

5. Model Framework

In developing the model framework, we considered the factors that contribute to the deadhead mile (the main component of the objective function) (Figure 4.40).

Additional assumptions made were as follows.

- *Travel routes* consist of only: US routes, state roads, and interstates.
- *Salt capacity* of snow removal trucks is adequate for the snow-removal routes assigned to that truck.
- The snow roads are *cleaned only once*. Assumption is made for planning purposes.
- After it is cleared, the *snow road* designation changes to *cruise road.*

6. Mathematical Model

6.1 Prelude

It is sought to travel on all snow links in a specified network in a manner that minimizes the total distance of the travel. Links may be travelled once or more. This is a classic case of the “Rural Postman” problem. The goal of INDOT is slightly different compared to the case of the traditional Rural Postman Problem. INDOT seeks to minimize the total deadhead distance.

The deadhead miles are calculated as the total travel distance – snow route distance. However, the snow routes (and, hence, their total distance) are fixed. Therefore, the INDOT goal can be restated as simply minimizing the total travel distance. In that case, the Rural Postman Problem is applicable. The snow removal time limit, snow removal speed, and cruise speed will be variable (input of the algorithm). Two basic types of edges/links are considered: (a) uncleaned road/service road (these need snow removal) and cleared road/cruise road (where the speed is higher than the uncleaned road but generate deadhead miles). Table 4.13 presents the mathematical model nomenclature.

6.2 Objective Function

$$\min(D_{v1}(S_1,C_1)+D_{v2}(S_2,C_2)+D_{v3}(S_3,C_3)+\ldots$$

$$+D_{v_n}(S_n,C_n))\text{(Equation 4.9)}$$

The objective function determines the minimum overall travel distance of all in-service trucks used to remove snow on the network’s links of interest

TABLE 4.12
Snow removal routing—characteristics and assumptions

Criterion Category	Criterion	Details	Assumptions of the Approach Described in This Chapter
Network-Related	Number of base facilities (units)	1 More than 1	One (1) unit. Routing carried out for trucks (and associated jurisdiction network), separately for the 101 units in Indiana
	Nature of demand (snow removal)	Deterministic Probabilistic	Determinsitic[1]
	Link direction status	Undirected Directed Hybrid	Directed
	Objective of the snow removal	Minimize distance or cost associated with total travel or deadhead travel Minimize number of vehicles required Maximize utility associated with travel routes (for objectives involving multiple criteria).	Minimize distance or cost associated with total travel or deadhead travel Minimize number of vehicles required
Vehicle Related	Size of vehicle fleet available	1 More than 1	More than 1 vehicle
	Uniformity of vehicle types	Uniform Non-uniform (depends on link types, etc.)	Uniform trucks
	Uniformity of vehicle size	No Yes	Uniformity is assumed[1]
Time Related	Any time constraint to serve a particular link?	No Yes	No
	Any overall time constraint to serve all links in the unit's network?	No Yes	Yes. 3 hours (as per INDOT website)
	Specified start or end times for each truck or route's snow removal operations?	No (problem is only a routing problem) Yes (problem is both a routing and scheduling problem)	No specified start or end times
Link Priority or Precedence	Priority relationships among links?	No Yes	None
	Precedence relationships among links?	No Yes	None

[1] *For planning purposes.*

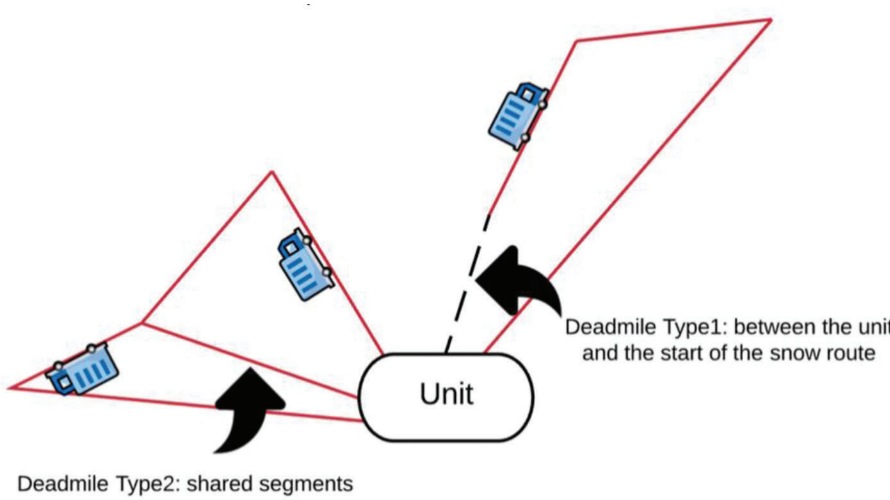


Figure 4.36 Two types of deadhead miles.

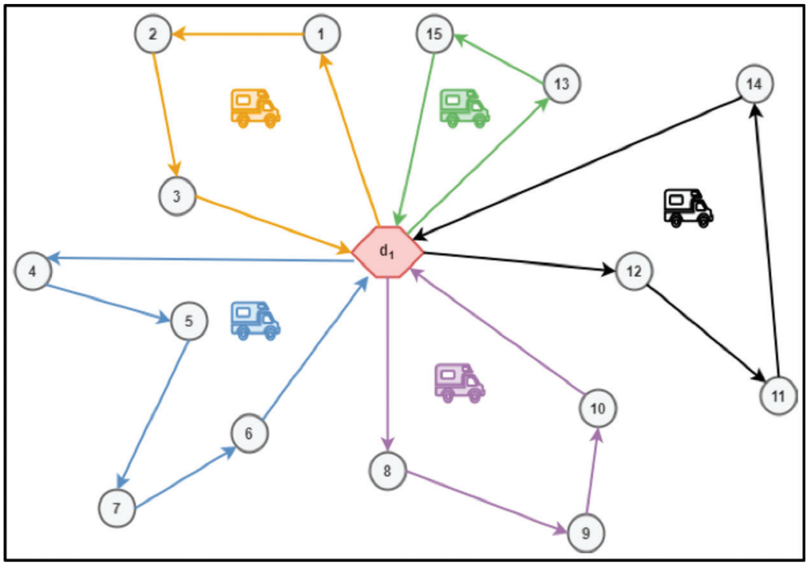


Figure 4.37 Conceptual figure (the travel distances may overlap).

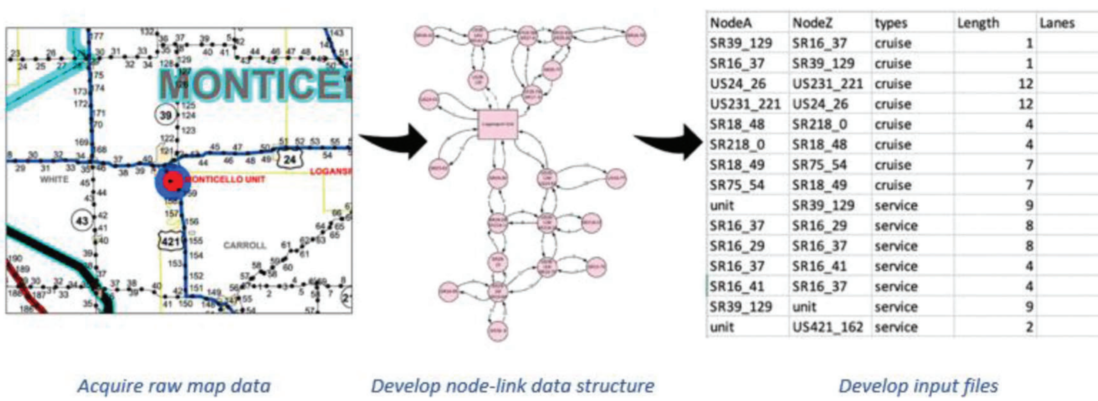


Figure 4.38 Sequence of the data processing.

NodeA	NodeZ	types	Length	Lanes
SR39_129	SR16_37	cruise	1	0
SR16_37	SR39_129	cruise	1	0

Figure 4.39 The five input data types.

(targeted for snow removal) as well as those that serve a role to provide access to the depot or to links targeted for snow removal.

D_{vn} represents the total travel miles of vehicle n under the condition of service roads set: S_n, cruise roads set:C_n.

6.3 Constraints

Constraint 1: A 3-hr time limit (which can be changed flexibly based on the real situations).

$$\sum_{i=1}^{n}\left(\frac{v_i D_{snow}}{v_{snow}} + \frac{v_i D_{cruise}}{v_{cruise}}\right) \leq 3hr \qquad \text{(Equation 4.10)}$$

Constraint 2: Snow removal speed is half of cruise speed (which can be changed based on real situations).

$$v_{snow} = \frac{1}{2} v_{cruise} \qquad \text{(Equation 4.11)}$$

6.4 Network Structure Example

As shown in Figure 4.42, the network structure includes nodes and edges/links that represent the road network in the vicinity of the unit. The input information to the heuristic algorithm is shown in Figure 4.43.

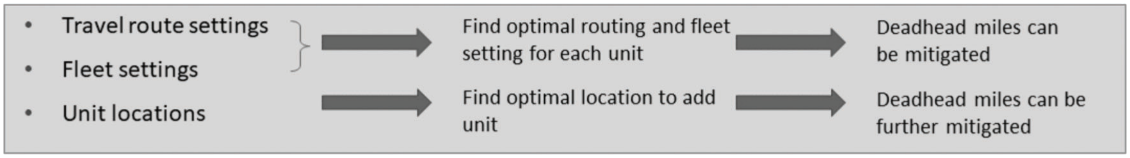


Figure 4.40 Factors affecting the severity of deadhead distance.

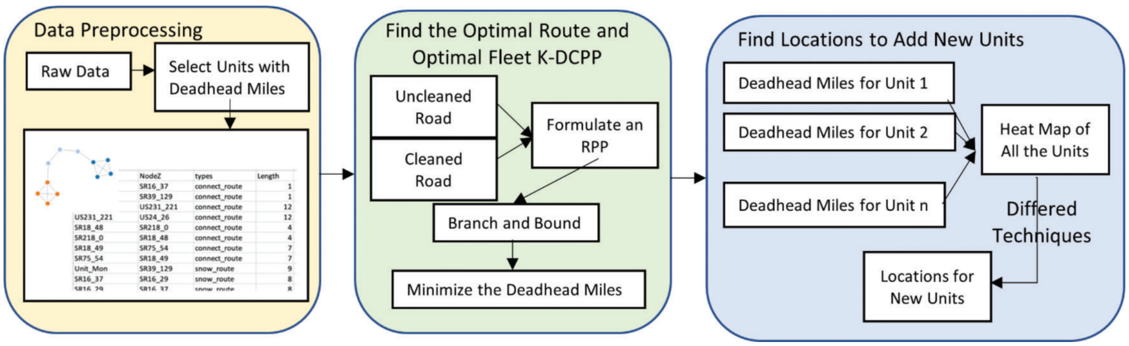


Figure 4.41 Overall framework for the analysis.

TABLE 4.13
Mathematical model nomenclature

Variables	Explanation
Edges	The links in the unit's network (roads)
Service_Edges	The links in the unit's network need to remove snow (service roads)
Cruise_Edges	The links in the unit's network no need remove snow (cruise roads)
Vertices	The nodes in the unit's network (intersection/milepost point)
Vertice_Num	Number of nodes in the unit's network
Labels_Sample	Vertices labels, for example: unit: "unit" milepost point: "US-12-25"
Weights_Sample	Link weight (road length)
Cruise_Speed	Travel speed of passing the cleaned road
Snow_Removal_speed	Snow removal speed
Time_Limit	Maximum time of finishing the snow removal and go back to the unit
Sub_Routes	Candidate routes for the trucks to select
Assigned_Routes	All the optimal routes assigned to the trucks
Assigned_Route	Optimal routes assigned in one time step
Truck_Num	Optimal number of trucks
Total_DH	Optimal total deadhead miles
New_Service	Updated Service_Edges after remove any nodes at each time step
New_Cruise	Updated Cruise_Edges after remove any nodes at each time step
New_Edges	Updated Edges after remove any nodes at each time step
Simple_Loops	Candidate routes by split the long Sub_routes

7. Solution Heuristic Algorithm
See Table 4.14.

8. Results
The results are presented herein for Monticello subdistrict as an example. There are three units in the Monticello subdistrict as shown in Figure 4.44. Using the algorithm, the results of the four analysis options can be obtained. In Table 4.15, we present the optimal number of trucks, optimal snow-removal route for each truck, and corresponding total deadhead miles. In Table 4.15, the snow removal time limit is 6 hrs, snow removal speed is 25 mph, and the cruise speed is 50 mph. In Table 4.16, we present the suggested maximum number of trucks (based on the existing number of trucks) and the corresponding optimal route for each truck is provided (deadhead miles are also shown).

9. Software and Input Files
The software is written in Python environment. The detailed install-and-run instructions are provided in the User Manual that accompanies this report. In the

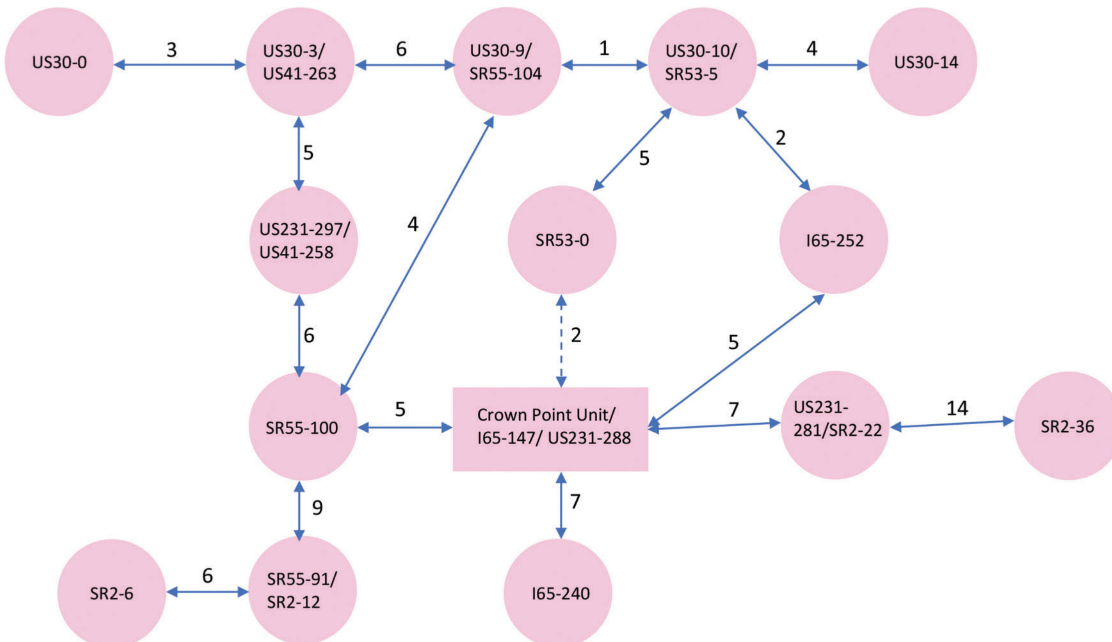


Figure 4.42 Network structure of Crown Point unit.

NodeA	NodeZ	types	Length	Lanes
unit	I65-240	service	7	1
I65-240	unit	service	7	1
unit	SR53-0	cruise	2	1
SR53-0	unit	cruise	2	1
SR53-0	US30-10/SR53-5	service	5	1
US30-10/SR53-5	SR53-0	service	5	1
US30-10/SR53-5	US30-14	service	4	1
US30-14	US30-10/SR53-5	service	4	1
US30-10/SR53-5	US30-9/SR55-104	service	1	1
US30-9/SR55-104	US30-10/SR53-5	service	1	1
US30-10/SR53-5	I65-252	cruise	2	1
I65-252	US30-10/SR53-5	cruise	2	1
I65-252	unit	service	5	1
unit	I65-252	service	5	1
unit	US231-281/SR2-22	service	7	1
US231-281/SR2-22	unit	service	7	1
US231-281/SR2-22	SR2-36	service	14	1
SR2-36	US231-281/SR2-22	service	14	1
unit	SR55-100	cruise	5	1
SR55-100	unit	cruise	5	1
SR55-100	SR55-91/SR2-12	service	9	1
SR55-91/SR2-12	SR55-100	service	9	1
SR55-91/SR2-12	SR2-6	service	6	1
SR2-6	SR55-91/SR2-12	service	6	1
SR55-100	US30-9/SR55-104	service	4	1
US30-9/SR55-104	SR55-100	service	4	1
US30-9/SR55-104	US30-3/US41-263	service	6	1
US30-3/US41-263	US30-9/SR55-104	service	6	1
US30-3/US41-263	US30-0	service	3	1
US30-0	US30-3/US41-263	service	3	1
US30-3/US41-263	US231-297/US41-258	service	5	1
US231-297/US41-258	US30-3/US41-263	service	5	1
US231-297/US41-258	SR55-100	service	6	1
SR55-100	US231-297/US41-258	service	6	1

Figure 4.43 Input information for the heuristic algorithm.

TABLE 4.14
Heuristic algorithm

Algorithm K-DCPP
1. Read the network, get the unit node.
2. Solve the Directed CPP for first vehicle with the 3-hr time limit constraint (distance constraint).
3. Change the service road to cruise road.
4. Solve the Directed CPP for other vehicles with the 3-hr time limit.
5. Repeat step 3~4 until all the snow routes have been cleaned.
6. Evaluate the objective function.

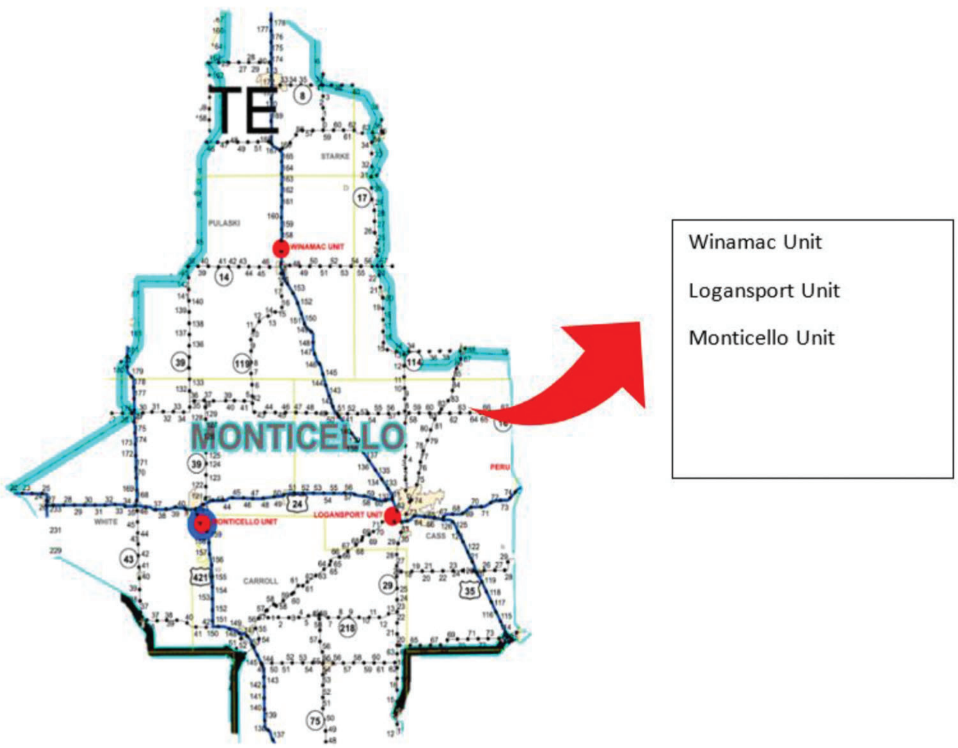


Figure 4.44 Units of the Monticello subdistrict.

manual, the input file includes the deadhead miles associated with each unit.

4.4.5.1.3 Identify any need for additional units, over entire state

1. Methodology

Technical justification. It is best to do this starting with a GIS or similar platform, and then use heat maps, Kriging techniques, Network theory, P-median problem, spatial econometrics, etc. to identify areas of high concentrations of units with high deadhead miles. Also, this may be done visually for a simple network. Then, the deserving locations can be ranked in order of the deadhead miles.

Economic justification. First, we assess the cost-effectiveness of adding an additional unit. We calculate the benefits and costs over a 30-year life cycle. Regarding the benefits, we translate the prospective benefits (reduction in deadhead miles) over 30 years into savings in terms of vehicle operation costs (depreciation, fuel, labor, maintenance, etc.). Regarding the costs, we calculate the expenses incurred over a 30-year life cycle in terms of land acquisition, facility construction, personnel costs, etc., for the new unit (each unit costs $4 million).

2. Results

From the deadhead miles associated with the optimal solution (as calculated by the heuristic algorithm, see Table 4.14), it was observed that the units that generate large deadhead miles are those with large network structures. For example: Winamac unit, Monticello unit. After optimizing the truck routes in order to reduce deadhead miles, one way to mitigate any remaining excessive deadhead miles is to reassign the snow routes to appropriate neighboring units. The other way is to add new units whose candidate locations should be in close proximity to the units with excess deadhead miles. Such technical

TABLE 4.15
Optimal number of trucks, optimal snow-removal route per truck, and corresponding total deadhead miles

Unit	Snow Removal Time	Snow Removal Speed	Cruise Speed	Optimal Route for Each Truck
Winamac	6 hr	25 mph	50 mph	unit → US35-158 → US35-168/SR10-52 → US35-171 → US35-173 → US35-178→ US35-173 → US35-171→ US35-168/SR10-52 → SR10-59/SR23-0 → SR23-11 → SR10-59/SR23-0 → SR10-65/SR17-36 → SR17-40 → SR10-65/SR17-36 → SR10-74 → SR10-65/SR17-36 → SR17-35 → SR14-57/SR17-23 → SR17-35 → SR10-65/SR17-36 → SR10-59/SR23-0 → US35-168/SR10-52 → US35-158 → unit unit → US35-156/SR14-47 → SR39-143/SR14-38 → SR39-131 →SR39-143/SR14-38 → US35-156/SR14-47 → unit unit → US35-156/SR14-47 → US35-155/SR119-18 → US35-141 → US35-155/SR119-18 → US35-156/SR14-47 → unit unit → US35-156/SR14-47 → SR14-57/SR17-23 → SR14-66 → SR14-57/SR17-23 → US35-156/SR14-47 → unit unit → US35-156/SR14-47 → US35-155/SR119-18 → SR119-5 → US35-155/SR119-18 → US35-156/SR14-47 → unit unit → US35-156/SR14-47 → SR14-57/SR17-23 → SR17-8 → SR14-57/SR17-23 → US35-156/SR14-47 → unit
Total DH miles: 32 miles; Optimized number of trucks: 6				
Monticello	6 hr	25 mph	50 mph	unit → US421_162 → US421_150 → US421_162 → US421_150 → SR18_48 → SR218_0 → SR18_48 → SR18_49 → SR75_54 → SR75_59 → SR218_0 → SR75_59 → SR218_14 → SR75_59 → SR75_54 → SR18_49 → US421_134 → SR18_49 → SR18_55 → SR18_49 → SR18_48 → US421_150 → unit unit → US421_162 → US24_42 → US24_35 → US24_26 → US231_221 → US231_116 → US231_221 → US24_26 → US24_35 → US421_176 → US24_35 → SR43_36 → US24_35 → US24_42 → US24_60 → US24_42 → US421_162 → unit unit → SR39_129 → SR16_37 → SR16_29 → SR16_37 → SR16_41 → SR16_37→ SR39_129 → unit
Total DH miles: 50 miles; Optimized number of trucks: 3				
Logansport	6 hr	25 mph	50 mph	unit → SR29-30 →SR29-26/SR218-17 → US35-120/SR218-25, → US35-114/SR18-75 → US35-120/SR218-25 → SR218-32 → US35-120/SR218-25 → SR29-26/SR218-17 → SR29-23 → SR29-20/SR18-64 → US35-114/SR18-75 →SR18-78 → US35-114/SR18-75 → SR29-20/SR18-64 → SR29-9 → SR29-20/SR18-64 → SR18-55 → SR29-20/SR18-64 → SR29-23 → SR29-26/SR218-17 → SR29-30 → unit unit → SR25-74/SR17-0 → SR25-77 → SR16-61/SR25-82 → SR16-70→ SR16-61/SR25-82 → SR25-77 → SR25-74/SR17-0 → SR16-58/SR17-8 → SR16-61/SR25-82 → SR16-58/SR17-8 → US35-141/SR16-51 → US35-132 → US35-141/SR16-51 → SR16-42 → US35-141/SR16-51→ SR16-58/SR17-8 → SR25-74/SR17-0 → unit unit → US35-126/US24-67 → US35-120/SR218-25 → US35-126/US24-67 → US24-77 → US35-126/US24-67→ unit Unit → SR25-61 → unit unit → US24-61 → unit
Total DH miles: 0 miles; Optimized number of trucks: 5				

TABLE 4.16
Existing trucks, optimal snow-removal route per truck, and corresponding total deadhead miles

Unit	Existing Number of Trucks	Suggested Number of Trucks	Optimal Route for Each Truck
Winamac	**7**	**7**	Truck 1 is: unit → US35-158 → US35-168/SR10-52 → SR10-59/SR23-0 → SR10-65/SR17-36 → SR10-74 → SR10-65/SR17-36 → SR17-40 → SR10-65/SR17-36 → SR10-59/SR23-0 → SR23-11 → SR10-59/SR23-0 → US35-168/SR10-52 → US35-171 → US35-173 → US35-178 → US35-173 → US35-171 → US35-168/SR10-52 → US35-158 → unit Truck 2 is: unit → US35-156/SR14-47 → SR39-143/SR14-38 → SR39-131 → SR39-143/SR14-38 → US35-156/SR14-47 → unit Truck 3 is: unit → US35-156/SR14-47 → US35-155/SR119-18 → US35-141 → US35-155/SR119-18 → US35-156/SR14-47 → unit Truck 4 is: unit → US35-156/SR14-47 → US35-155/SR119-18 → SR119-5 → US35-155/SR119-18 → US35-156/SR14-47 → unit Truck 5 is: unit → US35-156/SR14-47 → SR14-57/SR17-23 → SR14-66 → SR14-57/SR17-23 → US35-156/SR14-47 → unit Truck 6 is: unit→ US35-156/SR14-47→ SR14-57/SR17-23→ SR17-8→ SR14-57/SR17-23→ US35-156/SR14-47→ unit Truck 7 is: unit → US35-156/SR14-47 → SR14-57/SR17-23 → SR17-35 → SR10-65/SR17-36 → SR17-35 → SR14-57/SR17-23 → US35-156/SR14-47 → unit
Total DH miles: 54 miles			
Monticello	5	5	Truck 1 is: unit → US421_162 → US421_150→ SR18_48 → SR18_49 → SR18_55 → SR18_49 → SR18_48 → US421_150 → unit Truck 2 is: unit → US421_162 → US24_42 → US24_35 → US24_26 → US231_221 → US231_116 → US231_221 → US24_26 → US24_35 → US24_42 → US421_162 → unit Truck 3 is: unit → US421_162 → US24_42 → US24_35 → SR43_36 → US24_35 → US24_42 → US421_162 → unit Truck 4 is: unit → SR39_129 → SR16_37 → SR16_29 → SR16_37 → SR16_41 → SR16_37 → SR39_129 → unit → US421_162 → US421_150 → SR18_48 → SR18_49 → US421_134 → SR18_49 → SR75_54 → SR75_59 → SR218_14 → SR75_59 → SR218_0 → SR18_48 → US421_150 → unit Truck 5 is: unit→ US421_162 → US24_42 → US24_60 → US24_42 → US421_162 → unit → US421_162→ US24_42 → US24_35 → US421_176 → US24_35 → US24_42 → US421_162 → unit
Total DH miles: 120 miles			
Logansport	13	13	Truck 1 is: unit → US35-132 → US35-141/SR16-51 → SR16-58/SR17-8 → US35-141/SR16-51 → SR16-42 → US35-141/SR16-51 → US35-132 → unit Truck 2 is: unit → US24-61 → unit Truck 3 is: unit → US24-61 → unit Truck 4 is: unit → US35-126/US24-67 → US35-120/SR218-25 → SR29-26/SR218-17 → US35-120/SR218-25 → US35-126/US24-67 → unit Truck 5 is: unit → US35-126/US24-67 → US35-120/SR218-25 → US35-114/SR18-75 → SR18-78 → US35-114/SR18-75 → US35-120/SR218-25 → US35-126/US24-67 → unit Truck 6 is: unit → US35-126/US24-67 → US35-120/SR218-25 → US35-114/SR18-75 → SR29-20/SR18-64 → US35-114/SR18-75 → US35-120/SR218-25 → US35-126/US24-67 → unit Truck 7 is: unit → US35-126/US24-67 → US35-120/SR218-25 → SR218-32 → US35-120/SR218-25 → US35-126/US24-67 → unit Truck 8 is: unit → US35-126/US24-67 → US24-77 → US35-126/US24-67 → unit Truck 9 is: unit → SR29-30 → SR29-26/SR218-17 → SR29-23 → SR29-20/SR18-64 → SR29-9 → SR29-20/SR18-64 → SR29-23 → SR29-26/SR218-17 → SR29-30 → unit Truck 10 is: unit → SR25-74/SR17-0 → unit Truck 11 is: unit → SR25-74/SR17-0 → SR25-77 → SR16-61/SR25-82 → SR16-70 → SR16-61/SR25-82 → SR16-58/SR17-8 → SR25-74/SR17-0 → unit Truck 12 is: unit → SR29-30 → unit Truck 13 is: unit → SR29-30 → SR29-26/SR218-17 → SR29-23 → SR29-20/SR18-64 → SR18-55 → SR29-20/SR18-64 → SR29-23 → SR29-26/SR218-17 → SR29-30 → unit
Total DH miles: 44 miles			

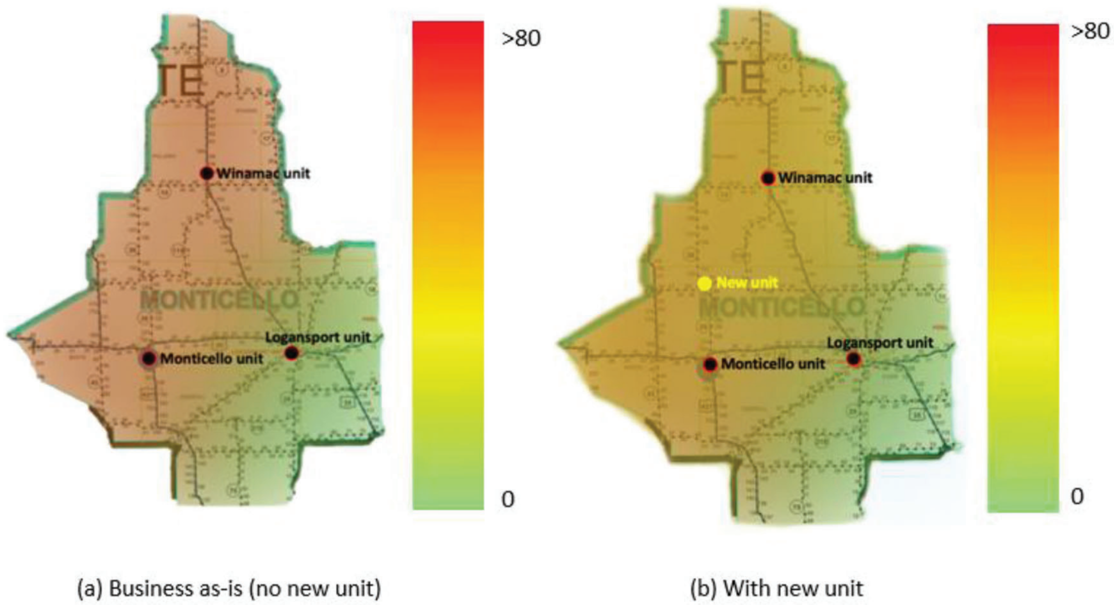


Figure 4.45 Heatmaps of deadhead mile severity in a selected subdistrict in LaPorte District (2 scenarios).

justification should be accompanied with economic justification.

Figure 4.45 presents the severity of deadhead miles across Monticello subdistrict. Green represents low deadhead miles and red represents high deadhead miles. The question is: "what threshold of deadhead severity should warrant the addition of a new unit?" In certain cases, any need for a new unit can be obviated by reassigning excess deadhead miles to neighboring units with relatively lower deadhead miles. However, that is not always an option. In this case, we consider placing a new unit at the yellow spot in Figure 4.45(b), roughly between of the two units with high deadhead miles. If that is done, we run the algorithms again and determined that the overall deadhead mile changes. The Winamac unit deadhead miles reduce by 21 deadhead miles, and Monticello's is reduced by 26 deadhead miles.

4.4.5.2 Conclusion. The above results are presented for units in LaPorte District. In Appendix G, we present the algorithm we developed for this purpose. The algorithm can be applied to any of the units in the state, to address the four questions (the optimal routes for each truck, the optimal number of trucks, the feasibility of reassigning some existing snow routes from a unit to other (neighboring) units (to reduce excess deadhead miles of the former unit), and identify any need for additional units, over entire state.

5. CONCLUSION

5.1 Implementation Plan

The heavy fleet and facilities optimization report provides the following insights that can assist INDOT.

- A detailed analysis into the current fleet of vehicles owned by INDOT, to understand the equipment mix, various corresponding costs associated with the equipment—maintenance cost, operations cost, cost of ownership—and performance indices: average age, average mileage.
- A detailed analysis of the current snow route network, existing facility locations, and distribution of trucks at each unit locations allowing to explore factors that affect the deadhead miles associated with snow routes.
- An optimization model to implement life-cycle cost analysis-based truck replacement strategy, based on the data of current fleet, customized for the northern, central, and southern region districts in Indiana such that the overall cost of ownership of the truck can be reduced.
- An optimization model to improve the current snow removal operations by allowing INDOT to adjust the current snow routes, facility locations, and distribution of trucks in the unit locations such that the associated deadhead miles are minimized. Two separate approaches are presented.

REFERENCES

Bodin, L., & Golden, B. (1981). Classification in vehicle routing and scheduling. *Networks*, *11*, 97–108.

Campbell, J. F., & Langevin, A. (1995). Operations management for urban snow removal and disposal. *Transportation Research Part A: Policy and Practice*, *29*(5), 359–370.

Campbell, J. F., & Langevin, A. (2000). Roadway snow and ice control. In M. Dror (Ed.), *Arc Routing* (pp. 389–418). https://doi.org/10.1007/978-1-4615-4495-1_10

Clarke, G., & Wright, J. (1964). Scheduling of vehicles from a central depot to a number of delivery. *Operations Research*, *12*, 568–581.

Cook, T. M., & Alprin, B. S. (1976). Snow and ice removal in an urban environment. *Management Science*, *23*(3), 227–234. https://doi.org/10.1287/mnsc.23.3.227

Cortina, R. S., & Low, T. A. (2001, August). Development of new routes for snow and ice control. *Public Works*, *132*(*9*), 20–23.

Dantzig, G. B., & Ramser, J. H. (1959). The truck dispatching problem. *Management Science*, *6*(1), 80–91. https://doi.org/10.1287/mnsc.6.1.80

Eglese, R. W. (1994). Routing winter gritting vehicles. *Discrete Applied Mathematics*, *48*(3), 231–244. https://doi.org/10.1016/0166-218x(92)00003-5

Eiselt, H. A., Gendreau, M., & Laporte, G. (1995a). Arc routing problems, Part I: The Chinese postman Problem. *Operations Research*, *43*(2), 231–242. https://doi.org/10.1287/opre.43.2.231

Eiselt, H. A., Gendreau, M., & Laporte, G. (1995b). Arc routing problems, Part II: The rural postman problem. *Operations Research*, *43*(3), 399–414. https://doi.org/10.1287/opre.43.3.399

Evans, J. R., & Weant, M. (1990). Strategic planning for snow and ice control vehicles using computer-based routing software. *Public Works*, *121*(4), 60–64.

FHWA. (2018, June). *Long-term pavement performance information management system* (Publication No. FHWA-RD-03-088). Federal Highway Administration. https://infopave.fhwa.dot.gov/InfoPave_Repository/files/LTPP_IMS_USER_GUIDE_2018_FINAL.pdf

Fleet Management Division. (2019). *Equipment maintenance and management policies manual*. Pennsylvania Department of Transportation. http://www.dot.state.pa.us/public/PubsForms/Publications/Pub 177.pdf

Gelinas, E. (1992). Le problème du postier chinois avec contraints générales de préséance [Master's Thesis, Ecole Polytechnique de Montreal].

Gilbert, J. (1989). *Générateur d'itinéraires d'enlèvement de la neige* (Publication CRT-648). University of Montreal Center for Research and Transportation.

Gransberg, D. D., & O'Connor, E. P. (2015, April). *Major equipment life-cycle cost analysis*. (Report No. 2015-16). Minnesota Department of Transportation. https://www.lrrb.org/pdf/201516.pdf

Gray, D. M., & Male, D. H. (1981). *Handbook of snow, principles, processes, management, and use*. Pergamon Press.

Haghani, A., & Qiao, H. (2001). Decision support system for snow emergency vehicle routing: Algorithms and application. *Transportation Research Record*, *1771*(1), 172–178. https://doi.org/10.3141/1771-22

Haghani, A., & Qiao, H. (2002). Snow emergency vehicle routing with route continuity constraints. *Transportation Research Record*, *1783*(1), 119–124. https://doi.org/10.3141/1783-15

Haslam, E., & Wright, J. R. (1991). Application of routing technologies to rural snow and ice control. *Transportation Research Record*, *1304*, 202–211. https://onlinepubs.trb.org/Onlinepubs/trr/1991/1304/1304-027.pdf

IndianaMap. (n.d.). *Mile markers–System 1 roads (INDOT)* [Webpage]. Retrieved May 2, 2021, from https://maps.indiana.edu/previewMaps/Infrastructure/Interstates_Mile_Markers_System1_INDOT.html

INDOT. (n.d.). *INDOT facts* [Webpage]. Indiana Department of Transportation. Retrieved August 20, 2021, from https://www.in.gov/indot/about-indot/indot-facts/

INDOT. (2021). *INDOT mission, goals, vision and values* [Webpage]. Retrieved May 12, 2021, from https://www.in.gov/indot/2341.htm

Keseling, J. R. (1994). Maryland's strategies for fighting winter storms. *Public Works*, *125*(4), 40–42.

Kriett, P. O., Mbugua, W. N., Kim, D. S., & Porter, J. D. (2010). *Equipment replacement at departments of transportation: Prioritization measures, software tools, and supplementary data*. Transportation Research Record, *2150*(1), 10–17. https://doi.org/10.3141/2150-02

Lemieux, P. F., & Gampagna, L. (1984). The snow ploughing problem solved by a graph theory algorithm. *Civil Engineering Systems*, *1*(6), 337–341. https://doi.org/10.1080/02630258408970368

Liebling, T. M. (1970). *Graphentheorie in Planungs-und Tourenproblem: am Beispiel des städtischen Straßendienstes.* Lecture Notes in Operations and Mathematical Systems (Vol. 21). Springer.

Liebling, T. M. (1973). Routing problems for street cleaning and snow removal. In R. Deininger (Ed.), *Models for Environmental Pollution Control* (pp. 363–372). Ann Arbor Science Publishers.

Lindsey, R. K., & Seely, M. S. (1999). Resource allocation study for snow removal. *Transportation Research Record 1672*(1), 23–27. https://doi.org/10.3141/1672-04

Lotan, T. D., Cattrysse, D., Van Oudheusden, D., & Leuven, K. U. (1996). Winter gritting in the province of Antwerp: A combined location and routing problem. *Belgian Journal of Operations Research*, *36*(2–3), 141–157.

Minsk, L. D. (1970, April 8–10). A short history of man's attempts to move through snow (Special Report 115). *Snow removal and ice control research: Proceedings of an international symposium* (pp. 1–7). Highway Research Board. https://onlinepubs.trb.org/Onlinepubs/sr/sr115/115.pdf

Minsk, L. D. (1979). *A systems study of snow removal* [PDF file]. US Army Cold Regions Research and Engineering/http://onlinepubs.trb.org/Onlinepubs/sr/sr185/185-036.pdf

MyGeodata Converter. (n.d.). *Convert SHP to latlong online* [Webpage]. Retrieved from https://mygeodata.cloud/converter/shp-to-latlong

ODOT. (2018, August 7). *Fleet life cycle in Ohio* [PowerPoint slides]. Ohio Department of Transportation. http://pavementvideo.s3.amazonaws.com/2018EMTSP/2018-08-01-Fleet_Life_Cycle_in_Ohio-Burke.pdf

Omer, M. (2007). *Efficient routing of snow removal vehicles* [Master's thesis, West Virginia University]. https://researchrepository.wvu.edu/etd/4325

Orloff, C. S. (1974). A fundamental problem in vehicle routing. *Networks*, *4*(1), 35–64. https://doi.org/10.1002/net.3230040105

Russell, G. L., & Sorenson, H. K. (1979). *A value engineering study of snow and ice control* [PDF file]. California Department of Transportation. https://onlinepubs.trb.org/Onlinepubs/sr/sr185/185-013.pdf

TxDOT. (2008, November). *TxDOT equipment replacement model*. Texas Department of Transportation. https://ftp.txdot.gov/pub/txdot-info/library/pubs/bus/maintenance/term_summary.pdf

Tucker, W. B., & Clohan, G. M. (1979). Computer simulation of urban snow removal. *Transportation Research Board Special Research Report 185*, 293–302. https://onlinepubs.trb.org/Onlinepubs/sr/sr185/185-048.pdf

Wang, J.-Y., Kandula, P., & Wright, J. R. (1995). Evaluation of computer-generated routes for improved snow and ice control. *Transportation Research Record*, *1509*, 15–21.

