Iowa DOT Office of Maintenance Snowplow Optimization

Final Report
February 2020

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16. Abstract

During winter road maintenance operations, the Iowa Department of Transportation (DOT) is responsible for servicing 24,000 lane miles of roadways, including Interstates, US highways, and Iowa roads. This project focused on operations for District 3, located in northwest Iowa, which services about 4,000 lane miles from 20 depots.

Two optimization problems were solved to determine the optimal snowplow routes in this district. The first problem was to design winter maintenance truck routes for single depots under the district's current responsibility maps. The second problem was to design routes for multiple depots with intermediate facilities, with the service boundaries among the depots able to be redesigned. Both optimization problems were solved as capacitated arc routing problems (CARPs) using a memetic algorithm (MA) and considering the constraints of road segment service cycle time, heterogeneous vehicle capacities, fleet size, road-vehicle dependency, and work duration.

The results from solving the single-depot optimization problem show a 13.2% reduction in deadhead distance compared to current operations. The deadhead savings could be even larger because while the optimized routes strictly satisfy all constraints, the current operations might not. For the multiple-depot optimization problem, due to the network structure and current depot locations, the difference between the optimized routes based on a multiple-depot configuration and those based on a single-depot configuration is insignificant.

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IOWA DOT OFFICE OF MAINTENANCE SNOWPLOW OPTIMIZATION

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EXECUTIVE SUMMARY

For winter road maintenance, a fleet of snowplow trucks is operated by government agencies to remove snow and ice on roadways and spread materials for anti-icing, de-icing, or increasing friction. Winter road maintenance is essential for providing safe and efficient service for road users (Usman et al. 2010). It is also expensive due to the high cost of equipment, crews, and materials.

According to a recent survey by the American Association of State Highway and Transportation Officials (AASHTO), 23 reporting states spent approximately $1.131 billion from October 2014 to mid-April 2015 to pretreat, plow, and spread chemicals and other materials on roadways (AASHTO 2015). Optimizing winter road maintenance operations could result in significant cost savings, improved safety and mobility, and reduced environmental and social impacts (Salazar-Aguilar et al. 2012).

The Iowa Department of Transportation (DOT) is responsible for servicing 24,000 lane miles of roadways, including Interstates, US highways, and Iowa roads. This project focused on District 3, located in northwest Iowa. District 3 has 20 depots and services about 4,000 lane miles.

Two optimization problems were solved to determine the optimal snowplow routes in this district. The first problem focused on designing routes for winter maintenance trucks for single depots under the current responsibility map. The second problem focused on designing routes for multiple depots with intermediate facilities, with the depot service boundaries among the multiple depots able to be redesigned. Both optimization problems were solved as capacitated arc routing problems (CARPs) using a memetic algorithm (MA) and considering the constraints of road segment service cycle time, heterogeneous vehicle capacities, fleet size, road-vehicle dependency, and work duration.

The results from solving the single-depot optimization problem show a 13.2% reduction in deadhead distance compared to current operations. The deadhead savings could be even larger because while the optimized routes strictly satisfy all constraints, the current operations might not. For the multiple-depot optimization problem, due to the network structure and current depot locations, the difference between the optimized routes based on a multiple-depot configuration and those based on a single-depot configuration is insignificant.

1. INTRODUCTION

Winter road maintenance activities include removal of snow and ice from roadways and spreading materials (e.g., salt and sand) to increase friction and provide anti-icing and de-icing. The Iowa Department of Transportation (DOT) is responsible for servicing 24,000 lane miles of roadways, including Interstates, highways, and Iowa roads.

This project focused on District 3, located in northwest Iowa. District 3 has 20 depots and services about 4,000 lane miles. Each depot has a fleet of trucks. Two types of maintenance trucks are used in Iowa, medium duty single trucks and heavy duty tandem trucks, each with different capacities. The roadways maintained by the district are categorized into different levels of service. Road segments with higher levels should be serviced more frequently than lower level roads. Snowplows generally push snow towards the right shoulder. However, on divided roadways with a median that is wide enough to store snow, trucks are able to push snow towards the median. The current routes for District 3 are designed based on staff knowledge and past experience.

To minimize the deadhead distance and meet service expectations, an optimization-based approach was used for this project. The first task was to design optimal routes under current configurations. That is, the snowplow routes were optimized while the depot responsibility areas and the fleets managed by the various depots remained unchanged. The second task was to design the depot responsibility areas and the routes simultaneously, allowing trucks to reload at other depots or reload stations than their own.

The report is organized as follows. Chapter 2 presents a brief literature review. The data used in this project are described in Chapter 3, followed by a description of the data preparation in Chapter 4. The practical constraints are discussed in Chapter 5. The formulation and solution algorithms are presented in Chapter 6. Chapter 7 presents the results and discussion. Conclusions and recommendations are summarized in Chapter 8.

2. LITERATURE REVIEW

A snowplow route optimization problem can be formulated as a capacitated arc routing problem (CARP). The CARP considers an undirected graph G=(V,E), where V represents the set of vertices and E represents the set of undirected edges that can be traversed in both directions. Each edge is associated with a demand (in this case, materials) and a cost (in this case, time or distance). The objective is to minimize the total travel cost of all trucks. All edges must be serviced by a fleet of vehicles, each vehicle with a predefined capacity of Q. All vehicles must start and end at the same depot.

When solving winter road maintenance routing problems, specific constraints concerning real-world operations have been considered in the literature. Haghani and Qiao (2001) considered time window, capacity, and route duration constraints. A heuristic algorithm was proposed to solve the problem. Later, Haghani and Qiao (2002) added the service continuity constraint, where a route can only consist of service arcs with possible deadhead from the depot to the beginning of the first service arc and from the end node of the last service arc to the depot. The problem was formulated as a capacitated minimum spanning tree and solved by the linear approximation of the problem.

Tagmouti et al. (2007) proposed a time-dependent service cost model. The model considered that the application of salt on road segments should be neither too early nor too late. This problem was formulated as a piecewise linear service cost function. The problem was solved by a column generation approach. Later, the same authors applied the variable neighborhood descent (VND) algorithm (Tagmouti et al. 2010) to solve the problem.

Perrier et al. (2008a) considered road hierarchical constraints. Specifically, road segments that are higher in the hierarchy must be serviced before road segments that are lower in the hierarchy. Different service and deadhead speeds, road-vehicle dependencies, load balances, and turn restrictions were also included in the formulation. A parallel construction heuristic and a cluster-first route-second heuristic were proposed to solve the problem.

Salazar-Aguilar et al. (2012) introduced the synchronized arc routing problem, where a multilane street must be plowed simultaneously by an echelon of vehicles. The problem was solved by the adaptive large neighborhood search algorithm.

Dussault et al. (2013) considered the fact that plowing uphill takes a much longer time than plowing downhill and that sometimes it is impossible to plow uphill. A variant of the windy postman problem was formulated and solved using a local search algorithm.

Hajibabai et al. (2014) formulated the snowplow routing problem as a vehicle routing problem considering plowing priorities, resource replenishment, turning delay, and U-turn allowance. The problem was solved by a constructive heuristic and local search algorithms. Later, some of these authors solved a stochastic version of the problem that considered uncertain service demand and service disruptions (Hajibabai and Ouyang 2016).

Kinable et al. (2016) considered heterogeneous capacity, fuel and salt limits, and intermediate facilities. The authors used an integer program, a constrained program, and a two-phase heuristic algorithm to solve the problem. They concluded that the heuristic algorithm performs best in terms of computation time and solution quality.

Quirion-Blais et al. (2017) introduced a constraint that requires streets to be plowed and spread sequentially. The authors also took into consideration turning restrictions, the various speeds of different truck types, road class hierarchy and operations, and road-vehicle dependency. The problem was solved using the adaptive large neighborhood search algorithm.

Gundersen et al. (2017) proposed a mixed integer model that considered road class hierarchy and road-vehicle dependency as constraints. The model was solved using a mixed integer program solver to find exact solutions.

The winter road maintenance routing problem becomes more complicated when the service boundaries can be redesigned. Assigning road segment service responsibilities to depots is considered to be a sector design problem. A simultaneous solution for the responsibility assignment and routing problems is considered a multiple-depot capacitated arc routing problem.

Muyldermans et al. (2002) introduced the salt spreading districting problem. Road segments were combined into small cycles and then assigned to depots heuristically. Later, Muyldermans et al. (2003) developed an integer programming model that minimizes the lower bound of the fleet size.

Perrier et al. (2008b) proposed using the sector design problem for snow disposal. The problem involved assigning disposal sites and road segments to each sector. The problem was solved using a two-phase approach. In particular, two integer programs were solved, one that assigned disposal sites to sector and one that assigned road segments to sector.

Jang et al. (2010) considered the problems of depot allocation, sector design, route design, fleet configuration, and vehicle scheduling as a whole. A heuristic approach iteratively solved these subproblems from higher to lower level decisions until all constraints were met. Road segment service frequency and vehicle capacity were considered in the formulation.

3. DATA DESCRIPTION

Area of Responsibility Maps

Table 3.1 shows the 20 depots in the service region of Iowa District 3, with each depot's responsibility region color-coded and labeled.

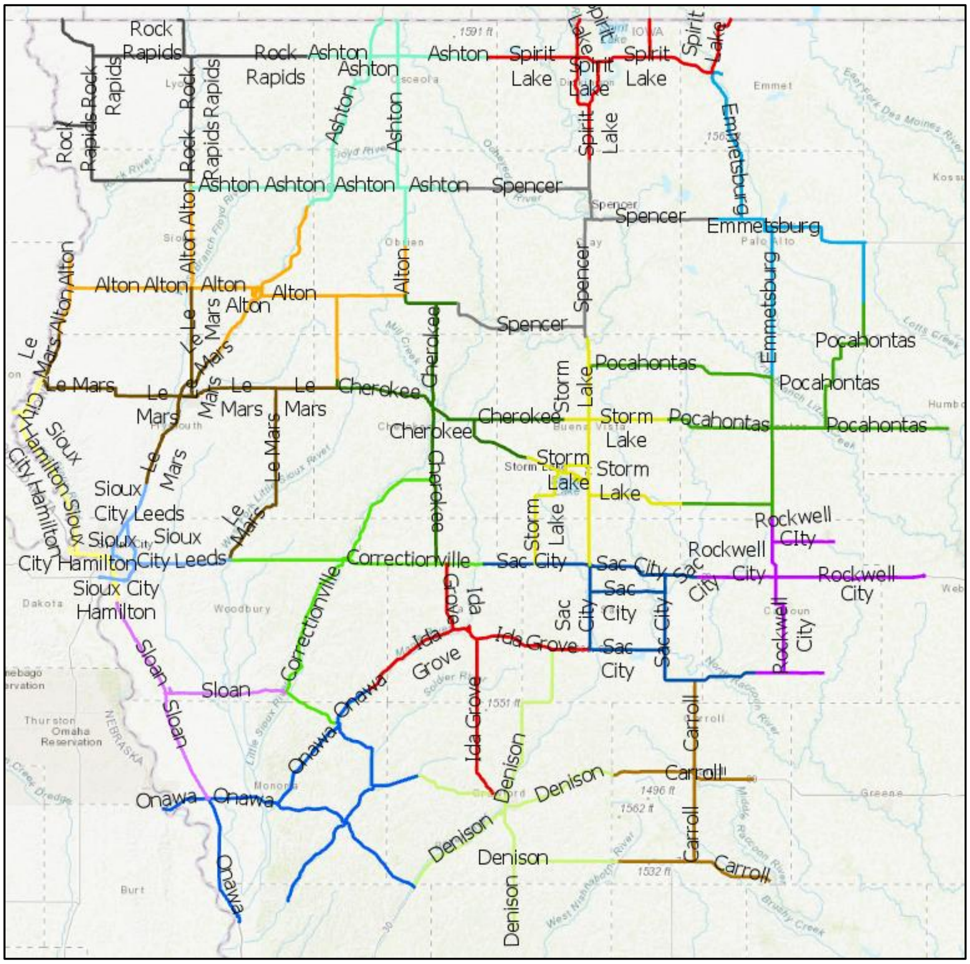


Figure 3.1. Service region of Iowa District 3, with 20 depots color-coded and labeled

These depots are separated into six sectors, as shown in Figure 3.2.

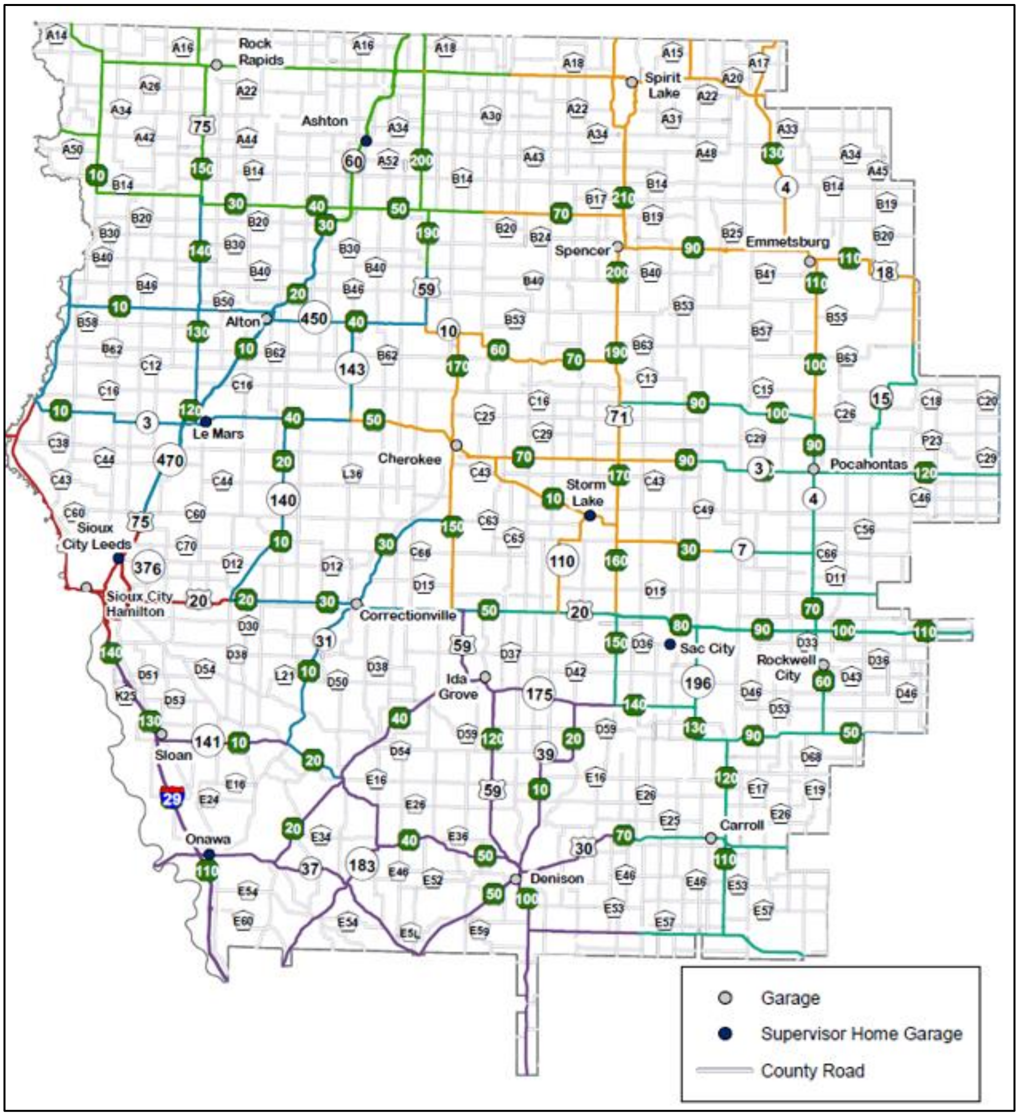


Figure 3.2. Sectors of District 3

The “Garage” and “Supervisor Home Garage” nodes represent the locations of the depots.

The current snowplow routes were provided by District 3. Figure 3.3 shows an example of the current routes originating from the Storm Lake depot.

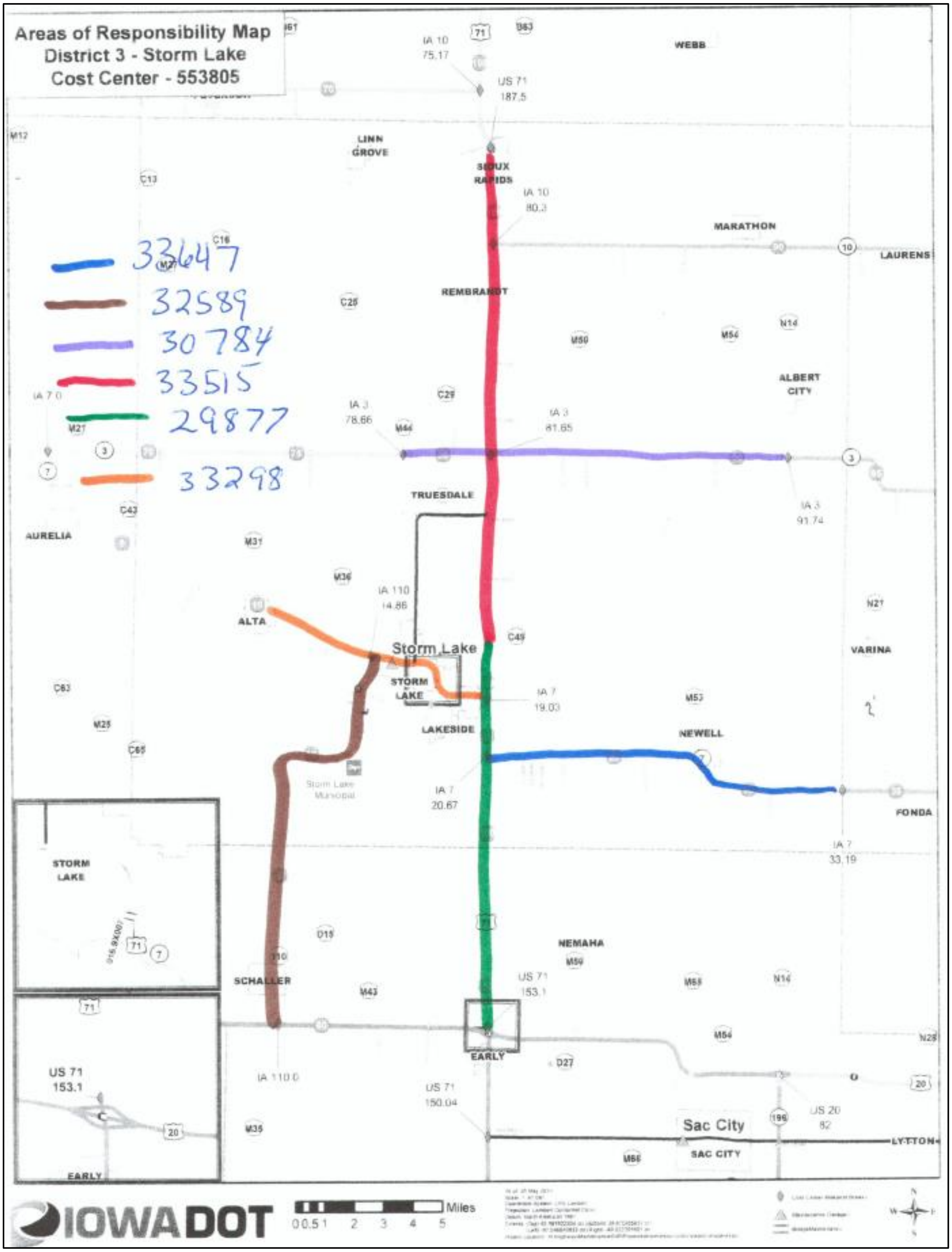


Figure 3.3. Area of responsibility map for the Storm Lake depot, color-coded with current routes

In Figure 3.3, the boundaries of the responsibility area are labeled by the mile markers. Each route is highlighted with a unique color. The number next to each color in the legend is the truck ID for that route.

Weather Data

Weather data were used to determine the snow dates and storm severities. Two winter seasons, from October 1, 2016 to April 1, 2017 and from October 1, 2017 to April 1, 2018, were considered in this study. The weather data were collected from three sources: the National Weather Service Cooperative Observer Program (NWS COOP), the Automated Surface Observing System (ASOS), and the Roadway Weather Information System (RWIS). NWS COOP reports daily snowfall and daily snow depth. This was the primary data source for determining storm severity. In this study, 0 to 4 inches of snow is considered to be a light storm, 5 to 8 inches is considered a moderate storm, and 9 inches and above is considered a severe storm. ASOS reports precipitation types and rates, which are updated every 5 minutes. However, the precipitation rates are measured as liquid precipitation (rain or melted snow). RWIS reports roadway surface conditions, such as “dry,” “trace moisture,” “wet,” “chemically wet,” “frost,” “ice watch,” and “ice warning,” which are recorded at 10-minute intervals. Since RWIS measures roadway surface conditions and truck plowing or spreading activities change the roadway surface conditions, data from this source might not accurately represent the storm conditions. Therefore, ASOS and RWIS data were used to verify the storm severity determined by NWS COOP. Figure 3.4, Figure 3.5, and Figure 3.6 show the locations of NWS COOP, ASOS, and RWIS stations in Iowa, respectively. The red dots on each map indicate the station locations, and the black square indicates the region of District 3.

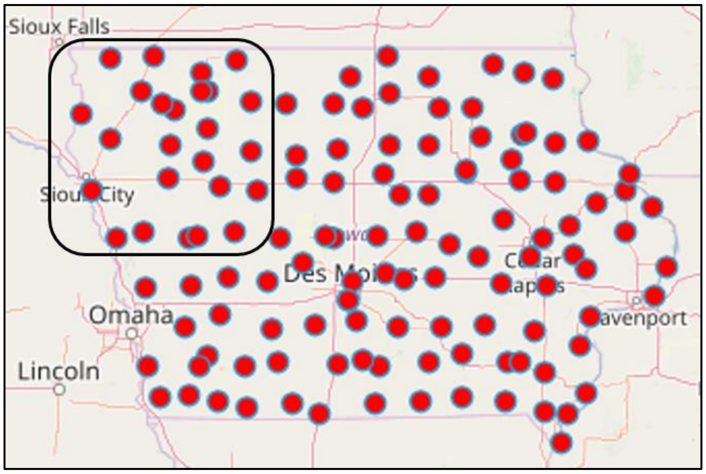


Figure 3.4. NWS COOP stations

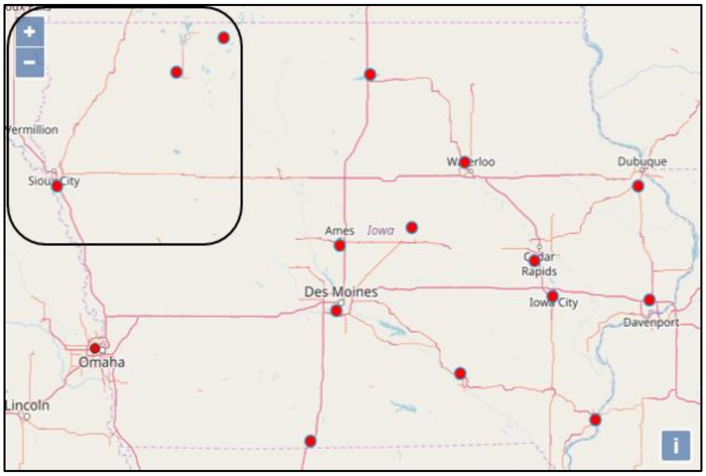


Figure 3.5. ASOS stations

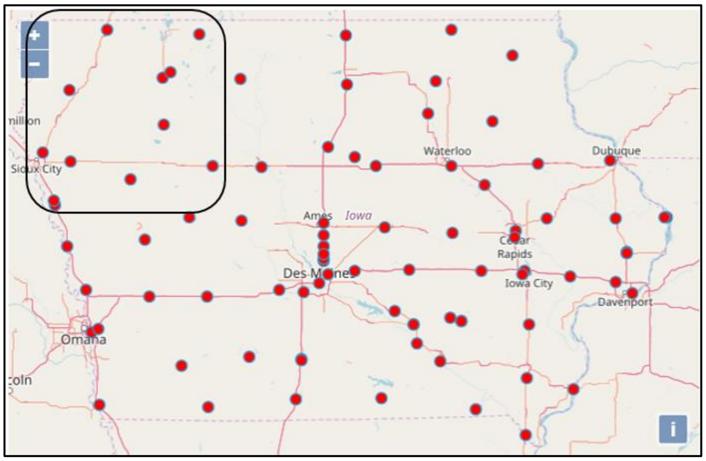
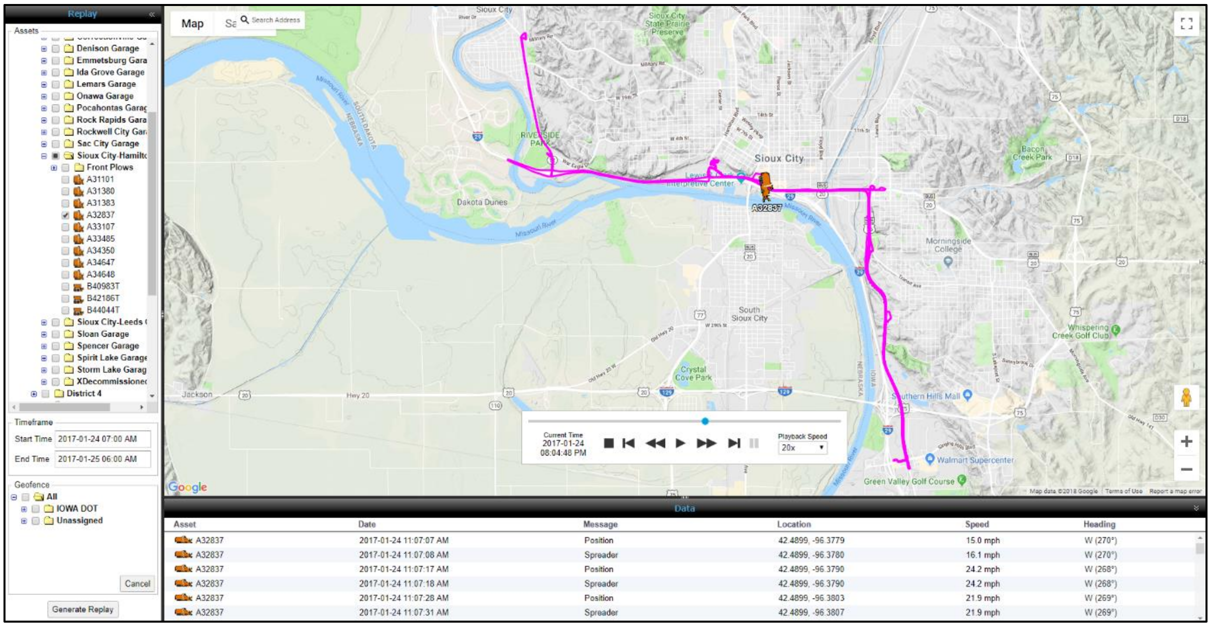