Retrieved April 6, 2022, from http://onlinepubs.trb.org/Onlinepubs/trr/1995/1509/1509-003.pdf
Wang, J.-Y., & Wright, J. R. (1994, November). Interactive design of service routes. *Journal of Transportation Engineering*, *120*(*6*), 897–913. https://doi.org/10.1061/(ASCE)0733-947X(1994)120:6(897)
Wright, J. (1994, April 15). *The computer aided system for planning efficient routes* (Report No. FHWA/IN/JHRP-93/8). Purdue University. https://doi.org/10.5703/1288284313329
Xie, W. (n.d.). *Snowplow route optimization for SDDOT* (Contract No. SD2020-05). South Dakota Department of Transportation. https://trid.trb.org/view/1843617

APPENDICES

Appendix A. All Unit Locations in Indiana

Appendix B. Truck Replacement Optimization Model for Approach 1

Appendix C. Results for Snow Route Optimization for Approach 1

Appendix D. Commonly Used Terms

Appendix E. Acronyms

Appendix F. Aspects of Network Theory Relevant to this Report

Appendix G. Algorithm Developed for Phase 2 of this Study

Appendix H. Supplementary Material

APPENDIX A. ALL UNIT LOCATIONS IN INDIANA

Table A.1 Indiana Unit Locations

Unit ID	Unit Name	Unit ID	Unit Name
1101	TERRE HAUTE UNIT 2	4101	LAPORTE UNIT 1
1102	ASHBORO UNIT 3	4102	WANATAH UNIT
1103	FORT HARRISON UNIT	4103	MICH CITY UNIT 3
1201	CRAWFORDSVILLE UNIT 1	4201	MONTICELLO UNIT 1
1202	BLOOMINGDALE UNIT 2	4202	LOGANSPORT UNIT 2
1203	NEWPORT UNIT 3	4204	WINAMAC UNIT
1204	VEEDERSBURG UNIT 4	4301	PLYMOUTH UNIT
1301	FOWLER UNIT 1	4302	MISHAWAKA UNIT
1302	CARBONDALE UNIT 2	4305	ROCHESTER UNIT
1303	LAFAYETTE UNIT 3	4402	RENSSELAER UNIT 2
1401	FRANKFORT UNIT 1	4403	ROSELAWN UNIT 3
1402	LEBANON UNIT 2	4406	MEDARYVILLE UNIT
1403	ROMNEY UNIT 3	4701	CROWN POINT UNIT 1
1501	CLOVERDALE UNIT 1	4702	MILLER
1502	BAINBRIDGE UNIT 2	4703	GARY UNIT 3
1503	LIZTON UNIT 3	4704	FREEWAY UNIT 4
1504	PLAINFIELD UNIT 4	4705	CHESTERTON UNIT
2201	ELKHART UNIT 1	5101	PENNTOWN UNIT 1
2204	SHIPSHEWANA UNIT	5103	AURORA UNIT 3
2205	WARSAW UNIT	5104	BROOKVILLE UNIT 4
2206	BRIMFIELD UNIT	5105	VERSAILLES UNIT 5
2301	FORT WAYNE UNIT 1	5202	MARTINSVILLE UNIT 2
2303	NEW HAVEN UNIT 3	5203	BLOOMINGTON UNIT 3
2305	WATERLOO UNIT	5205	BROWNSTOWN UNIT 5
2306	ANGOLA UNIT	5301	GREENSBURG UNIT 1
2501	WABASH UNIT 1	5302	AMITY UNIT 2
2502	PERU UNIT 2	5303	COLUMBUS UNIT 3
2506	LAUD UNIT	5402	SELLERSBURG UNIT 2
2601	BLUFFTON UNIT 1	5403	CORYDON UNIT 3
2603	MONROE UNIT 3	5501	MADISON UNIT 1
2604	GAS CITY UNIT 4	5502	NORTH VERNON UNIT 2
3101	BROOKVILLE UNIT	5504	SCOTTSBURG UNIT 4
3103	71ST ST UNIT	5505	SALEM UNIT
3104	65TH ST UNIT	6101	LINTON UNIT 1
3105	MADISON ST UNIT	6102	CRANE UNIT
3201	GREENFIELD UNIT 1	6103	SULLIVAN UNIT 3
3202	ANDERSON UNIT 2	6301	EVANSVILLE UNIT 1

3203	RUSHVILLE UNIT 3	6302	BOYLE LANE UNIT 2
3204	SHELBYVILLE UNIT 4	6303	POSEYVILLE UNIT 3
3301	SALISBURY UNIT 1	6304	CHANDLER UNIT 4
3302	CAMBRIDGE UNIT 2	6401	PAOLI UNIT 1
3303	NEW CASTLE UNIT 3	6403	BEDFORD UNIT 3
3304	LIBERTY UNIT 4	6404	JASPER UNIT 4
3501	TIPTON UNIT 1	6502	DERBY UNIT 2
3502	KOKOMO UNIT 2	6503	BIRDSEYE UNIT 3
3503	WESTFIELD UNIT 3	6504	DALE UNIT 4
3504	FORTVILLE UNIT 4	6505	CHRISNEY UNIT 5
3601	MUNCIE UNIT 1	6601	OAKLAND CITY UNIT
3603	ALBANY UNIT 3	6602	VINCENNES UNIT 2
3604	WINCHESTER UNIT 4	6607	LOOGOOTEE UNIT
3605	ALEXANDRIA UNIT 5		

APPENDIX B. TRUCK REPLACEMENT OPTIMIZATION MODEL FOR APPROACH 1

This appendix provides a snap of the truck replacement optimization model prepared for the northern, central, and southern regions.

V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK
Capital Cost	$ 110,000.00			Year	Ap - factor to convert Ownership into annuity	Operating Cost	PV factor past cost from year 1-N	PV of Ops cost from past	Af - factor to convert Ops into annuity	Miles	Cumulative Miles	Ownership Annuity	Operating Annuity	Total Annuity	Cost Per Mile
Salvage	20%			1	1.05	8514.068738	1.979931599	$ 8,514.07	1	11139	11139	$ 93,500.00	$ 8,514.07	$ 102,014.07	$ 9.16
Salvage Value	$ 22,000.00			2	0.537804878	9411.359899	1.885649142	$ 18,351.13	0.487804878	11139	22278	$ 48,426.83	$ 8,951.77	$ 57,378.60	$ 5.15
				3	0.367208565	10379.57468	1.795856326	$ 29,648.26	0.317208565	11139	33417	$ 33,414.35	$ 9,404.68	$ 42,819.04	$ 3.84
Interest Rate	5%			4	0.282011833	11423.69614	1.710339358	$ 42,554.37	0.232011833	11139	44556	$ 25,917.04	$ 9,873.12	$ 35,790.16	$ 3.21
				5	0.230974798	12549.03555	1.628894627	$ 57,231.13	0.180974798	11139	55695	$ 21,425.78	$ 10,357.39	$ 31,783.17	$ 2.85
				6	0.197017468	20213.02308	1.551328216	$ 80,305.71	0.147017468	9562	65257	$ 18,437.54	$ 11,806.34	$ 30,243.88	$ 2.78
				7	0.172819818	22198.09729	1.477455444	$ 106,519.09	0.122819818	9562	74819	$ 16,308.14	$ 13,082.66	$ 29,390.80	$ 2.75
Age	11139			8	0.154721814	24336.25098	1.407100423	$ 136,181.29	0.104721814	9562	84381	$ 14,715.52	$ 14,261.15	$ 28,976.67	$ 2.75
Age > 5	9562			9	0.14069008	26638.10509	1.340095641	$ 169,628.46	0.09069008	9562	93943	$ 13,480.73	$ 15,383.62	$ 28,864.35	$ 2.77
Age > 10	9681			10	0.129504575	29114.97482	1.276281563	$ 207,224.86	0.079504575	9562	103505	$ 12,496.40	$ 16,475.32	$ 28,971.73	$ 2.80
				11	0.120388891	31778.91332	1.21550625	$ 249,365.02	0.070388891	9681	113186	$ 11,694.22	$ 17,552.53	$ 29,246.75	$ 2.84
				12	0.11282541	34642.75804	1.157625	$ 296,476.03	0.06282541	9681	122867	$ 11,028.64	$ 18,626.23	$ 29,654.86	$ 2.90
				13	0.106455765	37720.17993	1.1025	$ 349,020.01	0.056455765	9681	132548	$ 10,468.11	$ 19,704.19	$ 30,172.30	$ 2.96
				14	0.101023969	41025.73563	1.05	$ 407,496.74	0.051023969	9681	142229	$ 9,990.11	$ 20,792.10	$ 30,782.21	$ 3.03
				15	0.096342288	44574.92283	1	$ 472,446.50	0.046342288	9681	151910	$ 9,578.12	$ 21,894.25	$ 31,472.37	$ 3.11

Figure B.1 Snap of modelling in northern region.

T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL
Capital Cost	$ 110,000.00					Year	Ap - factor to convert Ownership into annuity	Operating Cost	PV factor past cost from year 1-N	PV of Ops cost from past	Af - factor to convert Ops into annuity	Miles	Cum Miles	Ownership Annuity	Operating Annuity	Total Annuity	Cost Per Mile	Age
Salvage	20%					1	1.05	6093.077756	1.9799316	6093.07776	1	10130	10130	$ 93,500.00	6093.077756	$ 99,593.08	$ 9.83	1
Slvage value	$ 22,000.00					2	0.537804878	7590.230019	1.88564914	13987.9617	0.48780488	10130	20260	$ 48,426.83	6823.395933	$ 55,250.23	$ 5.45	2
						3	0.367208565	9363.285321	1.79585633	24050.6451	0.31720856	10130	30390	$ 33,414.35	7629.0706	$ 41,043.42	$ 4.05	3
Interest Rate	5%					4	0.282011833	11457.43909	1.71033936	36710.6164	0.23201183	10130	40520	$ 25,917.04	8517.297389	$ 34,434.34	$ 3.40	4
						5	0.230974798	13924.82745	1.62889463	52470.9747	0.1809748	10130	50650	$ 21,425.78	9495.92405	$ 30,921.71	$ 3.05	5
Age	10130					6	0.197017468	16825.55051	1.55132822	71920.0739	0.14701747	7126	57776	$ 18,437.54	10573.50717	$ 29,011.04	$ 3.01	6
Age > 5	7126					7	0.172819818	20228.84224	1.47745544	95744.9199	0.12281982	7126	64902	$ 16,308.14	11759.37367	$ 28,067.52	$ 3.03	7
Age >10	9673					8	0.154721814	17264.92478	1.40710042	117797.091	0.10472181	7126	72028	$ 14,715.52	12335.92497	$ 27,051.44	$ 3.00	8
						9	0.14069008	20216.88527	1.34009564	143903.83	0.09069008	7126	79154	$ 13,480.73	13050.64989	$ 26,531.38	$ 3.02	9
						10	0.129504575	23633.58943	1.27628156	174732.611	0.07950457	7126	86280	$ 12,496.40	13892.042	$ 26,388.44	$ 3.06	10
						11	0.120388891	27584.6748	1.21550625	211053.917	0.07038889	9673	95953	$ 11,694.22	14855.85125	$ 26,550.07	$ 3.04	11
						12	0.11282541	32149.8751	1.157625	253756.488	0.06282541	9673	105626	$ 11,028.64	15942.35538	$ 26,970.99	$ 3.06	12
						13	0.106455765	37420.44986	1.1025	303864.762	0.05645577	9673	115299	$ 10,468.11	17154.91764	$ 27,623.02	$ 3.11	13
						14	0.101023969	43500.81299	1.05	362558.813	0.05102397	9673	124972	$ 9,990.11	18499.1898	$ 28,489.30	$ 3.19	14
						15	0.096342288	50510.38754	1	431197.141	0.04634229	9673	134645	$ 9,578.12	19982.66193	$ 29,560.78	$ 3.29	15

Figure B.2 Snap of modelling for central region.

W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL
				Year	Ap - factor to convert Ownership into annuity	Operating Cost	PV factor past cost from year 1-N	PV of Ops cost from past	Af - factor to convert Ops into annuity	Miles	Cumulati	Ownership Annuity	Operating Annuity	Total Annuity	Cost Per mile
Capital Cost	$ 110,000.00			1	1.05	3008.369108	2.653297705	3008.369108	1	6349	6349	$ 93,500.00	3008.3691	$ 96,508.37	$ 15.20
Salvage	20%			2	0.537804878	5480.043161	2.526950195	8638.830724	0.487804878	6349	12698	$ 48,426.83	4214.0638	$ 52,640.89	$ 8.29
Salvage Value	$ 22,000.00			3	0.367208565	7083.765302	2.406619234	16154.53756	0.317208565	6349	19047	$ 33,414.35	5124.3577	$ 38,538.71	$ 6.07
				4	0.282011833	8378.720823	2.292018318	25340.98526	0.232011833	6349	25396	$ 25,917.04	5879.4084	$ 31,796.45	$ 5.01
Interest Rate	5%			5	0.230974798	9495.465936	2.182874588	36103.50046	0.180974798	6349	31745	$ 21,425.78	6533.8237	$ 27,959.61	$ 4.40
				6	0.197017468	10492.08151	2.078928179	48400.757	0.147017468	6692	38437	$ 18,437.54	7115.7567	$ 25,553.29	$ 3.99
				7	0.172819818	11400.57132	1.979931599	62221.36617	0.122819818	6692	45129	$ 16,308.14	7642.0169	$ 23,950.16	$ 3.71
				8	0.154721814	15275.49121	1.885649142	80607.92569	0.104721814	6692	51821	$ 14,715.52	8441.4082	$ 23,156.93	$ 3.57
				9	0.14069008	16426.39224	1.795856326	101064.7142	0.09069008	6692	58513	$ 13,480.73	9165.567	$ 22,646.29	$ 3.48
Age	6349			10	0.129504575	17502.01284	1.710339358	123619.9628	0.079504575	6692	65205	$ 12,496.40	9828.3526	$ 22,324.76	$ 3.42
Age > 5	6692			11	0.120388891	18515.25771	1.628894627	148316.2186	0.070388891	6717	71922	$ 11,694.22	10439.814	$ 22,134.04	$ 3.39
Age >10	6717			12	0.11282541	19475.74275	1.551328216	175207.7723	0.06282541	6717	78639	$ 11,028.64	11007.5	$ 22,036.14	$ 3.36
Age > 15	6156			13	0.106455765	20390.85577	1.477455444	204359.0167	0.056455765	6717	85356	$ 10,468.11	11537.245	$ 22,005.35	$ 3.35
				14	0.101023969	21266.41563	1.407100423	235843.3831	0.051023969	6717	92073	$ 9,990.11	12033.666	$ 22,023.77	$ 3.35
				15	0.096342288	22107.1007	1.340095641	269742.653	0.046342288	6717	98790	$ 9,578.12	12500.492	$ 22,078.61	$ 3.35
				16	0.092269908	22916.73819	1.276281563	306146.5238	0.042269908	6156	104946	$ 9,219.75	12940.785	$ 22,160.54	$ 3.38
				17	0.088699142	23698.50561	1.21550625	345152.3556	0.038699142	6156	111102	$ 8,905.52	13357.1	$ 22,262.62	$ 3.41
				18	0.085546222	24455.07498	1.157625	386865.0484	0.035546222	6156	117258	$ 8,628.07	13751.591	$ 22,379.66	$ 3.44
				19	0.08274501	25188.71842	1.1025	431397.0192	0.03274501	6156	123414	$ 8,381.56	14126.1	$ 22,507.66	$ 3.47
				20	0.080242587	25901.38699	1.05	478868.2572	0.030242587	6156	129570	$ 8,161.35	14482.215	$ 22,643.56	$ 3.50
				21	0.077996107	26594.77068	1	529406.4407	0.027996107	6156	135726	$ 7,963.66	14821.319	$ 22,784.98	$ 3.53

Figure B.3 Snap of the modelling in southern region.

APPENDIX C. RESULTS FOR SNOW ROUTE OPTIMIZATION FOR APPROACH 1

APPENDIX C provides the results for snow route optimization by Approach 1 across remaining 100 unit locations. These results are presented district-wise in the sections below.

C.1 Crawfordsville District

Summary

Table C.1 presents a brief summary of each unit in the district and corresponding deadhead miles for each district based on the approach taken from the mathematical model. It also mentions the node for relocation of the facility.

Table C.1 Crawfordsville District Summary

Unit No	First Scenario	Second Scenario	Recommended Location	Third Scenario	Fourth Scenario	Recommended Location
1103	66 mi	56 mi	S_63_33	30.8 mi	14 mi	U_40_6
1201	118 mi	70 mi	U_231_178	55 mi	45 mi	U_136_37
1202	53.6 mi	50.2 mi	S_236_0	20 mi	20 mi	N/A
1203	100 mi	94 mi	S_63_60	No reduction achieved		
1204	55 mi	55 mi	N/A	No reduction achieved		
1301	31 mi	31 mi	N/A	No reduction achieved		
1302	71 mi	71 mi	N/A	No reduction achieved		
1303	110 mi	100 mi	S_43_29	75 mi	60 mi	S_43_29
1401	150 mi	136 mi	U_421_123	107 mi	98 mi	U_421_123
1402	120 mi	120 mi	N/A	No reduction achieved		
1403	60 mi	34 mi	U_231_201	28 mi	20 mi	U_231_201
1501	48 mi	47 mi	N/A	48 mi	47 mi	N/A
1502	54 mi	44 mi	S_236_19	No reduction achieved		
1503	66 mi	45 mi	N/A	66 mi	45 mi	N/A
1504	105 mi	68 mi	I_70_66	74 mi	40 mi	I_70_66

Figure C.1 presents the percentage change in deadhead miles by scenario across all units in the Crawfordsville District. Figure C.2 represents the deadhead miles across units in Crawfordsville District. Figure C.3 through Figure C.5 present the percentage change in deadhead miles for each unit according to Scenarios 2, 3, and 4, respectively.

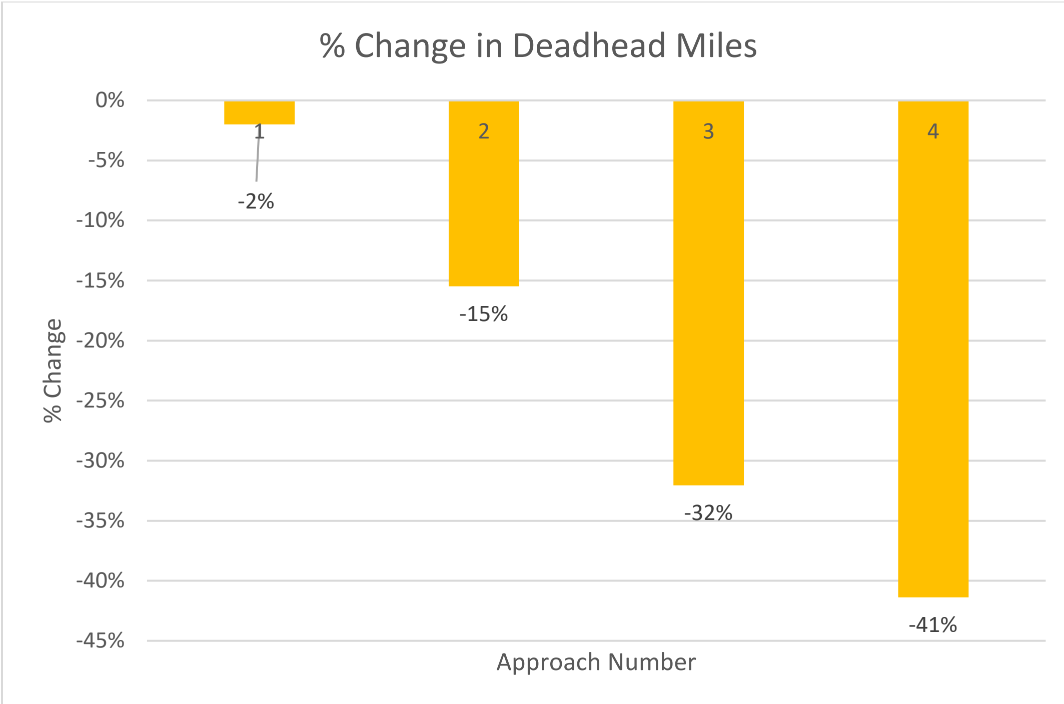


Figure C.1 Cumulative percentage change in deadhead miles across district by Scenario.

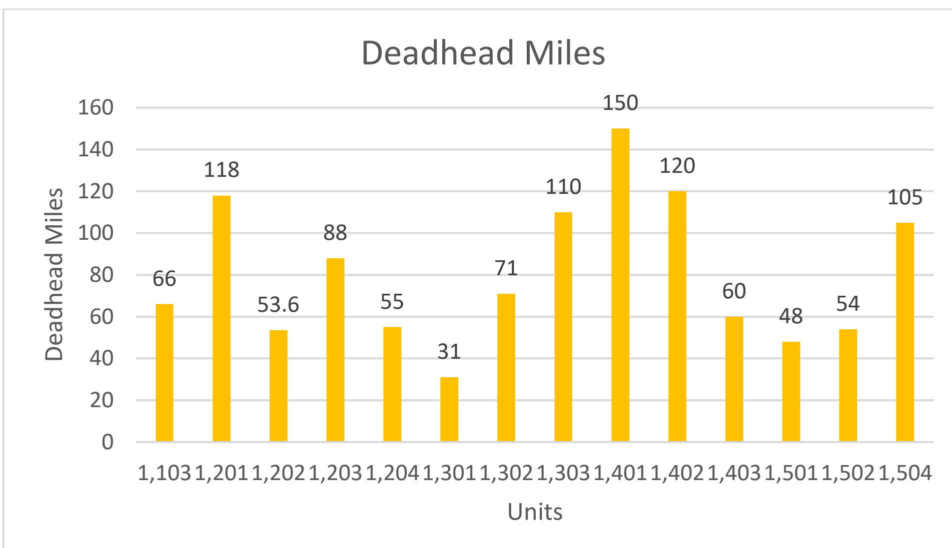


Figure C.1 Optimal deadhead miles across all units—Scenario 1.

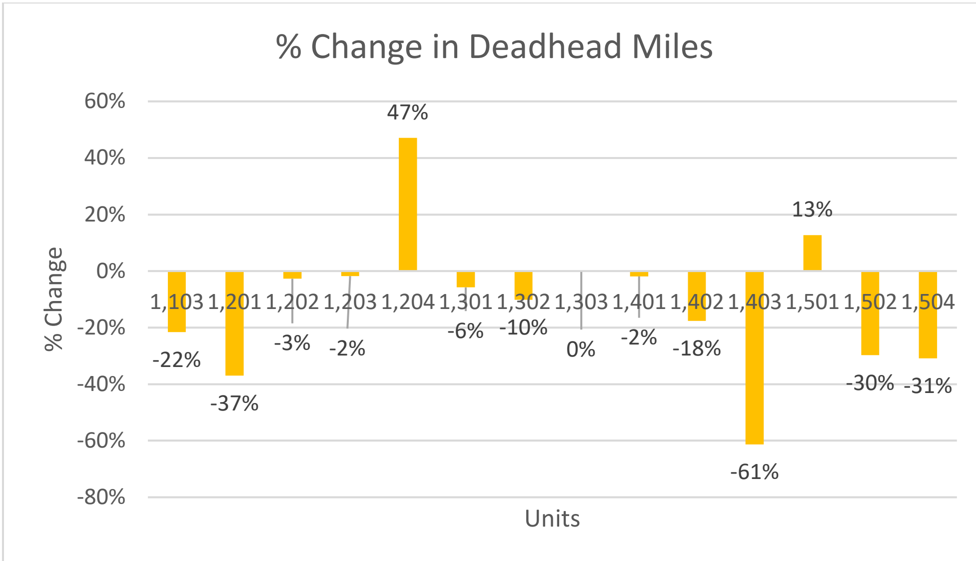


Figure C.2 Percentage change in deadhead miles across all units—Scenario 2.

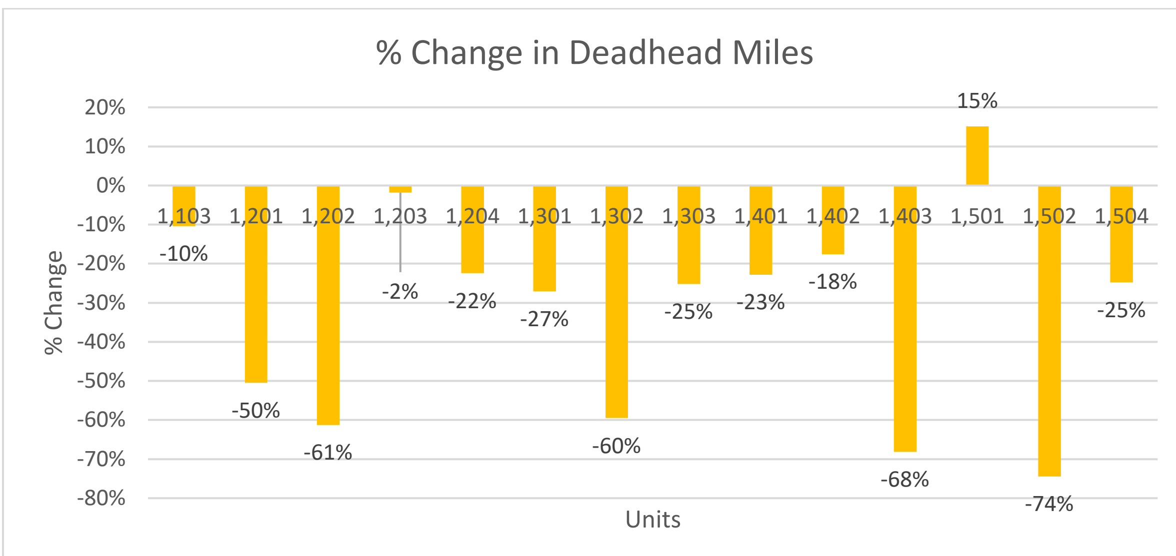


Figure C.4 Percentage change in deadhead miles across all unit—Scenario 3.

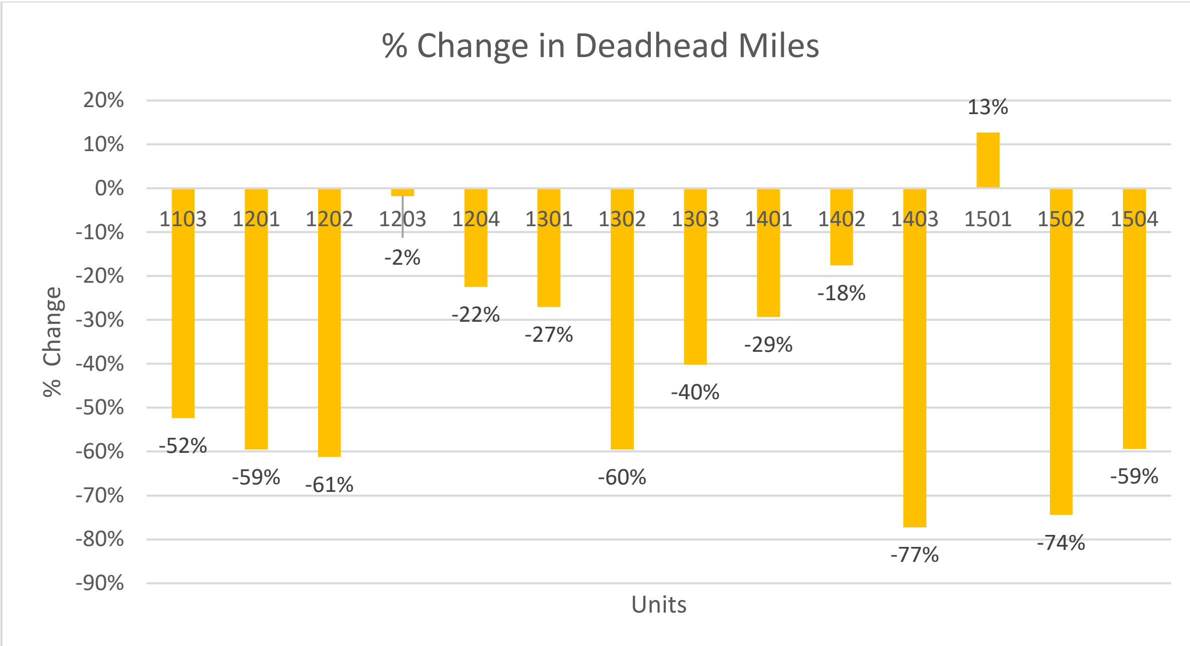


Figure C.3 Percentage change in deadhead miles across all units—Scenario 4.

Unit 1103

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 66 miles.

Scenario 2: With flexibility on facility location, node 3 is chosen to be the optimized location for minimal deadhead miles across the unit. Both the locations are showed in Figure C.6. In this case, the deadhead miles will be 56 miles.

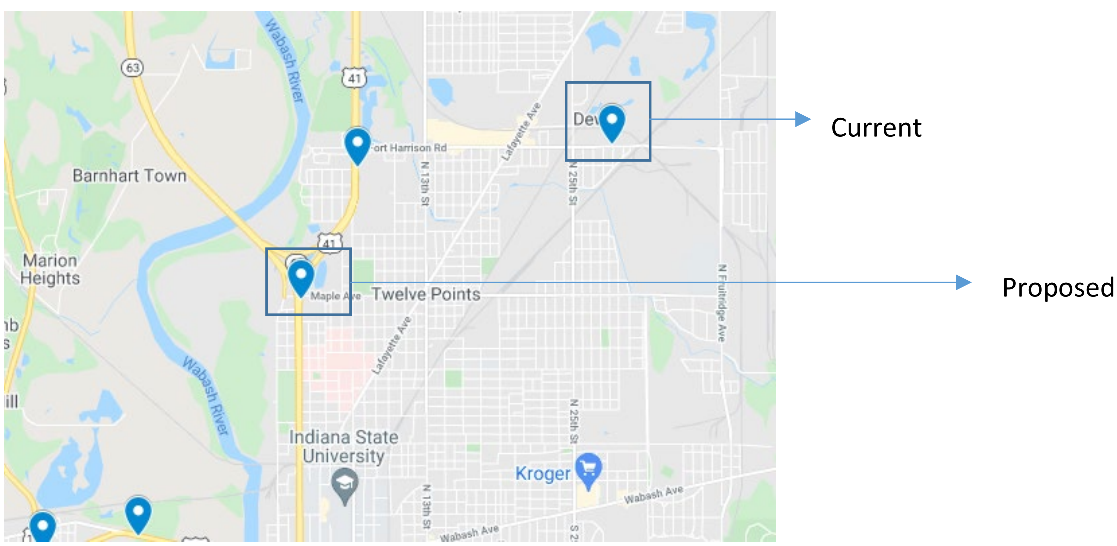


Figure C.4 Unit 1103 without additional routes.

Scenario 3: Additional routes are considered to minimize deadhead miles.
node 3, 4, 11, 10, 14, 12—New Route

With the existing route, Unit 1103 can have deadhead miles reduced to 31 miles if the location of the facility is kept where it is.

Scenario 4: However, if we are to incorporate the flexibility in facility's location, the minimum deadhead miles of 14 mi is achieved if the unit is based close to node 6. Figure C.7 shows the respective position of current and proposed facility location.

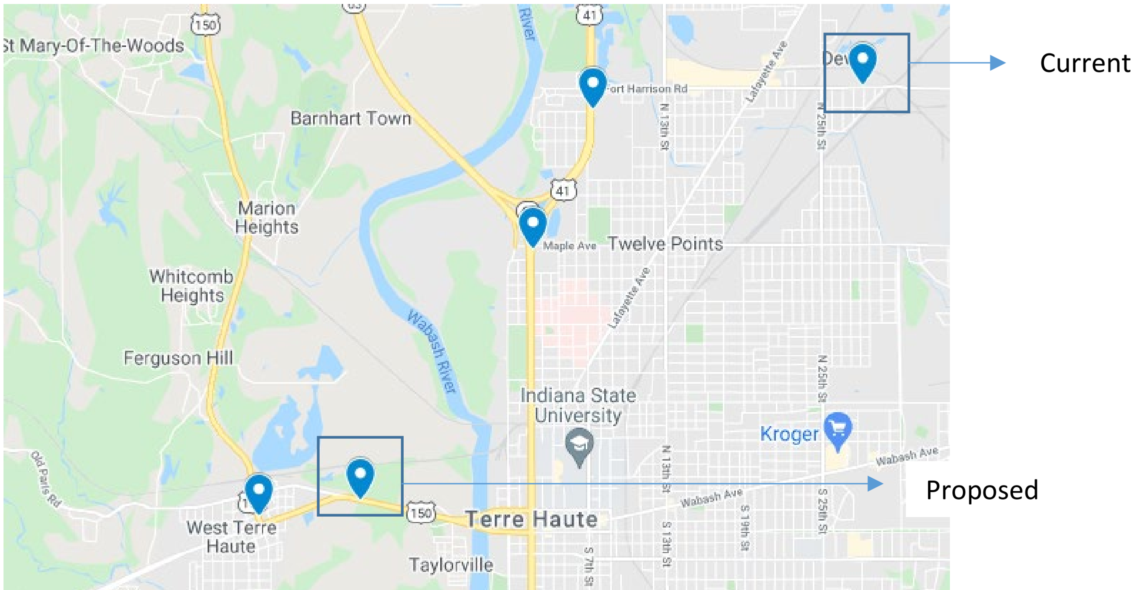


Figure C.5 Unit 1103 with additional routes.

Unit 1201

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 118.4 miles.

Scenario 2: With flexibility on facility location, node 13 is chosen to be the optimized location for minimal deadhead miles across the unit. Both the locations are showed in Figure C.8. In this case, the deadhead miles will be 69.8 miles.

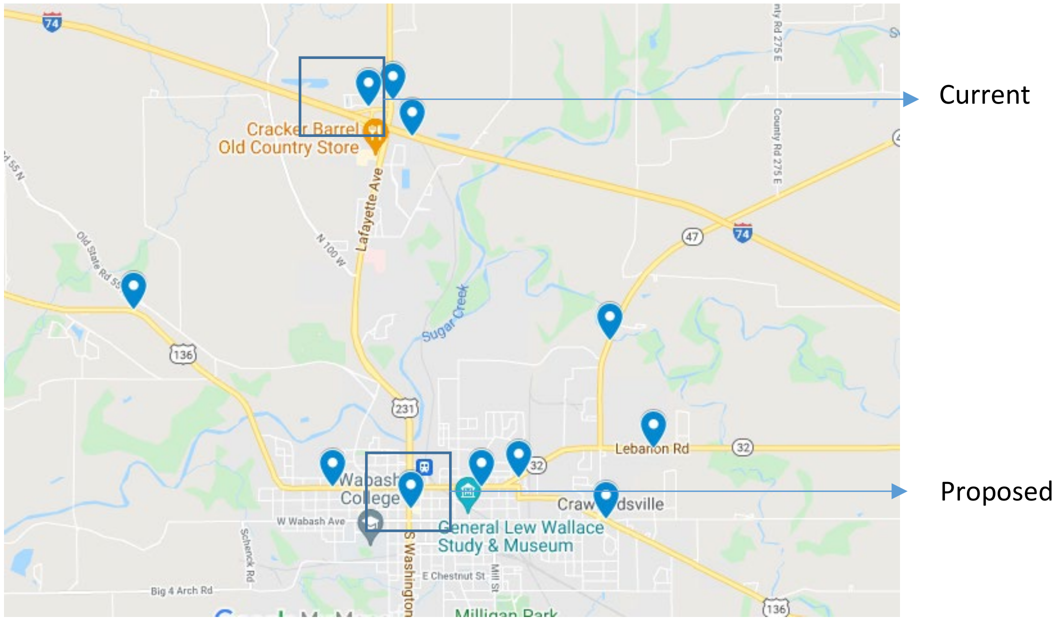


Figure C.6 Unit 1201 without additional routes.

Scenario 3: Additional routes are considered to minimize deadhead miles.
node 1, 2, 5, 7, 8, 9, 39—New Route 1; node 16, 17, 18, 19, 20, 21, 22, 23, 24—New Route 2
node 26, 27, 28, 29, 30, 40, 42, 44, 45, 47—New Route 3
With the existing route, Unit 1201 can have deadhead miles reduced to 55 miles, if the location of the facility is kept where it is, which is node 14.
Scenario 4: However, if we are to incorporate the flexibility in facility's location, the minimum deadhead of 45 miles is achieved if the unit is based close to node 50 (which is also very close to node 13). Figure C.9 shows the respective position of current and proposed facility location.

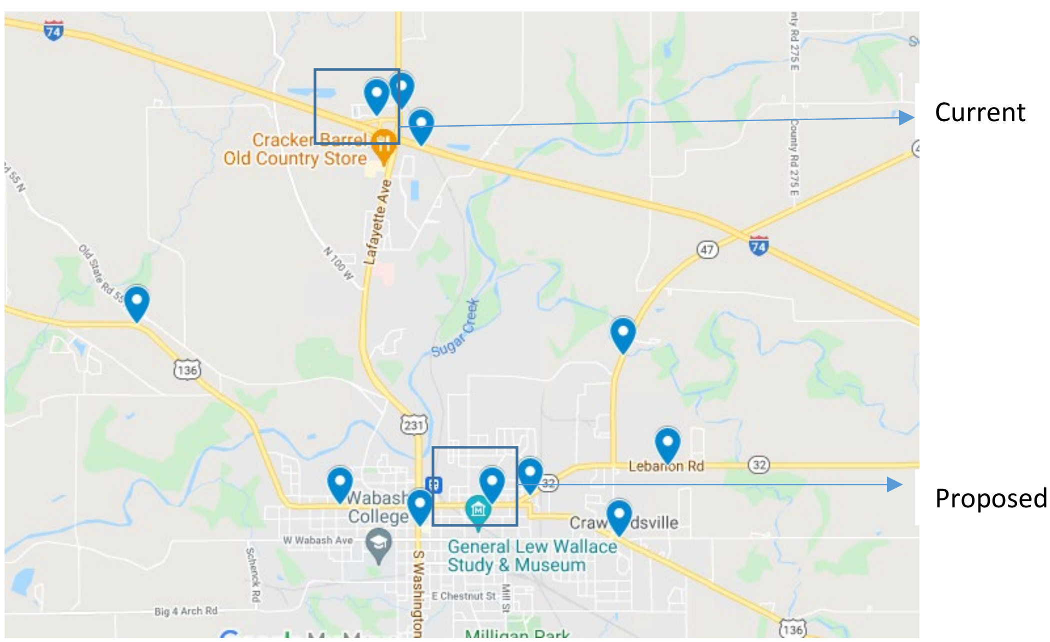


Figure C.7 Unit 1201 with additional routes.

Unit 1202

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 53.6 miles.

Scenario 2: With flexibility on facility location, node 8 is chosen to be the optimized location for minimal deadhead miles across the unit. Both the locations are showed in Figure C.10. In this case, the deadhead miles will be 50.2 miles.

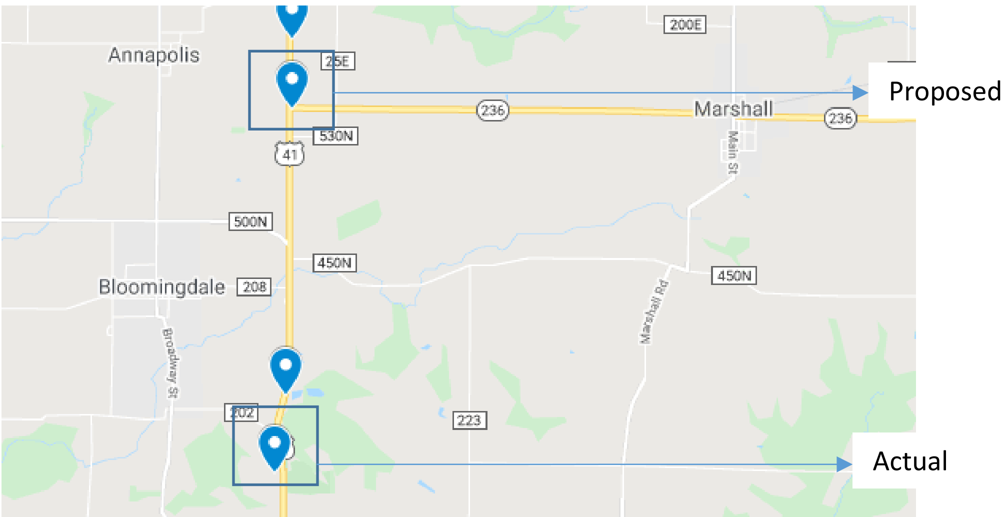


Figure C.8 Unit 1202 without additional routes.

Scenario 3: Additional routes are considered to minimize deadhead miles.
node 1, 6, 5, 13, 8, 9, 10, 11, 14—New Route 1
node 1, 2, 3, 4, 5, 17, 18, 19, 20—New Route 2
With the existing route, Unit 1202 can have deadhead miles reduced to 20 miles, if the location of the facility is kept where it is, which is node 6.

Scenario 4: However, if we are to incorporate the flexibility in facility's location, there's no significant change in the deadhead miles for this unit. Thus, with the additional routes, the current facility might already be in optimized location.

Unit 1203

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 100 miles.

Scenario 2: With flexibility on facility location, as shown in Figure C.11, node 11 is chosen to be the optimized location for minimal deadhead miles across the unit, which allows the minimum deadhead miles to go down to 94 miles. This means Unit 1203 already has optimized location for its facility, considering the current route.

Scenario 3: Additional routes are considered to minimize deadhead miles.
node 1, 3, 16, 20, 22, 23—New Route 1

Scenario 4: With the existing route, Unit 1203 cannot decrease deadhead miles any further.

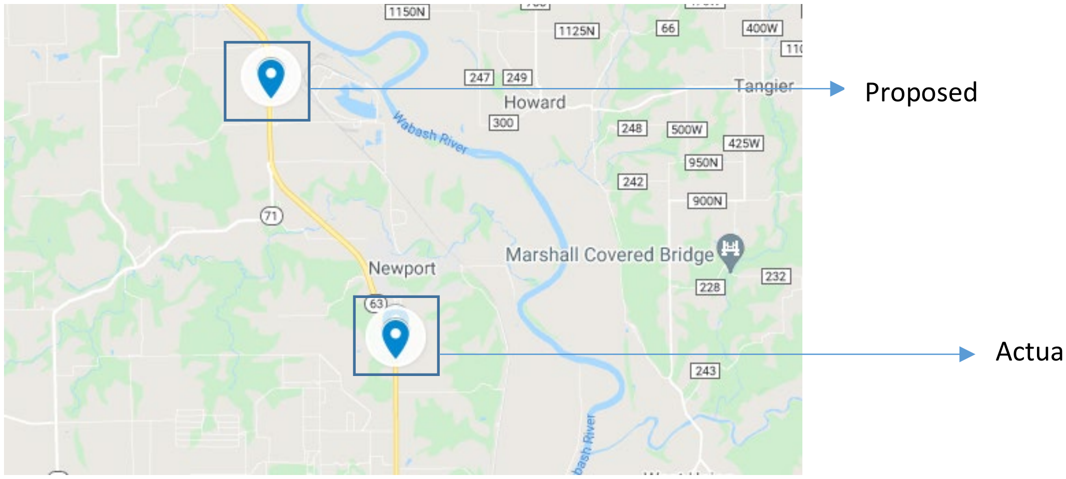


Figure C.9 Unit 1203 proposed location.

Unit 1204

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 55 miles.

Scenario 2: With flexibility on facility location, node 24 is chosen to be the optimized location for minimal deadhead miles across the unit. However, there is no significant change in deadhead miles, which means the facility location is already optimized.

Scenario 3: Additional routes are considered to minimize deadhead miles.

node 1, 2, 3, 4, 5, 6, 9—New Route 1

node 23, 24, 25, 26, 27, 28—New Route 2

With the existing route, Unit 1203 had a decreased deadhead mile of 28 miles with the new routes.

Scenario 4: The deadhead miles don't change significantly though for other facility locations. This means that deadhead miles are optimized for the current location with changes in these routes.

Unit 1301

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 31 miles.

Scenario 2: Interestingly, with flexibility on facility location, node 5 is chosen to be the optimized location for minimal deadhead miles across the unit. This means Unit 1301 already has optimized location for its facility, considering the current route.