Figure 3.6. RWIS stations

Maintenance Truck Operation Data

An automatic vehicle location (AVL) system records the operational data of each maintenance truck. The information collected includes the GPS location, plow position, spreading rate and type, truck speed and direction, truck ID, and timestamp. The data were retrieved from the SkyHawk data portal. The Iowa DOT collects the AVL data at a high resolution (less than 30-second intervals). Figure 3.7 illustrates the user interface for the SkyHawk system. In this example, the truck tracking tool shows an urban route in Sioux City.



Timeframe
Start Time 2017-01-24 07:00 AM
End Time 2017-01-25 06:00 AM

Current Time 2017-01-24 08:04:48 PM
Playback Speed 20x

Asset	Date	Message	Location	Speed	Heading
A32837	2017-01-24 11:07:07 AM	Position	42.4899, -96.3779	15.0 mph	W (270°)
A32837	2017-01-24 11:07:08 AM	Spreader	42.4899, -96.3780	16.1 mph	W (270°)
A32837	2017-01-24 11:07:17 AM	Position	42.4899, -96.3790	24.2 mph	W (268°)
A32837	2017-01-24 11:07:18 AM	Spreader	42.4899, -96.3790	24.2 mph	W (268°)
A32837	2017-01-24 11:07:28 AM	Position	42.4899, -96.3803	21.9 mph	W (269°)
A32837	2017-01-24 11:07:31 AM	Spreader	42.4899, -96.3807	21.9 mph	W (269°)

Figure 3.7. SkyHawk system showing an example truck route in Sioux City

On the morning of December 19, 2017, District 3 carried out a test run for this study to illustrate the routes included in its AVL system. The maintenance trucks traversed their current routes empty but had their spreaders on as if they were spreading material. An example of the test run routes for the Storm Lake depot is shown in Figure 3.8.

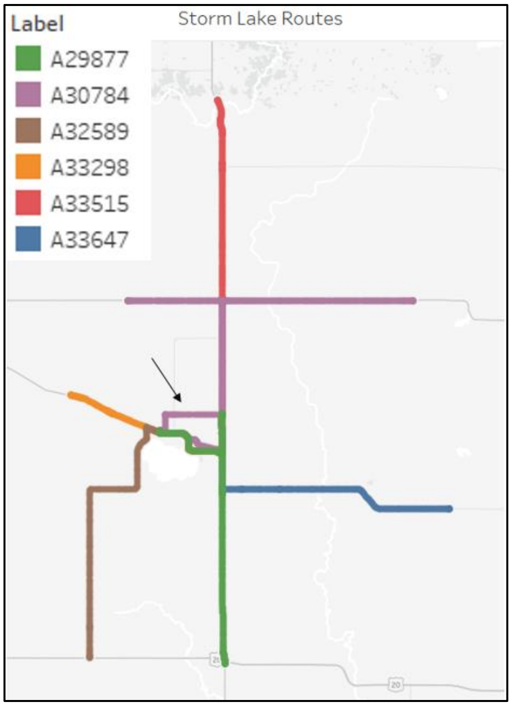


Figure 3.8. AVL route map for the Storm Lake depot

The total travel distance for each route was calculated based on the AVL data, and the turnaround locations were found by carefully scanning the vehicle trajectory data. Figure 3.9 illustrates an example of a U-turn location.

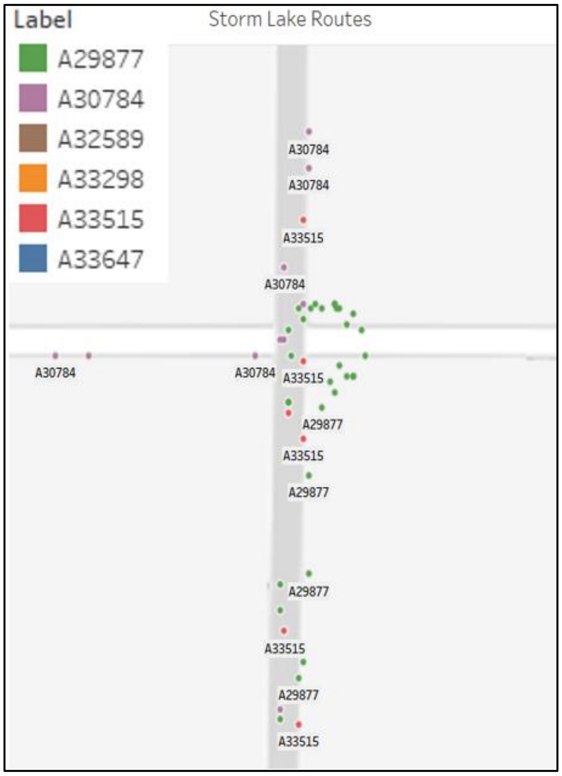


Figure 3.9. Example of a U-turn location as indicated by AVL data

Traffic Network

The Roadway Asset Management System (RAMS) was used to build the basic traffic network for this study. The RAMS database stores many types of roadway information in separate data layers. In particular, six data layers were utilized in this study, including linear referencing system (LRS) network, reference posts, facility type, and three maintenance-related layers: cost center, district, and service level. The next chapter will introduce the consolidation and editing methods used to process the data layers.

LRS Network and Reference Posts

The LRS organizes several types of roadway data into a single network by relating the data's linear locations. The reference posts layer, a subsystem of the LRS network, contains the mile markers along the roadways. This layer allows multiple locations of interest to be compared by linearly measuring each location from a reference post.

Facility Type

Six roadway types were considered in this study: one-way, two-way, ramp, non-mainline, non-inventory direction, and planned unbuilt. These are shown in Table 3.1.

Table 3.1. Facility types and codes

Facility Type	Code
ONE-WAY	1
TWO-WAY	2
RAMP	4
NON-MAINLINE*	5
NON-INVENTORY DIRECTION	6
PLANNED UNBUILT*	7

* Not considered in this study

One-way roadways represent the northbound or eastbound directions of divided roadways, while non-inventory direction roadways represent the southbound or westbound directions of divided roadways. Two-way roadways represent undivided roadways. Non-mainline and planned unbuilt roadways were not included in the analysis.

Maintenance-Related Data

The data layers for cost center, district, and service level indicate which garage and district a road segment belongs to and the maintenance service level, respectively. Each garage is assigned a unique six-digit cost center code. Road segments are divided into four categories based on service priority. Service Level A indicates a high service priority and is used for roadways that experience heavy traffic, such as Interstates. Service Level B represents highly traveled roads that are given a medium-level priority, such as US highways. Service Level C represents low travel demand roads, such as Iowa highways.

4. DATA PREPARATION

Estimating the Performance of Current Operations

Travel Distance

The AVL data collected during the test run on December 19, 2017 were used to calculate the total travel distance of each maintenance route in District 3. The location data from the AVL system were first snapped to the nearest roadways using the snapping tool in ArcGIS.

The distance traveled between consecutive timestamps was then calculated based on the real-world road network. The total distance traveled by each truck was computed as the sum of the distances traversed during all of the time intervals.

Truck Speed and Spreading Rate

Maintenance trucks, when plowing or spreading material, traverse road segments at a low speed. Typically, the service speed is around 20 to 35 mph and can be slower if the snow is heavy. When deadheading, maintenance trucks tend to travel at a higher speed. However, depending on the weather and road conditions, the deadhead speed could still be much lower than the speed limit. The spreading rate is usually set based on the precipitation type and surface temperature. Table 4.1 shows the salt application guidelines provided by Iowa DOT.

Table 4.1. Salt application rate guidelines for Iowa DOT (in pounds of salt)

Assumptions	Conditions	Surface Temperature (°F)					
		33–30	29–27	26–24	23–21	20–18	17–15
Prewetted salt, 12-foot lane, 2-hour run	Heavy frost, light snow	50	75	95	120	140	170
	Medium snow (1/2 inch/hour)	75	100	120	145	165	200
	Heavy snow (1 inch/hour)	100	140	185	250	300	350
	Freezing rain, drizzle, sleet	140	185	250	300	350	400
Prewetted salt, 2-foot lane, 3-hour run	Heavy frost, light snow	75	115	145	180	210	255
	Medium snow (1/2 inch/hour)	115	150	180	220	250	300
	Heavy snow (1 inch/hour)	150	210	275	375	450	525
	Freezing rain, drizzle, sleet	210	275	375	450	525	600

This section examines the service speeds, deadhead speeds, and spreading rates for the District 3 routes based on AVL data.

AVL data from the following dates were used to examine the truck speeds and spreading rates: January 24 and 25, 2017, January 22 and 23, 2018, and March 6, 2018. On these dates, light, medium, or heavy storms occurred. Furthermore, the AVL data on these dates cover all road types, including Interstates, US highways, and Iowa highways. Four routes were retrieved for each storm magnitude and road type combination. Thus, AVL data from 36 routes were extracted. These routes were classified as either urban or rural.

Figure 4.1 illustrates the service speeds for the 36 routes. The left boxplot shows the distribution of speeds in urban areas, while the right boxplot shows the distribution of speeds in rural areas.

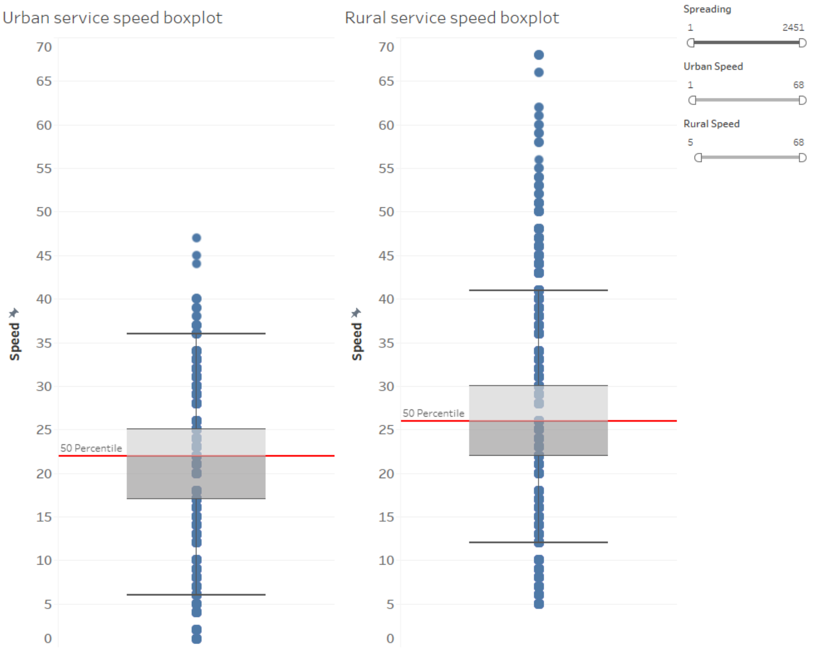


Figure 4.1. Service speed boxplot: urban (left) versus rural (right) routes

The service speeds were identified based on the set spread rate. When the spreading rate was greater than 0, the snowplow truck was considered to be in service. Since the AVL system recorded speeds approximately every 10 to 30 seconds, when a snowplow truck is traveling at a very low speed or is idling the AVL system collects many data points to skew the speed distribution. Therefore, records showing a speed of 0 mph in urban areas or less than 5 mph in rural areas were removed. In rural areas, maintenance trucks usually service the additional turning lanes of intersections by making U-turns, resulting in low traveling speeds. A 5-mph service and deadhead speed was assumed for trucks traveling on the road segments of rural intersections. The median speeds were used as the service speeds when designing the routes. The median speeds were 22 mph for urban areas and 26 mph for rural areas. Figure 4.2 illustrates the deadhead speeds for the 36 routes.