Scenario 3: Additional routes are considered to minimize deadhead miles.

node 1, 2, 3, 5, 22, 23—New Route 1

node 1, 2, 4, 5, 6, 7, 811—New Route 2

With the additional route, Unit 1301 can have a decrease in deadhead miles, which becomes 24 miles.

Scenario 4: However, the optimized facility location is still the same, which means the location is already optimized.

Unit 1302

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 71 miles.

Scenario 2: Interestingly, with flexibility on facility location, node 20 is chosen to be the optimized location for minimal deadhead miles across the unit. This means Unit 1302 already has optimized location for its facility, considering the current route.

Scenario 3: Additional routes are considered to minimize deadhead miles.
node 1, 2, 4, 18—New Route 1
node 2, 5, 6, 8, 9, 12, 20—New Route 2
With the additional route, Unit 1302 can have a decrease in deadhead miles, which becomes 32 miles.
Scenario 4: However, the optimized facility location is still the same, which means the location is already optimized.

Unit 1303

Assumptions:

- Routes 01 and 02 have significant overlap in one segment, which is considered once in the analysis.
- Routes 21 and 22 are considered same and included in the analysis only once.

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 110 miles.
Scenario 2: With flexibility on facility location, node 29 is chosen to be the optimized location for minimal deadhead miles across the unit which then becomes 100 miles. The actual and proposed locations are mentioned in the Figure C.12.
Scenario 3: Additional routes:

- Nodes 1, 2, 5, 6, 40—New Route 1
- Nodes 1, 9, 15, 16, 13—New Route 2

Even with the facility at existing location, the deadhead miles with these additional routes become 75 miles.
Scenario 4: Additional routes reduce the deadhead miles to 60 miles, with the facility location close to previously stated node 29 (as shown in Figure C.12).

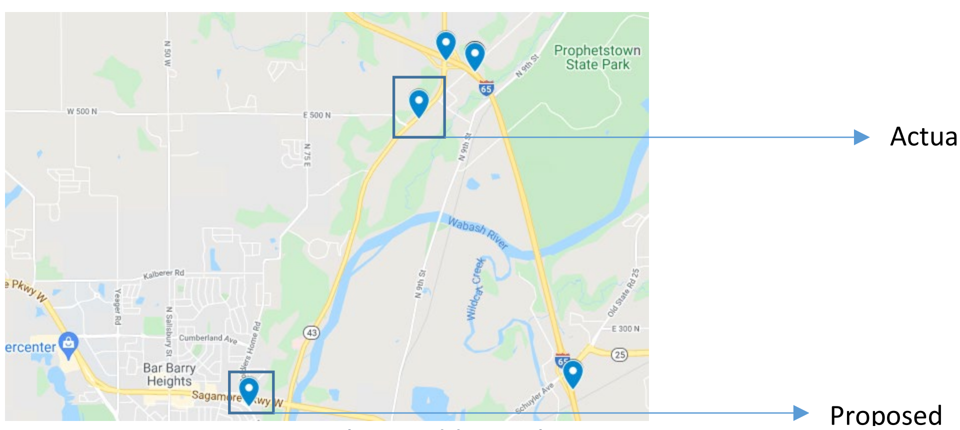


Figure C.10 Unit 1303 without additional routes.

Unit 1401

Assumptions: One segment is Route 09 is repeated in Route 04. For this analysis, they are considered singular as part of Route 09
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 150 miles.
Scenario 2: With flexibility on facility location, node 7 is chosen to be the optimized location for minimal deadhead miles across the unit which then becomes 136 miles. The actual and proposed locations are mentioned in the Figure C.13.
Scenario 3: Additional routes are considered to minimize deadhead miles

node 1, 2, 3—New Route 1
With the additional routes, the recommendation for facility remains as shown in Figure C.13. However, the deadhead miles for facility in its current location becomes 107 miles
Scenario 4: In the proposed location the total deadhead mile becomes 98 miles.

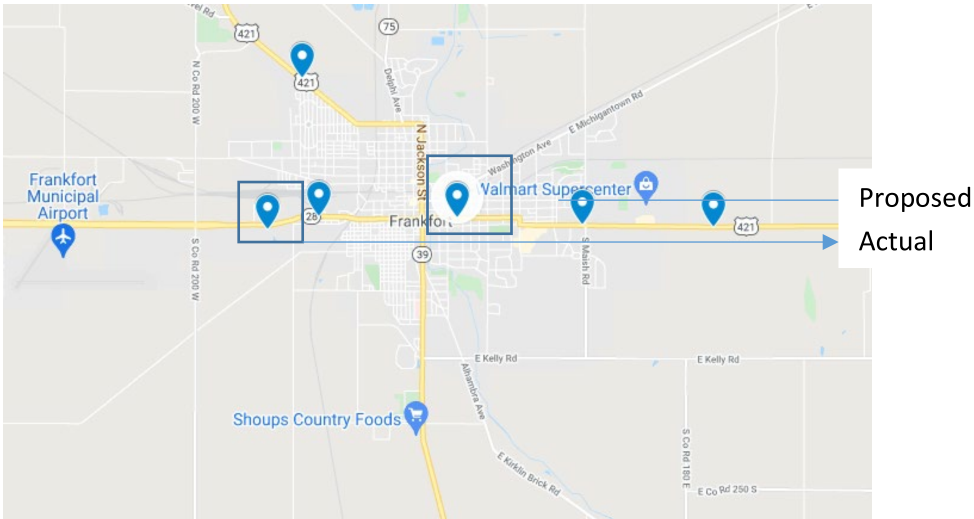


Figure C.11 Unit 1401 without additional routes.

Unit 1402
The optimized deadhead miles for this unit comes to be 120 miles, which suggests that the unit is already optimized in terms of facility location. Also, additional routes provide minimal reduction in deadhead miles, which suggests that the unit routes are also optimized.

Unit 1403
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 60 miles.
Scenario 2: With flexibility on facility location, node 10, which is shown as proposed location in Figure C.14, is chosen to be the optimized location for minimal deadhead miles across the unit. The minimum deadhead miles in this case becomes 34 miles.

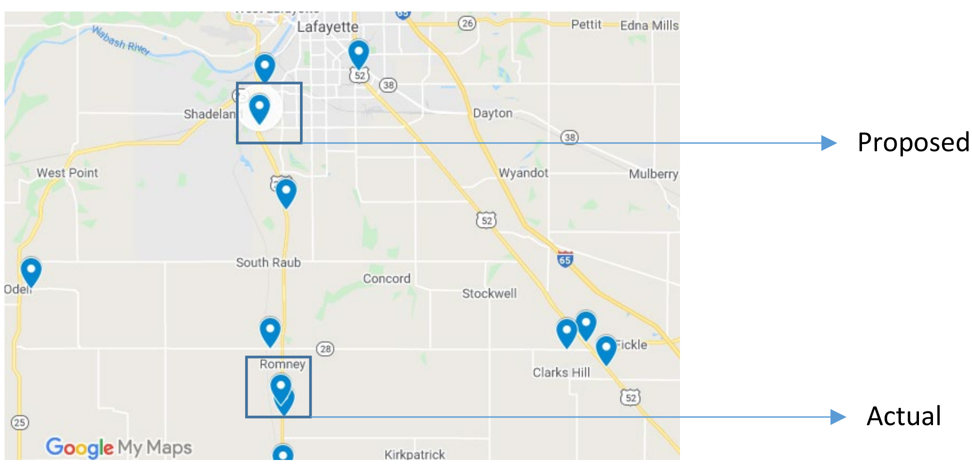


Figure C.12 Unit 1403 without additional routes.

Scenario 3: Additional routes are considered to minimize deadhead miles
node 1, 2, 311, 13—New Route 1
With the additional routes, the minimal location for the current facility location becomes 28 miles.
Scenario 4: With further flexibility in facility location, a new location is proposed for minimal deadhead miles, which is presented in Figure C.15. The deadhead miles for the new location then becomes 20 miles.

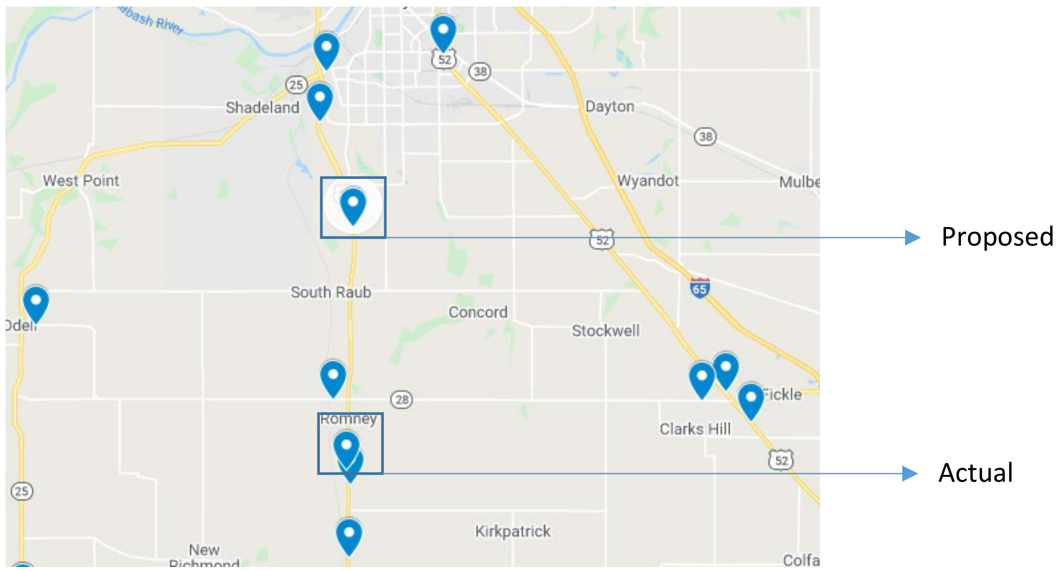


Figure C.13 Unit 1403 with additional routes.

Unit 1502
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 54 miles.
Scenario 2: With flexibility on facility location another location marked Proposed in Figure C.16 is chosen to be the optimized location for minimal deadhead miles across the unit. The minimum deadhead miles in this case becomes 44 miles.
Scenario 3: Additional routes are considered to minimize deadhead miles
node 4, 5, 6, 7, 8, 9—New Route 1
node 11, 12, 13, 15, 17—New Route 2
With the additional routes, the minimal location for the current facility location becomes 16 miles.
Scenario 4: With further flexibility in facility location, the deadhead mile still comes to be 16 miles with optimized location being the current one. This means that for additional routes in Unit 1502, the current facility location is already optimized.

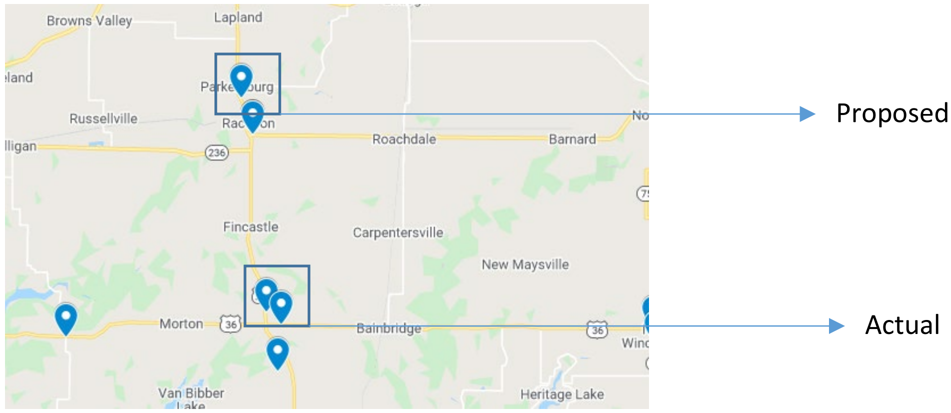


Figure C.14 Unit 1502 without additional routes.

Unit 1503

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 66 miles.

Scenario 2: With flexibility on facility location another location marked Proposed in Figure C.17 is chosen to be the optimized location for minimal deadhead miles across the unit. The minimum deadhead miles in this case becomes 45 miles.

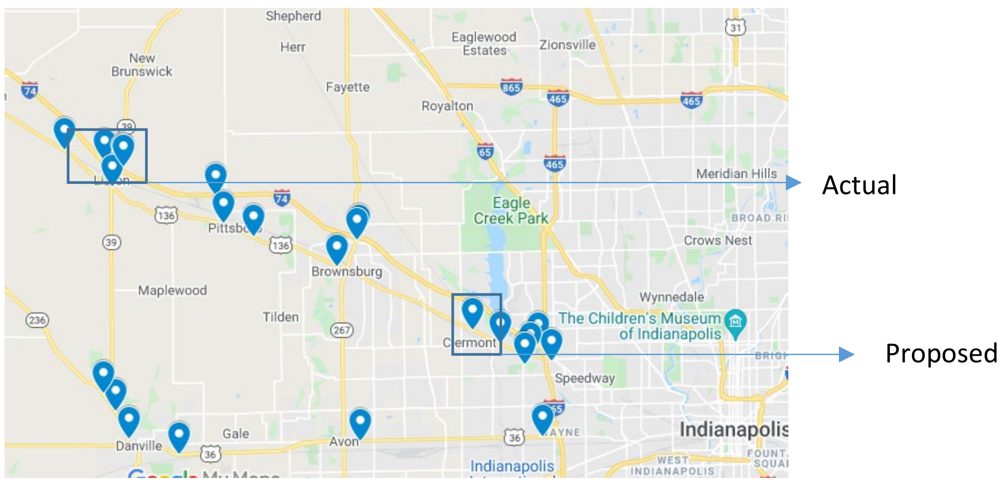


Figure C.15 Unit 1503 without additional routes.

Unit 1504

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 105 miles.

Scenario 2: With flexibility on facility location, node 7, which is shown as proposed location in Figure C.18, is chosen to be the optimized location for minimal deadhead miles across the unit. The minimum deadhead miles in this case becomes 68 miles.

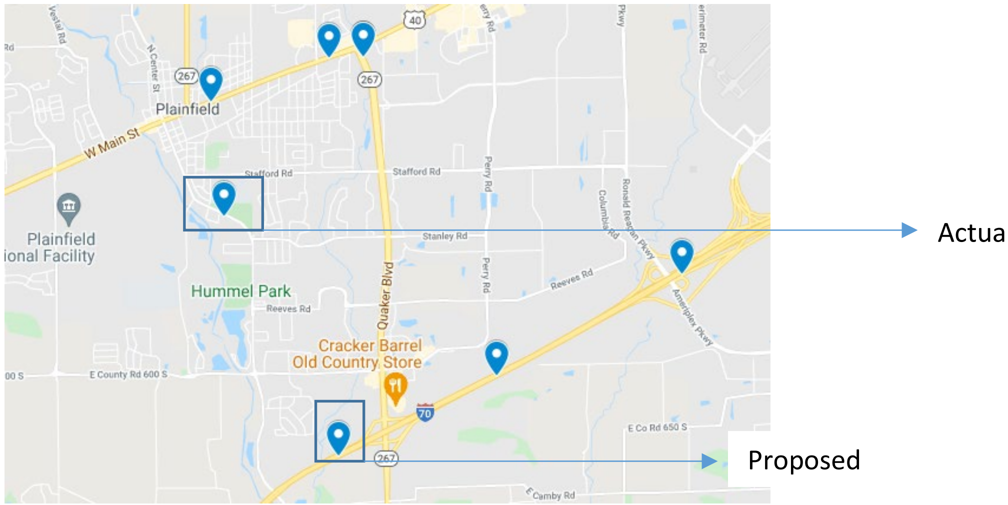


Figure C.16 Unit 1504 without additional routes.

Scenario 3: Additional routes
nodes: 15, 16, 17, 19, 20, 21—New Route 1
nodes: 9, 10, 11, 26—New Route 2
With additional routes for same facility location, the deadhead miles come out to be 74 miles.
Scenario 4: Further reduction to 40 mi can be achieved by shifting the facility location as proposed in Figure C.18.

C.2 Fort Wayne District

Summary

Table C.2 presents a brief summary of each unit in the district and corresponding deadhead miles for each district based on the scenario taken from the mathematical model. It also mentions the node for relocation of the facility.

Table C.2 Fort Wayne District Summary

Unit No	First Scenario	Second Scenario	Recommended Location	Third Scenario	Fourth Scenario	Recommended Location
2201	101 mi	61 mi	S_15_82	77 mi	57 mi	S_15_81
2204	58.6 mi	44 mi	S_5_91	N/A	N/A	N/A
2205	77 mi	63 mi	S_15_59	61 mi	39 mi	S_15_57
2206	47.8 mi	47.8 mi	N/A	No reduction achieved		
2301	242.8 mi	181.2 mi	I_69_309	220 mi	180 mi	I_69_309
2303	130 mi	130 mi	N/A	88 mi	No reduction achieved	
2305	72 mi	60 mi	S_8_62	57 mi	27 mi	S_8_62
2306	52 mi	43 mi	I_69_347	43 mi	36 mi	I_69_347
2501	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
2502	68 mi	60 mi	S_19_46	39 mi	28 mi	S_19_49
2506	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
2601	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				

2603	67.6 mi	56.2 mi	**U_27_86**	**60 mi**	**56.2 mi**	**U_27_86**
2604	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				

Figure C.19 presents the percentage change in deadhead miles by scenario across all units in the Fort Wayne District. Figure C.20 represents the deadhead miles across units in Fort Wayne District. Figure C.21 through Figure C.23 present the percentage change in deadhead miles for each unit according to Scenarios 2, 3, and 4, respectively.

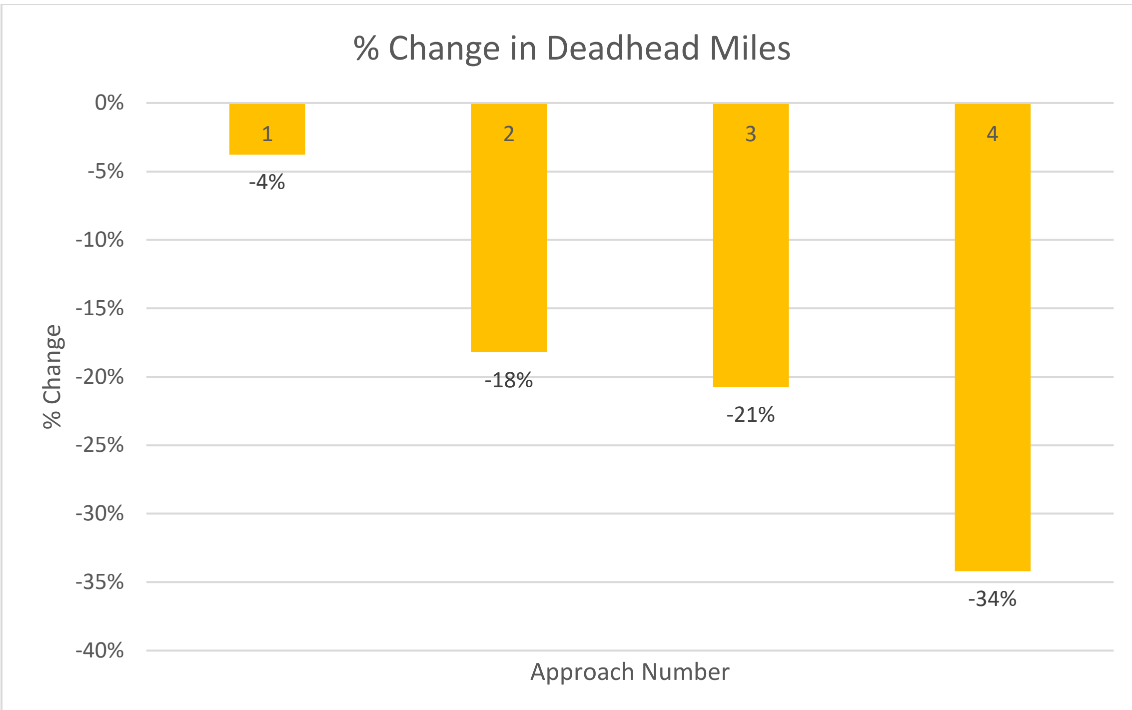


Figure C.17 Cumulative percentage change in deadhead miles across district by Scenario.

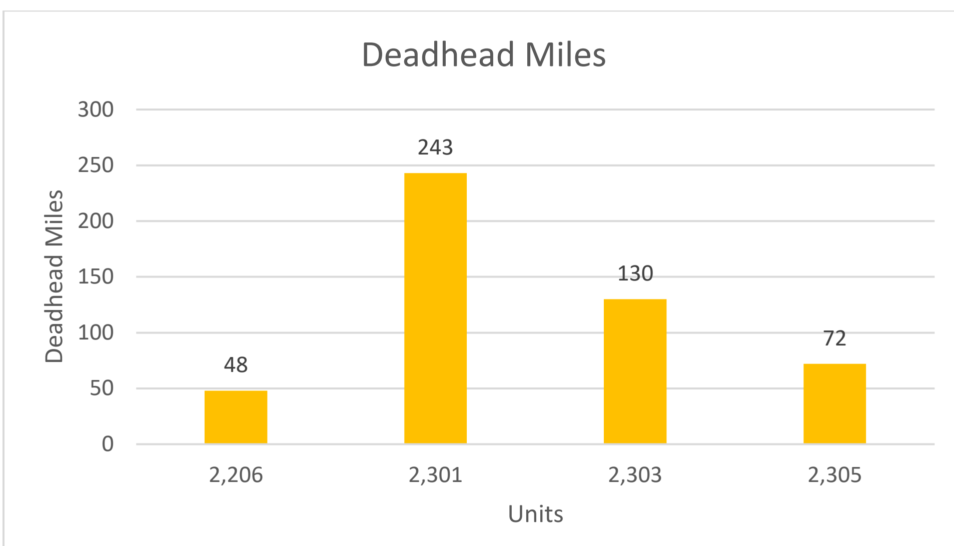


Figure C.18 Optimal deadhead miles across all units—Scenario 1.

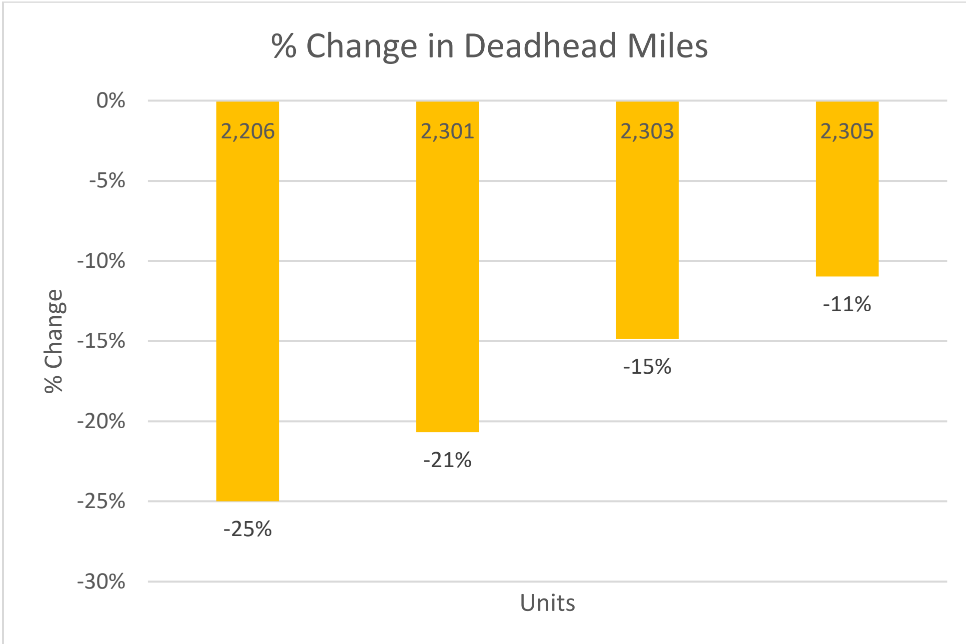


Figure C.19 Percentage change in deadhead miles across all units—Scenario 2.

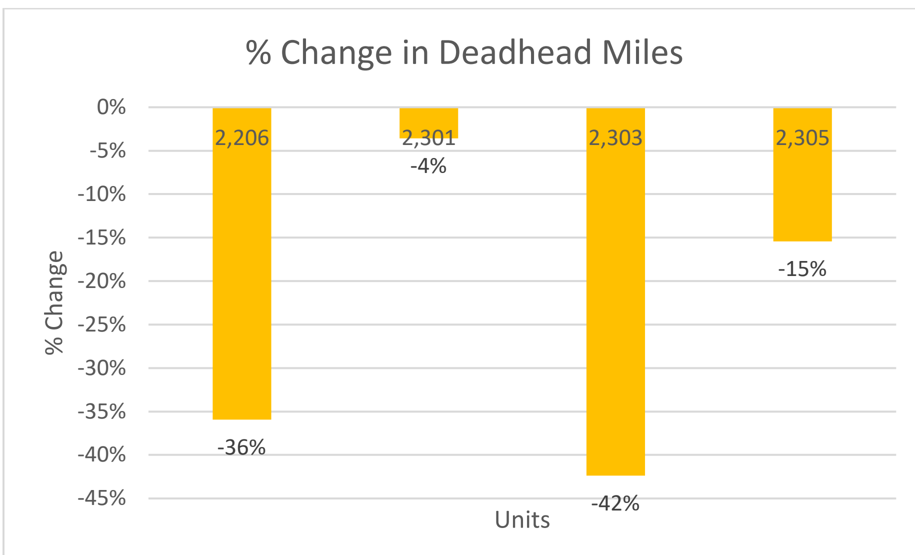


Figure C.20 Percentage change in deadhead miles across all units—Scenario 3.

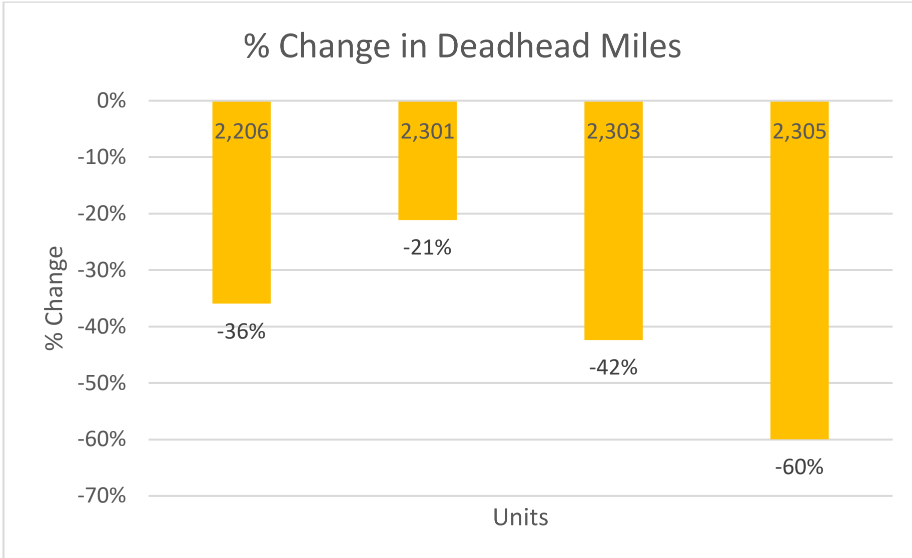


Figure C.21 Percentage change in deadhead miles across all units—Scenario 4.

Unit 2201

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 101 miles.

Scenario 2: The minimum deadhead miles are, however, for facility to be close to node 14, which is shown in the Figure C.24. The minimum deadhead miles then become 61 miles.

Scenario 3: Additional routes consider nodes or mileposts associated with Routes 201, 202, and 310 together. With this routing, the total deadhead miles are reduced to 77 miles.

Scenario 4: The deadhead miles can be further minimized to 57 miles by relocating the facility to node 32, as shown in Figure C.25.

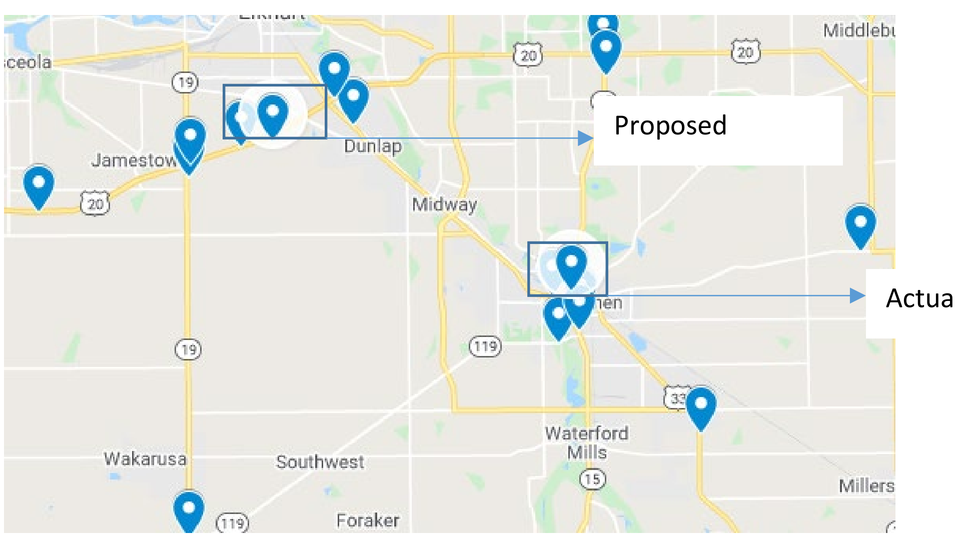


Figure C.22 Unit 2201 without additional routes.

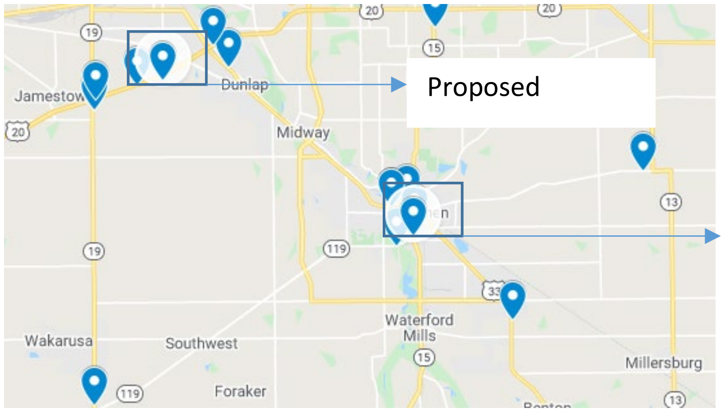


Figure C.23 Unit 2201 with additional routes.

Unit 2204

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 58.6 miles.

Scenario 2: The minimum deadhead miles are, however, reached for facility to be close to node 9, which is shown in the Figure C.26.The minimum deadhead miles then become 44 miles.

Scenario 3: Generating additional routes don't reduce the deadhead miles.

Scenario 4: Relocating the facility and generating additional routes don't reduce the deadhead miles.

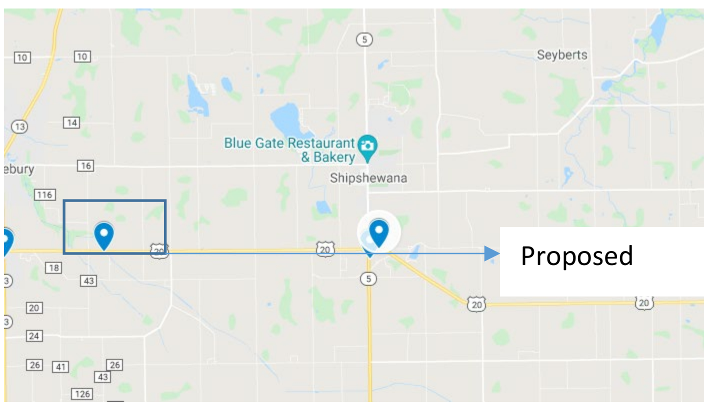


Figure C.24 Unit 2204 proposed location.

Unit 2205

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 77 miles.

Scenario 2: The minimum deadhead miles is, however, reached for facility to be close to node 7, which is shown in the Figure C.27. The minimum deadhead miles then become 63 miles.

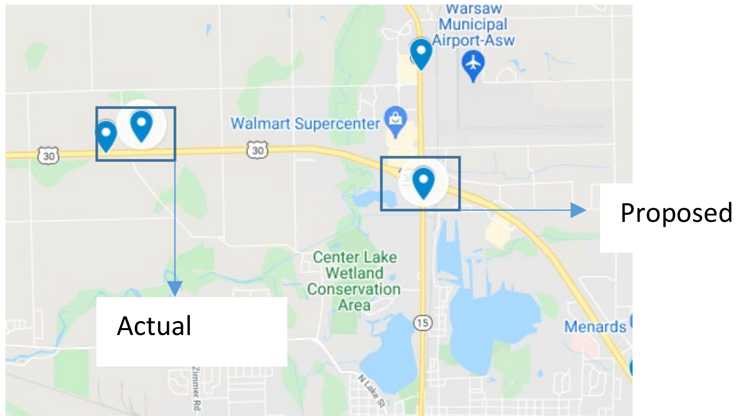


Figure C.25 Unit 2205 without additional units.

Scenario 3: Additional routes consider nodes or mileposts associated with Routes 303 and 307 together. With this routing, the total deadhead miles are reduced to 61 miles.

Scenario 4: The deadhead miles can be further minimized to 39 miles by relocating the facility to node 6 (Figure C.28).

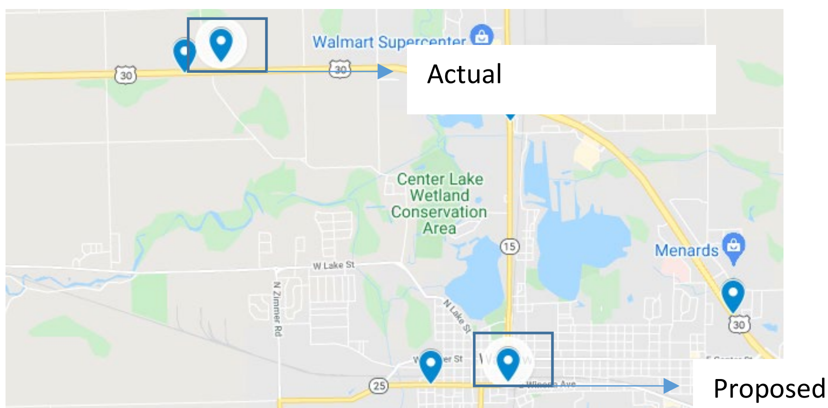


Figure C.26. Unit 2205 with additional routes.

Unit 2206

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 47.8 miles.

Scenario 2: With flexibility on facility location, node 1 is chosen to be the optimized location for minimal deadhead miles across the unit. This means Unit 2206 already has optimized location for its facility, considering the current route.

Scenario 3: Additional routes are considered to minimize deadhead miles.

Routes 206 and 303 are considered to be single route. With this additional route, the total deadhead mile goes down to 44.8 miles for current facility location.

Scenario 4: No reduction is achieved by flexing facility location, which means the facility location is optimized for this unit.

Unit 2301

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 242.8 miles.

Scenario 2: When the facility is relocated to the proposed site with the current snow route network, the deadhead miles reduce to 181.2 miles.
Scenario 3: When additional routes are generated to replace the current snow routes, the deadhead miles are 220 miles. Combining node for Snow Routes 204 and 205 generates an additional route.
Scenario 4: For the changed location proposed in the Figure C.29, the deadhead miles will be 180 miles.

Figure C.27 Unit 2301.

Unit 2303
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 130 miles.
Scenario 2: When the facility is relocated to the proposed site, the deadhead miles remain the same.
Scenario 3: When additional routes are generated to replace the current snow routes, the deadhead miles are 88 miles. Combining node for Snow Routes 212 and 314 generates an additional route.
Scenario 4: Deadhead miles are minimum for the current facility with additional routes. Hence, the facility location is optimal.

Unit 2305
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 72 miles.
Scenario 2: When the facility is relocated to the proposed site with the current snow route network, the deadhead miles reduce to 60 miles.
Scenario 3: When additional routes are generated to replace the current snow routes, the deadhead miles are 57 miles. Combining nodes for Routes 201 and 207 generate an additional route. While assembling nodes for Routes 203 and 204 generate another additional route.
Scenario 4: Upon relocating the facility to the proposed location, as shown in the Figure C.30, with the new additional routes, the deadhead miles are 27 miles.

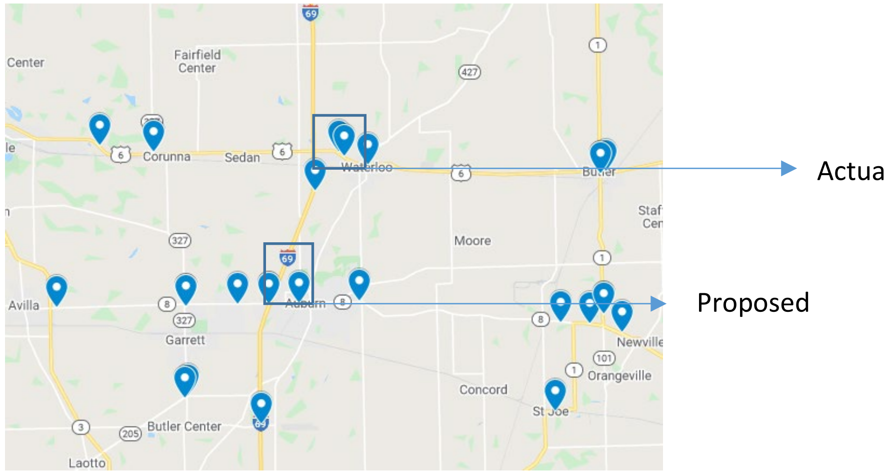


Figure C.28 Unit 2305.

Unit 2306

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 52 miles.

Scenario 2: The minimum deadhead miles is, however, reached for facility to be close to node 2, which is shown in the Figure C.31. The minimum deadhead miles then become 43 miles.

Scenario 3: Additional routes consider nodes or mileposts associated with Routes 206 and 208 together. With this routing, the total deadhead miles are reduced to 43 miles.

Scenario 4: It can be further minimized to 36 miles by relocating the facility to node 2, as shown in Figure C.31.

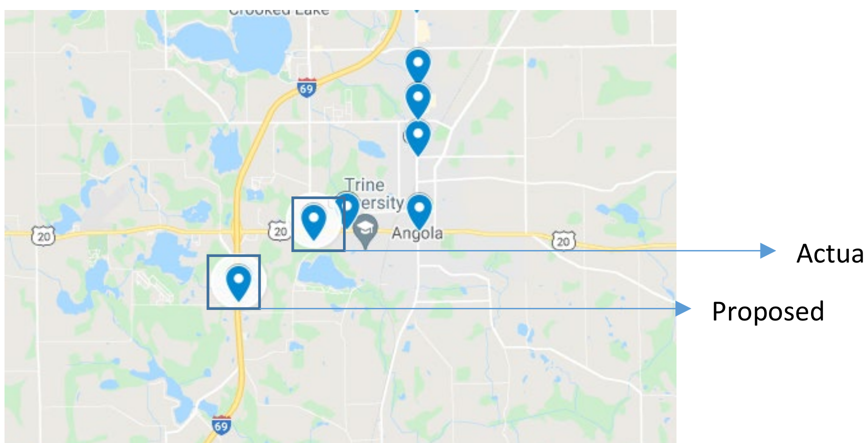


Figure C.29 Unit 2306 with and without additional routes.

Unit 2502

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 68 miles.

Scenario 2: Upon relocating the facility to node 20, as shown in the Figure C.32, the deadhead miles are reduced to 60 miles.

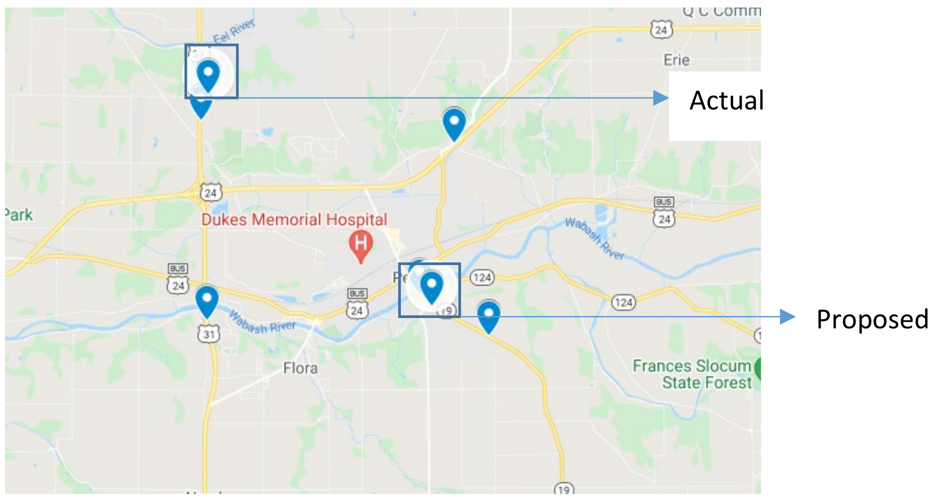


Figure C.30 Unit 2502 without additional routes.

Scenario 3: Additional routes framed by merging Routes 101 to 105 and 206 and 308 into one separate route provides total deadhead miles to be 39 mi for current location.
Scenario 4: Upon relocating the facility to node 8, as shown in the Figure C.33, with the new additional routes, the deadhead miles reduce to 28 miles.

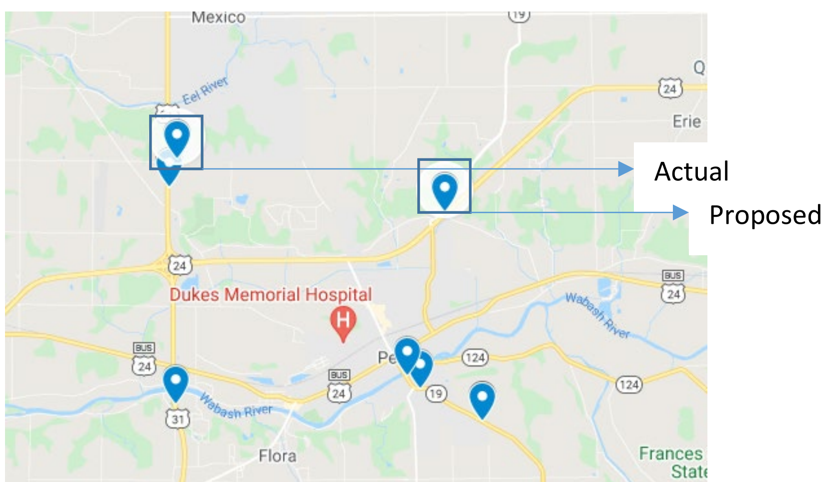


Figure C.31 Unit 2502 with additional routes.

Unit 2603
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 67.6 miles.
Scenario 2: When the facility is relocated to the proposed site, the deadhead miles reduce to 56.2 miles.
Scenario 3: When additional routes are generated to replace the current snow routes, the deadhead miles are 60 miles. Assembling nodes for routes 101 and 107 generate an additional route.
Scenario 4: Upon relocating the facility to the proposed location, as shown in the Figure C.34, with the new additional routes, the deadhead miles are 56.2 miles.