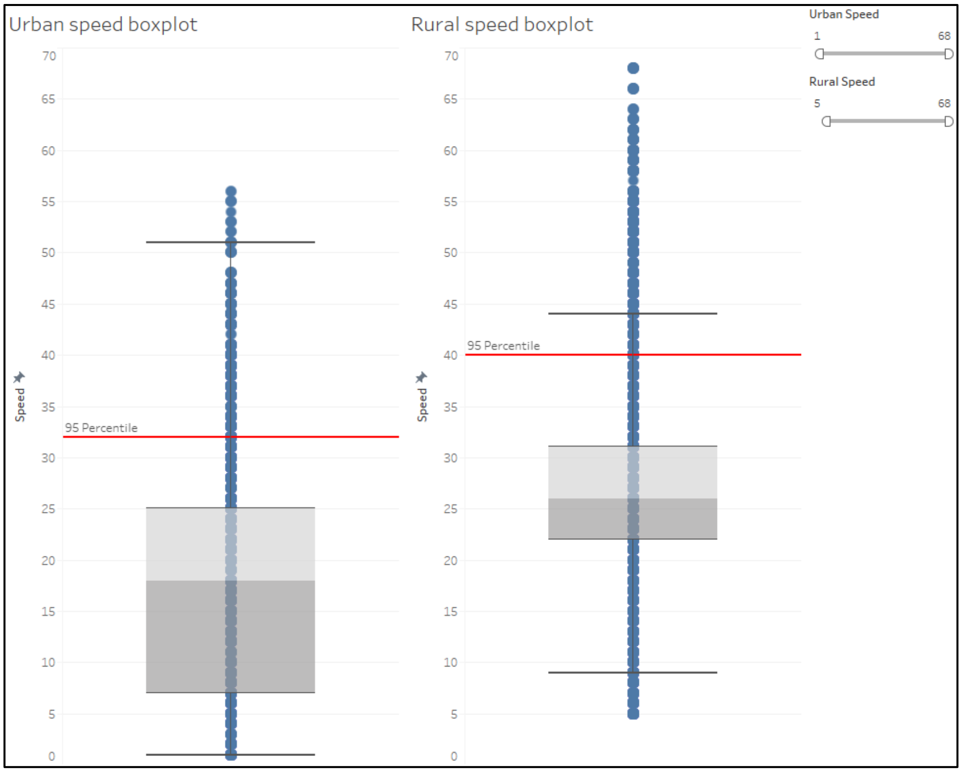


Figure 4.2. Deadhead speed boxplot: urban (left) versus rural (right) routes

Since it is possible for snowplow trucks to plow without spreading material and the "plow up/down" data in the AVL records are not reliable, the deadhead speed was estimated using the 95th percentile of all of the speed records. Accordingly, the urban deadhead speed was set at 32 mph and the rural deadhead speed was set at 40 mph.

Figure 4.3 shows boxplots of the spreading rates. In the left graph, the spreading rates are categorized by road type: Interstate, US highway, and Iowa highway. In the right graph, the spreading rates are categorized by storm magnitude: light (0 to 4 inches of snow), moderate (5 to 8 inches of snow), and heavy (9 or more inches of snow).

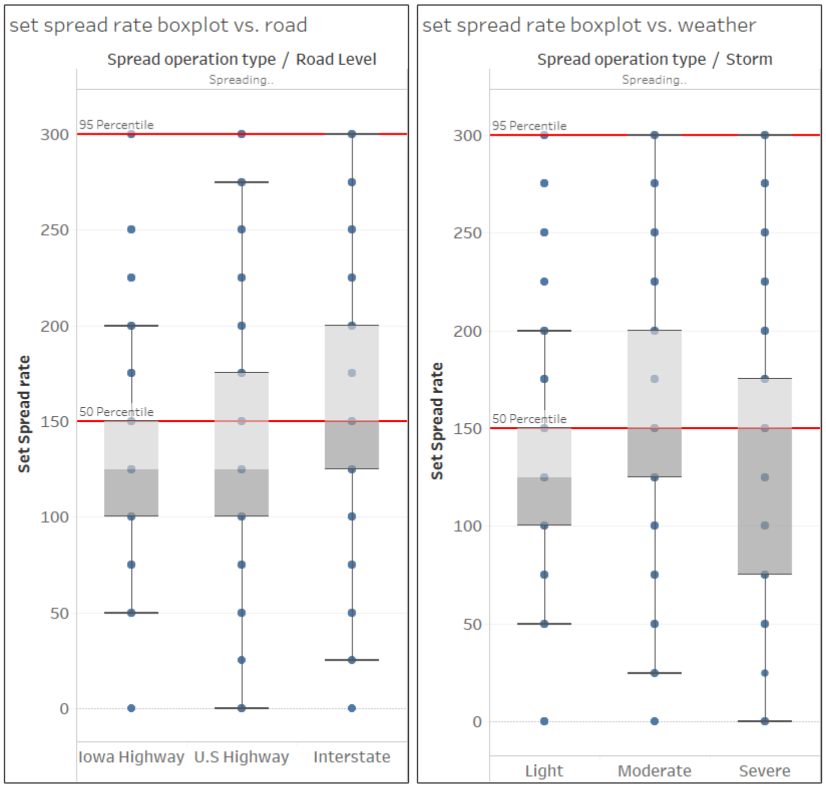


Figure 4.3. Spreading rate versus roadway type (left) and storm magnitude (right)

The figure shows that the maximum set spread rate is 300 lbs per lane mile and the median is 150 lbs per lane mile. More material is spread on Interstates than US highways and Iowa roads. In addition, more severe storms correspond to more variation in the spreading rates.

Building the Traffic Network

The traffic network used in this study was based on the roadway layers from RAMS. However, the following issues needed to be addressed.

First, undivided roadways in RAMS are represented by one polyline for the inventory direction (north or east), but there is no polyline to represent the non-inventory direction. While the inventory polyline record includes the total number of lanes in both directions, it was crucial for the routing algorithm to know the number of lanes in each direction.

Second, the traffic network needed to include some non-service road segments, such as the local roads that connect the depot to the service road segments and the turnaround locations. To separate the service road segments from the non-service road segments, an attribute called "Service Flag" was added to the database.

Third, the data needed careful inspection for missing and erroneous data records. The estimated service and deadhead speeds for urban and rural areas were also attached to the corresponding road segments.

The detailed procedure that was used to manually fix the network is presented in Appendix A. After the network was built, the shapefile was exported. Using the NetworkX library in Python, the shapefile was converted to edge lists and saved as a series of comma-separated value (CSV) files. Table 4.2 summarizes the network attributes, including the number of nodes and number of arcs.

Table 4.2. Network attributes

Depot	# of Nodes	Arcs Req.	Arcs Not Req.	Depot	# of Nodes	Arcs Req.	Arcs Not Req.
Alton	253	489	131	Pocahontas	81	96	14
Ashton	166	320	66	Rock Rapids	64	89	11
Carroll	128	211	53	Rockwell City	87	142	35
Cherokee	122	174	43	Sac City	85	106	37
Correctionville	62	93	13	Sioux City Hamilton	208	418	141
Denison	112	151	34	Sioux City Leeds	253	525	119
Emmetsburg	82	101	30	Sloan	49	78	12
Ida Grove	53	57	17	Spencer	65	91	18
Le Mars	134	219	44	Spirit Lake	83	134	23
Onawa	117	138	33	Storm Lake	97	116	41

The “Arcs Req.” column indicates the number of arcs that require service, whereas the “Arcs Not Req.” column represents the number of non-service arcs.

5. PRACTICAL CONSTRAINTS

Maintenance Trucks

Maintenance trucks are capable of plowing and spreading materials simultaneously or separately. Figure 5.1 shows a typical snowplow truck used by the Iowa DOT. It has a front plow, a wing plow that helps clean wider roadways, an underbody scraper, a preset tank, and a dump body.

Iowa DOT

Figure 5.1. Winter road maintenance truck

The Iowa DOT has three types of snowplow trucks. A single-axle truck has a capacity of 12,000 lbs for solid material. A tandem-axle truck has a capacity of 16,000 lbs. A tow-plow is a steerable trailer-mounted component that is pulled behind a truck. It is equipped with a snowplow and a tank for spreading materials. A tow-plow can service two lanes simultaneously. In District 3, tow-plows are only used in Sioux City Leeds and Sioux City Hamilton.

Practical Constraints

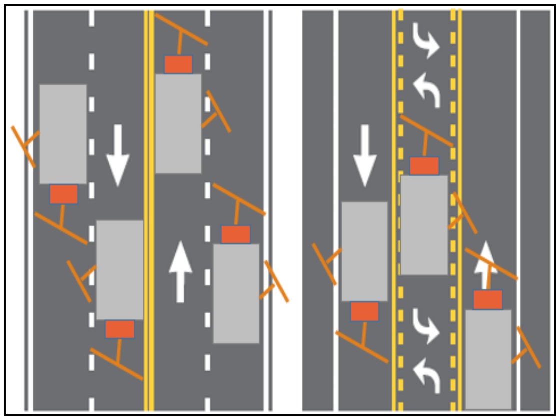
Four types of practical constraints were considered in this project. The first was the capacity of the maintenance trucks, that is, 12,000 lbs for single-axle trucks and 16,000 for tandem-axle trucks.

The second was the fleet size. Each depot has a limited number of snowplow trucks of each type. The truck inventory is shown in Table 5.1.

Table 5.1. Truck inventory of District 3 depots

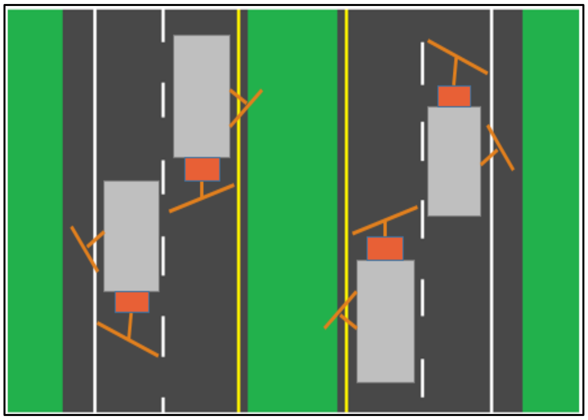
Garage name	Medium duty (single-axle trucks)	Heavy duty (tandem-axle trucks)	Total
Alton	4	5	9
Ashton	7	8	15
Carroll	3	2	5
Cherokee	5	2	7
Correctionville	3	3	6
Denison	5	3	8
Emmetsburg	2	3	5
Ida Grove	2	2	4
Le Mars	2	7	9
Onawa	3	6	9
Pocahontas	3	4	7
Rock Rapids	2	3	5
Rockwell City	2	5	7
Sac City	2	4	6
Sioux City-Hamilton	6	3	9
Sioux City-Leeds	3	4	7
Sloan	2	4	6
Spencer	1	5	6
Spirit Lake	5	4	9
Storm Lake	3	4	7

The third constraint was road-truck dependency. In Iowa, all trucks can be equipped with either a left-wing plow or a right-wing plow. Road-truck dependency arises when snow and ice must be pushed to one side, either to the median or to the shoulder. Figure 5.2 and Figure 5.3 illustrate the snowplow setup when plowing undivided and divided multilane highways, respectively.



Background roadway diagram from Knapp et al. 2014, FHWA

Figure 5.2. Undivided multilane road, all trucks with right-wing plows



Background roadway diagram from Knapp et al. 2014, FHWA

Figure 5.3. Divided multilane road, with an inner-lane truck with a left-wing plow and an outer-lane truck with a right-wing plow

Roadways that do not have a wide median need to be serviced by right-wing plow trucks. But for roadways with a median that is wide enough to hold snow, the snow on the inner lane can be pushed to the left.

The fourth constraint was the road segment cycle time, which corresponds to the service frequency of the road level. Some urban roads are serviced every 1 hour. Interstates are serviced every 1.25 hours. Most US highways are serviced every 2 hours. Most Iowa roads are serviced every 2.5 hours. Table 5.2 summarizes the service cycle times of different road levels.

Table 5.2. Service cycle times

Index	Road Level	Cycle Time (Hours)
Metro	Urban Area	1
A	Interstate	1.25
B	US Highway	2
C	Iowa Road	2.5

6. MATHEMATICAL MODELS

In this chapter, mathematical models are presented to solve two problems. The first problem is formulated as a single-depot winter maintenance routing problem (SDWMRP). The second problem is formulated as a multiple-depot winter maintenance routing problem with reload/intermediate facilities (MDWMRP).

Single-Depot Winter Maintenance Routing Problem

The single-depot winter maintenance routing problem is solved for each depot, where there is only one depot and the maintenance truck must start and end at the depot. The demand road segments must be serviced, with all of the constraints stated in Chapter 5 satisfied. The objective of the solution is to minimize the total travel distance.

The following notation is used:

$G = (V, A)$: A connected directed graph, where V is the node set and A is the arc set.

A_R: The set of service arcs.

v_0: The depot node.

c_{ij}: The cost of traversing arc (i, j) in G.

q_{ij}: The demand of arc (i, j). If $q_{ij} > 0$, the arc needs to be serviced; if $q_{ij} = 0$, the arc is a non-service demand arc.

H_1 and H_2: The set of single-axle and tandem-axle trucks, respectively.

m_1 and m_2: The fleet size of the two types of vehicles, respectively.

Q_h: The capacity of a truck, $h \in H_1 \cup H_2$.

f_{ij}: The service cycle time of arc (i, j).

f_k: The route cycle time for route k.

$\mathcal{F}$: The set of service cycle times.

t'_{ij}: The service time on arc (i, j).

t_{ij}: The deadhead time on arc (i, j).

r_{ij}: The arc plow direction on arc (i, j). $r_{ij} = 1$ represents a right-wing plow, and $r_{ij} = -1$ represents a left-wing plow.

The decision variables are as follows:

$$x_{ij}^{k} = \begin{cases} 1 & if\ route\ k\ service\ (i,j)\ from\ i\ to\ j \\ 0 & otherwise \end{cases}$$

$$y_{ij}^{k} = \begin{cases} 1 & if\ route\ k\ traverse\ (i,j)\ from\ i\ to\ j \\ 0 & otherwise \end{cases}$$

$$u_{kh} = \begin{cases} 1 & if\ the\ hth\ truck\ services\ route\ k \\ 0 & otherwise \end{cases}$$

$f_k \in \mathcal{F}$

The formulation is shown as follows:

$$\sum_{(i,j)\in A, k\in K} c_{ij}(x_{ij}^{k} + y_{ij}^{k}) \tag{1}$$

$$\sum_{(i,j)\in A}(x_{ij}^{k} + y_{ij}^{k}) - \sum_{(j,i)\in A}(x_{ji}^{k} + y_{ji}^{k}) = 0 \qquad \forall k \in K, i \in V \tag{2}$$

$$\sum_{(0,i)\in A}(x_{0i}^{k} + y_{0i}^{k}) = 1 \qquad \forall k \in K, i \in V \tag{3}$$

$$\sum_{(i,0)\in A}(x_{i0}^{k} + y_{i0}^{k}) = 1 \qquad \forall k \in K, i \in V \tag{4}$$

$$\sum_{\forall k\in K} x_{ij}^{k} = 1 \qquad \forall (i,j) \in A_R \tag{5}$$

$$\sum_{(i,j)\in A} q_{ij}\, x_{ij}^{k} \leq \sum_{h\in H_1\cup H_2} Q_h u_{kh} \qquad \forall k \in K \tag{6}$$

$$\sum_{h\in H_1\cup H_2} u_{kh} = 1 \qquad \forall k \in K \tag{7}$$

$$\sum_{k\in K} u_{kh} \leq 1 \qquad \forall h \in H_1 \cup H_2 \tag{8}$$

$$\sum_{k\in K, h\in H_1} u_{kh} \leq m_1 \tag{9}$$

$$\sum_{k\in K, h\in H_2} u_{kh} \leq m_2 \tag{10}$$

$$f_k \le f_{ij} x_{ij}^k \qquad \forall k \in K, (i,j) \in A_R \tag{11}$$

$$\sum_{(i,j)\in A} (x_{ij}^k t'_{ij} + y_{ij}^k t_{ij}) \le f_k \qquad \forall k \in K (12)(12)$$

$$x_{ij}^k r_{ij} = x_{i'j'}^k r_{i'j'} \qquad \forall k \in K, (i,j) \in A_R, (i',j') \in A_R \tag{13}$$

$$x_{ij}^k, y_{ij}^k, u_{kh} \in \{0,1\} \qquad \forall k \in K, h \in H_1 \cup H_2, \forall (i,j) \in A \tag{14}$$

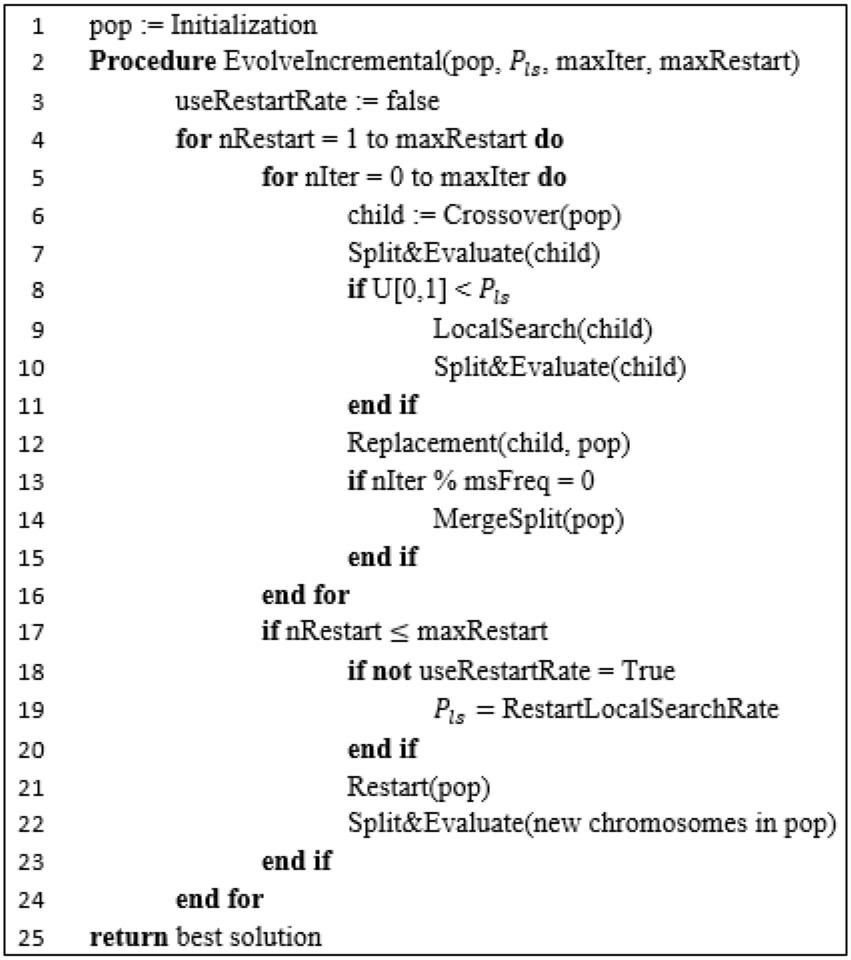
$$f_k \in \mathcal{F} \qquad \forall k \in K \tag{15}$$

The objective of the solution is to minimize the total travel cost. Constraint (2) is the flow conservation equation for each route. Constraints (3) and (4) ensure that all routes must start and end at the depot. Constraint (5) ensures that the service demand arcs are all serviced exactly once. Constraint (6) is the capacity constraint. Constraint (7) guarantees that each route is served by exactly one vehicle. Constraint (8) states that each vehicle at most services one route. In other words, some vehicles might not service any route. Constraints (9) and (10) are the fleet size constraints. Constraint (11) states that the service cycle time of a route is greater than the service cycle time of any arc in that route. Constraint (12) ensures that the travel time for each route never exceeds the route cycle time. Constraint (13) ensures road-truck dependency by forcing the arc plow direction within a route to stay the same.

Solution Algorithm

A memetic algorithm (MA) was used to solve the single-depot winter maintenance routing problem. An MA is similar to a genetic algorithm (GA), but in an MA a local search is employed instead of the mutation operator used in a GA. Each solution is represented by a chromosome (a sequence of arcs), and a set of chromosomes comprises a population set. The evolutionary process of the population depicts the improvement of the population set in terms of the fitness values of the chromosomes. At every iteration, new chromosomes (children) are produced based on selected existing chromosomes (parents). The desired new chromosomes replace some existing chromosomes. The procedures for selecting parents to reproduce, generating children, and replacing some parents with children are called the selection operator, reproduction operator, and replacement operator, respectively. The strategies employed by the operators are often problem specific.

The framework of the MA used in this study is shown in Figure 6.1.



```
1   pop := Initialization
2   Procedure EvolveIncremental(pop, $P_{ls}$, maxIter, maxRestart)
3       useRestartRate := false
4       for nRestart = 1 to maxRestart do
5           for nIter = 0 to maxIter do
6               child := Crossover(pop)
7               Split&Evaluate(child)
8               if U[0,1] < $P_{ls}$
9                   LocalSearch(child)
10                  Split&Evaluate(child)
11              end if
12              Replacement(child, pop)
13              if nIter % msFreq = 0
14                  MergeSplit(pop)
15              end if
16          end for
17          if nRestart $\leq$ maxRestart
18              if not useRestartRate = True
19                  $P_{ls}$ = RestartLocalSearchRate
20              end if
21              Restart(pop)
22              Split&Evaluate(new chromosomes in pop)
23          end if
24      end for
25  return best solution
```

Figure 6.1. Pseudocode showing the framework of the MA used in this study

After the initialization of the population, the MA generates a new chromosome using the Crossover operator. The local search is performed on the new chromosome with a fixed probability of P_{ls}. Then, the new chromosome replaces an existing chromosome in the population. The iterative local search is employed in the Replacement function (i.e., line 12 in Figure 6.1). The entire population goes through a MergeSplit (MS) operator every *msFreq* iterations. The main search process (i.e., lines 5 through 16 in Figure 6.1) are looped *maxRestart* times. In the restart phase, the local search probability P_{ls} is updated, and new chromosomes are generated.

Parallel Metaheuristic

A parallel metaheuristic approach was developed to improve the solution quality and computational efficiency of the algorithms. The parallel metaheuristic was designed at the iteration level using a master-worker model. In this approach, an elite chromosome set is maintained by a master CPU. Other worker CPUs work on a population set and run the MA. The worker CPUs communicate with the master CPU at a predefined frequency, at which point the elite set replaces the partial worker populations and the workers return newly evaluated solutions to the master. Figure 6.2 shows a diagram of the parallel MA approach.

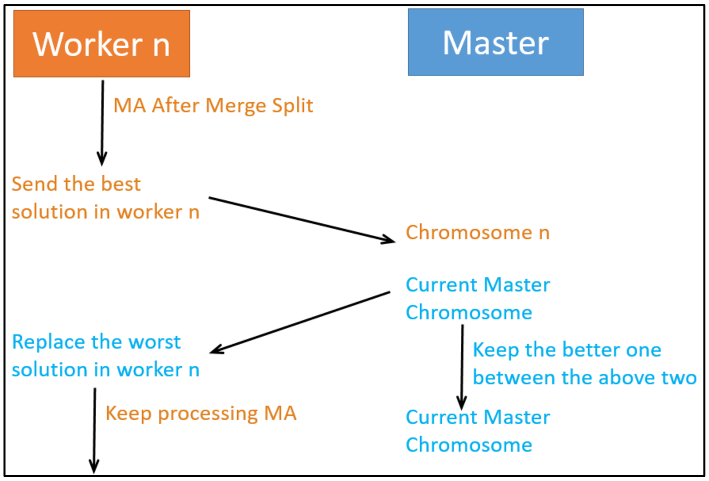


Figure 6.2. Parallel MA scheme

As the figure shows, each of the workers sends its best chromosome to the master immediately after every MS operation and replaces the worst chromosome in the worker's population with the chromosome sent by the master. The master holds only one chromosome, and this chromosome is sent to the worker immediately after the master receives communication from a worker. Then, the master compares the two chromosomes, i.e., the one it is currently holding and the other received from the worker. The better chromosome is left in the master. In this way, all workers remain largely independent of each other but are continuously updated with the best known chromosome.

Table 6.1 presents the results of 10 runs of single-CPU computation on 18 instances (depots).