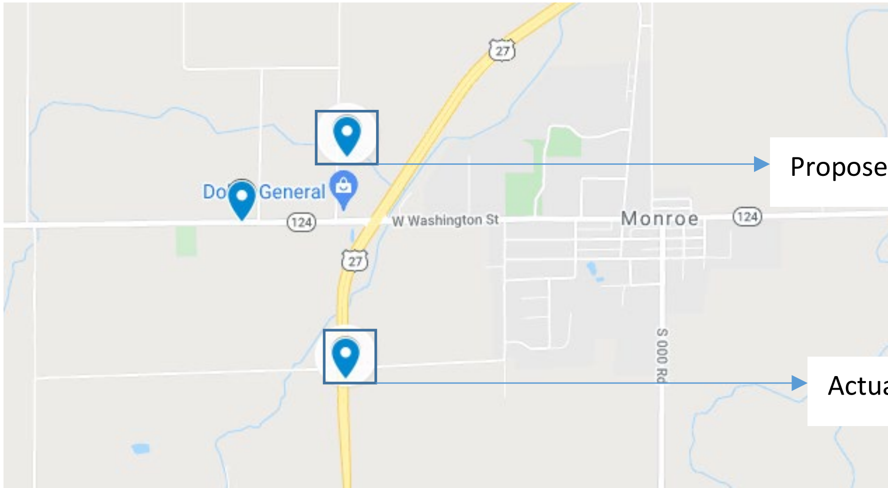


Figure C.32 Unit 2603 proposed location.

C.3 Greenfield District

Summary

Table C.3 presents a brief summary of each unit in the district and corresponding deadhead miles for each district based on the scenario taken from the mathematical model. It also mentions the node for relocation of the facility.

Table C.3 Greenfield District Summary

Unit No	First Scenario	Second Scenario	Recommended Location	Third Scenario	Fourth Scenario	Recommended Location
3101	210 mi	156 mi	I_465_47	210 mi	156 mi	N/A
3103	125 mi	70 mi	I_465_16	90 mi	42 mi	I_465_16
3104	86 mi	45 mi	I_465_37	75 mi	40 mi	I_465_36
3105	125 mi	100 mi	I_70_78	No reduction achieved		
3201	125 mi	125 mi	N/A	115 mi	115 mi	N/A
3202	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
3203	13 mi	6.5 mi	S_44_55	8.4 mi	8.4 mi	N/A
3204	50 mi	18 mi	S_9_29	25 mi	~2 mi	S_9_29
3301	45 mi	36 mi	U_27_26	40 mi	34 mi	U_35_8
3302	42 mi	3 mi	U_40_131	16.6 mi	1.5 mi	U_40_131
3303	54 mi	52 mi	S_38_93	20.2 mi	10 mi	N/A
3304	70 mi	60 mi	U_27_8	46 mi	42 mi	U_27_8
3501	44.6 mi	42.6 mi	S_28_84	23.2 mi	11.4 mi	S_28_89
3502	35 mi	35 mi	N/A	No reduction achieved		
3503	38 mi	30 mi	U_31_132	No reduction achieved		
3504	32 mi	32 mi	N/A	~2 mi	~2 mi	N/A
3601	65 mi	62 mi	S_32_126	52 mi	52 mi	N/A
3603	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
3604	19 mi	19 mi	N/A	~2 mi	~2 mi	N/A

3605	82 mi	62 mi	S_332_0	36 mi	36 mi	N/A

Figure C.35 presents the percentage change in deadhead miles by scenario across all units in the Greenfield District. Figure C.36 represents the deadhead miles across units in Greenfield District. Figure C.37 through Figure C.39 present the percentage change in deadhead miles for each unit according to Scenarios 2, 3, and 4, respectively.

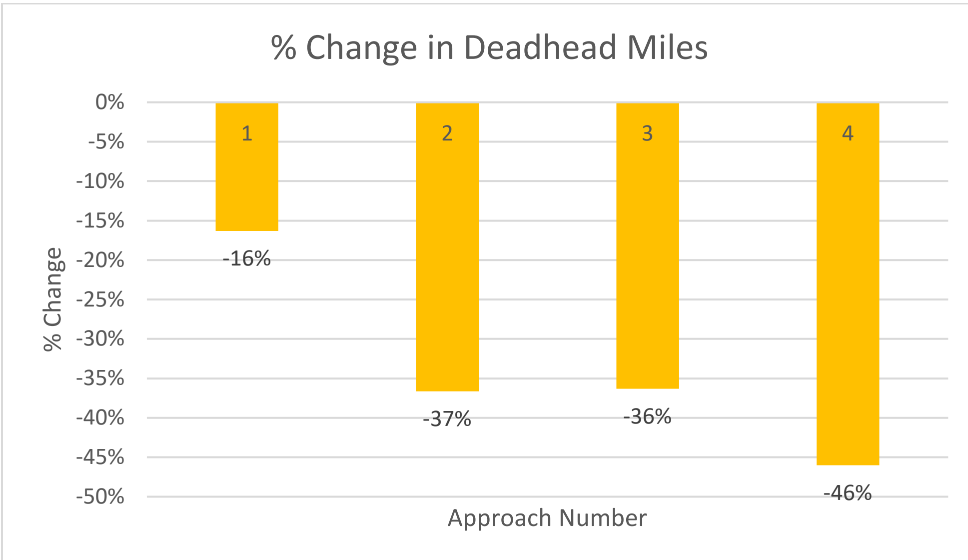


Figure C.33 Cumulative percentage change in deadhead miles across district by Scenario.

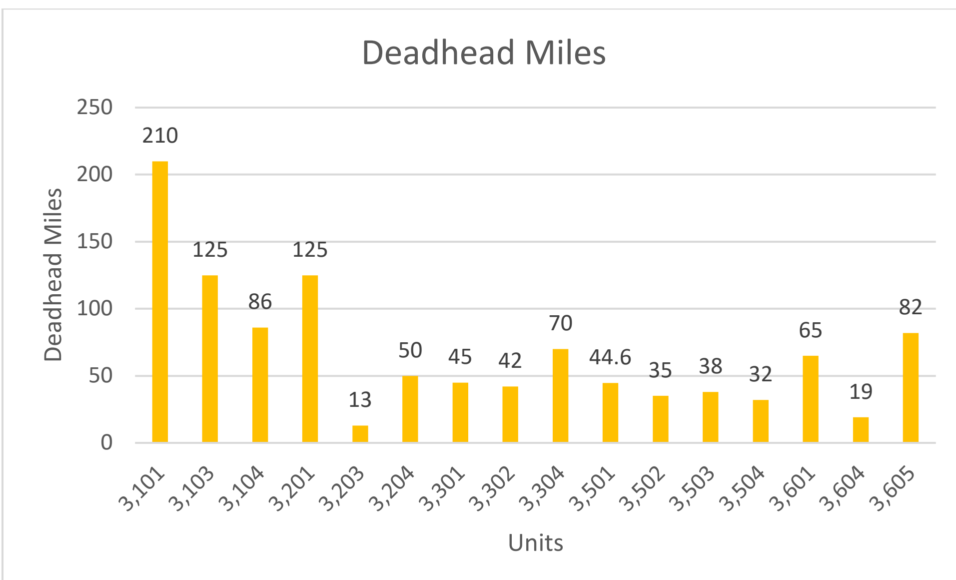


Figure C.34 Optimal deadhead miles across all units—Scenario 1.

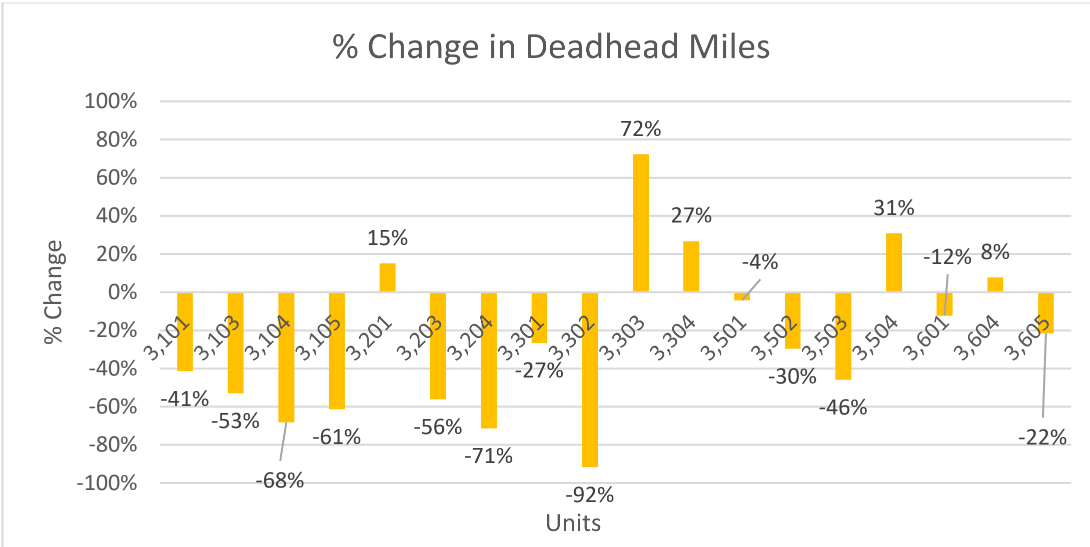


Figure C.35 Percentage change in deadhead miles across all units—Scenario 2.

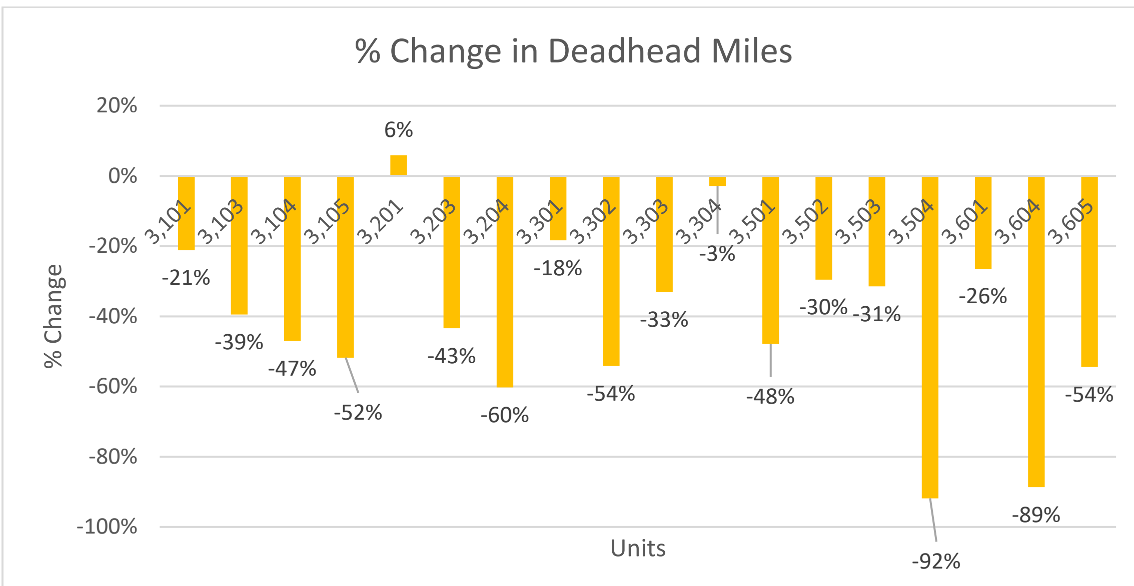


Figure C.36 Percentage change in deadhead miles across all units—Scenario 3.

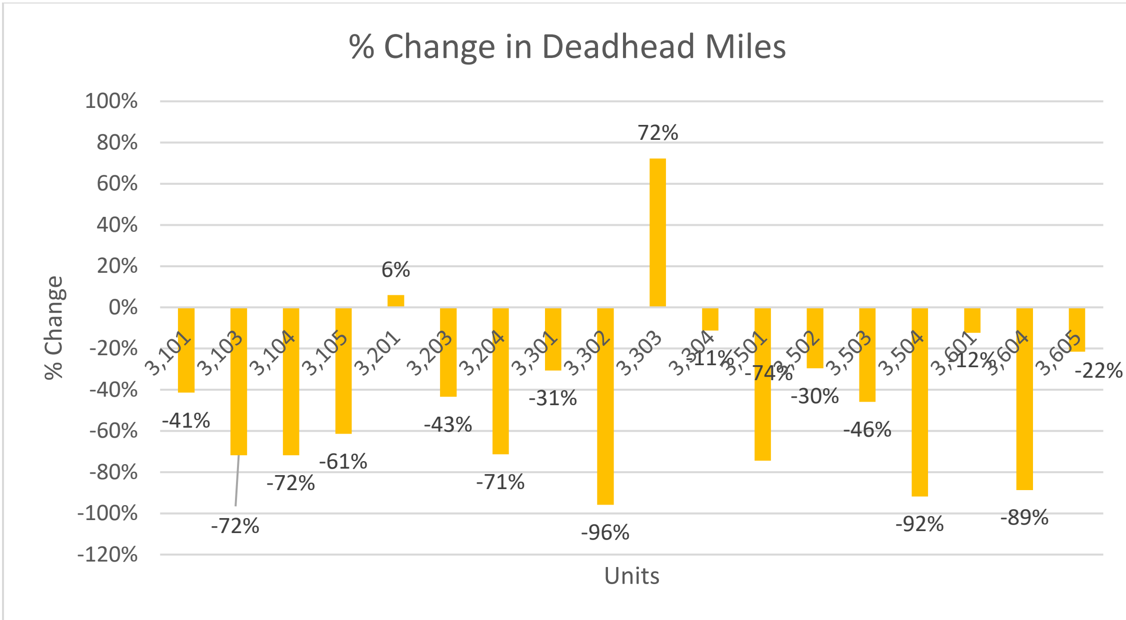


Figure C.37 Percentage change in deadhead miles across all units—Scenario 4.

Unit 3101

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 210 miles.

Scenario 2: When relocating the facility to a different location—node 2, the deadhead miles reduce to 156 miles. The current and proposed locations are shown in the Figure C.40.

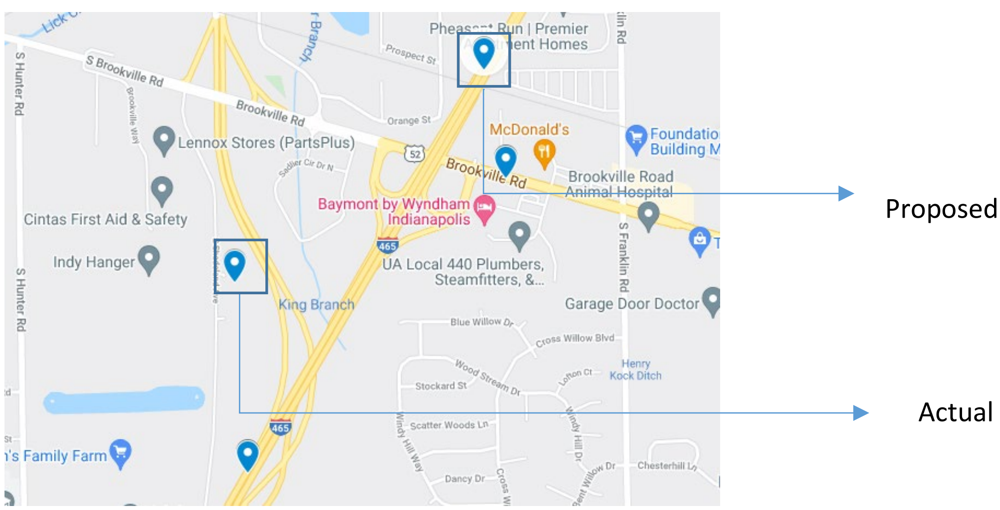


Figure C.38 Unit 3101 without additional routes.

Scenario 3: Generating additional routes don't reduce the deadhead miles.

Scenario 4: Relocating the facility and generating additional routes don't reduce the deadhead miles.

Unit 3103

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 125 miles.

Scenario 2: The deadhead miles reduce to 70 miles, when the facility location is chosen at node 8, as shown in the Figure C.41.

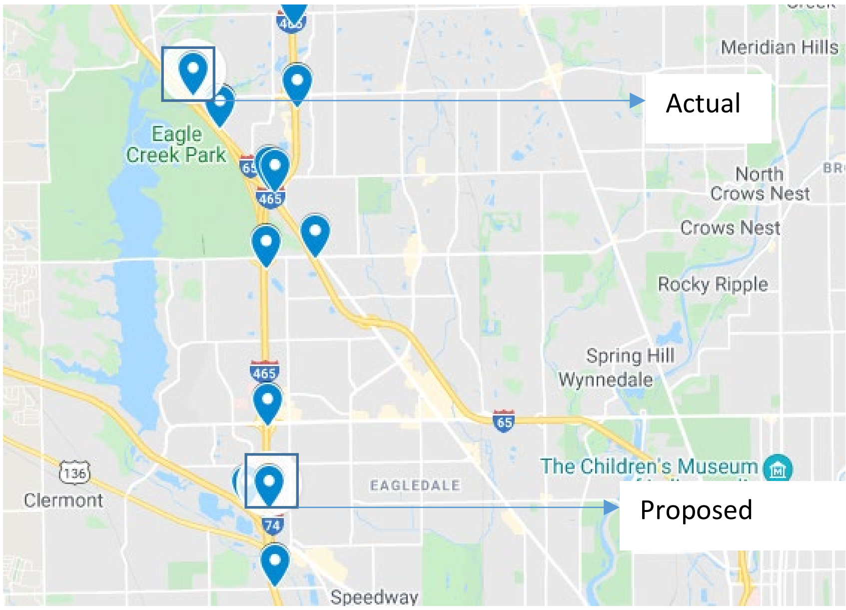


Figure C.39 Unit 3103 without additional routes.

Scenario 3: If additional routes are established to support 2-3-BR and 3-1-BR as one and 3-21 and 3-28 as one, a significant reduction in deadhead mile is achieved, which comes to be 90 miles.
Scenario 4: Further, if the location of facility is relocated as proposed in the Figure C.42, the total deadhead will become 42 miles.

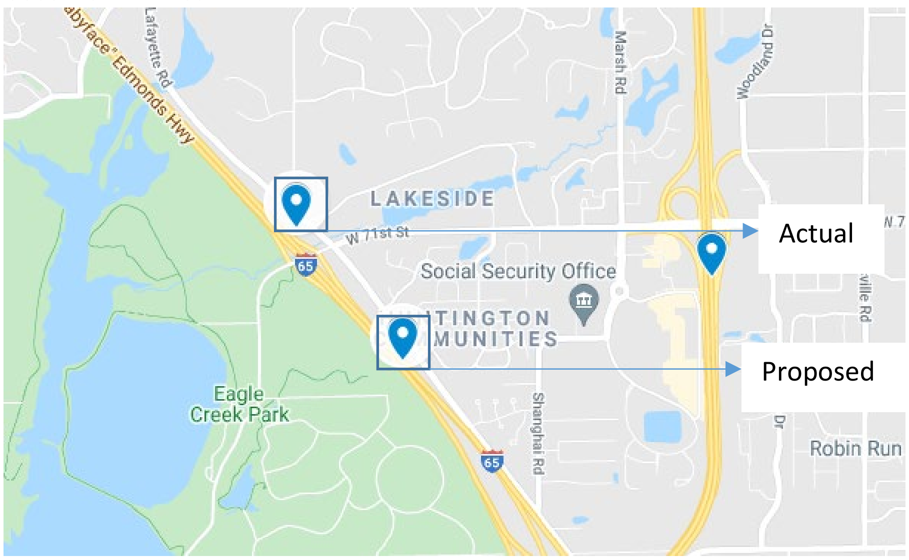


Figure C.40 Unit 3103 with additional units.

Unit 3104
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 86 miles.

Scenario 2: However, with the current routing, a significant reduction in deadhead miles can be achieved by relocating the facility as shown in the Figure C.43. The resulting deadhead miles equal to 45 miles.

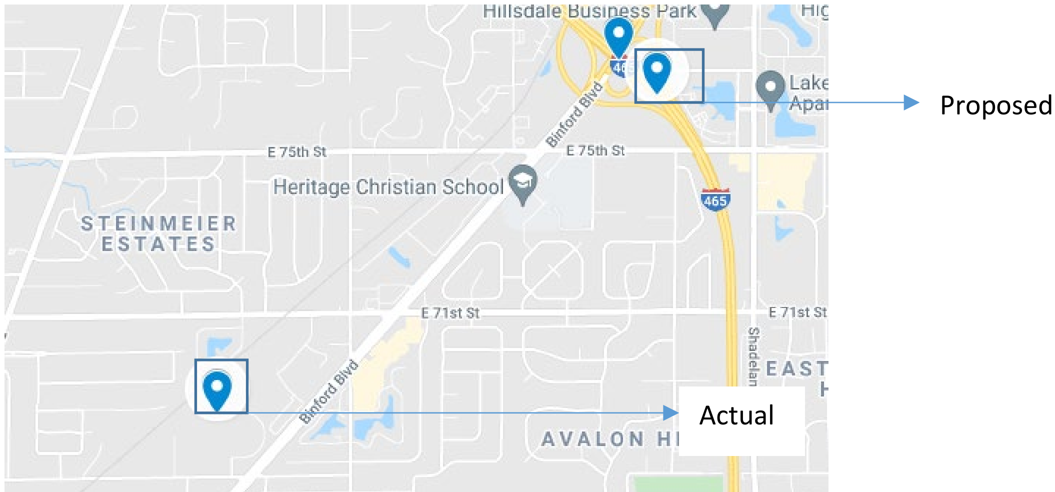


Figure C.41 Unit 3104 without additional routes.

Scenario 3: Generating additional routes don't reduce the deadhead miles.
Scenario 4: Relocating the facility and generating additional routes, as shown in Figure C.44, don't reduce the deadhead miles.

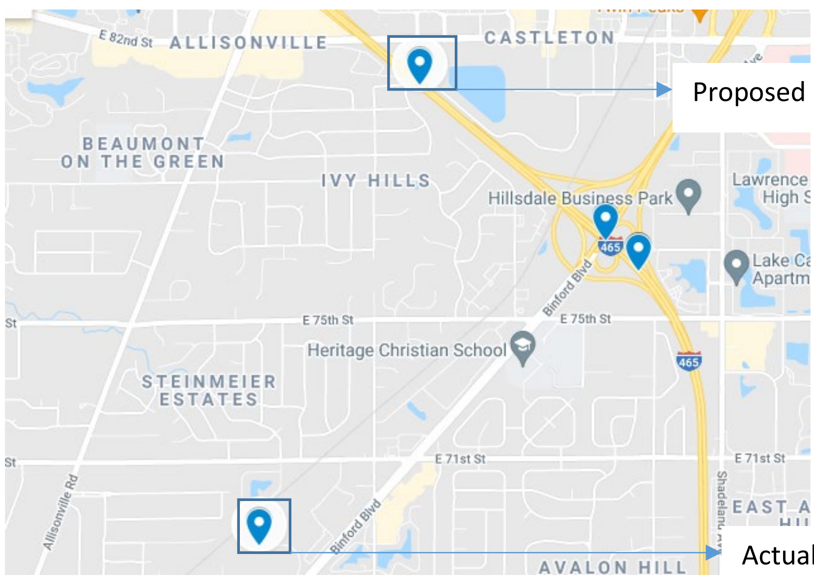


Figure C.44 Unit 3104 with additional routes.

Unit 3105
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 125 miles.
Scenario 2: The deadhead miles are reduced to 100 miles when the facility is relocated to node 13.
Scenario 3: Generating additional routes don't reduce the deadhead miles.
Scenario 4: Relocating the facility and generating additional routes don't reduce the deadhead miles.

Unit 3201

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 115 miles.

Scenario 2: There's no significant change in deadhead miles when facility is relocated. This means that the unit has its facility at the optimal location.

Scenario 3: When additional routes are generated, the total deadhead miles change slightly from 125 to 115 miles if nodes for route 2 and route 7 are considered to form a new route.

Scenario 4: The deadhead miles would be the same as in scenario 3–115 miles as the relocation of the facility does not reduce the deadhead miles significantly.

Unit 3202

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 40 miles.

Scenario 2: Upon relocating the facility to node 3, the reduced deadhead miles would be 20 miles. No reduction is achieved by generating new routes.

Unit 3203

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 13 miles.

Scenario 2: The deadhead miles change significantly when the facility is relocated from its current location to the proposed location as shown in the Figure C.45. The deadhead miles reduce to be 6.5 miles.

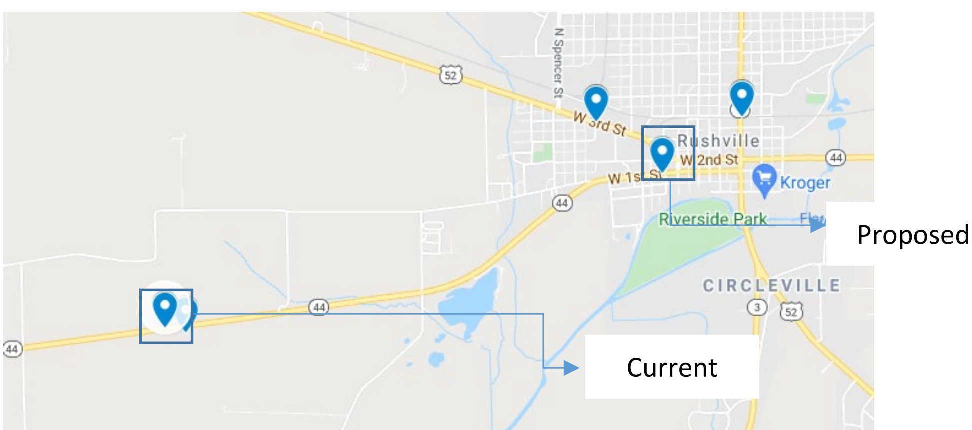


Figure C.42 Unit 3203 without additional units.

Scenario 3: Further measure to reduce the deadhead miles can be achieved through adding new alternate routes. Either aggregating the nodes associated with Snow Routes 29 and 30 or Snow Routes 29 and 32 can provide the reduction in deadhead miles. A reduction of 5 miles (total deadhead miles = 8.4) is achieved.

Scenario 4: However, with relocating the facility and generating the above proposed new routes, no significant change in deadhead miles is achieved.

Unit 3204

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 50 miles.

Scenario 2: If flexibility in facility location is taken into account, the minimum deadhead miles is achieved at node 4 as shown in Figure C.46. This proposed location will bring the total deadhead miles to 18.

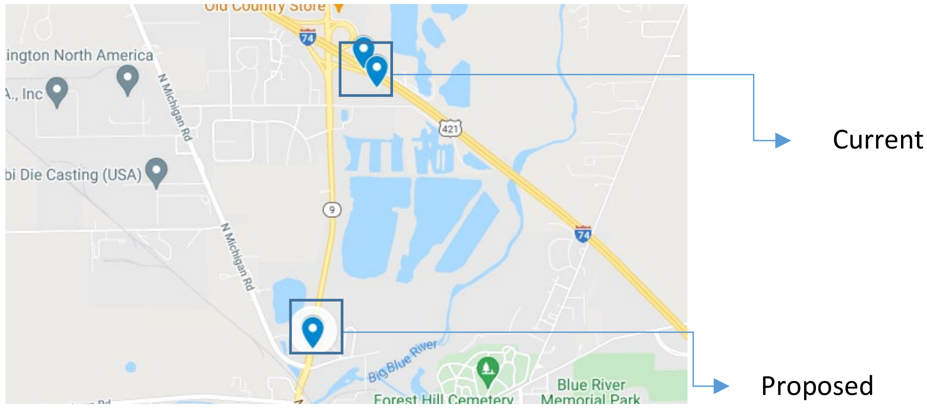


Figure C.46 Unit 3204 without additional routes.

Scenario 3: By considering nodes along Routes 23 and 26 to be one, the total deadhead miles for current facility location comes to be 25 miles.

Scenario 4: Alongside, if the facility is relocated as shown in the Figure C.46, the total deadhead miles become close to zero.

Unit 3301

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 45 miles.

Scenario 2: This can be reduced by relocating the facility while maintaining the current routes. By moving the facility to node 13 (as shown in the Figure C.47), the deadhead miles reduce to 36 miles.

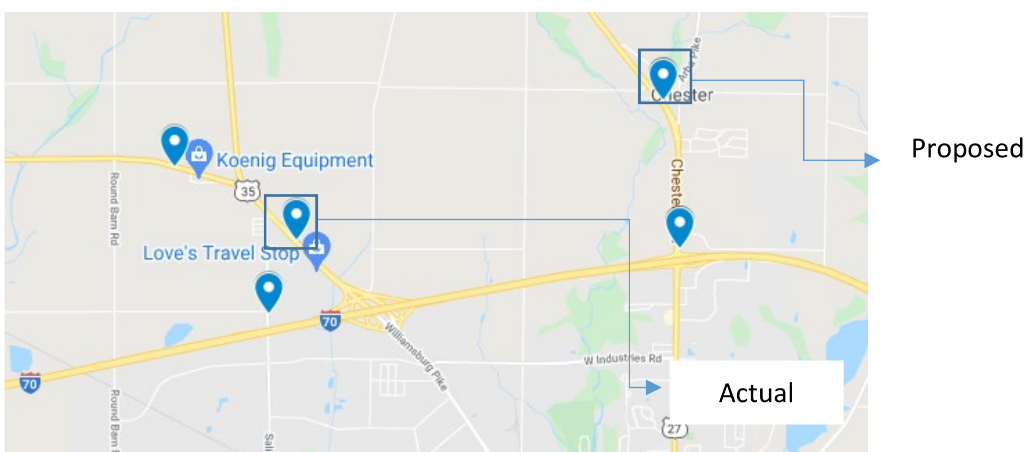


Figure C.47 Unit 3301 without additional routes.

Scenario 3: An additional route can be formed by merging the nodes from 14 and 15 route numbers. This results in total deadhead miles to be 40 miles, with the current facility location as it is.

Scenario 4: With the new routes, the facility location can be move to node 22 as shown in the Figure C.48. This will result in minimum total deadhead miles of 34 miles.

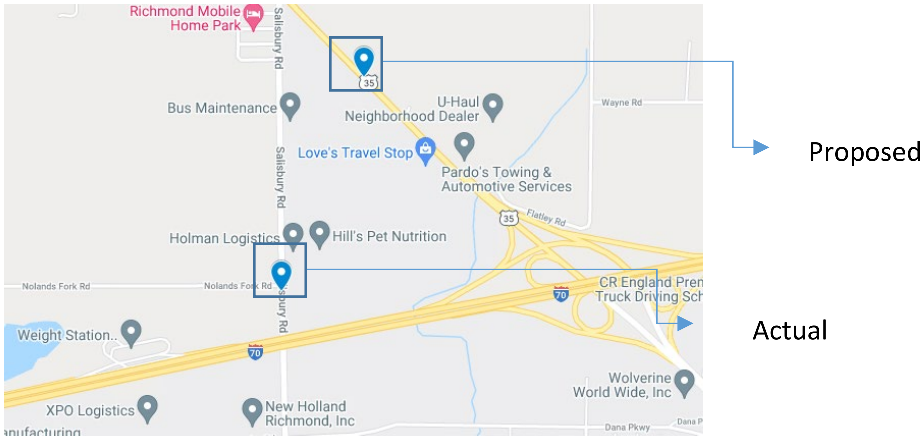


Figure C.48 Unit 3301 with additional routes.

Unit 3302

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 42 miles.

Scenario 2: This calculation is for current facility, and with flexibility in facility location, the deadhead miles reduce to 3 miles. The proposed facility location is node 2 as shown in the Figure C.49.

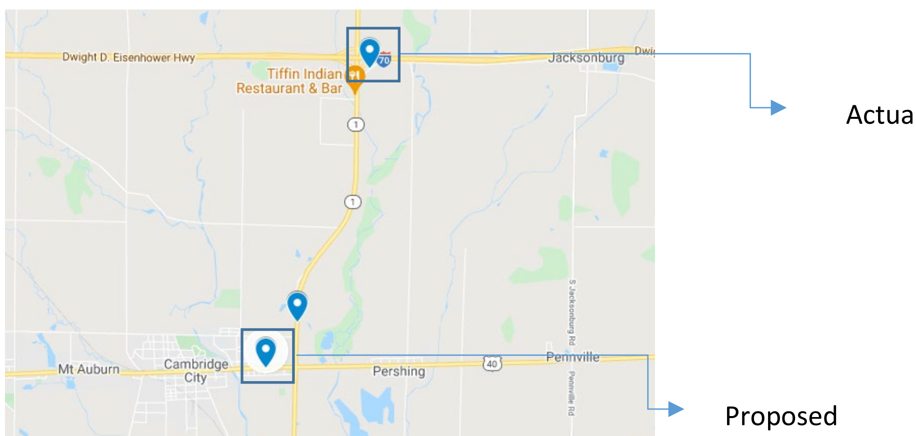


Figure C.49 Unit 3302 without additional units.

Scenario 3: With additional routes, the deadhead miles reduce to 16.6 miles. To achieve this, the nodes along Routes 22, 24, and 25 to be single route and similarly Routes 26 and 27 to be another one. This results in achieving the reduction in deadhead miles without any alteration to current facility.

Scenario 4: With relocation of facility to the location proposed in Figure C.39, the deadhead miles can be further reduced to 1.5 miles.

Unit 3303

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 54 miles.

Scenario 2: A relocation of the current facility to node 2 will result in the deadhead miles to be 52 miles. The current and proposed location for this is mentioned in the Figure C.50.

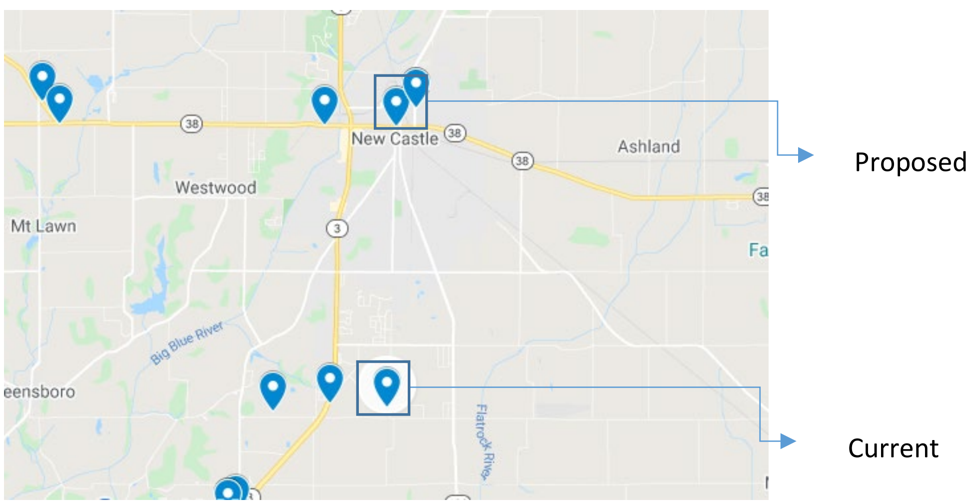


Figure C.50 Unit 3303 without additional routes.

Scenario 3: An additional route can be considered for reducing deadhead miles. This route will have the nodes from Routes 31, 33, and 38. The deadhead miles for the current facility location will be 20.2 miles.
Scenario 4: A relocation of the current facility to node 2 will result in the deadhead miles to be 10 miles

Unit 3304
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 70 miles. This is higher than expected and attributed to the assumptions. However, this is for the current facility location.
Scenario 2: The total deadhead mile reduces to 60 mile if the facility is relocated to node 6, as shown in Figure C.51.

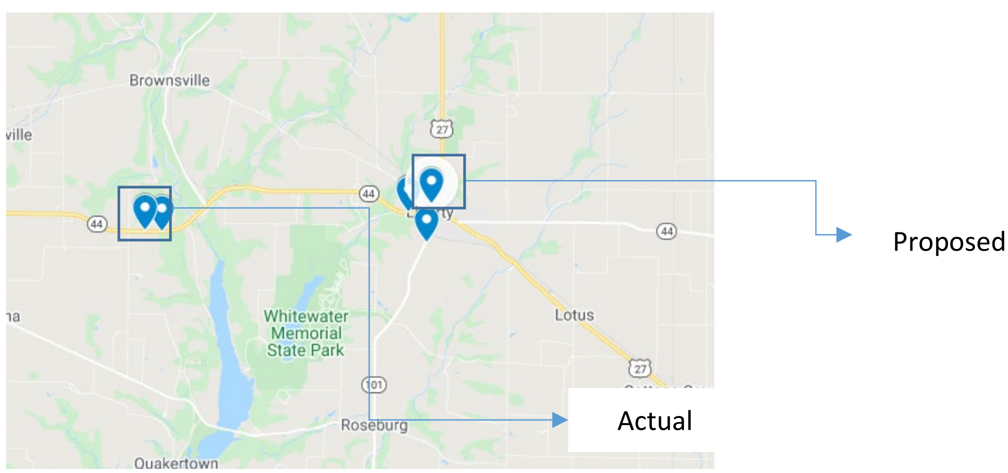


Figure C.51 Unit 3304 nodes.

Scenario 3: For additional routes, the nodes from Routes 42 and 43 are considered to be another route. This results in total deadhead miles to be 46 miles.
Scenario 4: The deadhead miles reduce further to 42 miles when the facility is relocated to node 6.

Unit 3501

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 44.6 miles.

Scenario 2: If the location is shifter to node 10 (as shown in Figure C.52), the total deadhead miles equal to 42.6 mi.

Scenario 3: Additional routes are considered for this unit. If nodes from Routes 1, 3, and 4 are considered to be a single route, the total deadhead mile goes down to 23.2 mi and the facility location becomes optimum.

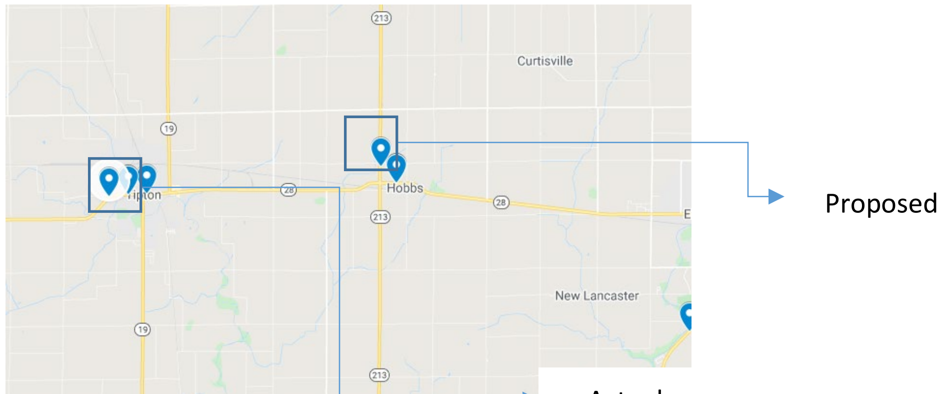


Figure C.52 Unit 3501 without addition

Unit 3502

Unit 3502 has several mileposts that are far away from the others. The optimization model suggests that the current facility and routes are optimized for this unit. The data used are presented in the Figure C.53.

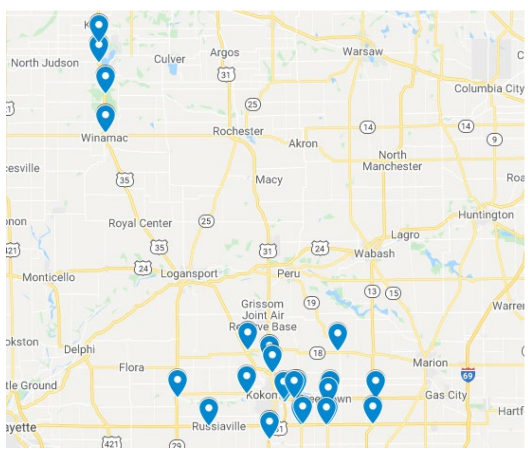


Figure C.53 Unit 3502 nodes.

Unit 3503

Figure C.54 shows the outlying nodes for this unit.

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 38 miles.

Scenario 2: If flexibility on facility location is considered, the deadhead mile reduces to 30 miles and facility relocates to node 2. Both locations are shown in Figure C.55.

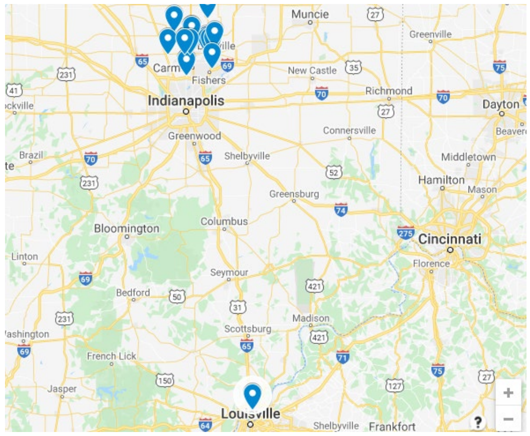


Figure C.54 Outlying MPs for Unit 3503.

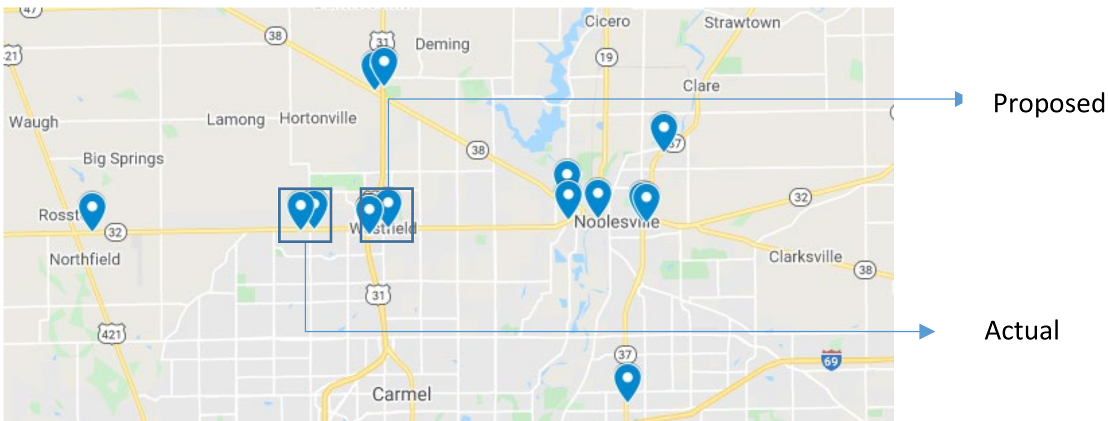


Figure C.55 Unit 3503 without additional routes.

No significant changes in deadhead mile is achieved by altering or adding new routes.

Unit 3504

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 32 miles.

Scenario 2: If the facility location is kept flexible, the deadhead mile doesn't reduce at all. Our optimization suggests that the facility is optimally located to serve the unit.