Table 6.1. Results of 10 runs of a single CPU

Depot	Min. Total Fitness	Median Total Fitness	Max. Total Fitness	Std. dev. of Total Fitness	RSD Total Fitness
Ashton	540.59	557.36	569.31	9.00	1.62%
Carroll	205.46	211.32	233.71	13.13	6.01%
Cherokee	212.01	213.58	213.58	0.50	0.23%
Correctionville	254.68	254.68	254.68	0.00	0.00%
Denison	252.38	253.11	253.11	0.23	0.09%
Emmetsburg	169.52	169.52	169.62	0.03	0.02%
Ida Grove	139.31	139.31	140.95	0.52	0.37%
Le Mars	335.13	337.19	338.64	1.34	0.40%
Onawa	489.09	518.08	525.70	12.38	2.41%
Pocahontas	259.55	259.55	259.55	0.00	0.00%
Rockwell City	276.19	276.19	276.24	0.02	0.01%
Sac City	313.83	314.79	314.79	0.38	0.12%
Sioux City-Hamilton	331.93	347.48	382.84	20.70	5.86%
Sioux City-Leeds	251.13	266.59	270.22	6.04	2.28%
Sloan	162.87	162.87	162.87	0.00	0.00%
Spencer	206.98	213.37	245.26	12.55	5.78%
Spirit Lake	223.76	226.18	240.91	4.95	2.18%
Storm Lake	231.65	231.65	231.89	0.07	0.03%

The minimum, median, and maximum of the total fitness values are presented, along with the standard deviation and relative standard deviation (RSD) of the 10 runs. The instances with an RSD larger than 1% are colored red. It can be seen that 11 instances have an RSD less than 1%, which means that all 10 runs provided solutions of almost the same quality. This indicates that the proposed MA can generate stable solutions for these instances, and parallel computation would not result in a significant improvement in these instances. Therefore, only instances with an RSD larger than 1% were tested for parallel computation. The results of this test are shown in Figure 6.3 and Figure 6.4.

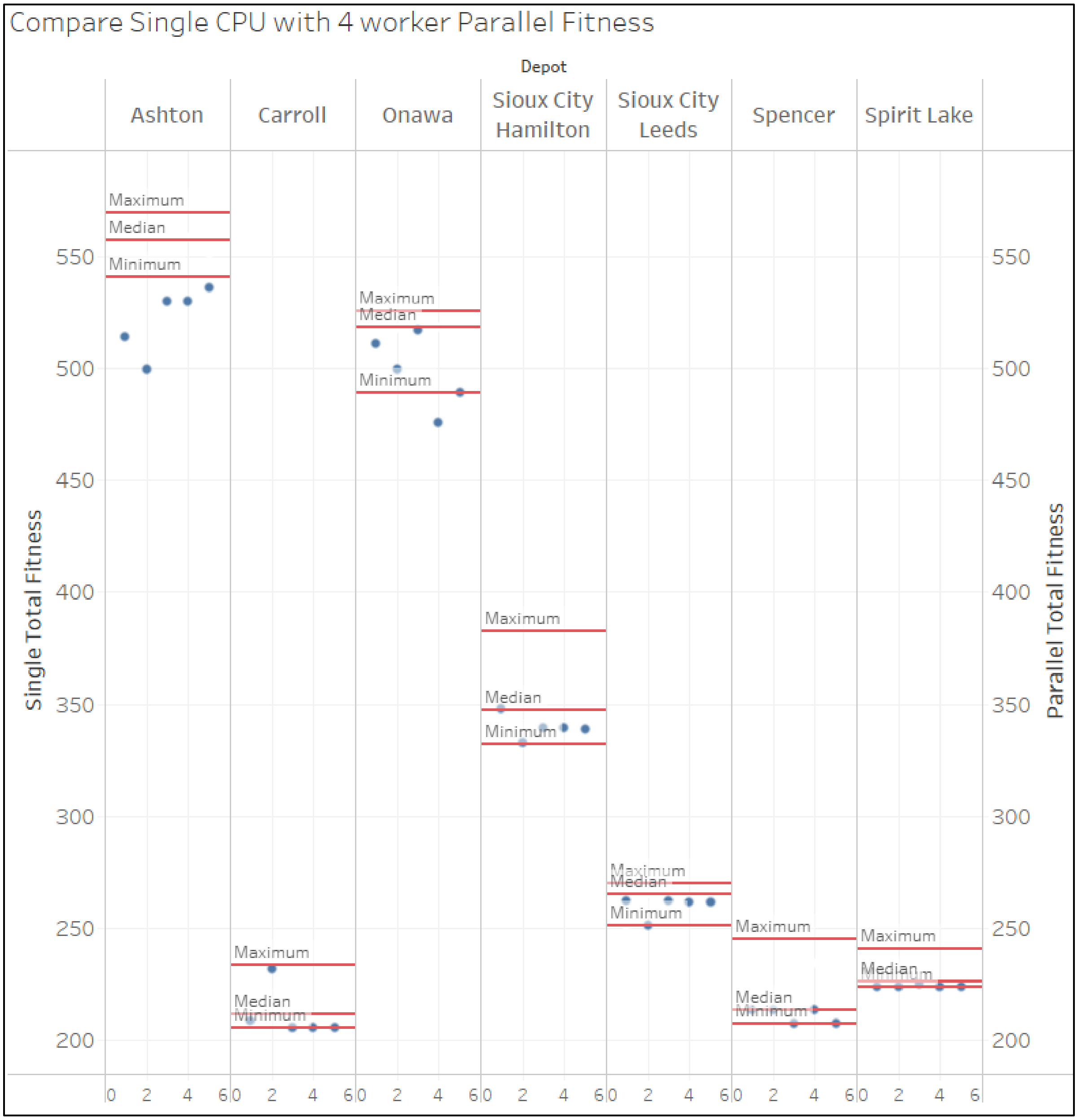


Figure 6.3. Comparison of the total fitness values of single-CPU (red lines) versus parallel (blue dots) computation

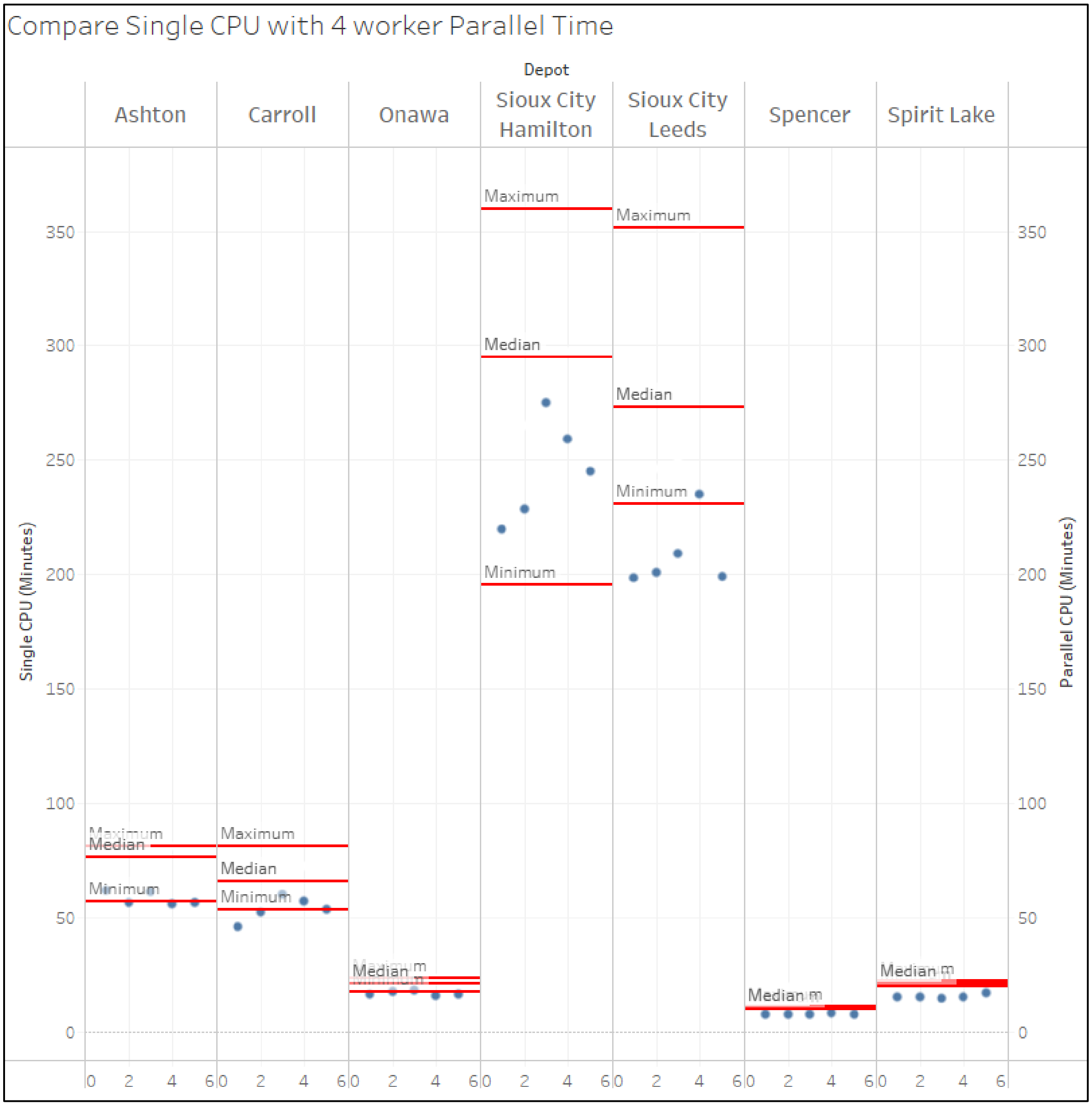


Figure 6.4. Comparison of the computational times of single-CPU (red lines) versus parallel (blue dots) computation

Parallel computation was run five times. Figure 6.3 compares the total fitness values resulting from the parallel computation and the single-core CPU computation runs. Each blue dot represents one run of the parallel computation. The red lines represent the minimum, median, and maximum values from the 10 runs of the single-CPU computation.

Figure 6.3 shows that parallel computation produced better solutions for two of the seven depots. In 18 out of 35 instances, parallel computation found a solution better than or equal to the best solution found by the single-CPU computation. In only one instance did parallel computation not find a solution better than the median. These results indicate that parallel computation can enhance solution quality.

Figure 6.4 compares the computational times of the single-CPU and parallel computations. The stopping criterion in this study was a fixed number of iterations. Therefore, significant improvement in the computational time was not expected. Nevertheless, almost all of the parallel computation instances took less time than the median computational time of the single-CPU computation. This indicates that parallel computation can enhance computational efficiency.

Multiple-Depot Winter Maintenance Routing Problem with Reload/Intermediate Facilities

As a hypothetical scenario, this section explores a different business model for District 3’s routing. In this scenario, the depot boundaries within each of the six sectors, shown in Figure 3.2, were permitted to be redesigned. Within each of the six sectors, the maintenance trucks were required to start and end at their home depot, but they could reload at any depot or reload station (if any) within the sector. All other constraints remained the same as in the SDWMRP.

The set of routes assigned to a truck is called a rotation. Each rotation ends at the same home depot where the truck starts. The same route travel time constraint as in the single-depot model applies. Let a node set $B \subset A$ represent the depot locations. Let m_1^l and m_2^l, where $l \in B$, represent the fleet sizes of the two types of vehicles assigned to each depot, respectively.

The decision variables are defined as follows:

$$x_{ij}^{kp} = \begin{cases} 1 & \mathit{if\ route\ k\ of\ rotation\ p\ service\ (i,j)\ from\ i\ to\ j} \\ 0 & \mathit{otherwise} \end{cases}$$

$$y_{ij}^{kp} = \begin{cases} 1 & \mathit{if\ route\ k\ of\ rotation\ p\ traverse\ (i,j)\ from\ i\ to\ j} \\ 0 & \mathit{otherwise} \end{cases}$$

$$u_{ph} = \begin{cases} 1 & \mathit{if\ the\ hth\ truck\ service\ rotation\ p} \\ 0 & \mathit{otherwise} \end{cases}$$

The MDWMRP is formulated as follows:

$$\sum_{(i,j)\in A,k\in K,p\in P} c_{ij}(x_{ij}^{kp} + y_{ij}^{kp}) \qquad (1)$$

$$\sum_{(i,j)\in A}(x_{ij}^{kp} + y_{ij}^{kp}) - \sum_{(j,i)\in A}(x_{ji}^{kp} + y_{ji}^{kp}) = 0 \qquad \forall k \in K, p \in P, i \in V \qquad (2)$$

$$\sum_{(l,i)\in A,k\in K} (x_{li}^{kp} + y_{li}^{kp}) = 1 \qquad \forall p \in P, i \in V, l \in B \qquad (3)$$

$$\sum_{(i,l)\in A,k\in K} (x_{il}^{kp} + y_{il}^{kp}) = 1 \qquad \forall p \in P, i \in V, l \in B \qquad (4)$$

$$\sum_{\forall k\in K,p\in P} x_{ij}^{kp} = 1 \qquad \forall (i,j) \in A_R \qquad (5)$$

$$\sum_{(i,j)\in A} q_{ij}\, x_{ij}^{kp} \le \sum_{h\in H_1\cup H_2} Q_h u_{ph} \qquad \forall k \in K, p \in P \tag{6}$$

$$\sum_{h\in H_1\cup H_2} u_{ph} = 1 \qquad \forall p \in P \tag{7}$$

$$\sum_{p\in P} u_{ph} \le 1 \qquad \forall h \in H_1 \cup H_2 \tag{8}$$

$$\sum_{p\in P, h\in H_1} u_{ph} \le m_1^l \qquad \forall l \in B \tag{9}$$

$$\sum_{p\in P, h\in H_2} u_{ph} \le m_2^l \qquad \forall l \in B \tag{10}$$

$$f_k \le f_{ij} x_{ij}^{kp} \qquad \forall k \in K, p \in P, (i,j) \in A_R \tag{11}$$

$$\sum_{(i,j)\in A} (x_{ij}^{kp} t'_{ij} + y_{ij}^{kp} t_{ij}) \le f_k \qquad \forall k \in K, p \in P \tag{12}$$

$$x_{ij}^{kp} r_{ij} = x_{i'j'}^{kp} r_{i'j'} \qquad \forall p \in P, (i,j) \in A_R, (i',j') \in A_R \tag{13}$$

$$x_{ij}^{kp}, y_{ij}^{kp}, u_{ph} \in \{0,1\} \qquad \forall k \in K, p \in P, h \in H_1 \cup H_2, \forall (i,j) \in A \tag{14}$$

$$f_k \in \mathcal{F} \qquad \forall k \in K \tag{15}$$

In this formulation, constraints (3) and (4) ensure that all rotations must start and end at a depot, and each rotation must end where it starts. Constraint (7) ensures that each rotation is assigned to one truck. Constraint (8) ensures that each truck services at most one rotation. Other constraints are the same as in the SDWMRP.