Scenario 3: If additional routes are considered, very minimal deadhead miles can be achieved. To do so, we considered creating a route that will serve Routes 23, 24, and 25 and another route that will serve Routes 20 and 21. In this case, the total deadhead miles can be reduced to ~2 miles for the current facility location.

Unit 3601

This unit is optimized in terms of facility location. With the current route and current facility location, the deadhead mile is 65 miles. By flexing the location of facility, total deadhead miles equal to 62 miles, which means the facility is optimally located.

However, for additional route, the deadhead miles can be reduced further to 53 miles. This can be done by considering 36-1-4 and 36-1-4-BR a single snow route. Facility location still remains unchanged.

Unit 3603

This unit is optimized in terms of facility location. With the current route and current facility location, the deadhead mile is 60 miles.

However, for additional route, the deadhead miles can be reduced further to 31 miles. This can be done by considering Routes 10 and 12 a single snow route and same for Routes 11 and 14. Facility location still remains unchanged.

Unit 3604

The current location is already optimized, which is shown in the Figure C.56. The total deadhead miles are 19 miles.

However, a significant reduction in deadhead miles can be achieved if Routes 15 and 16 or Routes 16 and 18 are treated as a single route. This way the total deadhead miles go down ~2 miles. This still doesn’t require any changes in facility location, which means the facility location is perfectly optimized.

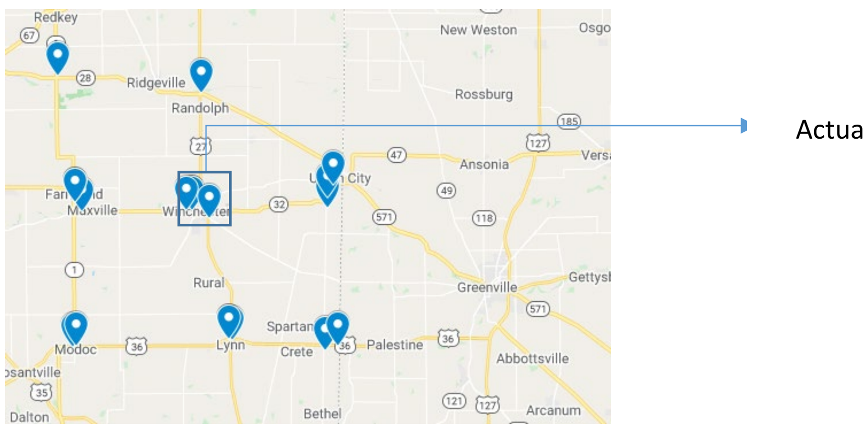


Figure C.56 Unit 3604 with current facility location.

Unit 3605

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 82 miles.

Scenario 2: Facility at the proposed location will yield total deadhead miles of 62 miles.

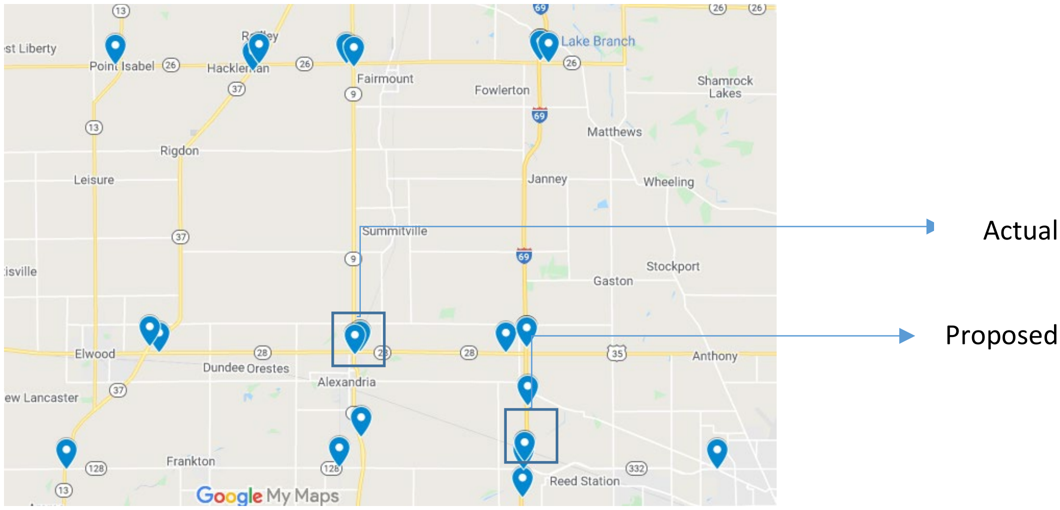


Figure C.57 Unit 3605 without additional routes.

Scenario 3: An additional route with nodes supporting route 5-2, 5-3, and 5-22 was created. The total deadhead miles with this additional route becomes 36 miles for the current location.
Scenario 4: With these routes, the current location will not only be optimum but also serve optimal routes.

C.4 LaPorte District

Summary

Table C.4 presents a brief summary of each unit in the district and corresponding deadhead miles for each district based on the scenario taken from the mathematical model. It also mentions the node for relocation of the facility.

Table C.4 LaPorte District Summary

Unit No	First Scenario	Second Scenario	Recommended Location	Third Scenario	Fourth Scenario	Recommended Location
4101	95 mi	90 mi	U_35_195	67 mi	62 mi	N/A
4102	65 mi	53 mi	U_421_220	38 mi	33 mi	U_421_215
4103	16 mi	15 mi	U_20_44	No reduction achieved		
4201	77 mi	65 mi	U_24_41	35 mi	15.6 mi	U_24_35
4202	56 mi	37.6 mi	U_24_62	40.8 mi	23.8 mi	N/A
4204	79.4 mi	79.4 mi	N/A	No reduction achieved		
4301	164 mi	123 mi	U_6_69	No reduction achieved		
4302	49.6 mi	36 mi	S_933_110	38.2 mi	26 mi	S_933_110
4305	107 mi	71.4 mi	U_31_211	64.6 mi	44.6	S_331_5
4402	180 mi	130 mi	S_114_16	145 mi	110 mi	S_16_15
4403	135 mi	135 mi	N/A	80 mi	80 mi	N/A
4406	69 mi	62 mi	S_10_36	35 mi	35 mi	N/A
4701	54 mi	40 mi	U_231_288	54 mi	40 mi	U_231_288
4702	42 mi	34 mi	I_80_15	20 mi	15 mi	U_6_17
4703	33 mi	5 mi	U_20_7	33 mi	33 mi	N/A
4704	70 mi	30 mi	I_80_1	50 mi	7 mi	I_80_2

4705	19 mi	14 mi	U_20_30	19 mi	14 mi	N/A

Figure C.48 presents the percentage change in deadhead miles by scenario across all units in the LaPorte District. represents the deadhead miles across units in LaPorte District. Figure C.60 through Figure C.62 present the percentage change in deadhead miles for each unit according to Scenarios 2, 3, and 4, respectively.

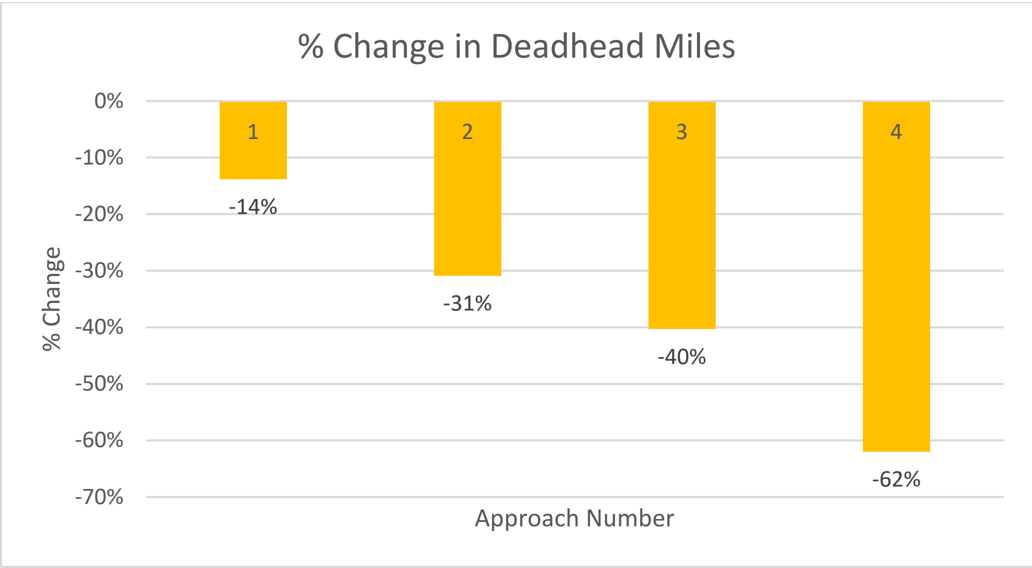


Figure C.58 Cumulative percentage change in deadhead miles across district by Scenario.

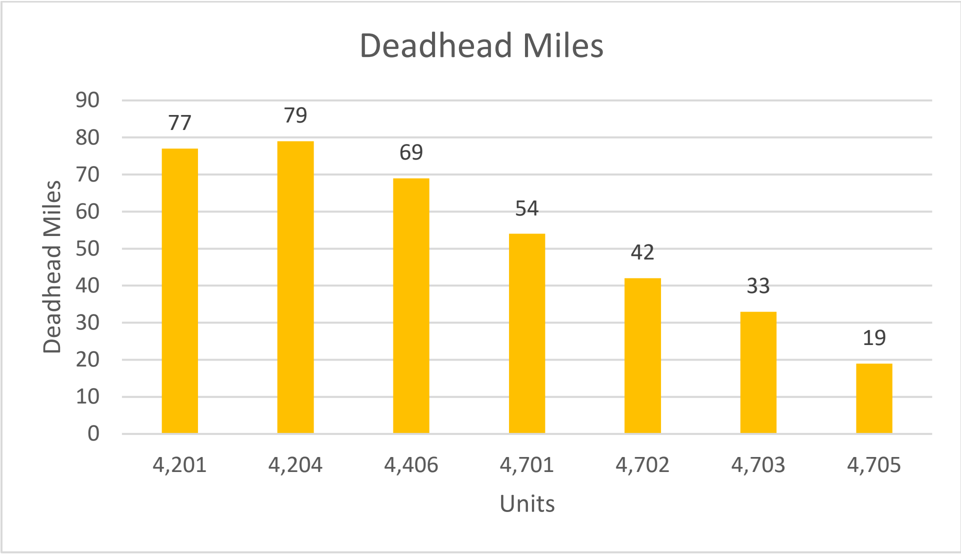


Figure C.59 Optimal deadhead miles across all units—Scenario 1.

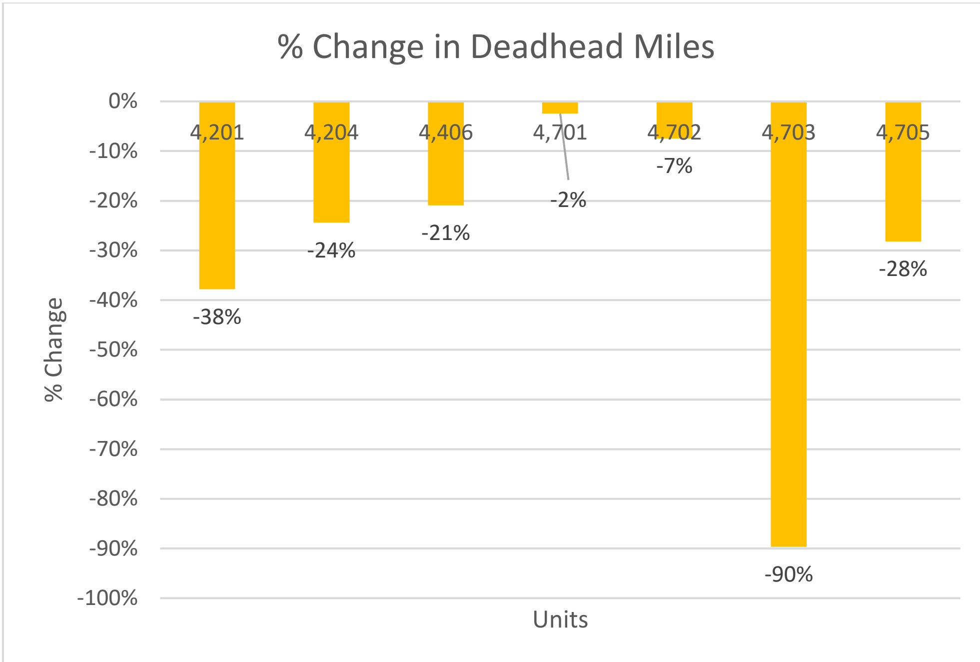


Figure C.60 Percentage change in deadhead miles across all units—Scenario 2.

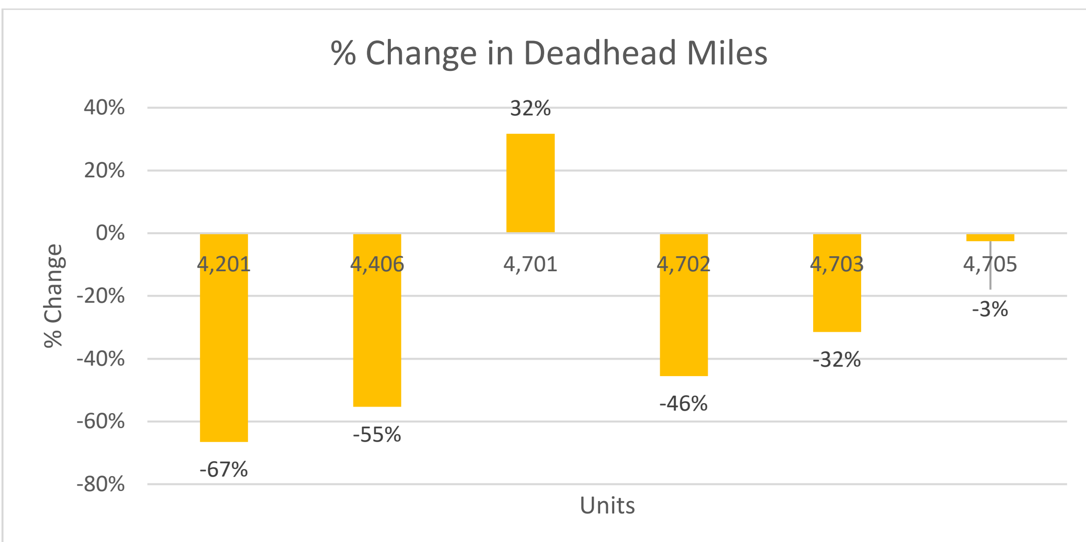


Figure C.61 Percentage change in deadhead miles across all units—Scenario 3.

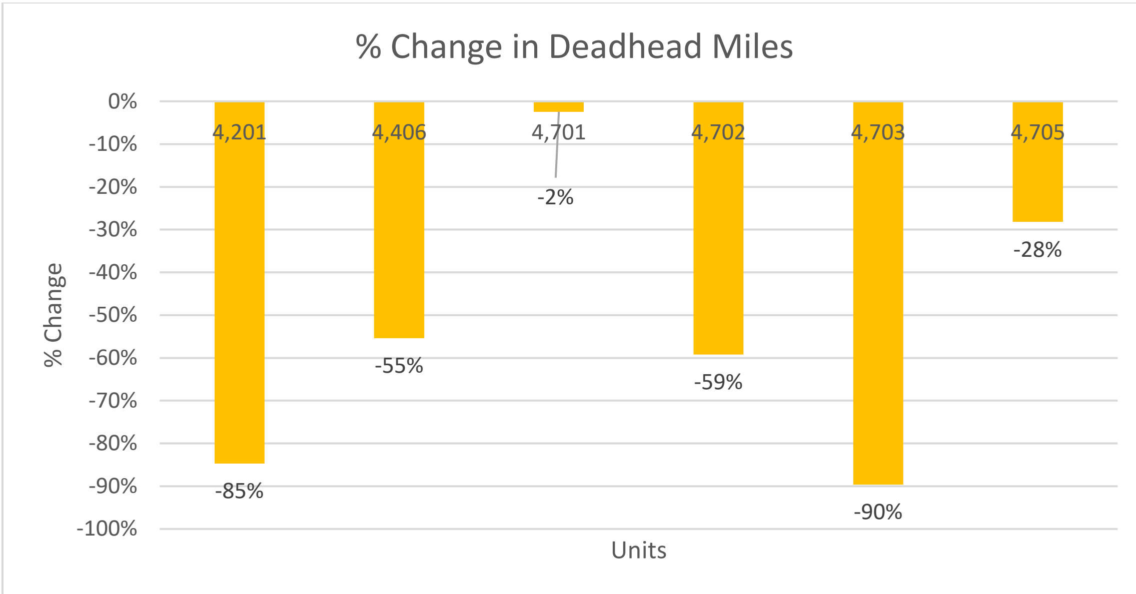


Figure C.62 Percentage change in deadhead miles across all units—Scenario 4.

Unit 4101

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 95 miles.

Scenario 2: The total changes if the facility is relocated to node 6 and reduces to 90 miles. The current and recommended locations are presented in Figure C.63.

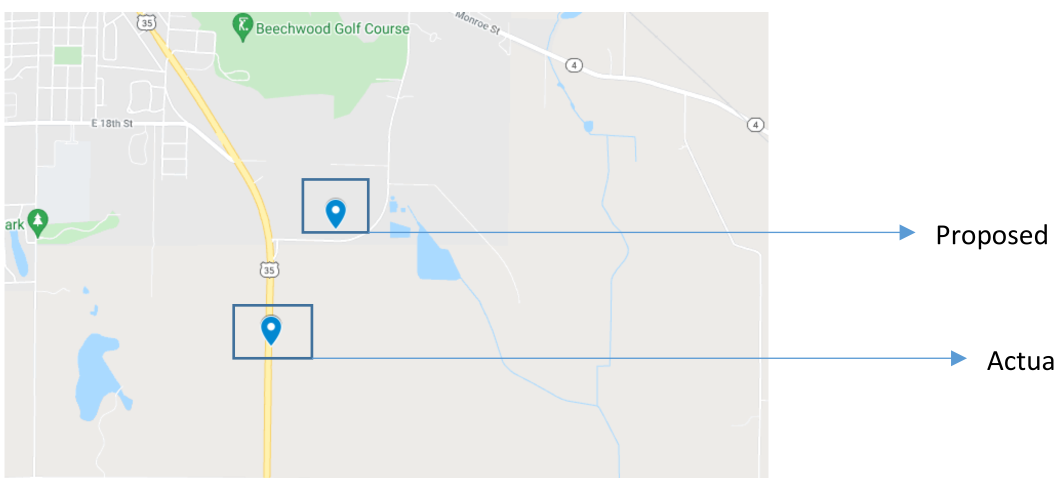


Figure C.63 Unit 4401 without additional routes.

Scenario 3: Additional routes connecting nodes for Routes 1 and 2 and nodes for Routes 8 and 9 separately allow the deadhead miles to reduce further. The minimal deadhead miles thus become 67 mi.

Scenario 4: If facility is relocated according to the figure, it further reduces to 62 mi.

Unit 4102

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 65 miles.

Scenario 2: The total changes if the facility is relocated to node 20 and reduces to 53 miles. The current and recommended locations are presented in Figure C.64.

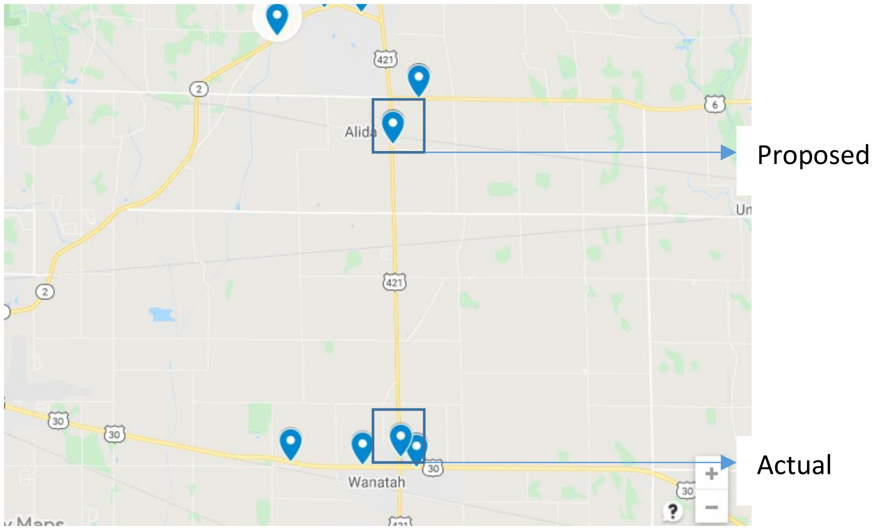


Figure C.64 Unit 4102 without additional routes.

Scenario 3: Additional routes connecting nodes for Routes 1 and 2 and nodes for Routes 8 and 9 separately allow the deadhead miles to reduce further. The minimal deadhead miles thus become 67 mi.
Scenario 4: In this case, the current location becomes optimal, so no relocation is necessary.

Unit 4103
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 16 miles.
Scenario 2: The total changes if the facility is relocated to node 16 and reduces to 15 miles. The current and recommended locations are presented in Figure C.65

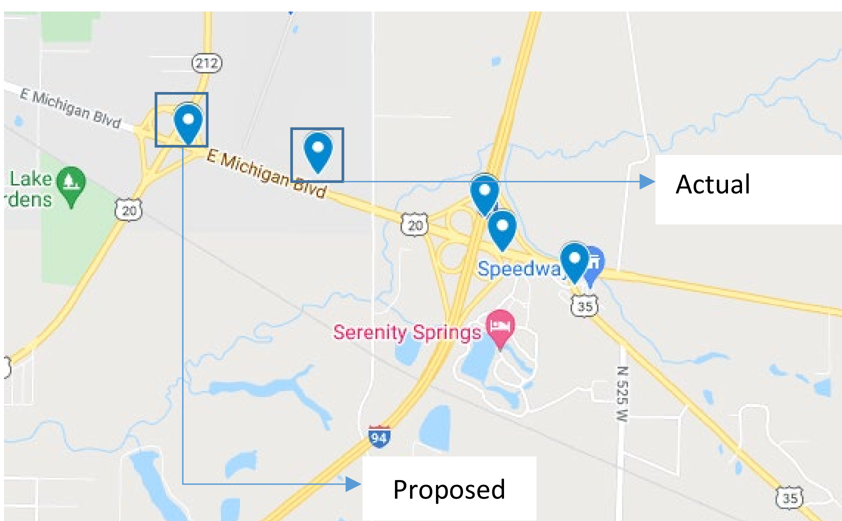


Figure C.65 Unit 4103 without additional units.

Considering additional routes doesn't yield any result for this unit. This means that the unit is already optimized.

Unit 4201
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 77 miles.
Scenario 2: The total changes if the facility is relocated to node 10 and reduces to 65 miles. The current and recommended locations are presented in the Figure C.66.

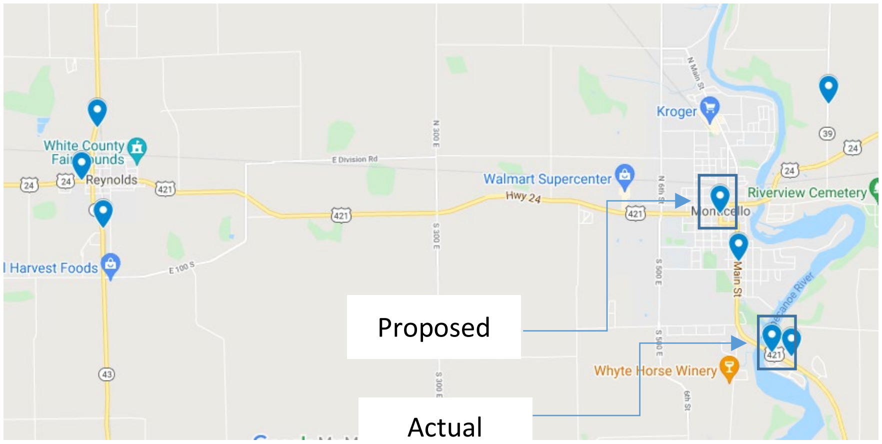


Figure C.66 Unit 4201 without additional routes.

Scenario 3: By combining the nodes for Routes 2 and 3 and for Routes 5 and 6, the total deadhead miles become 35 miles.
Scenario 4: However, the minimum deadhead mile of 15.6 miles is achieved from using these additional routes and relocating the facility to node 7, as shown in the Figure C.67.

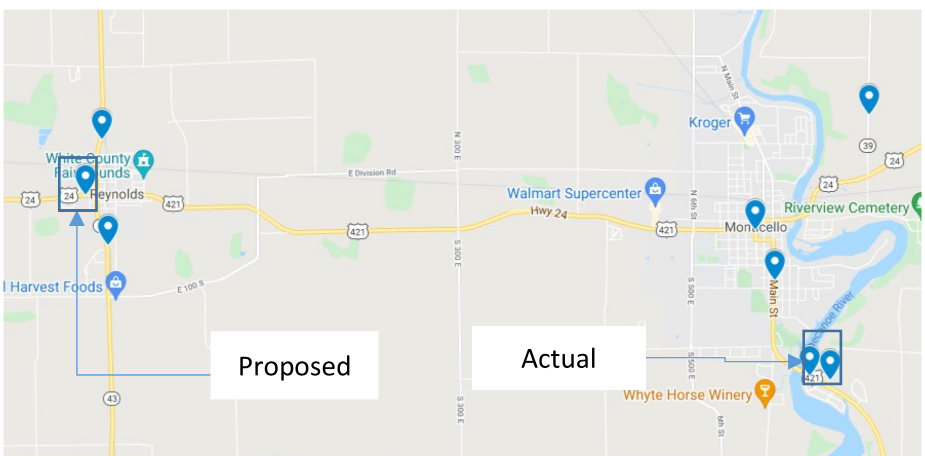


Figure C.67 Unit 4201 with additional routes.

Unit 4202
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 56 miles.
Scenario 2: The total changes if the facility is relocated to node 25 and reduces to 37.6 miles. The current and recommended locations are presented in the Figure C.68.
Scenario 3: By combining the nodes for Routes 3, 4, and 5, the total deadhead miles become 40.8 miles.

Scenario 4: However, the minimum deadhead mile of 23.8 miles is achieved from using these additional routes and relocating the facility to node 25, as shown in the Figure C.68.

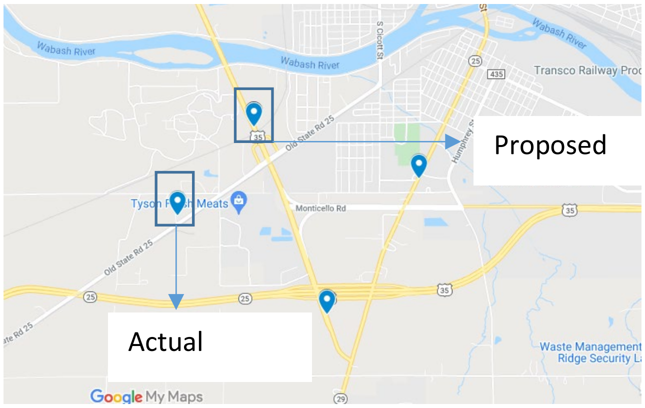


Figure C.68 Unit 4202.

Unit 4204

Unit 4204 is already optimized and the deadhead miles for this unit is 80 miles. Both routes and facility location are optimal for this unit.

Unit 4301

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 164 miles.

Scenario 2: The total changes if the facility is relocated to node 3 and reduces to 123 miles. The current and recommended locations are presented in the Figure C.69.

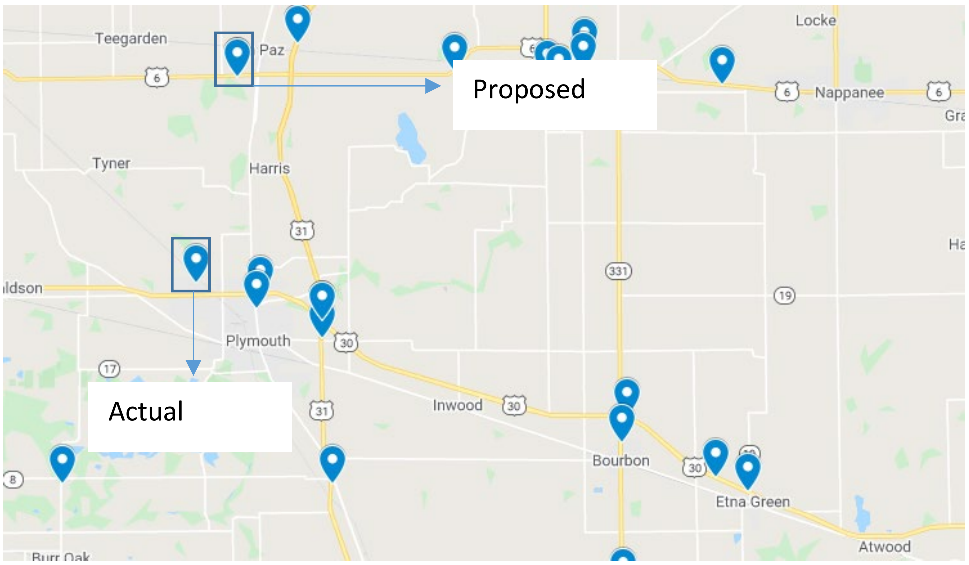


Figure C.69 Unit 4301 without additional routes.

Unit 4302

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 49.6 miles.

Scenario 2: The total changes if the facility is relocated to node 16 and reduces to 36 miles. The current and recommended locations are presented in the Figure C.70.

Scenario 3: Additional routes formed from the nodes of Routes 7 and 14 reduce the deadhead miles for the current facility location to 38.2 mi.

Scenario 4: With further shifting of facility site as shown in the Figure C.70, the minimum deadhead miles come as 26 mi.

Figure C.70 Unit 4302 locations.

Unit 4305

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 107 miles.

Scenario 2: The total changes if the facility is relocated to node 7 and reduces to 71.2 miles. The current and recommended locations are presented in the Figure C.71.

Scenario 3: Additional routes formed from the nodes of Routes 02 and 03 and Routes 7 and 8 reduce the deadhead miles for the current facility location to 64.6 mi.

Scenario 4: With further shifting of facility site to node 18 as shown in the Figure C.72, the minimum deadhead miles come as 44.6 mi.

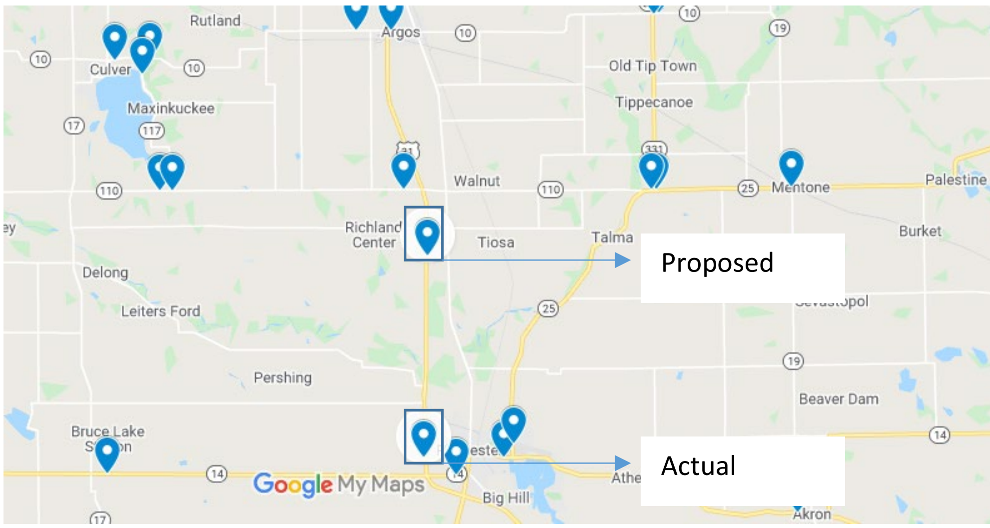


Figure C.71 Unit 4305 without additional units.

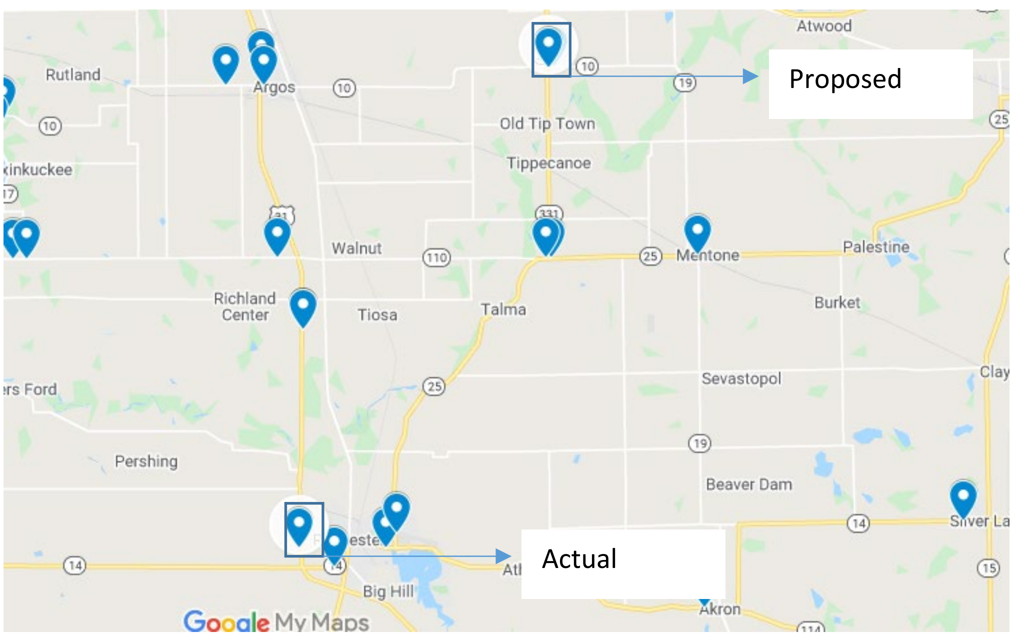


Figure C.72 Unit 4305 with additional units.

Unit 4402

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 180 miles.

Scenario 2: The minimum deadhead miles is, however, reached for facility to be close to node 8, which is shown in the Figure C.73. The minimum deadhead miles then become 130 miles.

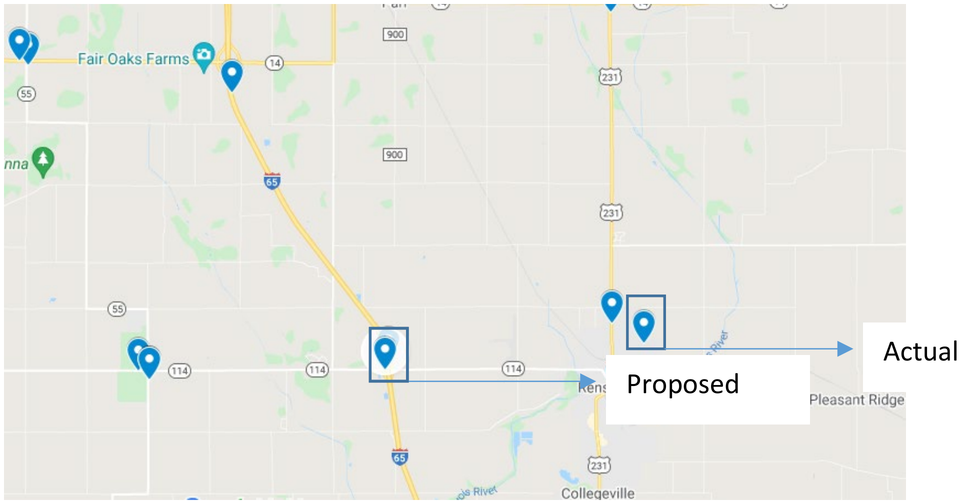


Figure C.73 Unit 4402 without additional routes.

Scenario 3: Additional routes for Snow Route 12 and 13 and Routes 05 and 11 are considered. With this routing, the total deadhead miles can be reduced to 110 miles.
Scenario 4: This is, however, possible for the facility to be close to node 14 as shown in the Figure C.74. For the current location, the deadhead miles in this proposed routing will be 145 miles.

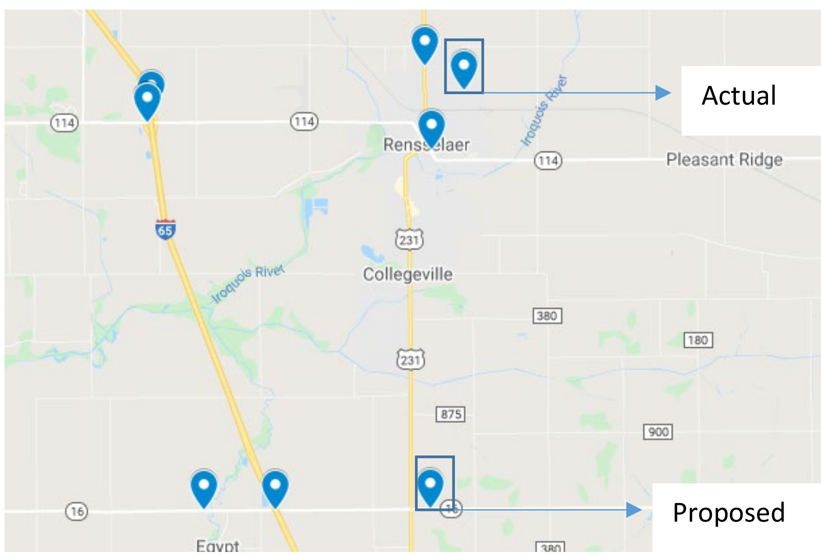


Figure C.74 Unit 4402 with additional routes.

Unit 4403

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 135 miles.

Scenario 2: This, however, is the minimum deadhead miles that can be achieved with the current routes for this unit. This means the facility location is already optimized.

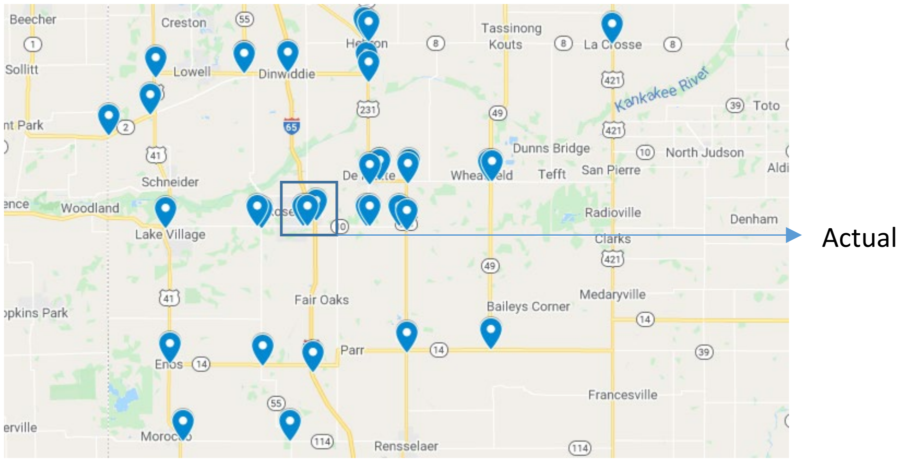


Figure C.75 Unit 4403 without additional routes.

Scenario 3: Additional routes are taken into consideration by merging Routes 6 and 7 and creating connection between Route 09 and 08. With these changes, the minimum deadhead miles will be equal to 80 miles.

Scenario 4: However, no further reduction can be achieved through facility location.

Unit 4406

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 69 miles.

Scenario 2: However, the minimum deadhead miles is achieved at node 25 for which location is shown in Figure C.76. In this case, the deadhead mile is 62 miles.

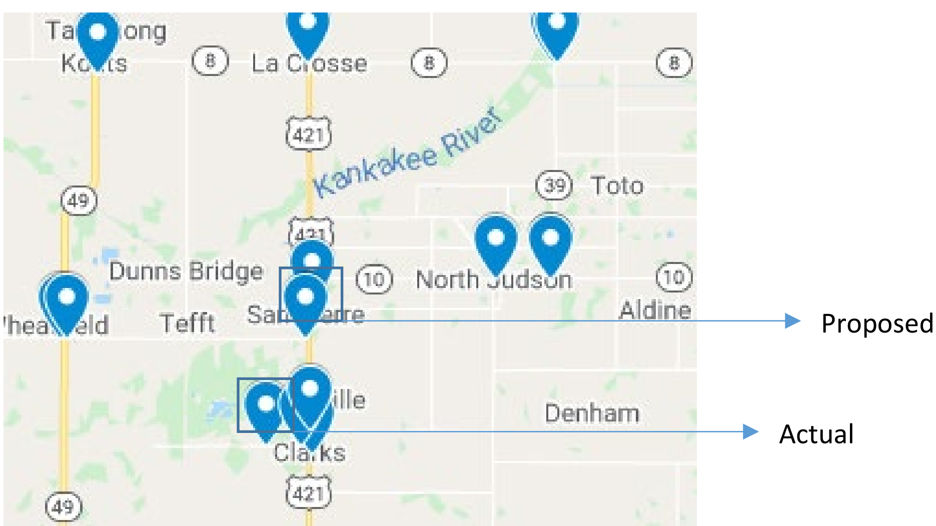


Figure C.76 Unit 4406 without additional routes.

Scenario 3: For additional routes, Routes 4 and 6 and Routes 1 and 2 are merged. This provides a reduction to 35 miles for the current facility location.
Scenario 4: No significant change in deadhead miles is achieved in this case for other facility location.

Unit 4701
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 54 miles.
Scenario 2: However, the minimum deadhead miles are achieved at location shown in the Figure C.77. In this case, the deadhead mile is 40 miles.
Scenario 3: There is no significant change achieved through additional route engagement. The additional route was designed to serve Snow Route 04, 05, and 06.
Scenario 4: The additional route also suggests that the minimal deadhead miles is achieved as proposed in the Figure C.77.

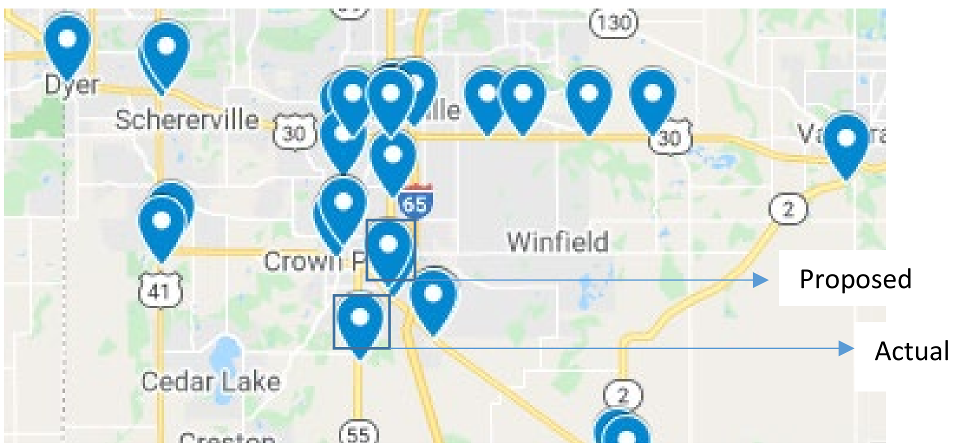


Figure C.77 Unit 4701.

Unit 4702
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 42 miles.
Scenario 2: The minimum can be achieved at a different location as shown in the Figure C.78. The resulting deadhead will be 34 miles.

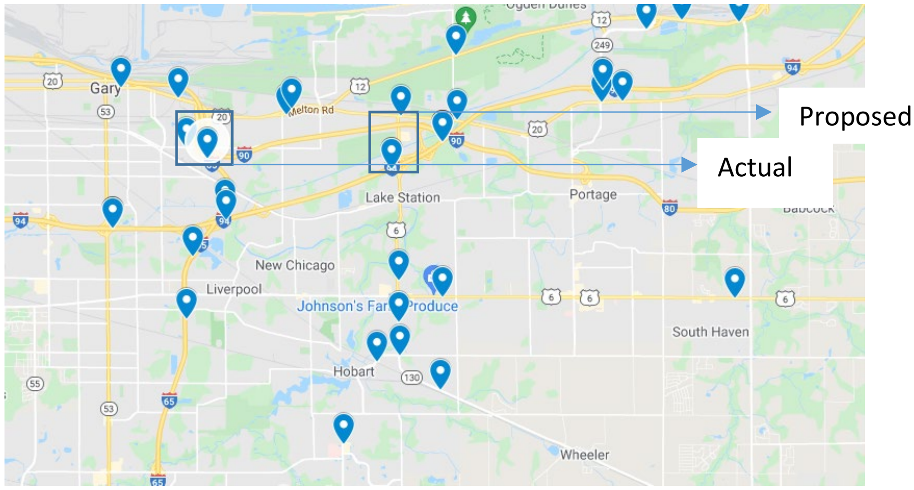


Figure C.78 Unit 4702 without additional routes.

Scenario 3: To see additional routes, we used aggregating Snow Routes 03, 04, and 05 and separately create another route cater the current route for 09 and 12. This way for the current facility location, the deadhead mile becomes 20 miles.

Scenario 4: Further reduction is achieved for facility location as proposed in the Figure C.79. In this case, the deadhead mile comes to be 15 miles.

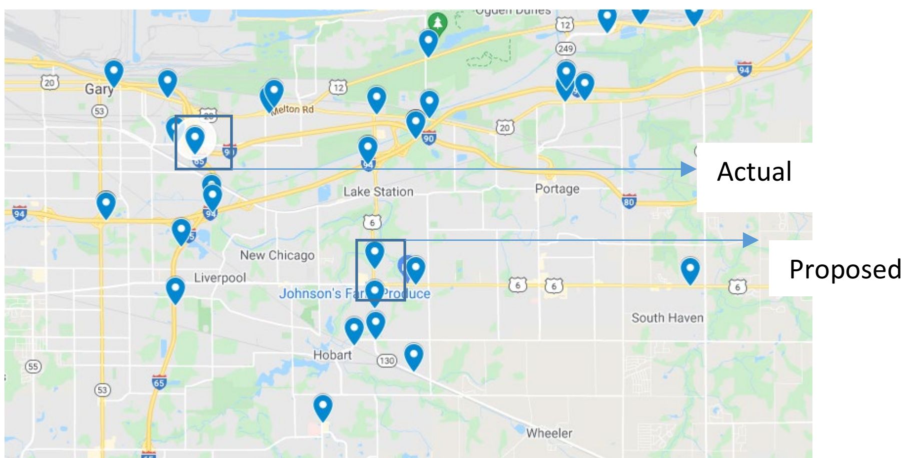


Figure C.79 Unit 4702 with additional routes

Unit 4703

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 33 miles.

Scenario 2: However, the minimum deadhead miles are achieved for node 1 as shown in the Figure C.80, which is equal to 5 miles.

Figure C.80 Unit 4703 without additional routes.

Scenario 3: With additional routes made by having different combination, the model still chooses the existing routes. This means that the unit is already optimized with respect to routes.

Unit 4704

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 70 miles.

Scenario 2: However, the minimum deadhead miles are achieved for node 1 as shown in the Figure C.81, which is equal to 30 miles.

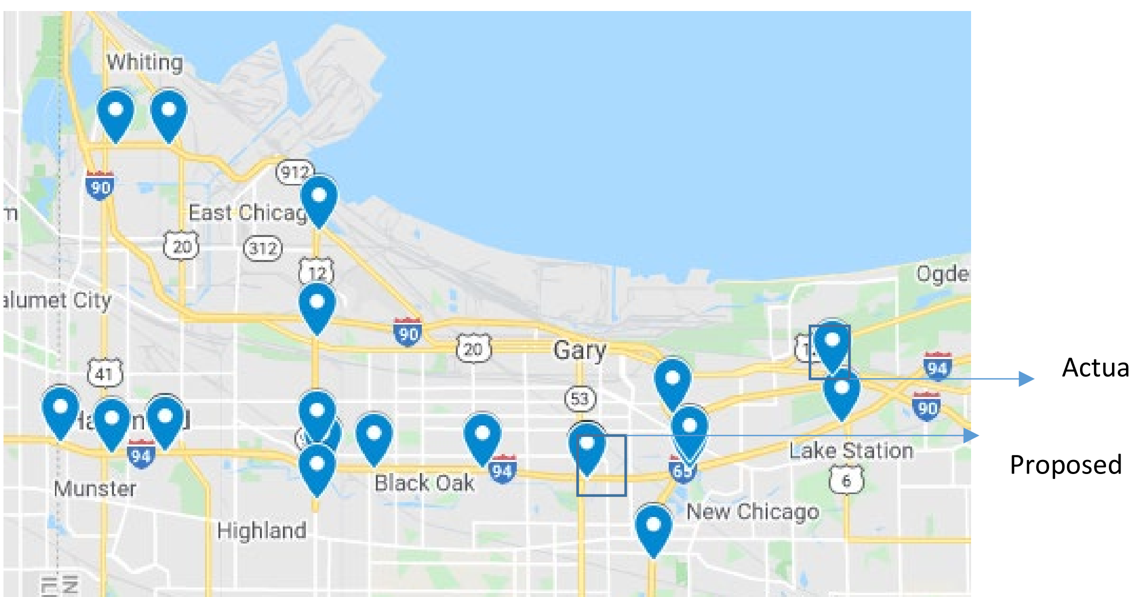


Figure C.81 Unit 4704 without additional routes.

Scenario 3: With additional routes that merge route node 2, 4, 5, 13, 14, 29, 32, the total deadhead reduces to 50 miles.

Scenario 4: With flexibility on facility location, the minimal deadhead mile is achieved in the location shown in the Figure C.82, which is 7 miles.

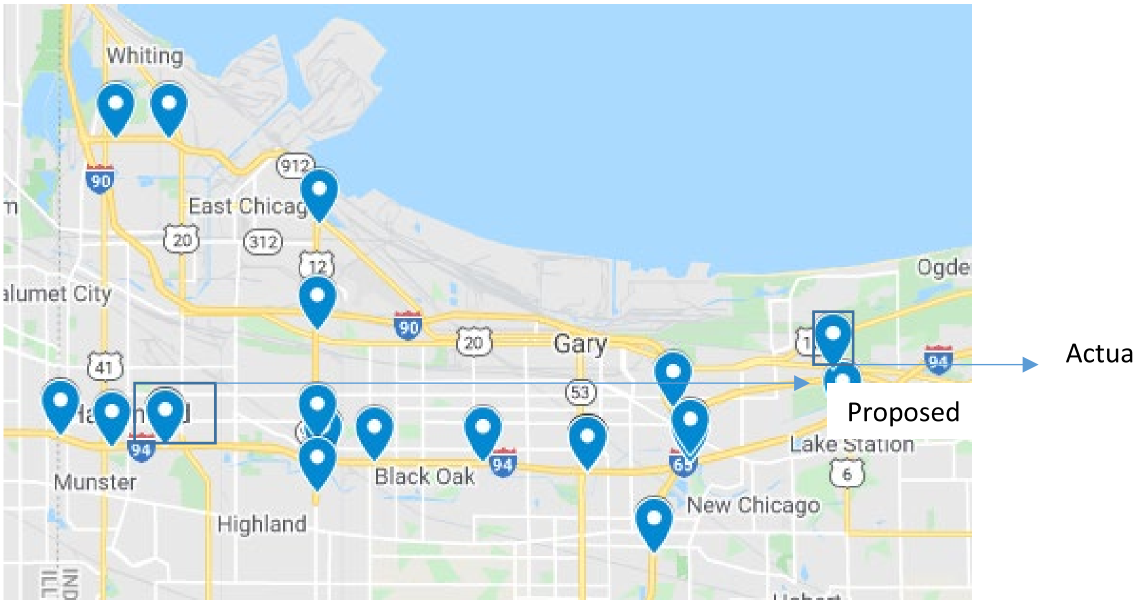


Figure C.82 Unit 4704 with additional routes.

Unit 4705

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 19 miles.

Scenario 2: the proposed location for reduced deadhead miles of 14 miles is shown in the Figure C.83.

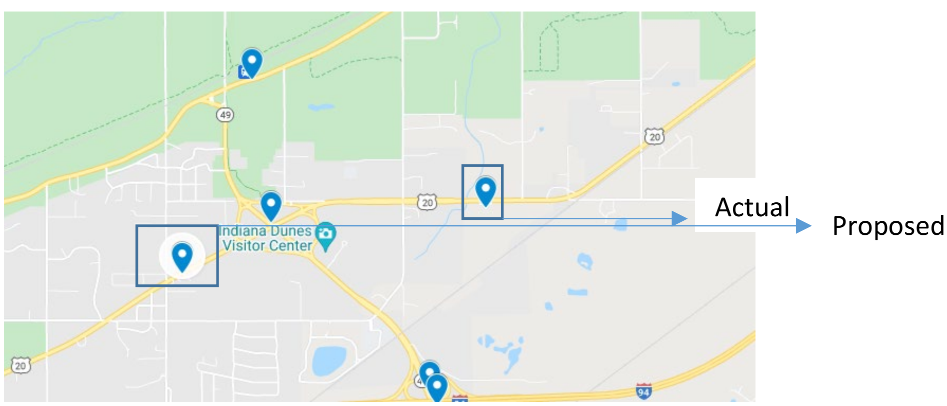


Figure C.83 Unit 4705 without additional units.

There's not enough opportunity to reduce the deadhead miles by changing or adding routes. This unit is optimized in terms of routes operation.

C.5 Seymour District

Summary

Table C.5 presents a brief summary of each unit in the district and corresponding deadhead miles for each district based on the scenario taken from the mathematical model. It also mentions the node for relocation of the facility.

Table C.5 Seymour District Summary

Unit No	First Scenario	Second Scenario	Recommended Location	Third Scenario	Fourth Scenario	Recommended Location
5101	25.6 mi	25.6 mi	N/A	6.3 mi	3.4 mi	S_101_17
5103	187 mi	139 mi	S_56_193	120 mi	80.6 mi	S_148_5
5104	42 mi	17.8 mi	U_52_155	22 mi	17.8 mi	U_52_155
5105	105 mi	98.8 mi	S_129_19	41.4 mi	38 mi	S_129_25
5202	103 mi	79.4 mi	S_39_18	87.8 mi	72.4 mi	S_39_18
5203	130 mi	94 mi	S_37_103	66.6 mi	58.4 mi	S_45_41
5205	79.2 mi	79.2 mi	N/A	64 mi	64 mi	N/A
5301	22.9 mi	18.6 mi	S_3_70	18 mi	9.2 mi	U_421_51
5302	112 mi	69 mi	I_65_90	84.4 mi	67 mi	I_65_90
5303	184 mi	68 mi	I_65_69	184 mi	68 mi	I_65_69
5402	118 mi	103 mi	S_60_60	81 mi	77 mi	U_31_6
5403	193 mi	187 mi	S_337_12	187 mi	181 mi	S_135_15
5501	107 mi	55 mi	S_7_3	77 mi	45 mi	S_62_192
5502	33 mi	21 mi	S_3_43	15 mi	9 mi	S_7_26
5504	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
5505	55 mi	13 mi	S_56_99	38 mi	12 mi	S_56_99

Figure C.84 presents the percentage change in deadhead miles by scenario across all units in the Seymour District. Figure C.85 represents the deadhead miles across units in Seymour District. Figure C.86 through Figure C.88 present the percentage change in deadhead miles for each unit according to Scenarios 2, 3, and 4, respectively.

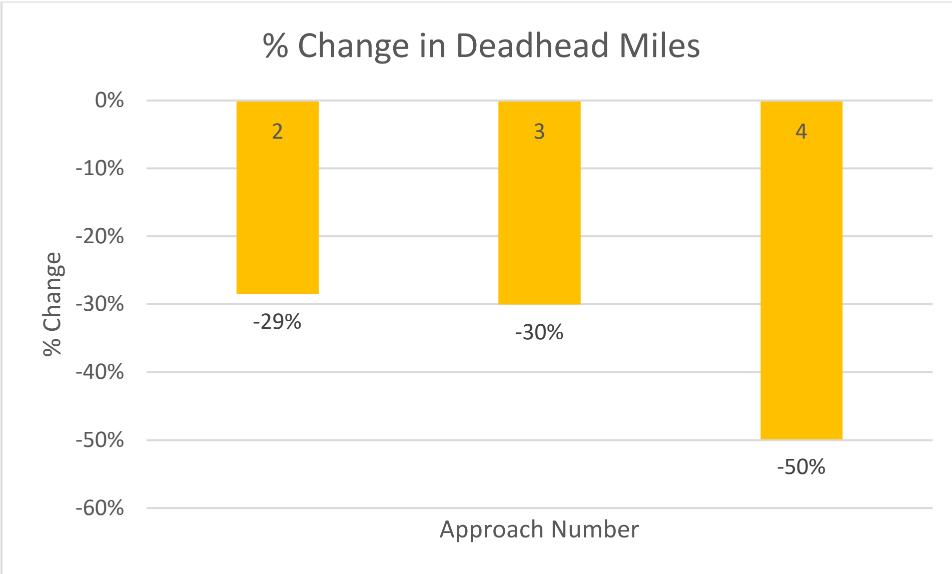


Figure C.84 Cumulative percentage change in deadhead miles across district by Scenario.

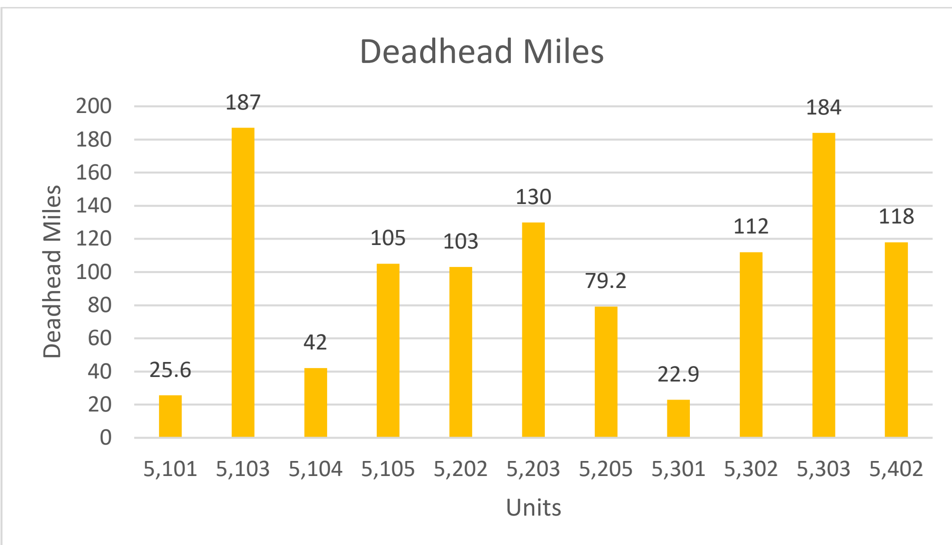


Figure C.85 Optimal deadhead miles across all units—Scenario 1.

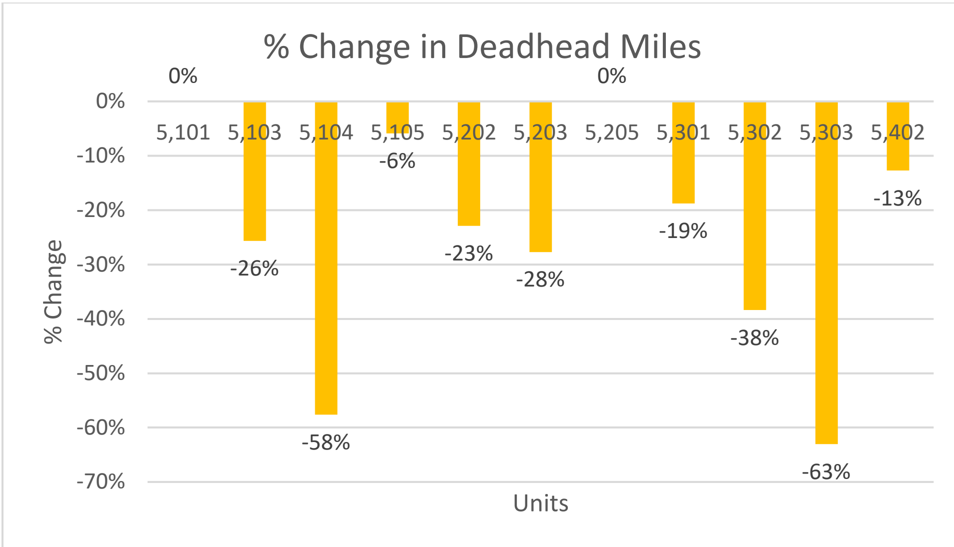


Figure C.86 Percentage change in deadhead miles across all units—Scenario 2.

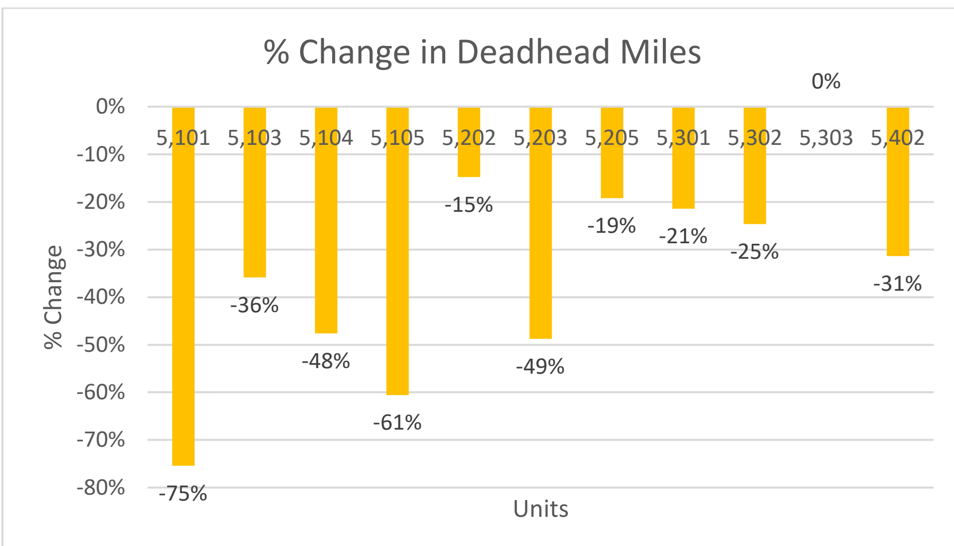


Figure C.87 Percentage change in deadhead miles across all units—Scenario 3.

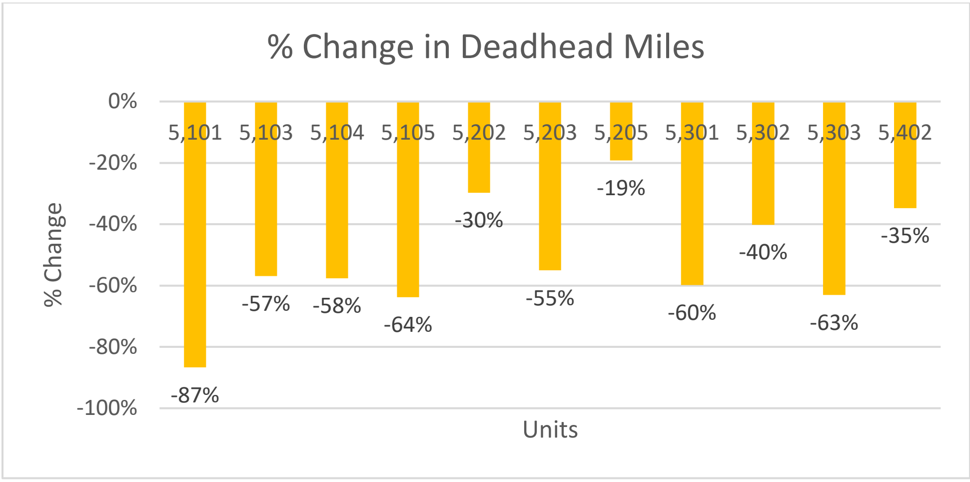


Figure C.88 Percentage change in deadhead miles across all units—Scenario 4.

Unit 5101

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 25.6 miles.

Scenario 2: the location of facility is optimized for the current route structure.

Scenario 3: If additional routes are incorporated by assembling current Routes 01, 02, and 03 as a new one and current Routes 07 and 08 as another one, the total deadhead miles go down to 6.3 mi for current facility location.

Scenario 4: If the facility is relocated (as shown in the Figure C.89), the total deadhead reduces to 3.4 mi.

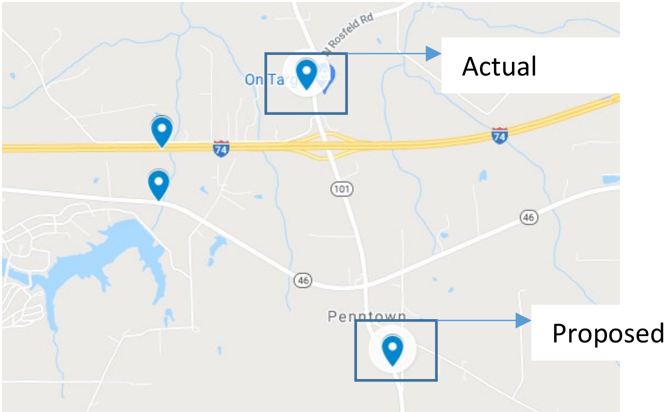


Figure C.89 Unit 5101 with additional routes.

Unit 5103

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 187 miles.

Scenario 2: The total deadhead miles go down to 139 miles if the facility location is relocated as shown the Figure C.90.

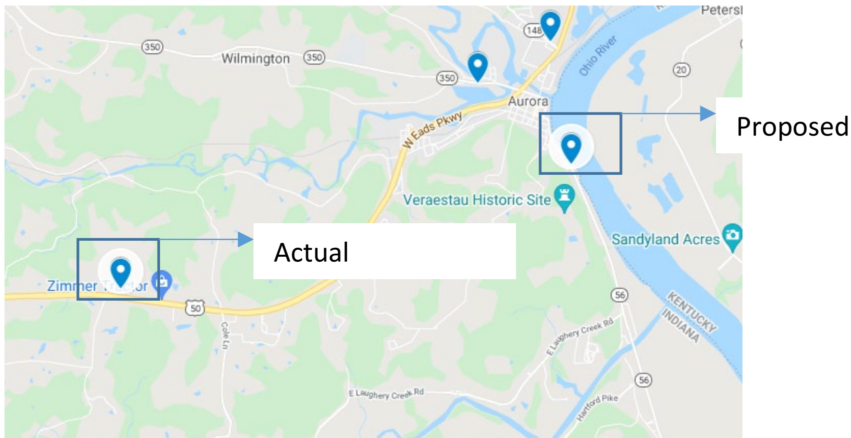


Figure C.90 Unit 5103 without additional routes.

Scenario 3: If additional routes are incorporated by assembling current route 02, 03-01, and 03-103 as a new one and current Routes 03 and 05 as another route, the total deadhead miles go down to 120 mi for current facility location.

Scenario 4: If the facility is relocated to node 12 (as shown in the 1), the total deadhead reduces to 80.6 mi.

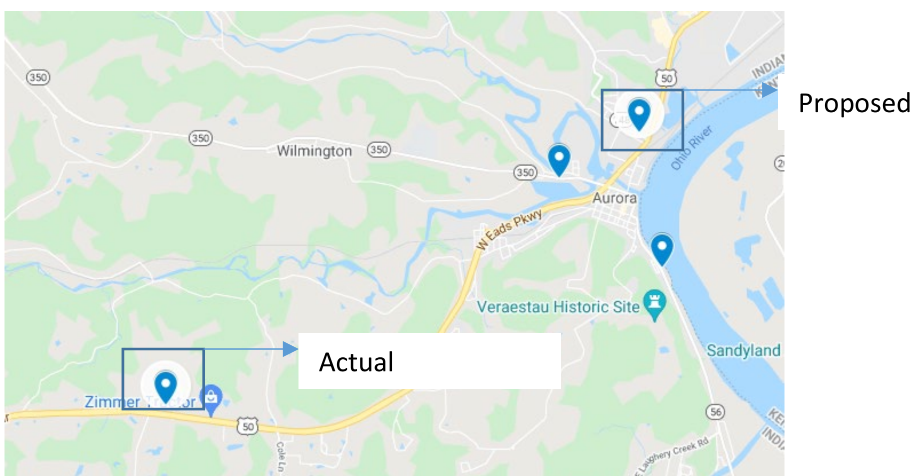


Figure C.91 Unit 5103 with additional routes.

Unit 5104

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 103 miles.

Scenario 2: The total deadhead miles go down to 79.4 mi if the facility location is relocated as shown in the Figure C.92.

Scenario 3: If additional routes are incorporated by assembling current Routes 102 and 104 as a new one, the total deadhead miles go down to 22 mi for current facility location.
Scenario 4: If the facility is relocated to node 1 (as shown in the Figure C.92), the total deadhead miles reduce to 17.8 mi.

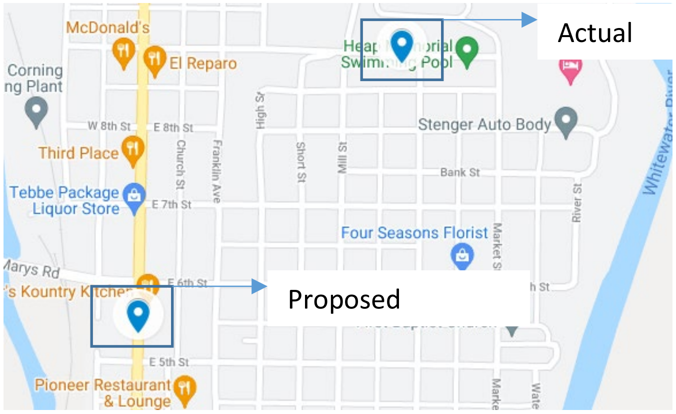


Figure C.92 Unit 5104 proposed location.

Unit 5105
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 105 miles.
Scenario 2: The total deadhead miles go down to 98.8 mi, if the facility location is relocated to node 26, as shown in the Figure C.93.

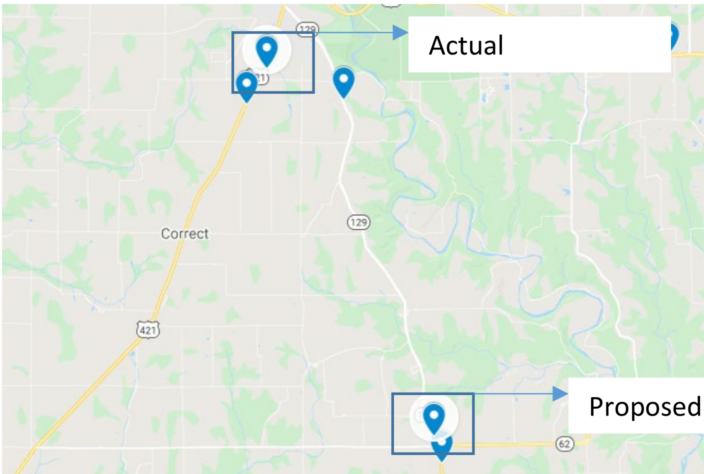


Figure C.93 Unit 5105 without additional routes.

Scenario 3: If additional routes are incorporated by merging current Routes 01 and 04 and 05-03 and 05-04 as two separate routes, the total deadhead miles go down to 41.4 mi for current facility location.
Scenario 4: If the facility is relocated to node 22 (as shown the Figure C.94), the total deadhead reduces to 38 mi.

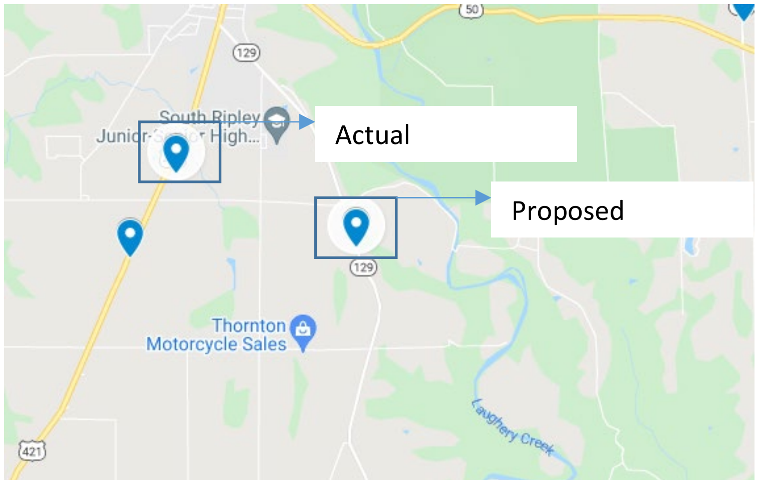


Figure C.94 Unit 5105 with additional routes.

Unit 5202

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 105 miles.

Scenario 2: The total deadhead miles go down to 98.8 mi, if the facility location is relocated to node 26, as shown in the Figure C.95.

Scenario 3: If additional routes are incorporated by merging current Routes 101 and 102 and 103 and 104 as two separate routes, the total deadhead miles go down to 87.8 mi for current facility location.

Scenario 4: If the facility is relocated to node 22 (as shown in the Figure C.95), the total deadhead reduces to 72.4 mi.

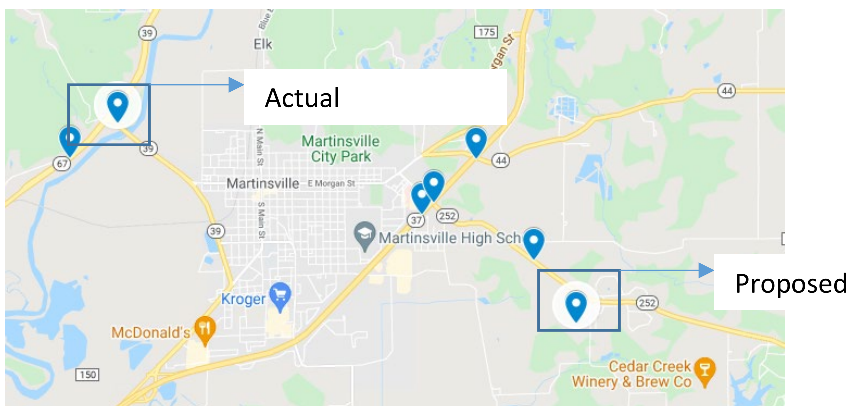


Figure C.95 Unit 5202 proposed locations.

Unit 5203

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 130 miles.

Scenario 2: The total deadhead miles go down to 94 mi, if the facility location is relocated to node 10, as shown in Figure C.96.

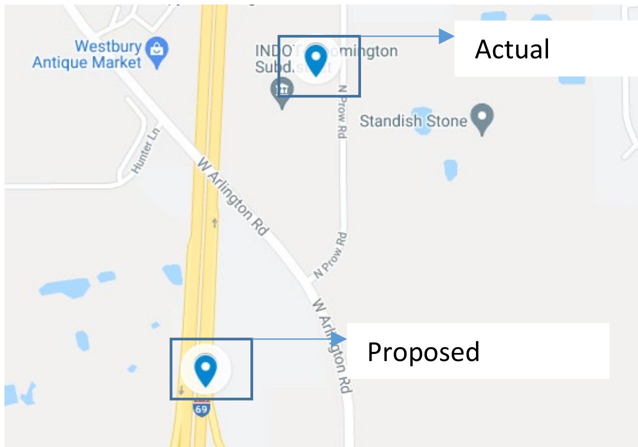


Figure C.96 Unit 5203 without additional routes.

Scenario 3: If additional routes are incorporated by merging current route 03-101 to 03-105 as one separate routes, the total deadhead miles go down to 66.6 mi for current facility location.

Scenario 4: If the facility is relocated to node 19 (as shown in the Figure C.97), the total deadhead reduces to 58.4 mi.

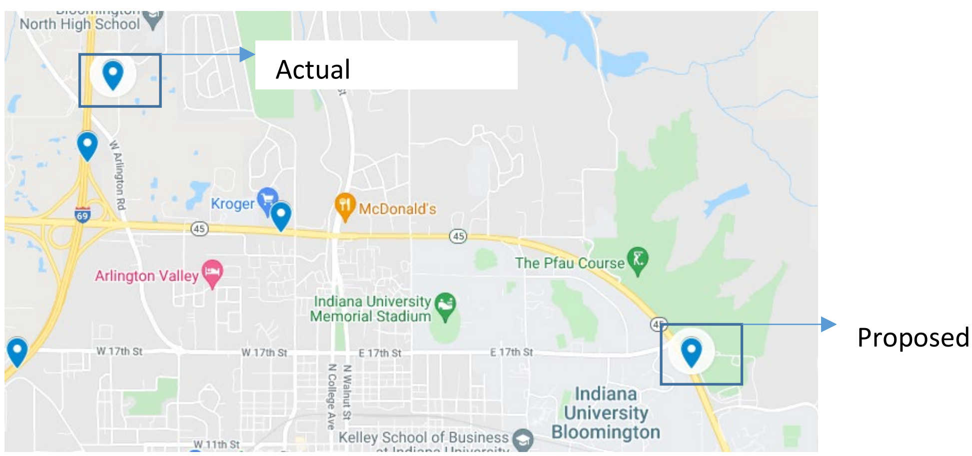


Figure C.97 Unit 5203 with additional routes.

Unit 5205

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 79.2 miles.

Scenario 2: The facility location is optimal.

Scenario 3: If additional routes are incorporated by merging current Routes 05 and 04 as one separate routes, the total deadhead miles go down to 64 mi for current facility location.

Scenario 4: The facility location is optimal.

Unit 5301

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 22 miles.

Scenario 2: The total deadhead miles go down to 18.6 mi, if the facility location is relocated to node 10, as shown in the Figure C.98.

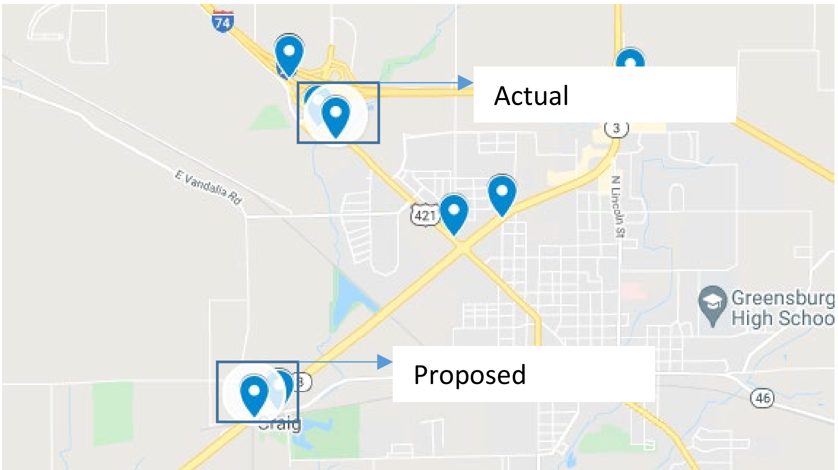


Figure C.98 Unit 5301 without additional routes.

Scenario 3: If additional routes are incorporated by merging current Routes 01 and 02 as one separate route, the total deadhead miles go down to 18 mi for current facility location.
Scenario 4: If the facility is relocated to node 15 (as shown in the Figure C.99), the total deadhead reduces to 9.2 mi.

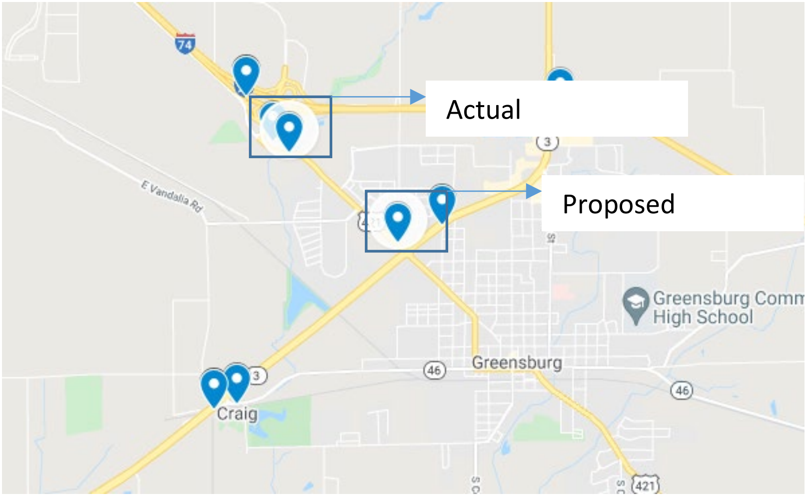


Figure C.43 Unit 5301 with additional routes.

Unit 5302
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 112 miles.
Scenario 2: The total deadhead miles go down to 69 mi, if the facility location is relocated to node 41, as shown in the Figure C.100.
Scenario 3: If additional routes are incorporated by merging current Routes 01 and 02 as separate routes, the total deadhead miles go down to 84.4 mi for current facility location.
Scenario 4: If the facility is relocated to node 41 (as shown in the Figure C.100), the total deadhead reduces to 67 mi.

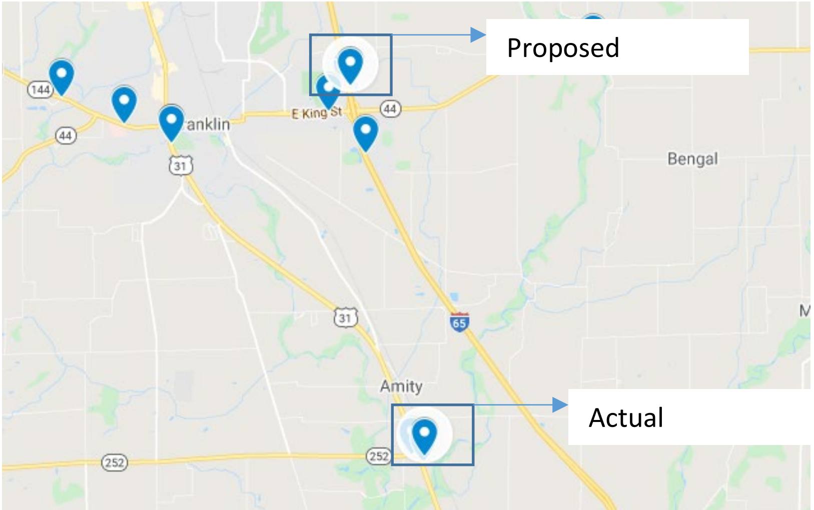


Figure C.100 Unit 5302 with and without additional routes.

Unit 5303

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 184 miles.

Scenario 2: The total deadhead miles go down to 69 mi, if the facility location is relocated to node 28, as shown in the Figure C.101.

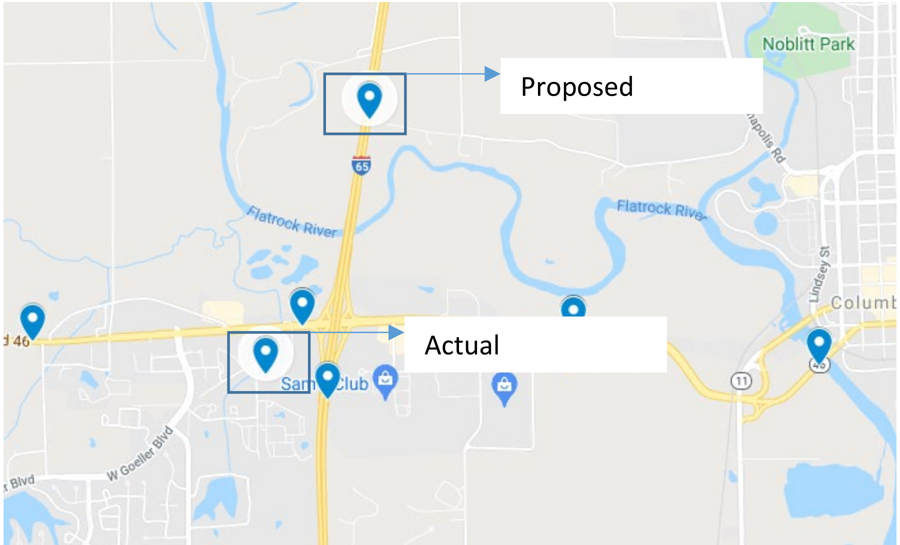


Figure C.101 Unit 5303 proposed location.

Additional routes can't reduce deadhead miles for this unit.

Unit 5402

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 118.6 miles.

Scenario 2: The total deadhead miles go down to 103.2 mi, if the facility location is relocated to node 6, as shown in the Figure C.102.

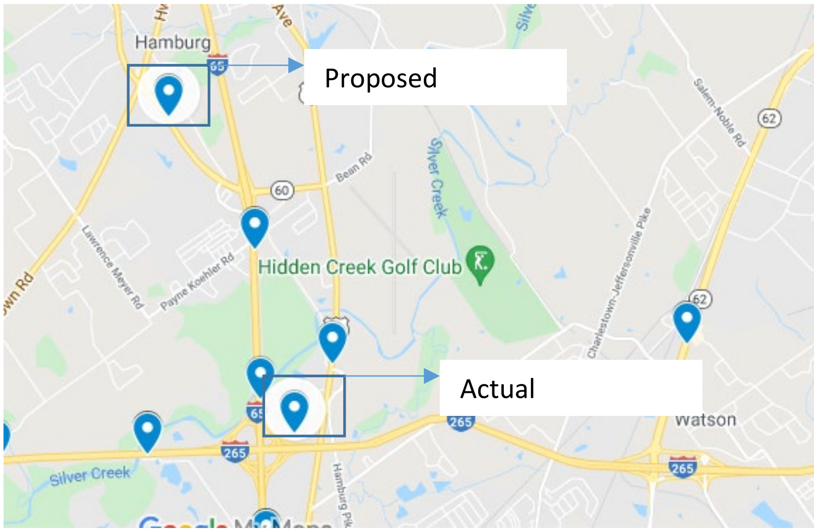


Figure C.102 Unit 5402 without additional routes.