7. RESULTS

Single-Depot Winter Maintenance Routing Problem

This section presents the optimized routes generated for each sector in District 3 by solving the single-depot maintenance routing problem. Among the 20 depots in District 3, the Alton and Rock Rapids depots each use one truck from the Rock Valley depot. Therefore, the routing problems for the Alton and Rock Rapids depots are treated as multiple-depot problems and are presented in the next section. Table 7.1 presents the results for the remaining 18 depots.

Table 7.1. Sector service lane miles, test run travel distance, and optimized distance in miles, current and optimized number of routes

Depot Name	Service Distance	Test Run Distance	Optimized Distance	Current # of routes	Optimized # of routes	Result
Ashton	307.4	738.0*	499.6	10	10	Change boundary, Change route due to time constraint
Carroll	151.5	255.4	205.4	5	4	Saving deadhead and truck
Cherokee	180.3	219.1	212.01	6	6	Saving deadhead
Correctionville	192.9	227.0*	254.7	4	6	Add # of lanes, Change route due to capacity constraint
Denison	237.4	320.1*	252.4	6	6	Change boundary
Emmetsburg	150.2	225.0*	169.5	5	4	Saving deadhead
Ida Grove	128.6	177.0*	139.3	4	3	Saving truck
Le Mars	264.0	375.4	335.1	8	7	Saving deadhead
Onawa	298.3	504.1	475.7	7	10	Saving deadhead, Change route due to time constraint
Pocahontas	229.6	298.5*	259.6	6	6	Saving deadhead
Rockwell City	199.4	259.7	276.2	6	6	Change route due to time constraint
Sac City	185.6	434.1*	313.8	5	7	Add # of lanes
Sioux City Hamilton	189.7	504.7*	332.6	9	10	Change route due to time constraint
Sioux City Leeds	157.0	376.0*	251.1	7	8	Change route due to time constraint
Sloan	126.6	163.7	162.9	6	5	Currently efficient
Spencer	171.5	297.3*	207.0	6	5	Currently efficient
Spirit Lake	176.7	424.9	223.8	8	5	Saving deadhead and truck
Storm Lake	163.8	243.1	231.7	6	5	Saving deadhead and truck

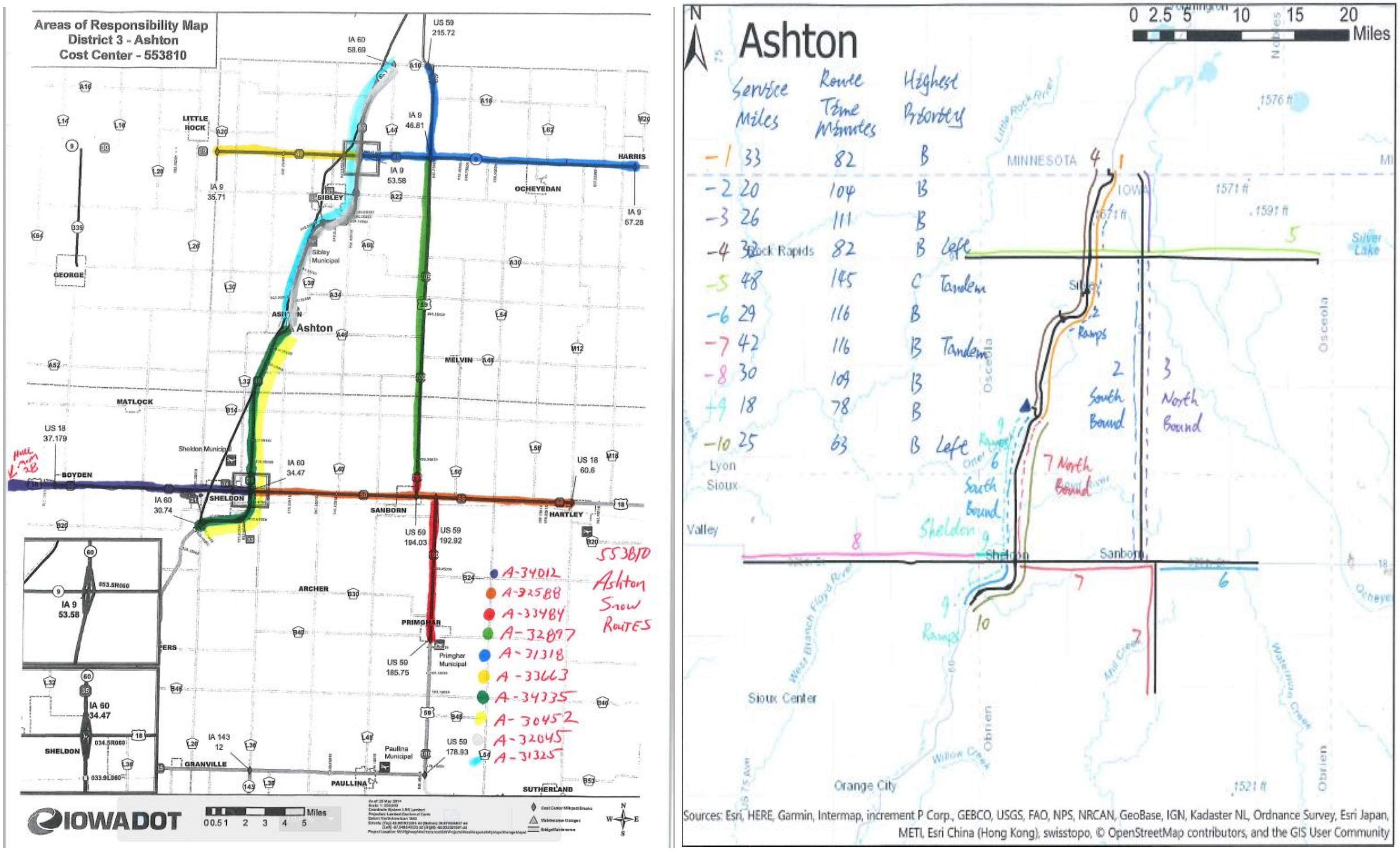
* Test run included duplicated distances on multiple road segments

The “Service Distance” column shows the responsibility distance for each depot in lane miles. The “Test Run Distance” column shows the total distance traveled by all trucks in a given depot, which was calculated from the test run AVL data. The test run distance indicates the actual travel distance under current operations and can be viewed as the baseline. However, due to unknown reasons, several trucks traveled some unnecessary distances during the test run. The depots to which these trucks are assigned are labeled with an asterisk. The “Optimized Distance” column shows the travel distance of the optimized routes. The “Fleet Size” column lists the total number of trucks at each depot, including both single-axle and tandem-axle trucks. The “Optimized Fleet Size” column shows the number of trucks needed to serve the optimized routes. Note that four depots need one additional truck because the changes to the road network or current operations prevent the time constraint from being satisfied.

The “Result” column summarizes the optimized route solutions. In particular, the label “saving” in this column indicates that the optimized routes can reduce deadhead distance by altering the current routes. The label “efficient” indicates that the current routes are efficient, and no change is needed. The label “change boundary” indicates that the service responsibility maps for Ashton and Denison are changed slightly for the optimal solution, which is taken into account in the optimized routes but not in the current routes. The label “change route” indicates that the current routes should be changed because some of the current routes are too long to be serviced due to the cycle time constraint. The label “add # of lanes” is listed for the Correctionville and Sac City depots because the reconstruction of US 20 in those regions would change the road from an undivided two-lane road to a divided four-lane road after April 2019. For depots with savings or changes, detailed route maps are provided for each depot and compared to the current operational maps in the following section.

Optimized Routes by Solving SDWMRP

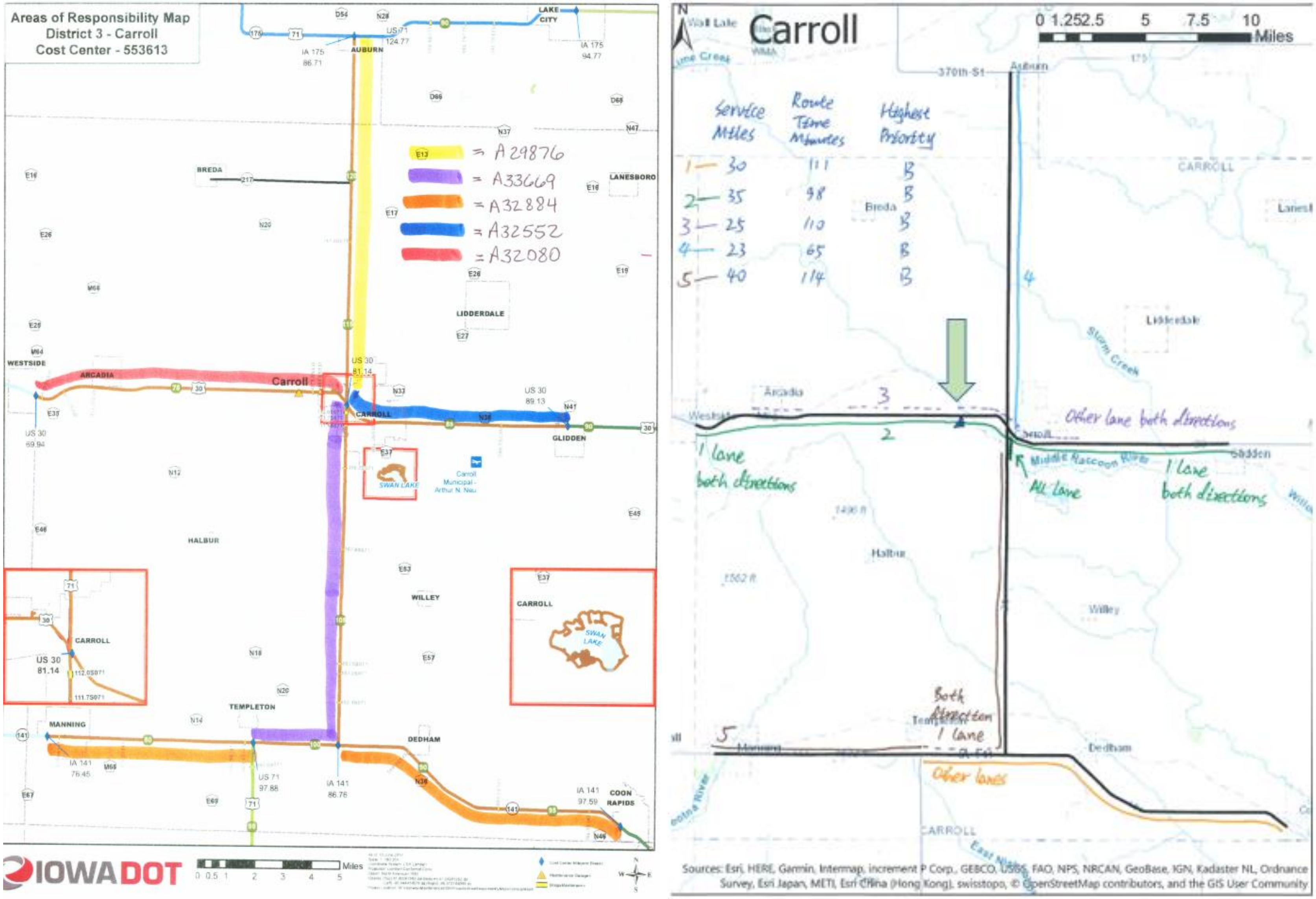
Figures 7.1 through 7.18 show the current and optimized routes for each depot.