Scenario 3: If additional routes are incorporated by merging current Routes 101, 102, and 104 as a separate Route and 106 and 107 as another separate route, the total deadhead miles go down to 81.4 mi for current facility location.

Scenario 4: If the facility is relocated to node 47 (as shown in the Figure C.103), the total deadhead reduces to 77 mi.

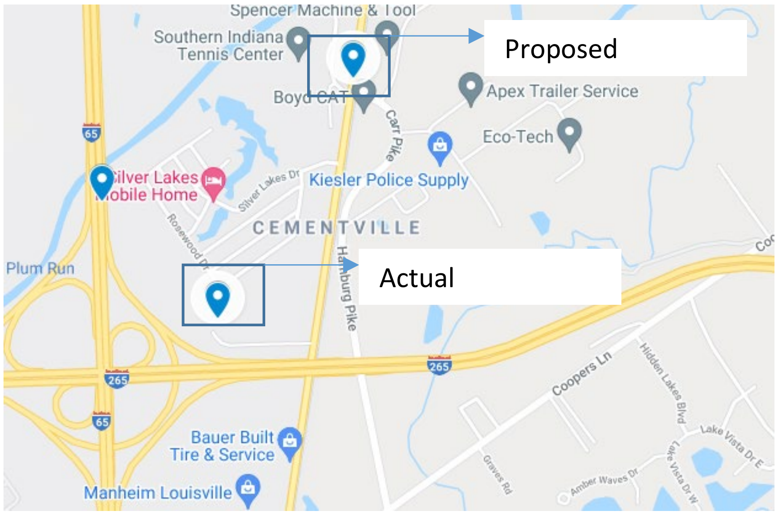


Figure C.103 Unit 5402 with additional routes.

Unit 5403

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 193 miles.

Scenario 2: this can be further optimized to 187 mi by relocating the facility to node 2, as shown in the Figure C.104.

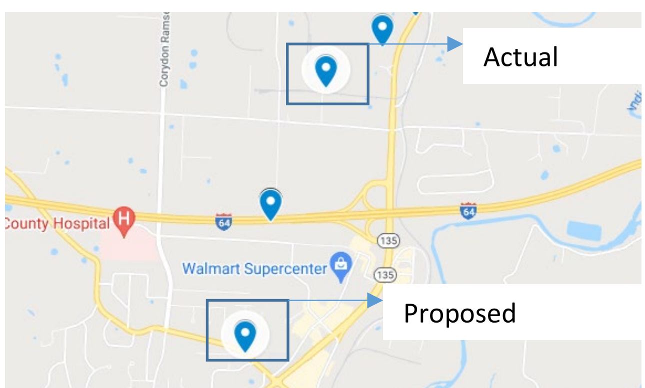


Figure C.104 Unit 5403 without additional routes.

Scenario 3: If additional routes are incorporated by assembling current Routes 104, 108, and 16 as a new one, the total deadhead miles go down to 187 mi for current facility location.
Scenario 4: If the facility is relocated to node 27 (as shown in the Figure C.105), the total deadhead reduces to 181 mi.

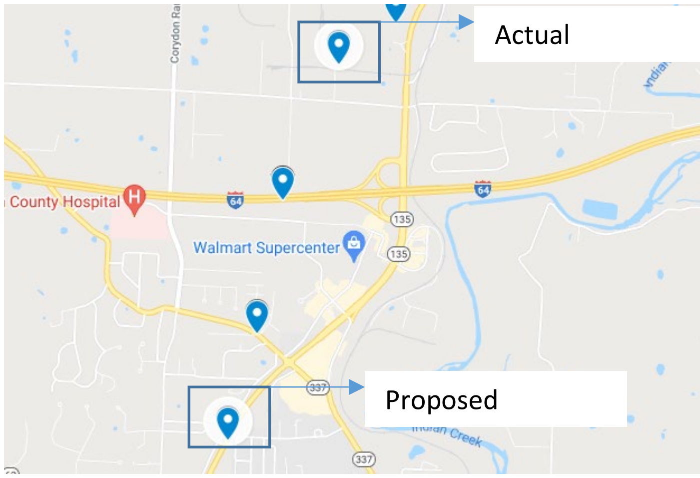


Figure C.105 Unit 5403 with additional routes.

Unit 5501
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 107 miles.
Scenario 2: this can be further optimized to 55 mi by relocating the facility to node 11, as shown in the Figure C.106.

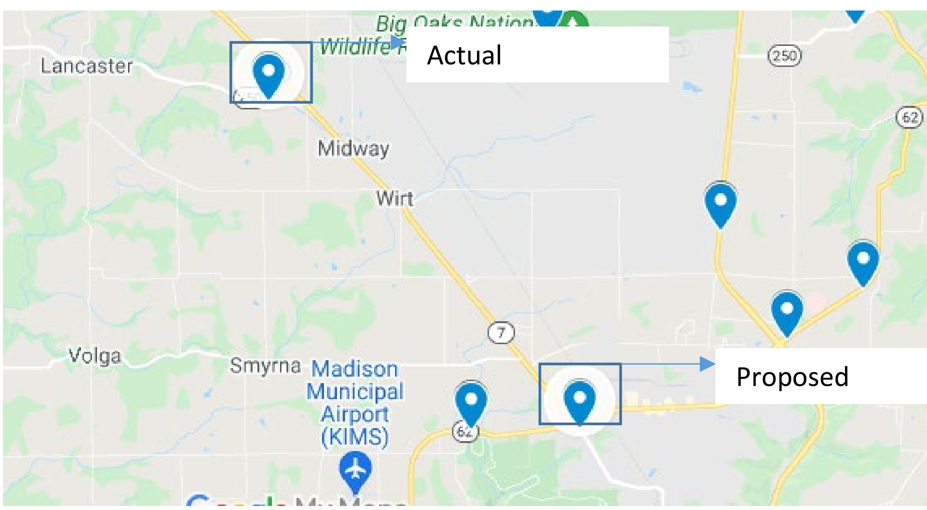


Figure C.106 Unit 5501 without additional units.

Scenario 3: If additional routes are incorporated by assembling current Routes 03 and 04 as a new one and 07 and 09 as another route, the total deadhead miles go down to 77 mi for current facility location.
Scenario 4: If the facility is relocated to node 3 (as shown in the Figure C.107), the total deadhead reduces to 45 mi.

Figure C.44 Unit 5501 with additional units.

Unit 5502
Far away mileposts are ignored, as these were considered outliers. These nodes are shown in the Figure C.108.

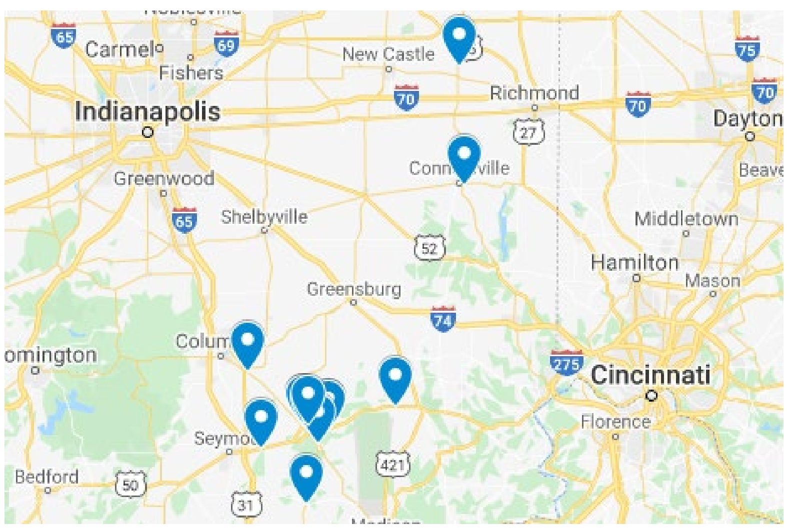


Figure C.108 Unit 5502 outliers.

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 33 miles.
Scenario 2: this can be further optimized to 21 mi by relocating the facility to node 8, as shown in the Figure C.109.

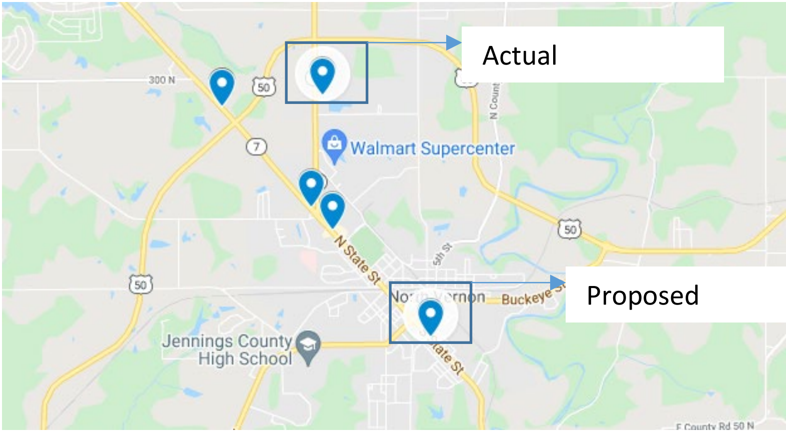


Figure C.109 Unit 5502 without additional routes.

Scenario 3: If additional routes are incorporated by assembling current Routes 01 and 02 as a new one and 05 and 06 as another route, the total deadhead miles go down to 15 mi for current facility location.
Scenario 4: If the facility is relocated to node 1 (as shown in the Figure C.110), the total deadhead reduces to 9 mi.

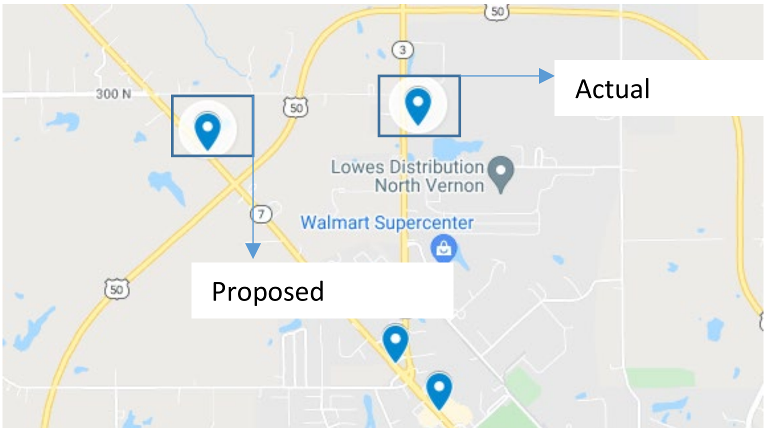


Figure C.110 Unit 5502 with additional routes.

Unit 5505

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 55 miles.

Scenario 2: This can be further optimized to 13 mi by relocating the facility to node 14, as shown in the Figure C.111.

Scenario 3: If additional routes are incorporated by assembling current Routes 101, 103, and 105 as another route, the total deadhead miles go down to 38 mi for current facility location.

Scenario 4: If the facility is relocated to node 14 (as shown in Figure C.111), the total deadhead reduces to 12 mi.

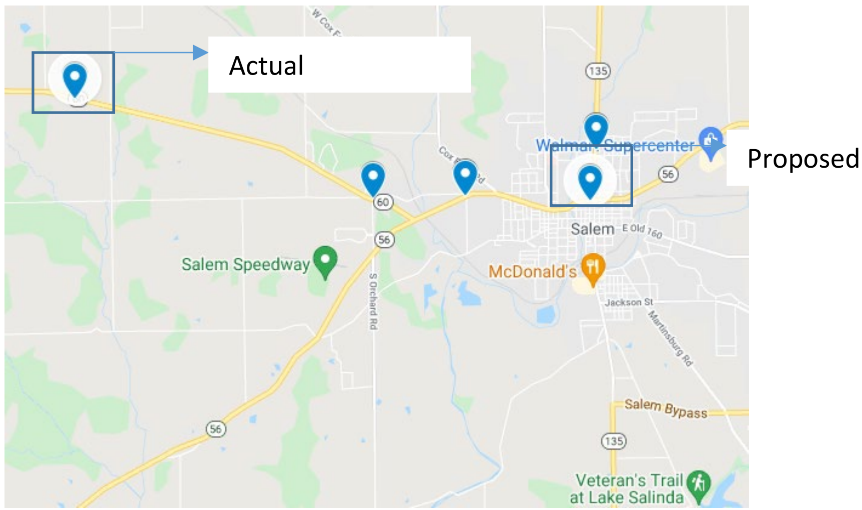


Figure C.111 Unit 5505 proposed location.

C.6 Vincennes District

Summary

Table C.6 presents a brief summary of each unit in the district and corresponding deadhead miles for each district based on the scenario taken from the mathematical model. It also mentions the node for relocation of the facility.

Table C.6 Vincennes District Summary

Unit No	First Scenario	Second Scenario	Recommended Location	Third Scenario	Fourth Scenario	Recommended Location
6101	30.8 mi	18 mi	S_54_31	30.8 mi	18 mi	N/A
6102	118 mi	111 mi	S_54_38	63 mi	53 mi	S_58_47
6103	46.6 mi	40.6 mi	N/A	46.6 mi	40.6 mi	N/A
6301	30.6 mi	24.4 mi	S_62_24	24.4 mi	14.4 mi	U_41_4
6302	62.2 mi	59 mi	I_64_25	62.2 mi	59 mi	N/A
6303	94.8 mi	81 mi	S_66_0	62.4 mi	54.8 mi	S_66_0
6304	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
6401	37 mi	25 mi	U_150_133	37 mi	25 mi	N/A
6403	42.3 mi	42.3 mi	N/A	28 mi	28 mi	N/A

6404	56.6 mi	37.2 mi	U_231_47	50.2 mi	37.2 mi	U_231_47
6502	98.4 mi	98.4 mi	N/A	61 mi	61 mi	N/A
6503	126 mi	113 mi	I_64_73	108 mi	95 mi	I_64_73
6504	65 mi	23 mi	S_161_31	38 mi	12 mi	S_161_31
6505	80.4 mi	78.2 mi	S_62_58	46 mi	30 mi	S_62_58
6601	153 mi	140 mi	S_57_35	75 mi	67 mi	S_61_45
6602	71 mi	63 mi	S_241_0	52 mi	30 mi	S_67_0
6607	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				

Figure C.112 presents the percentage change in deadhead miles by scenario across all units in the Vincennes District. Figure C.113 represents the deadhead miles across units in Vincennes District. Figure C.114 through Figure C.116 present the percentage change in deadhead miles for each unit according to Scenarios 2, 3, and 4, respectively.

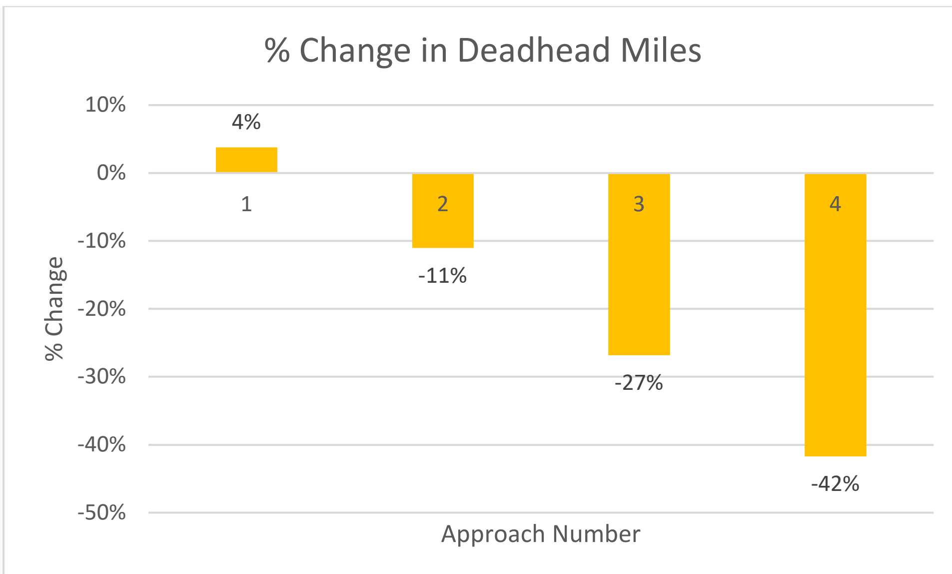


Figure C.112 Cumulative percentage change in deadhead miles across district by Scenario.

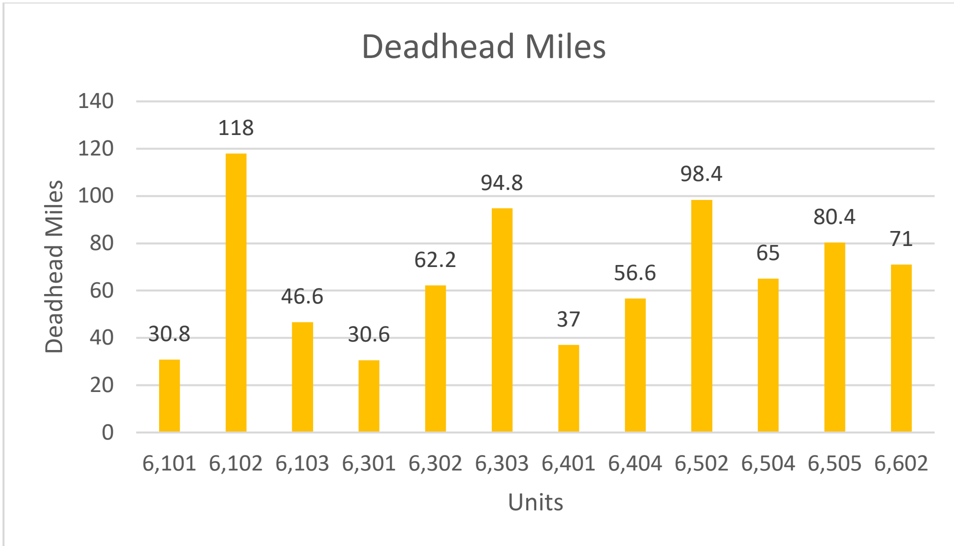


Figure C.113 Optimal deadhead miles across all units—Scenario 1.

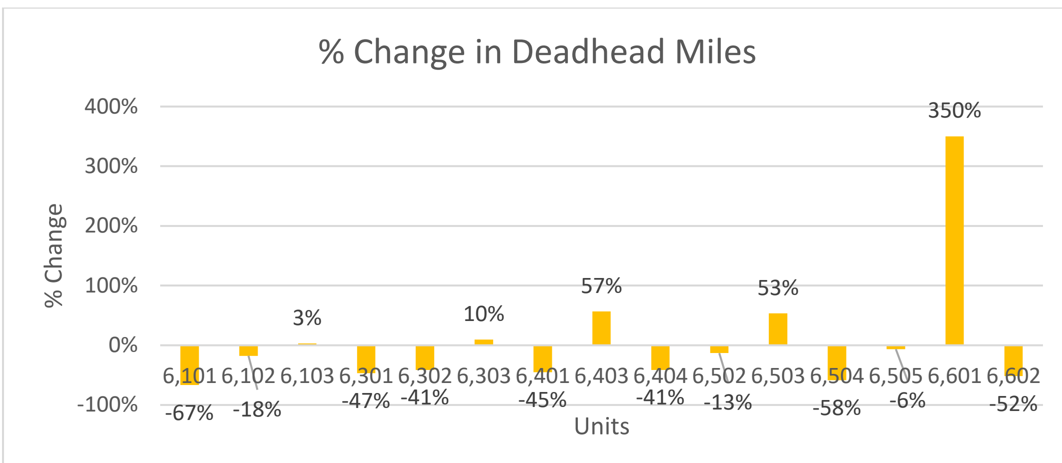


Figure C.114 Percentage change in deadhead miles across all units—Scenario 2.

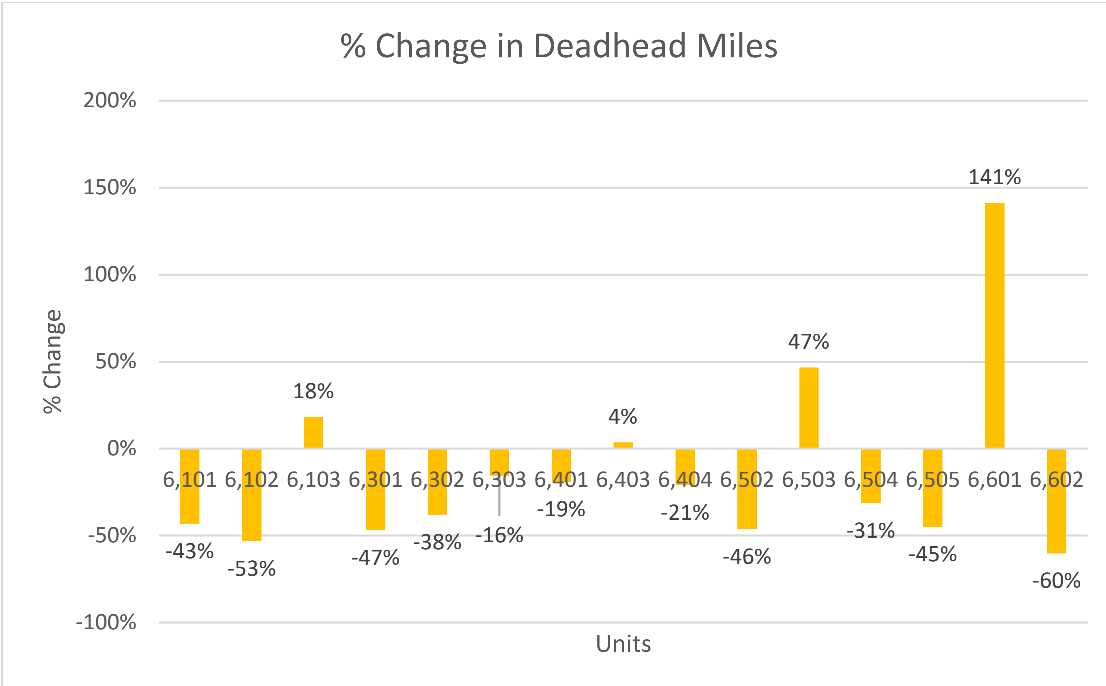


Figure C.115 Percentage change in deadhead miles across all units—Scenario 3.

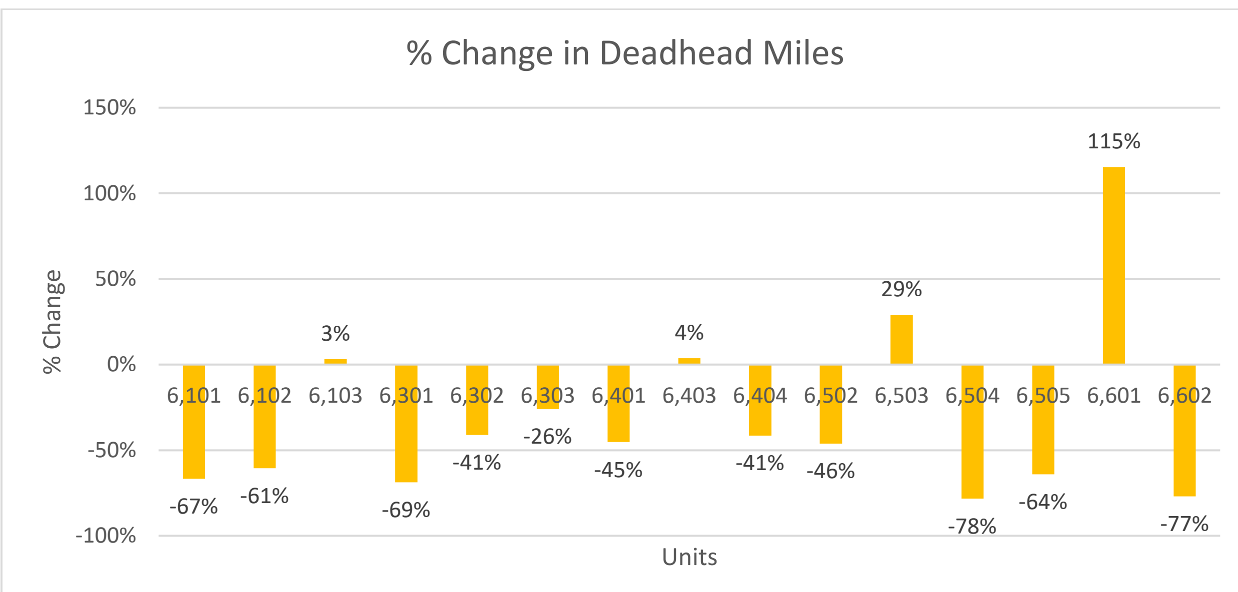


Figure C.116 Percentage change in deadhead miles across all units—Scenario 4.

Unit 6101

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 30.8 miles.

Scenario 2: By relocating the facility location to node 3, it can further be reduced to 18 miles. The current and proposed locations are shown in the Figure C.117.

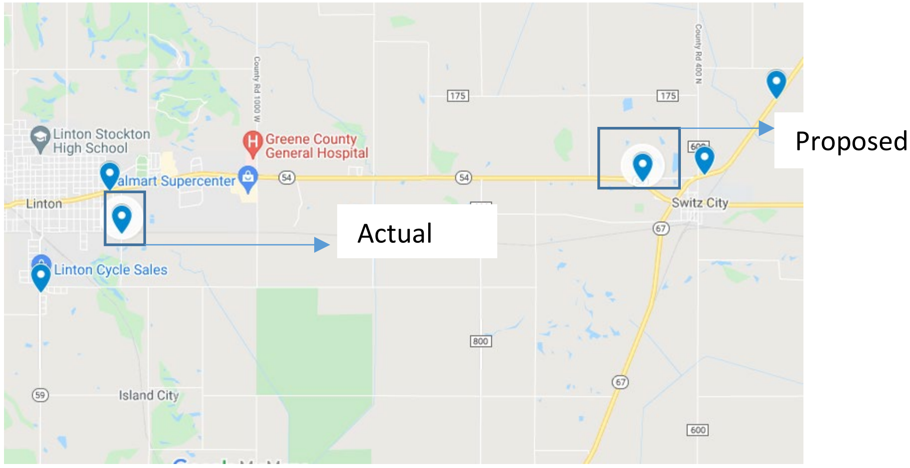


Figure C.117 Unit 6101 without additional units.

No significant reduction can be achieved by adding or altering routes.

Unit 6102

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 118 miles.

Scenario 2: The deadhead miles can be reduced to 111 miles by shifting the facility to node 1 as shown in the Figure C.118.

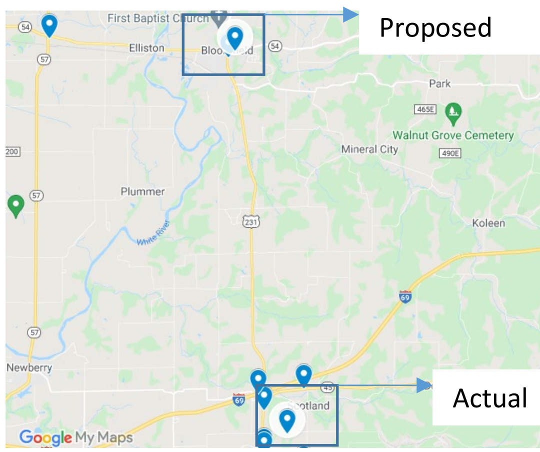


Figure C.118 Unit 6102 without additional routes.

Scenario 3: Additional route is considered by aggregating the nodes for Routes 1, 2, and 5. This will allow to reduce the total deadhead miles to 63 miles.

Scenario 4: with further reduction to 53 miles if facility is relocated to node 14 as shown in the Figure C.119.

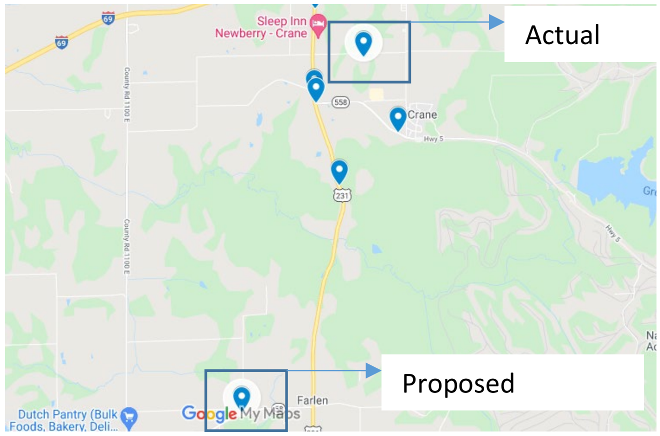


Figure C.119 Unit 6102 with additional units.

Unit 6103
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 46.6 miles.
Scenario 2: Further reduction can't be achieved by relocation of facility.
Scenario 3: Additional routes can be constructed by merging the nodes for Routes 05 and 06. This will result in total deadhead miles of 40.6 miles.
Scenario 4: Further reduction can't be achieved by relocation of facility.

Unit 6301
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 30.6 miles.
Scenario 2: The deadhead miles can be reduced to 24.4 miles by shifting the facility to node 6 as shown in the Figure C.120.

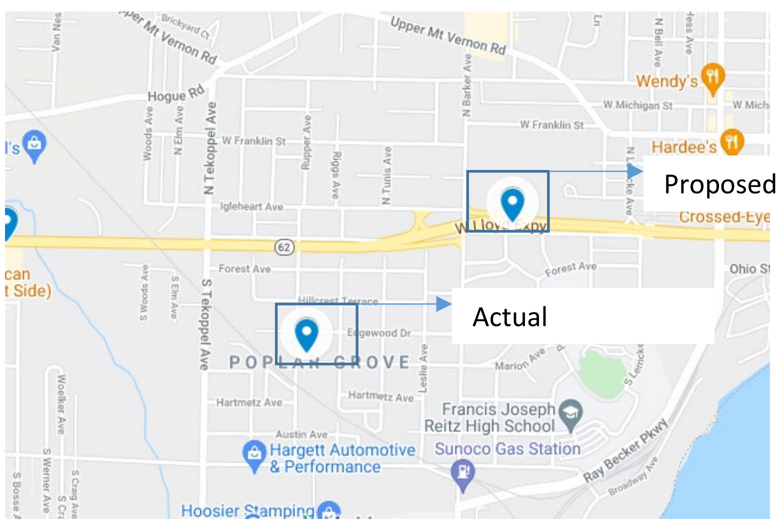


Figure C.120 Unit 6301 without additional routes.

Scenario 3: Additional route is considered by aggregating the nodes for Routes 09 and 10. This will allow to reduce the total deadhead miles to 24.4 miles.
Scenario 4: with further reduction to 14.4 miles if the facility is relocated to node 2 as shown in the Figure C.121.

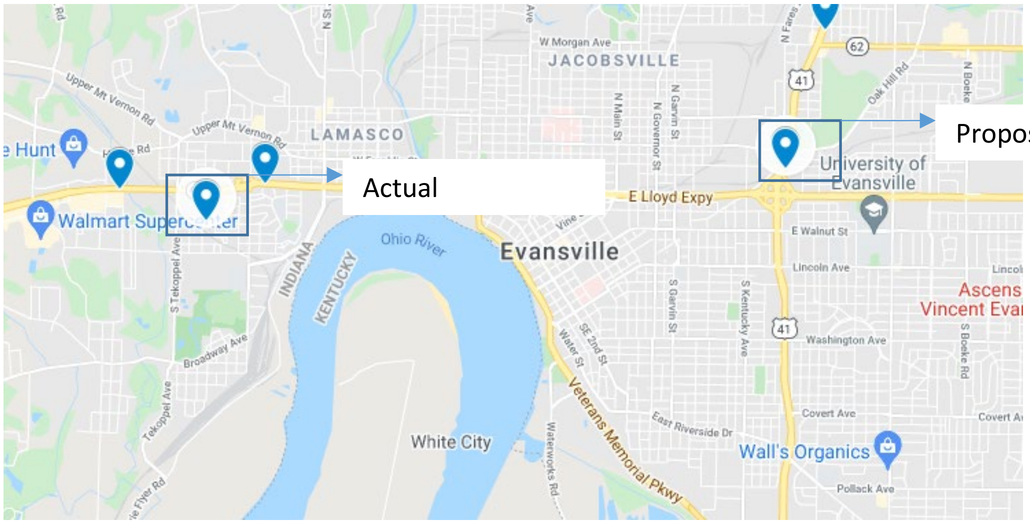


Figure C.121 Unit 6301 with additional routes.

Unit 6302

Data was unavailable for two nodes for this unit.

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 62.2 miles.
Scenario 2: The deadhead miles can be reduced to 59 miles by shifting the facility to node 2 as shown in the Figure C.121.
Additional routes don't result in reducing the deadhead miles significantly.

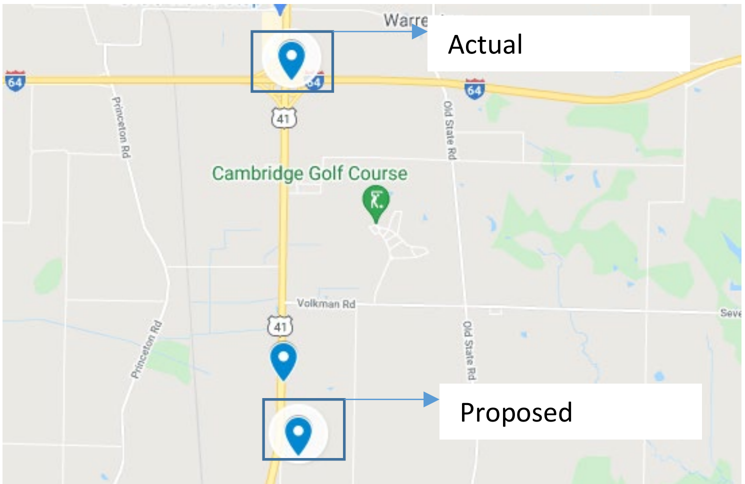


Figure C.122 Unit 6302 without additional routes.

Unit 6303

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 94.8 miles.

Scenario 2: The deadhead miles can be reduced to 81 miles by shifting the facility to node 15 as shown in the Figure C.123.
Scenario 3: Additional route is considered by aggregating the nodes for Routes 01 and 02 and the nodes for Routes 04 and 06. This will allow to reduce the total deadhead miles to 62.4 miles.
Scenario 4: with further reduction to 54.8 miles if facility is relocated to node 15 as shown in the Figure C.123.

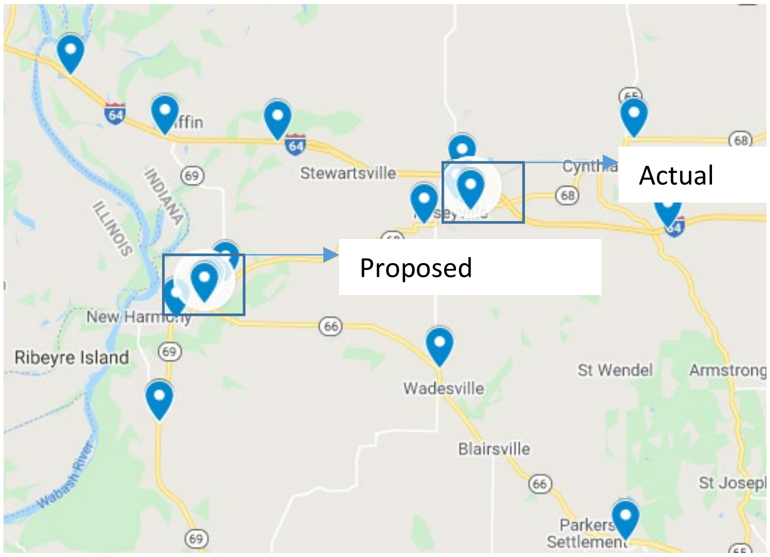


Figure C.123 Unit 6303 with or without additional routes.

Unit 6304
The mileposts for this unit don't provide any insight to geographical coordinates. The data is insufficient to create a modelling.

Unit 6401
As shown in the Figure C.124, the nodes far off are ignored.

Figure C.124 Unit 6401 far off nodes.

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 37 miles.

Scenario 2: On allowing relocation of facility, the minimal deadhead miles come to be 25 miles, for which the facility relocates to node 12, as shown in the Figure C.125.

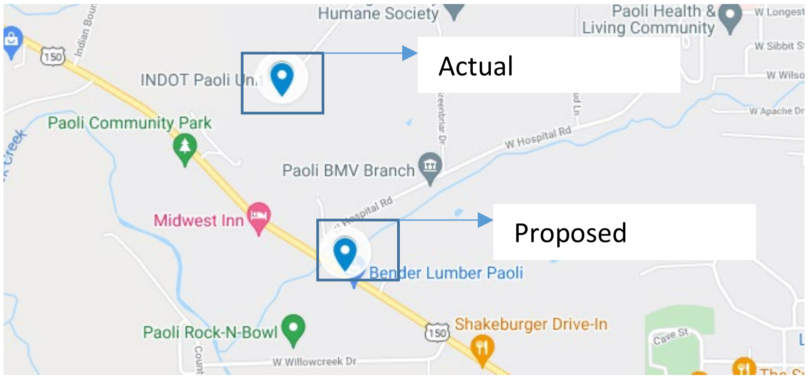


Figure C.125 Unit 6401 without additional units.

No reduction in deadhead mile is achieved by altering or generating new routes.

Unit 6403

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 42.4 miles.

Scenario 2: The facility location is optimized to have the minimal deadhead miles. One node has been ignored due to lack of data.

Scenario 3: Additional routes can be constructed by merging nodes for Routes 10 and 08 as one route and for Routes 05, 03, and 01 as another route. This will result in minimal deadhead miles of 28 miles.

Scenario 4: No reduction in deadhead miles is achieved by relocation of facility. The location is optimized.

Unit 6404

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 57 miles.

Scenario 2: The deadhead miles can be reduced to 37.2 miles by shifting the facility to node 13 as shown in the Figure C.126.

Scenario 3: Additional route is considered by aggregating the nodes for Routes 04 and 05. This will allow to reduce the total deadhead miles to 50.2 miles.

Scenario 4: with further reduction to 37.2 miles if facility is relocated to node 13 as shown in the Figure C.126.

Figure C.126 Unit 6404 with and without additional routes.

Unit 6502
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 98.8 miles.
Scenario 2: Further reduction can't be achieved by relocation of the facility.
Scenario 3: Additional routes can be constructed by merging the nodes for Routes 65-2-1 and 65-2-1 and nodes for Route 65-2-7 and 65-2-8. This will result in total deadhead miles of 61 miles.
Scenario 4: Further reduction can't be achieved by relocation of facility.

Unit 6503
Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 126 miles.
Scenario 2: The deadhead miles can be reduced to 113 miles by shifting the facility to node 21 as shown in the Figure C.127.
Scenario 3: Additional routes can be constructed by merging the nodes for Routes 65-3-4 and 65-3-5. This will result in total deadhead miles of 108 miles.
Scenario 4: By relocating facility to node 21, further reduction can be achieved, and the total deadhead will be 95 miles.

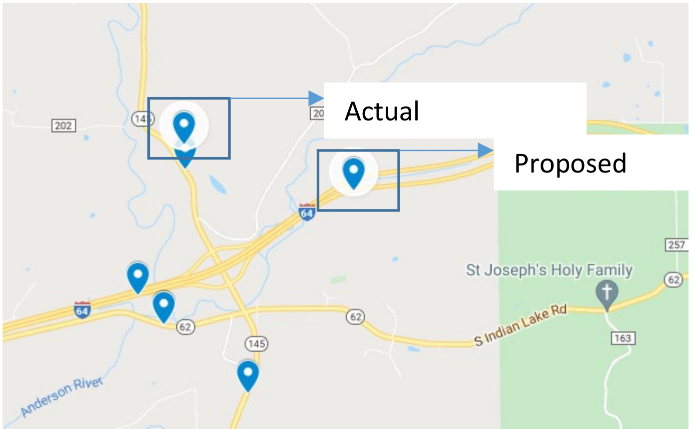


Figure C.127 Unit 6503 with and without additional routes.

Unit 6504

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 65 miles.

Scenario 2: By relocating facility to node 7, as shown in Figure C.128, further reduction can be achieved, and the total deadhead will be 23 miles.

Scenario 3: Additional routes can be constructed by merging the nodes for Routes 06 and 09 and for 01, 07, and 08. This will result in total deadhead miles of 38 miles.

Scenario 4: By relocating facility to node 7, further reduction can be achieved, and the total deadhead will be 12 miles.

Figure C.128 Unit 6504 proposed location.

Unit 6505

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 80.4 miles.

Scenario 2: By relocating facility to node 26, as shown in Figure C.129, further reduction can be achieved, and the total deadhead will be 78.2 miles.

Scenario 3: Additional routes can be constructed by merging the nodes for Routes 02, 03, and 04. This will result in total deadhead miles of 46 miles.

Scenario 4: By relocating facility to node 26, further reduction can be achieved, and the total deadhead will be 30 miles.

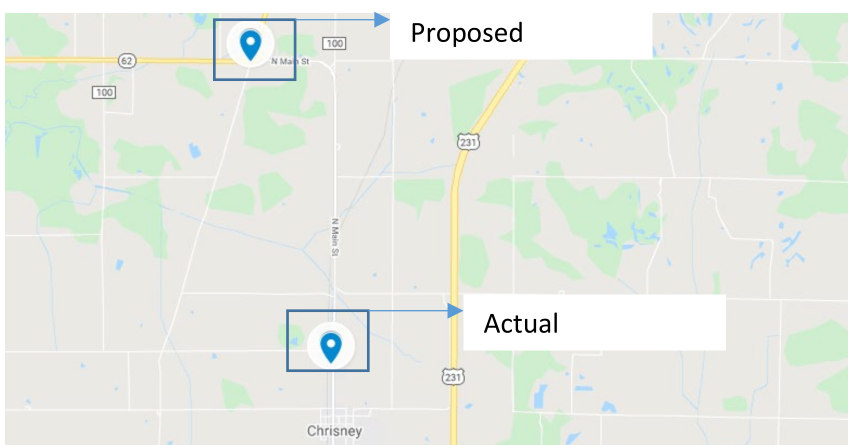


Figure C.129 Unit 6505 proposed location.

Unit 6601

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 153 miles.

Scenario 2: By relocating facility to node 21, as shown in Figure C.131, further reduction can be achieved, and the total deadhead will be 140 miles.

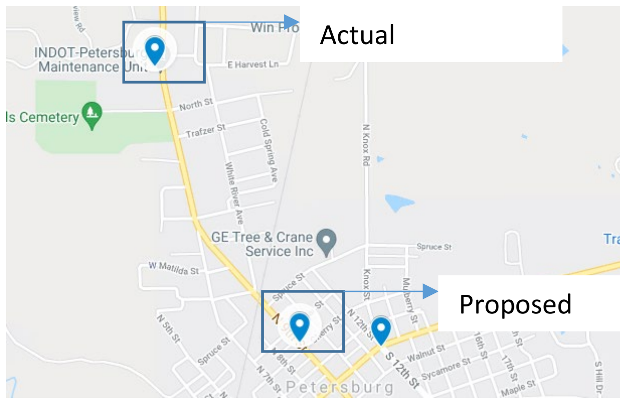


Figure C.130 Unit 6601 with additional routes.

Scenario 3: Additional routes can be constructed by merging the nodes for Routes 01, 02, and 03. This will result in total deadhead miles of 75 miles.

Scenario 4: By relocating facility to node 3, as shown in Figure C.130, further reduction can be achieved, and the total deadhead will be 67 miles.

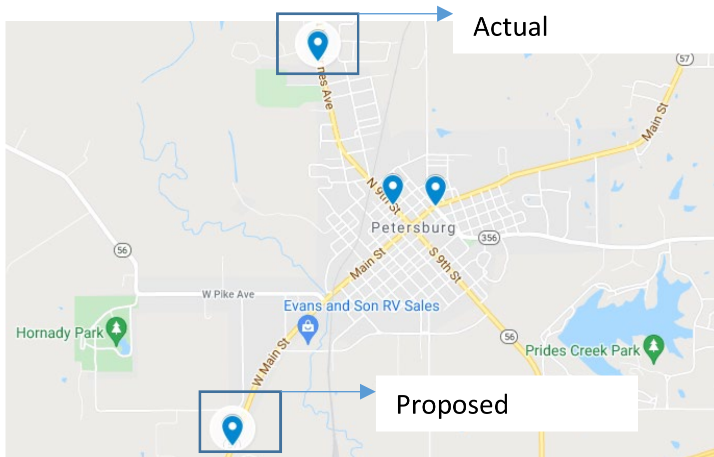


Figure C.131 Unit 6601 without additional routes.

Unit 6602

Scenario 1: The optimized deadhead miles with the current facility location and snow route network are 71 miles.

Scenario 2: By relocating facility to node 5, as shown in Figure C.132, further reduction can be achieved, and the total deadhead will be 63 miles.

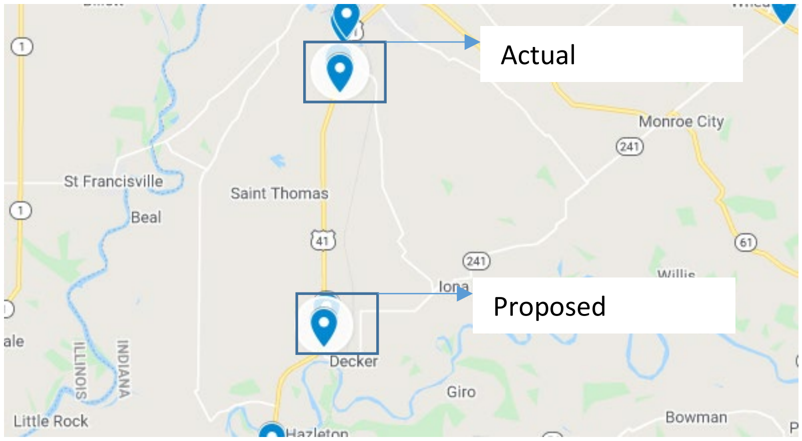


Figure C.132 Unit 6602 without additional routes.

Scenario 3: Additional routes can be constructed by merging the nodes for Routes 01 and 10. This will result in total deadhead miles of 52 miles.
Scenario 4: By relocating facility to node 7, as shown in Figure C.133, further reduction can be achieved, and the total deadhead will be 30 miles.

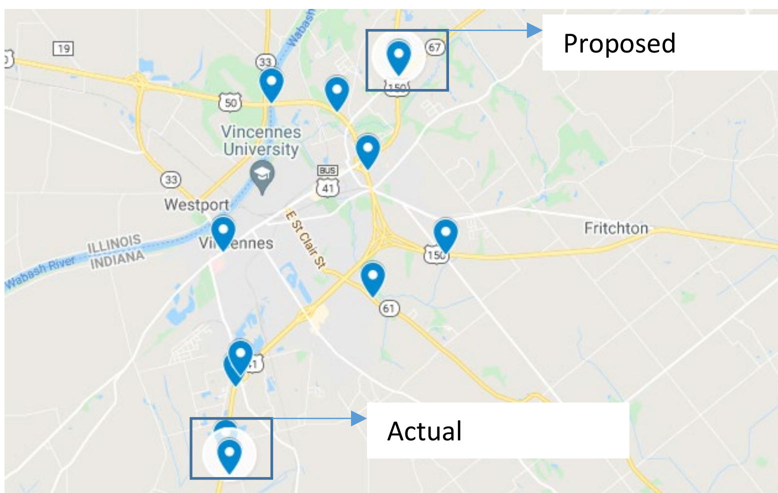


Figure C.133 Unit 6602 with additional routes.

C.7 State Summary

Following provides summary of all units across Indiana. The names of each unit associated with unit IDs is mentioned in Appendix A.

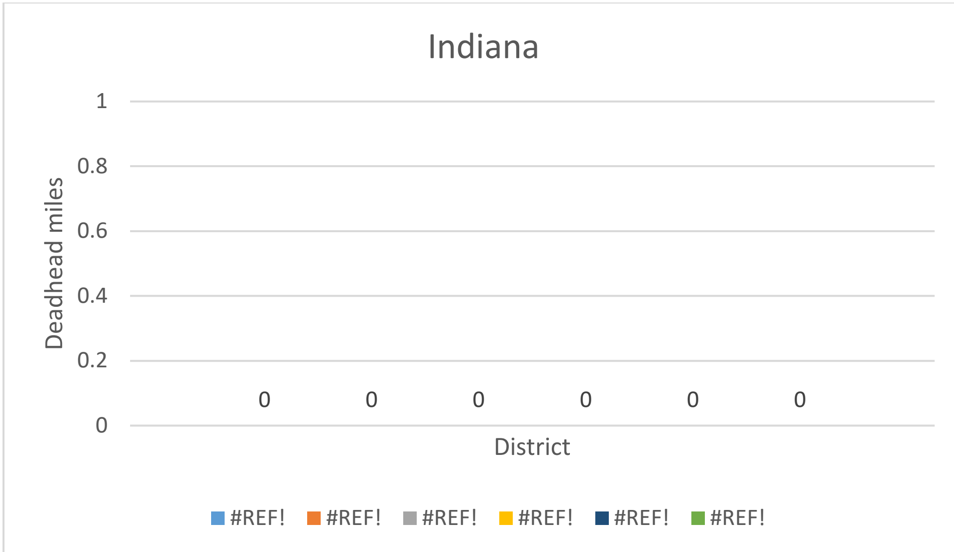


Figure C.134 Deadhead miles in every district of Indiana.

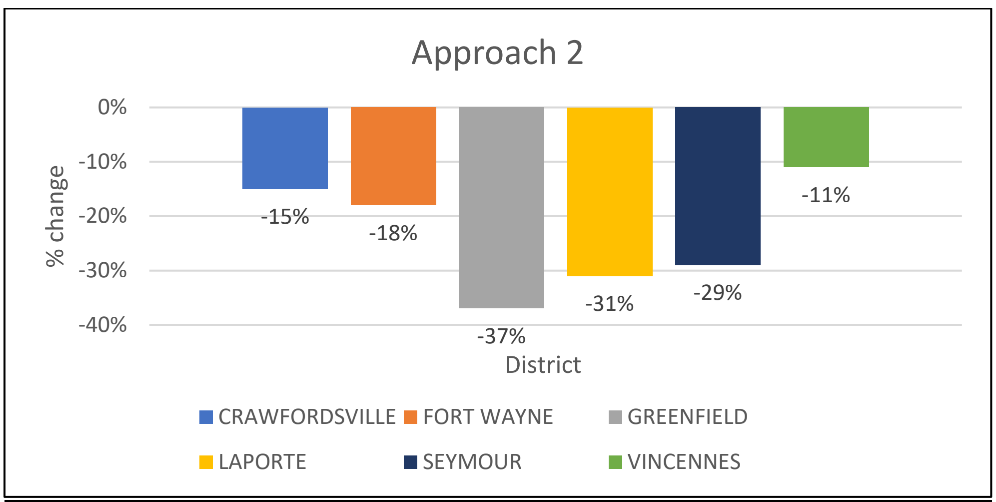


Figure C.135 Percentage change in deadhead miles in every district—Scenario 2.

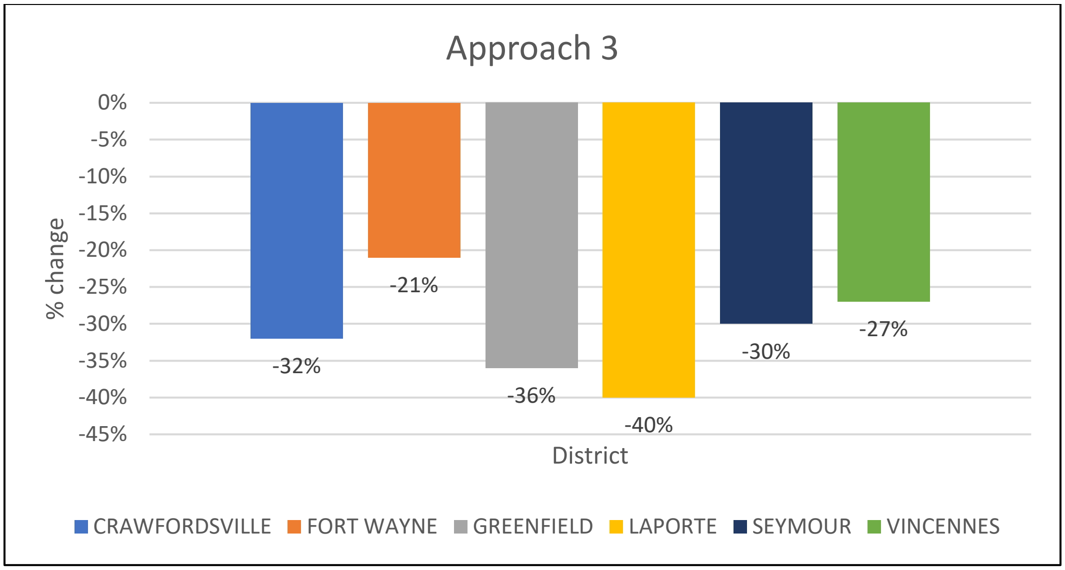


Figure C.136 Percentage change in deadhead miles in every district—Scenario 3

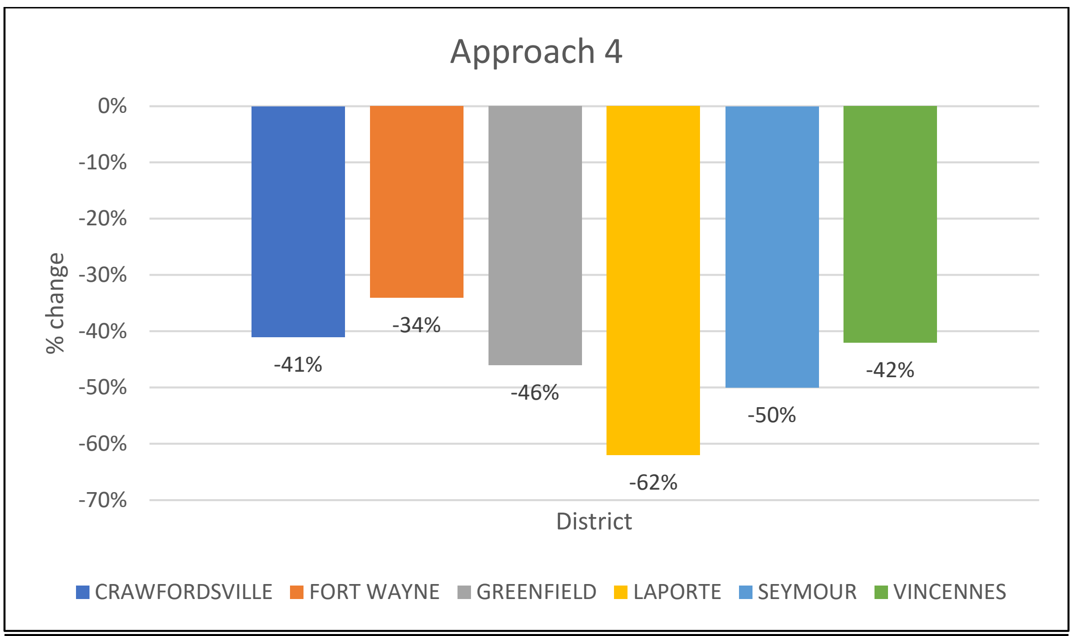


Figure C.137 Percentage change in deadhead miles in every district—Scenario 4.

As is evident from the analysis of summary for all districts in Indiana, Crawfordsville District has the highest number of deadhead miles according to Scenario 1 (Figure C.134) which gives us optimized deadhead miles for the current facility location and snow route network. Crawfordsville District is followed by Seymour District and then by Greenfield District.

Employing Scenario 2, as shown in Figure C.135, a maximum reduction in deadhead miles is observed for Greenfield District followed by LaPorte District—greater than 30%. Scenario 2 refers to relocating the facility with the current snow route network.

According to Scenario 3, as shown in Figure C.136, a maximum reduction in deadhead miles is observed for LaPorte District followed by Greenfield District, Crawfordsville District, and Seymour District,

respectively—all greater than 30%. Scenario 3 refers to generating additional routes to replace/add to the current snow route network with current facility location.
Based on Scenario 4, as shown in Figure C.137, it can be inferred that all districts except Fort Wayne have a reduction in deadhead miles in excess of 40%. LaPorte District has the maximum reduction in deadhead miles (62%) followed by Seymour District (50%).
Table C.7 provides a tabular summary of how the deadhead miles change across scenarios for all the units across six districts.

Table C.7 Summary of All Units in Indiana

Unit No	First Scenario	Second Scenario	Recommended Location	Third Scenario	Fourth Scenario	Recommended Location
1103	66 mi	56 mi	S_63_33	30.8 mi	14 mi	U_40_6
1201	118 mi	70 mi	U_231_178	55 mi	45 mi	U_136_37
1202	53.6 mi	50.2 mi	S_236_0	20 mi	20 mi	N/A
1203	100 mi	94 mi	S_63_60	No reduction achieved		
1204	55 mi	55 mi	N/A	No reduction achieved		
1301	31 mi	31 mi	N/A	No reduction achieved		
1302	71 mi	71 mi	N/A	No reduction achieved		
1303	110 mi	100 mi	S_43_29	75 mi	60 mi	S_43_29
1401	150 mi	136 mi	U_421_123	107 mi	98 mi	U_421_123
1402	120 mi	120 mi	N/A	No reduction achieved		
1403	60 mi	34 mi	U_231_201	28 mi	20 mi	U_231_201
1501	48 mi	47 mi	N/A	48 mi	47 mi	N/A
1502	54 mi	44 mi	S_236_19	No reduction achieved		
1503	66 mi	45 mi	N/A	66 mi	45 mi	N/A
1504	105 mi	68 mi	I_70_66	74 mi	40 mi	I_70_66
2201	101 mi	61 mi	S_15_82	77 mi	57 mi	S_15_81
2204	58.6 mi	44 mi	S_5_91	N/A	N/A	N/A
2205	77 mi	63 mi	S_15_59	61 mi	39 mi	S_15_57
2206	47.8 mi	47.8 mi	N/A	No reduction achieved		
2301	242.8 mi	181.2 mi	I_69_309	220 mi	180 mi	I_69_309
2303	130 mi	130 mi	N/A	No reduction achieved		
2305	72 mi	60 mi	S_8_62	57 mi	27 mi	S_8_62
2306	52 mi	43 mi	I_69_347	43 mi	36 mi	I_69_347
2501	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
2502	68 mi	60 mi	S_19_46	39 mi	28 mi	S_19_49
2506	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
2601	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
2603	67.6 mi	56.2 mi	U_27_86	60 mi	56.2 mi	U_27_86

2604	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
3101	210 mi	156 mi	I_465_47	210 mi	156 mi	N/A
3103	125 mi	70 mi	I_465_16	90 mi	42 mi	I_465_16
3104	86 mi	45 mi	I_465_37	75 mi	40 mi	I_465_36
3105	125 mi	100 mi	I_70_78	No reduction achieved		
3201	125 mi	125 mi	N/A	115 mi	115 mi	N/A
3202	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
3203	13 mi	6.5 mi	S_44_55	8.4 mi	8.4 mi	N/A
3204	50 mi	18 mi	S_9_29	25 mi	~2 mi	S_9_29
3301	45 mi	36 mi	U_27_26	40 mi	34 mi	U_35_8
3302	42 mi	3 mi	U_40_131	16.6 mi	1.5 mi	U_40_131
3303	54 mi	52 mi	S_38_93	20.2 mi	10 mi	N/A
3304	70 mi	60 mi	U_27_8	46 mi	42 mi	U_27_8
3501	44.6 mi	42.6 mi	S_28_84	23.2 mi	11.4 mi	S_28_89
3502	35 mi	35 mi	N/A	No reduction achieved		
3503	38 mi	30 mi	U_31_132	No reduction achieved		
3504	32 mi	32 mi	N/A	~2 mi	~2 mi	N/A
3601	65 mi	62 mi	S_32_126	52 mi	52 mi	N/A
3603	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
3604	19 mi	19 mi	N/A	~2 mi	~2 mi	N/A
3605	82 mi	62 mi	S_332_0	36 mi	36 mi	N/A
4101	95 mi	90 mi	U_35_195	67 mi	62 mi	N/A
4102	65 mi	53 mi	U_421_220	38 mi	33 mi	U_421_215
4103	16 mi	15 mi	U_20_44	No reduction achieved		
4201	77 mi	65 mi	U_24_41	35 mi	15.6 mi	U_24_35
4202	56 mi	37.6 mi	U_24_62	40.8 mi	23.8 mi	N/A
4204	79.4 mi	79.4 mi	N/A	No reduction achieved		
4301	164 mi	123 mi	U_6_69	No reduction achieved		
4302	49.6 mi	36 mi	S_933_110	38.2 mi	26 mi	S_933_110
4305	107 mi	71.4 mi	U_31_211	64.6 mi	44.6	S_331_5
4402	180 mi	130 mi	S_114_16	145 mi	110 mi	S_16_15
4403	135 mi	135 mi	N/A	80 mi	80 mi	N/A
4406	69 mi	62 mi	S_10_36	35 mi	35 mi	N/A
4701	54 mi	40 mi	U_231_288	54 mi	40 mi	U_231_288
4702	42 mi	34 mi	I_80_15	20 mi	15 mi	U_6_17
4703	33 mi	5 mi	U_20_7	33 mi	33 mi	N/A
4704	70 mi	30 mi	I_80_1	50 mi	7 mi	I_80_2
4705	19 mi	14 mi	U_20_30	19 mi	14 mi	N/A

5101	25.6 mi	25.6 mi	N/A	6.3 mi	3.4 mi	S_101_17
5103	187 mi	139 mi	S_56_193	120 mi	80.6 mi	S_148_5
5104	42 mi	17.8 mi	U_52_155	22 mi	17.8 mi	U_52_155
5105	105 mi	98.8 mi	S_129_19	41.4 mi	38 mi	S_129_25
5202	103 mi	79.4 mi	S_39_18	87.8 mi	72.4 mi	S_39_18
5203	130 mi	94 mi	S_37_103	66.6 mi	58.4 mi	S_45_41
5205	79.2 mi	79.2 mi	N/A	64 mi	64 mi	N/A
5301	22.9 mi	18.6 mi	S_3_70	18 mi	9.2 mi	U_421_51
5302	112 mi	69 mi	I_65_90	84.4 mi	67 mi	I_65_90
5303	184 mi	68 mi	I_65_69	184 mi	68 mi	I_65_69
5402	118 mi	103 mi	S_60_60	81 mi	77 mi	U_31_6
5403	193 mi	187 mi	S_337_12	187 mi	181 mi	S_135_15
5501	107 mi	55 mi	S_7_3	77 mi	45 mi	S_62_192
5502	33 mi	21 mi	S_3_43	15 mi	9 mi	S_7_26
5504	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
5505	55 mi	13 mi	S_56_99	38 mi	12 mi	S_56_99
6101	30.8 mi	18 mi	S_54_31	30.8 mi	18 mi	N/A
6102	118 mi	111 mi	S_54_38	63 mi	53 mi	S_58_47
6103	46.6 mi	40.6 mi	N/A	46.6 mi	40.6 mi	N/A
6301	30.6 mi	24.4 mi	S_62_24	24.4 mi	14.4 mi	U_41_4
6302	62.2 mi	59 mi	I_64_25	62.2 mi	59 mi	N/A
6303	94.8 mi	81 mi	S_66_0	62.4 mi	54.8 mi	S_66_0
6304	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				
6401	37 mi	25 mi	U_150_133	37 mi	25 mi	N/A
6403	42.3 mi	42.3 mi	N/A	28 mi	28 mi	N/A
6404	56.6 mi	37.2 mi	U_231_47	50.2 mi	37.2 mi	U_231_47
6502	98.4 mi	98.4 mi	N/A	61 mi	61 mi	N/A
6503	126 mi	113 mi	I_64_73	108 mi	95 mi	I_64_73
6504	65 mi	23 mi	S_161_31	38 mi	12 mi	S_161_31
6505	80.4 mi	78.2 mi	S_62_58	46 mi	30 mi	S_62_58
6601	153 mi	140 mi	S_57_35	75 mi	67 mi	S_61_45
6602	71 mi	63 mi	S_241_0	52 mi	30 mi	S_67_0
6607	Data N/A	Data unavailable on several parts leading to inappropriate model and major deviation in result				

APPENDIX D. COMMONLY USED TERMS

Unit (also, depot, or base). The facility that serves as a garage for the snow removal vehicles. It also serves as a storage for deicing chemicals.

Deadhead miles. The distance traveled by a specific on routes where that vehicle is not removing snow. For example, distance traveled between the base and the snow removal routes, and between disjoint snow removal routes. These may be snow removal routes for other snow removal vehicles.

APPENDIX E. ACRONYMS

ADT = Average Daily Traffic
LRP = Link Routing Problem
CLRP = Capacitated Link Routing Problem
CCPP = Capacitated Chinese Postman Problem
CPP = Chinese Postman Problem
DCPP = Directed Chinese Postman Problem
DRPP = Direct Rural Postman Problem
HCPP = Hierlinkhical Chinese Postman Problem
MCPP = Mixed Chinese Postman Problem
RPP = Rural Postman Problem
UCLRP = Undirected Capacitated Link Routing Problem
URPP = Undirected Rural Postman Problem

APPENDIX F. ASPECTS OF NETWORK THEORY RELEVANT TO THIS REPORT

- Network: A network is a collection of nodes and lines joining all or only some of these nodes. Some authors use the term edge for a line with no direction and the term link for a line with direction. In this research, the term link will be used for a line connecting two nodes irrespective of the direction of the line connecting two nodes.
- Undirected Network: If all the links in the network have no direction, the network is called an undirected network.
- Directed Network: If all the links in the network have directions, the network is called a directed network.
- Mixed Network: If both directed and undirected links exist in a network, the network is called a mixed network.
- Path: A path is a sequence of consecutive edges in a network.
- Connected Network: An undirected network is connected if there is a path connecting all nodes or vertices.
- Strongly Connected Network: A directed network is strongly connected if there is a path connecting all nodes or vertices.
- Degree: The degree of a node is the number of links connected at that node. For a directed network, the degree of a node is the sum of in-degree and out-degree (explained below) of that node.
- In-Degree (directed network): In a directed network, the in-degree of a node is the number of links entering into that node.
- Out-Degree (directed network): In a directed network, the out-degree of a node is the number of links emanating from that node.
- Even-Degree Node or Vertex: A node or vertex for which the degree is an even number.
- Odd-Degree Node or Vertex: A node or vertex for which the degree is an odd number.
- Eulerian or Unicursal Network: A connected network is said to be Eulerian or unicursal if there exists a closed tour in the network containing each link exactly once and each vertex at least once. The closed tour is called Eulerian circuit or Eulerian tour.

APPENDIX G. ALGORITHM DEVELOPED FOR PHASE 2 OF THIS STUDY

G.1 The K-DCPP Heuristic Algorithm—Optimize K and Routing

Algorithm Initialization:

```
#Initialization
import pandas as pd
from sklearn.preprocessing import MinMaxScaler
from sklearn.cluster import KMeans
import matplotlib.pyplot as plt
import seaborn as sns
import copy
import networkx as nx
from copy import deepcopy
import queue
import pandas as pd
import re
from random import randrange
```

Directed CPP—Find Euler path function:

```
def FindEuler(self, start_label: str):
    """
    Finding Euler cycle in graph G1
    :param: start_label - starting vertex label
    :return:
    """
```

Functions used in the K-DCPP-Heuristic Algorithm:

(1) Find the sub route from the DCPP.

```
# Functions that going to use in the Heuristic Algorithm
def find_sub_list(l):
    results=[]
    location = []
    for i in range(0,len(l)):
        if l[i] == 'unit' and i == 0:
            location.append(i)
        if l[i] == 'unit' and i != 0:
            location.append(i+1)

    for j in range(0,len(location)-1):
        if j == 0:
            sublist = l[location[j]:location[j+1]]
        if j != 0:
            sublist = l[location[j]-1:location[j+1]]
        results.append(sublist)
    return results
```

(2) Find the weight (travel miles) of the sub routes.

```python
def find_sub_list_weight(l):
    weights=[]
    location = []
    for i in range(0,len(l)):
        if l[i] == 0 and i == 0:
            location.append(i)
        if l[i] == 0 and i != 0:
            location.append(i+1)

    for j in range(0,len(location)-1):
        if j == 0:
            sublist = l[location[j]:location[j+1]]
        if j != 0:
            sublist = l[location[j]-1:location[j+1]]
        weights.append(sublist)

    return weights
```

(3) Find all the loops of long sub routes.

```python
def dfs(graph, start, end):
    fringe = [(start, [])]
    while fringe:
        state, path = fringe.pop()
        if path and state == end:
            yield path
            continue
        for next_state in graph[state]:
            state_count = 0
            for i in range(0,len(path)):
                if path[i] == next_state:
                    state_count += 1
            if next_state in path and state_count > 1:
                continue
            fringe.append((next_state, path+[next_state]))
```

Initialize the Input of the Heuristic Algorithm:

(1) Input files (take Gary Unit as an example):

input_Gary — Edited

```
Edges = [(0,1),(1,0),(1,2),(2,1),(1,6),(6,1),(1,3),(3,1),(3,4),(4,3),(4,5),(5,4),
(6,7),(7,6),(7,8),(8,7),(8,9),(9,8),(7,10),(10,7),(8,10),(10,8),(10,11),(11,10),
(11,12),(12,11),(12,13),(13,12),(13,14),(14,13),(0,13),(13,0)]

Service_Edges = [(1,2),(2,1),(1,3),(3,1),(3,4),(4,3),(4,5),(5,4),
(6,7),(7,6),(7,8),(8,7),(8,9),(9,8),(7,10),(10,7),(8,10),(10,8),(10,11),(11,10),
(11,12),(12,11),(12,13),(13,12),(13,14),(14,13)]

Cruise_Edges = [(0,1),(1,0),(1,6),(6,1),(0,13),(13,0)]

labels_sample = ["unit", "US41-269", "US41-263", "US41-274", "US41-276", "US41-278",
"SR152-0", "US20-7/SR152-2", "US12-5", "US12-0", "US20-10", "US20-13/US12-12", "US12-14/
US53-14", "SR53-11", "SR53-5"]

weights_sample = [4, 4, 6, 6, 1, 1, 5, 5, 2, 2, 2, 2, 2, 2, 2, 2, 5, 5, 3, 3, 5, 5, 3, 3,
2, 2, 3, 3, 6, 6, 6, 6]

Vertices_num = 15

Vertices = [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]
```

The input information needed includes the following:

1. Edges/links: which are the snow removal roads (that need to remove snow) and cruise roads (no need to remove snow).
2. Service_Edges: the roads that need to remove snow.
3. Cruise_Edges: the roads that no need to remove snow.

4. Vertices: the intersections or the Milepost points that connect the roads.
5. Vertices_num: number of Vertices
6. labels_sample: the label of Vertices, for example unit: “Unit”, milepost point: “US41-269”
7. weights_sample: the length of roads/edges

The input file information needs to be copy and paste into the Algorithm Initialization part, which is introduced as shown below.

(1) Input codes (Take Gary Unit as an example):

As shown in the red square in the figure below, the Assigned_Route represents all the optimal routes in the unit. the Total_DH, which count for the optimal deadhead miles. Both are initialized here. We also initialize the Truck_num = 0.

```
#Heuristic Algorithm
#Generate the Service road set {} and get the number of service roads

#Initialize the Network with Edges, Service_Edges, Cruise_Edges
Edges = [(0,1),(1,0),(1,2),(2,1),(1,6),(6,1),(1,3),(3,1),(3,4),(4,3),(4,5),(5,4),
(6,7),(7,6),(7,8),(8,7),(8,9),(9,8),(7,10),(10,7),(8,10),(10,8),(10,11),(11,10),
(11,12),(12,11),(12,13),(13,12),(13,14),(14,13),(0,13),(13,0)]

Service_Edges = [(1,2),(2,1),(1,3),(3,1),(3,4),(4,3),(4,5),(5,4),
(6,7),(7,6),(7,8),(8,7),(8,9),(9,8),(7,10),(10,7),(8,10),(10,8),(10,11),(11,10),
(11,12),(12,11),(12,13),(13,12),(13,14),(14,13)]

Cruise_Edges = [(0,1),(1,0),(1,6),(6,1),(0,13),(13,0)]

labels_sample = ["unit", "US41-269", "US41-263", "US41-274", "US41-276", "US41-278", "SR152-0", "US20-7/SR152-2", "U

weights_sample = [4, 4, 6, 6, 1, 1, 5, 5, 2, 2, 2, 2, 2, 2, 2, 2, 5, 5, 3, 3, 5, 5, 3, 3,
2, 2, 3, 3, 6, 6, 6, 6]

Vertices_num = 15

Vertices = [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]

#Initial Node_Removed and Node_removed_labels to store the node that can be removed from the graph
Node_removed_accumulate = []
Node_removed = []
Node_removed_labels = []
Assigned_Route = []
Total_DH = 0

# Initialize the dictionary
# Dictionay of Node and the Weight, key: Nodes ('Cxx','Cxx')
Node_Weight = {}
for i in range(len(Edges)):
    Node_Weight[Edges[i]] = weights_sample[i]

# Dictionary of the Road and Road Types ('Cxx', 'Cxx'): 'Cruise'/'Service'
Road_Type = {}
for i in range(len(Edges)):
    if Edges[i] in Service_Edges:
        Road_Type[Edges[i]] = 'Service'
    if Edges[i] in Cruise_Edges:
        Road_Type[Edges[i]] = 'Cruise'
```

```
Truck_num = 0
```

Algorithm Starts:

Still using Gary Unit as an example.

Step 1

Add new Truck:

```
Truck_num += 1 # add one truck to the network
```

Using iNetwork to generate network structure:

```
g = Graph(directed=True) # initialize the network graph, follows with vertices, vertices_num, and add_edges
g.add_vertices(15)
g.add_edges(Edges)
```

Make sure whether there are removed vertices/nodes, and change the Vertices_num:

```
if Node_removed_accumulate != []:
    g.delete_vertices(Node_removed_accumulate)
    #     for i in range(len(Node_removed_accumulate)-1, 0, -1):
    #         print(Node_removed_accumulate[i])
    #         g.delete_vertices(Node_removed_accumulate[i]) # Since backward the i will not include first Node_remov
    #     g.delete_vertices(Node_removed_accumulate[0]) # add first element Node_removed[0]
Vertices_num = Vertices_num - len(Node_removed_accumulate)
```

Determine the DCPP for the entire unit's network:

```
#print(Truck_num, g.get_adjacency()) #shows the adjacency_matrix
full_adjacency_matrix = PartiallyDirectedGraph.transform_adj_mat_to_full(g.get_adjacency())
#print(Truck_num, full_adjacency_matrix) #shows the full_adjacency_matrix
g = PartiallyDirectedGraph(full_adjacency_matrix, weights_sample, labels_sample)
g1= G1(g)

# Get the DCPP Algorithm to Solve a Postman tour
deg_list = [] # for storing vertices degrees(our degree = DegIn - degOut)

if not g1.have_euler_tour(deg_list):
    g1.graph.vs["deg"] = deg_list
    g2 = g1.add_penaltyTm_edges(3) #create G2 as mentioned in documentation
    gd, iNeg = g1.create_complete_bipart(deg_list, g2)
    if gd != None:
        ipenCnt =  g1.GraphBalancing(gd, g2)
        print("Number of penalty edges added: {}".format(ipenCnt))
        g1.FindEuler("unit")
else:
    #print("Graph already has Euler tour")
    Route = g1.FindEuler("unit")
```

DCPP for the whole unit network:

```
0unit -> 13SR53-11 -> 14SR53-5 -> 13SR53-11 -> 12US12-14/US53-14 -> 13SR53-11 -> 0unit -> 1US41-269 -> 6SR152-0 ->
7US20-7/SR152-2 -> 10US20-10 -> 11US20-13/US12-12 -> 12US12-14/US53-14 -> 11US20-13/US12-12 -> 10US20-10 -> 8US12-5
-> 10US20-10 -> 7US20-7/SR152-2 -> 8US12-5 -> 9US12-0 -> 8US12-5 -> 7US20-7/SR152-2 -> 6SR152-0 -> 1US41-269 -> 3US
41-274 -> 4US41-276 -> 5US41-278 -> 4US41-276 -> 3US41-274 -> 1US41-269 -> 2US41-263 -> 1US41-269 -> 0unit
```

Step 2

Step 2.1: Test all the sub routes and find whether certain edges need to be deleted:

```
which_sublists = {}
for k in range(0,len(sub_lists)):
    Connected_Cruise = []
    for i in range(0,len(sub_lists[k])-1):
        if i == len(sub_lists[k])-2:
            break
        if Road_Type[(sub_lists[k][i],sub_lists[k][i+1])] == 'Service':
            continue
        if Road_Type[(sub_lists[k][i],sub_lists[k][i+1])] == 'Cruise' and Road_Type[(sub_lists[k][i+1],sub_lists[k][
            Connected_Cruise.append(sub_lists[k][i])
            Connected_Cruise.append(sub_lists[k][i+1])
    which_sublists[k] = Connected_Cruise

#In calculate the sublist's length, get a new sublist and calculate new weight
#delete one of the edge in connected_cruise
#which_sublists, key is the sublists num, and value is the element that need to be deleted
for i in range(0,len(which_sublists)):
    if which_sublists[i] != []:
        for j in range(0,len(which_sublists[i])):
            sub_lists[i].remove(which_sublists[i][j])
```

Step 2.2: Calculate the total time spend for each sub routes (Since a time limit is considered).

```
#get the Cruise edge num and Service edge num of each sub_lists and calculate weight
Cruise_sublists = []
Service_sublists = []
Weight_sublists = []
for i in range(0,len(sub_lists)):
    Cruise_edge = []
    Service_edge = []
    Cruise_weight = 0
    Service_weight = 0
    for j in range(0,len(sub_lists[i])-1):
        if Road_Type[(sub_lists[i][j],sub_lists[i][j+1])] == 'Service':
            Service_edge.append((sub_lists[i][j],sub_lists[i][j+1]))
            Service_weight += Node_Weight[(sub_lists[i][j],sub_lists[i][j+1])]
        if Road_Type[(sub_lists[i][j],sub_lists[i][j+1])] == 'Cruise':
            Cruise_edge.append((sub_lists[i][j],sub_lists[i][j+1]))
            Cruise_weight += Node_Weight[(sub_lists[i][j],sub_lists[i][j+1])]
    Cruise_sublists.append(Cruise_edge)
    Service_sublists.append(Service_edge)
    Weight_sublists.append((Service_weight,Cruise_weight))
```

Step 2.3: Select the sub routes that satisfy the time limit constraint and add to candidate_route. Cruise_speed, Snow_removal_speed and Time can be changed flexibly based on real situations. Here we use Cruise_speed: 30mph, Snow_removal_speed: 15mph and Time <= 3 hr.

```
Cruise_speed = 30
Snow_removal_speed = Cruise_speed/2

candidate_route = []
sublists_length = []
for k in range(0,len(sub_lists)):
    if (Weight_sublists[k][0]/Snow_removal_speed) + (Weight_sublists[k][1]/Cruise_speed) <= 3:
        candidate_route.append(k)
    sublists_length.append((Weight_sublists[k][0]/Snow_removal_speed) + (Weight_sublists[k][1]/Cruise_speed))
# if there are exist route within time limit, get the one with least Cruise edges
#update Vertices
if Truck_num > 1:
    Vertices = Update_Vertices
```

Step 3

Based on Step2, we obtain the candidate routes.

Step 3.1: if there are candidate routes exist, then we will select the routes with least cruise mile (to minimize the deadhead miles).

Update the Total_DH, Assigned_Route.

```
Cruise_length = []
for i in range(0,len(candidate_route)):
    Cruise_length.append(len(Cruise_sublists[candidate_route[i]]))
min_value = min(Cruise_length) # get the least cruise length
assigned_route_index = Cruise_length.index(min_value)#get the index of the route that will be assigned to the tr
assigned_route = sub_lists[candidate_route[assigned_route_index]] # get the assigned route
Total_DH += Weight_sublists[candidate_route[assigned_route_index]][1] # add the cruise/deadhead miles into the t
#generate all the edges in the assigned route:
assigned_route_edges = []
for i in range(0,len(assigned_route)-1):
    assigned_route_edges.append((assigned_route[i],assigned_route[i+1]))

original_assigned_route = []
original_assigned_route_edge = []
for i in range(0,len(assigned_route)):
    original_assigned_route.append(Vertices[assigned_route[i]])
    original_assigned_route_edge.append(labels_sample[assigned_route[i]])
Assigned_Route.append(original_assigned_route_edge)


#change the service road into cruise road, update both service and cruise edges
for i in range(0,len(assigned_route_edges)):
    if assigned_route_edges[i] in New_Service:
        New_Service.remove(assigned_route_edges[i])
        New_Cruise.append(assigned_route_edges[i])
```

Change the service_road into cruise_road and update the Road_Type.

```
#update the road_type dictionary
Road_Type = {}
for i in range(len(New_Edges)):
    if New_Edges[i] in New_Service:
        Road_Type[New_Edges[i]] = 'Service'
    if New_Edges[i] in New_Cruise:
        Road_Type[New_Edges[i]] = 'Cruise'
```

Remove the nodes with in-degree and out-degree are all Cruise_roads based on the conditions.

```
#remove the node and edges with node in and out all equals to 'Cruise'
Node_removed = []
Node_removed_labels = []
Vertice_original_location = {}
for i in range(0,len(Node_Attribute)):
    if Node_Attribute[i][0] == Node_Attribute[i][1] == 'Cruise' and i!= 0:
        Node_removed_labels.append(labels_sample[i])
        Node_removed.append(Vertices[i])
        Node_removed_accumulate.append(Vertices[i])
```

Step 3.1: if there no candidate routes exist, then we will split the longest sub route into different loops and find the routes that satisfy the time limits.
Find all the simple loops in the longest sub route.

```python
min_value = min(sublists_length)
potential_route_index = sublists_length.index(min_value)# pick the sublist with the least length
potential_route = sub_lists[potential_route_index]
#find all the simple loops for the assigned_route start with unit and end with unit
#find all
#simple loops of assigned routes
partial_graph = {}
partial_vertices = list(set(potential_route))
partial_edges = []
for i in range(0,len(potential_route)-1):
    partial_edges.append((potential_route[i],potential_route[i+1]))
for i in range(0,len(partial_vertices)):
    successor_vertices = []
    for j in range(0,len(partial_edges)):
        if partial_vertices[i] == partial_edges[j][0]:
            successor_vertices.append(partial_edges[j][1])
    partial_graph[partial_vertices[i]] = successor_vertices

#get all the simple loops from 0 to 0 (unit)
cycles = [[node]+path  for node in partial_graph for path in dfs(partial_graph, node, node)]
simple_loops = []
for path in cycles:
    if path[0] == 0:
        simple_loops.append(path)
```

Delete the loops with only cruise edges in it.
Delete the loops that exceed the time limit.

```python
#get rid of the loops with only cruise edges in it
loop_drop = []
loop_Cruise = []
index_drop = []
for i in range(0,len(simple_loops)):
    loops_edge_type = []
    loops_cruise_weight = 0
    loops_service_weight = 0
    for j in range(0,len(simple_loops[i])-1):
        if Road_Type[(simple_loops[i][j],simple_loops[i][j+1])] == 'Cruise':
            loops_edge_type.append('Cruise')
            loops_cruise_weight += Node_Weight[(simple_loops[i][j],simple_loops[i][j+1])]
        if Road_Type[(simple_loops[i][j],simple_loops[i][j+1])] == 'Service':
            loops_edge_type.append('Service')
            loops_service_weight += Node_Weight[(simple_loops[i][j],simple_loops[i][j+1])]
    if len(set(loops_edge_type)) == 1 and list(set(loops_edge_type))[0] == 'Cruise':
        loop_drop.append(simple_loops[i])
        index_drop.append(i)
    if (loops_service_weight/Snow_removal_speed) + (loops_cruise_weight/Cruise_speed) > 3:
        loop_drop.append(simple_loops[i])
        index_drop.append(i)
    loop_Cruise.append(loops_cruise_weight)#get the cruise_weights of all the loops
loop_drop = [list(i) for i in set(map(tuple, loop_drop))]
index_drop = list(set(index_drop))
#loop_drop
for i in range(0,len(loop_drop)):
    simple_loops.remove(loop_drop[i])
#cruise_weight drop
for index in sorted(index_drop, reverse=True):
    del loop_Cruise[index]
simple_loops_length = []
for i in range(0,len(simple_loops)):
    simple_loops_length.append(len(simple_loops[i]))
```

Then select the sub route, update the Total_DH, Assigned_Route.
Similar with step 3.1, the vertices/nodes with in-degree links and out-degree links are all cruise roads are removed. However, some situations when vertices need to work as interconnect vertices need to be kept in the network. Thus:

```
for i in range(0,len(Node_removed)):
    sp = []
    Node_not_removed = []
    for j in range(0,len(Edges)):
        if Edges[j][0] == Node_removed[i]:
            sp.append(Edges[j][1])
    res = all(ele not in Node_removed for ele in sp)
    print(res)
    if res == False:
        sp = []
    if res == True and len(sp) == 2:
        Node_need_stay = Node_removed[i]
    Node_not_removed.append(Node_need_stay)
print(Node_not_removed)
```

Step 4: Repeat from step 1 ~ step 3 until all the service roads are covered in the assigned routes.
Output:

1. Number of Trucks: Turcks_num
2. Assigned routes: Assigned_Routes
3. Deadhead miles: Total_DH

APPENDIX H. SUPPLEMENTARY MATERIALS

Heavy Fleet and Facilities Optimization: Electronic Tool for Generating Optimal Snow Routes:
https://purr.purdue.edu/publications/4005/2

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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