	Service Miles	Route Time Minutes	Highest Priority	
-1	33	82	B	
-2	20	104	B	
-3	26	111	B	
-4	32	82	B	Left
-5	48	145	C	Tandem
-6	29	116	B	
-7	42	116	B	Tandem
-8	30	109	B	
-9	18	78	B	
-10	25	63	B	Left

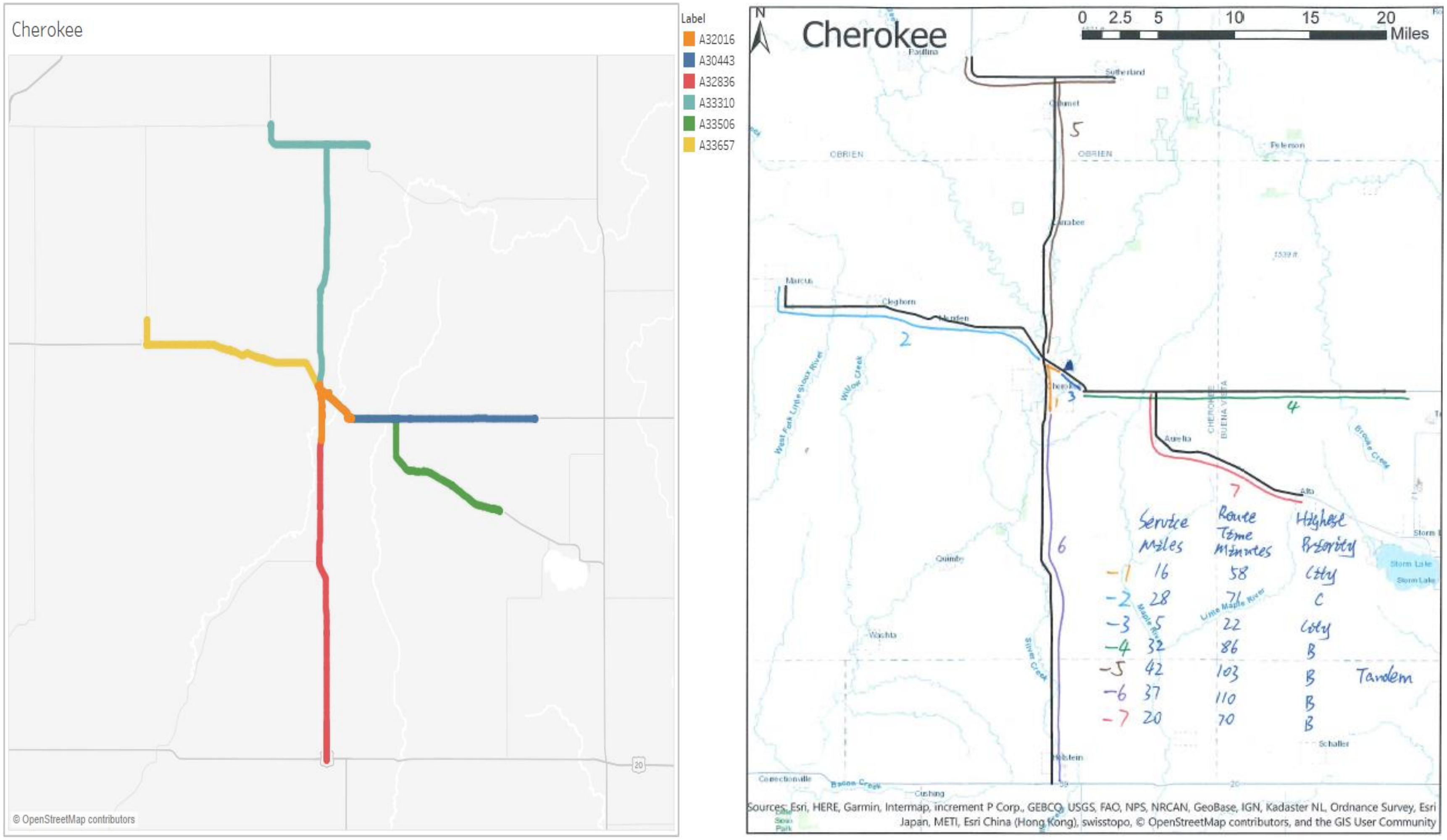
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 7.1. Ashton routes – current (left), optimized (right)



	Service Miles	Route Time Minutes	Highest Priority
1	30	111	B
2	35	98	B
3	25	110	B
4	23	65	B
5	40	114	B

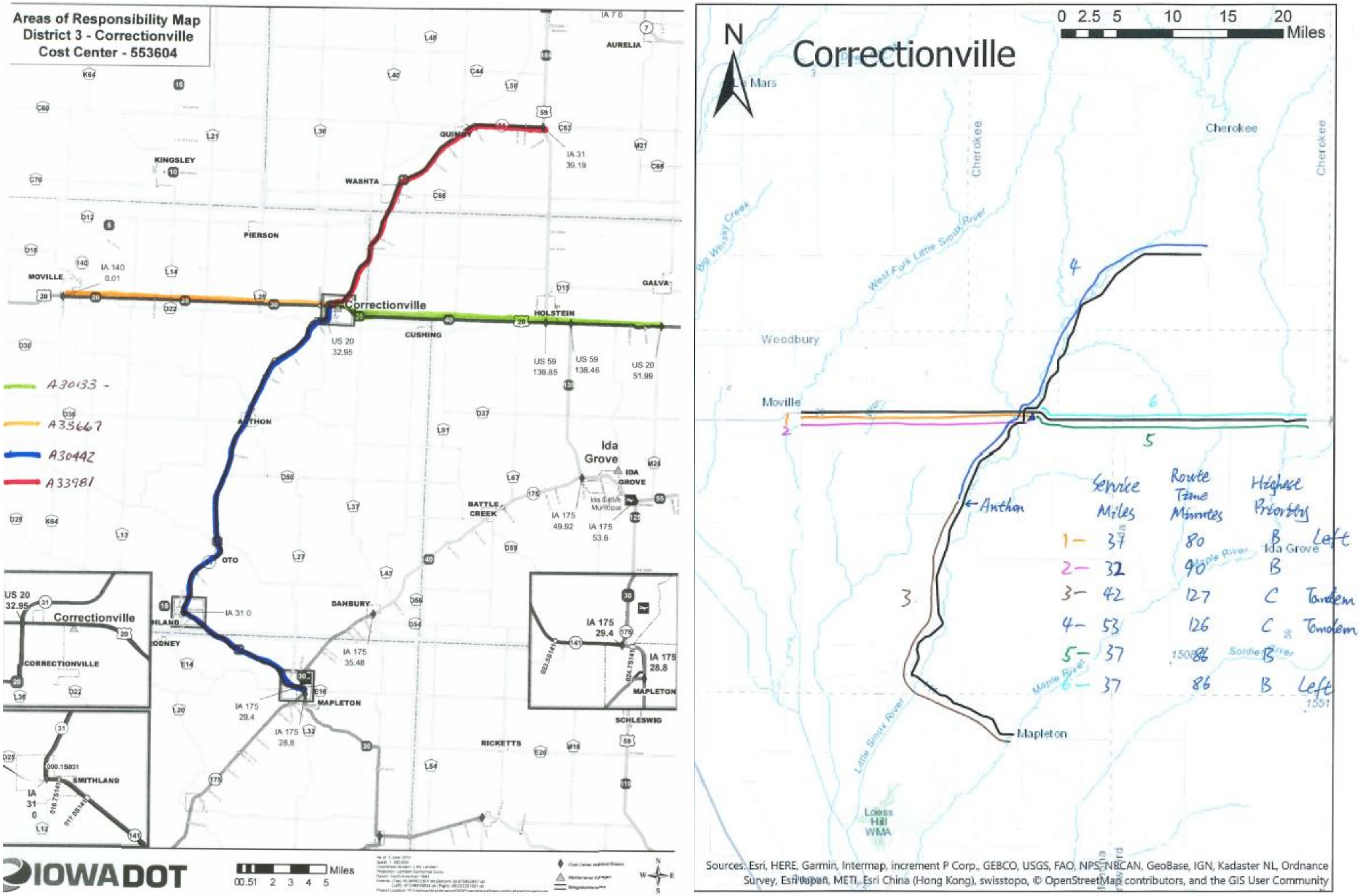
Figure 7.2. Carroll routes – current (left), optimized (right)



	Service Miles	Route Time Minutes	Highest Priority	
-1	16	58	City	
-2	28	71	C	
-3	5	22	City	
-4	32	86	B	
-5	42	103	B	Tandem
-6	37	110	B	
-7	20	70	B	

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

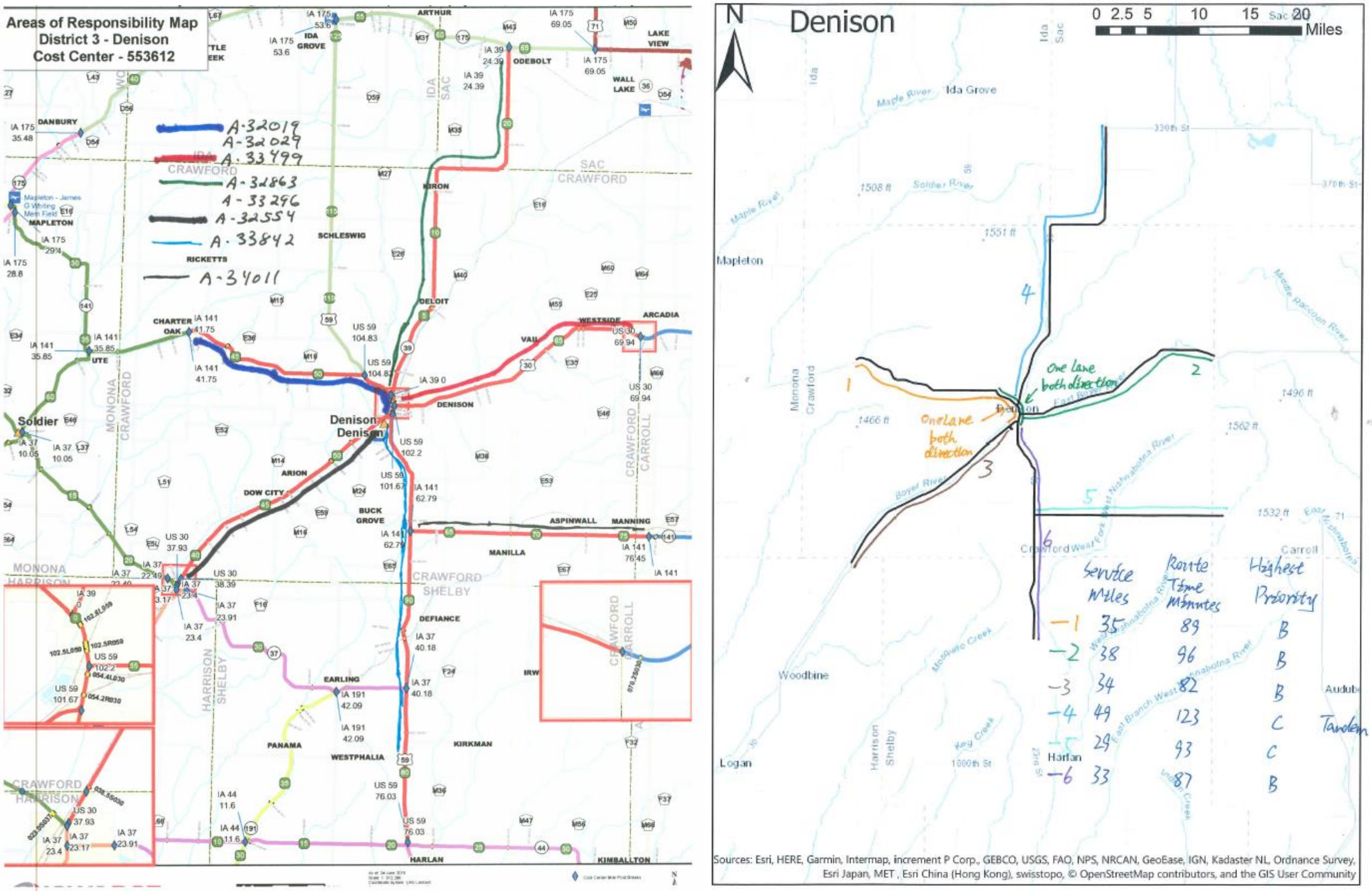
Figure 7.3. Cherokee routes – current (left), optimized (right)



	Service Miles	Route Time Minutes	Highest Priority	
1–	37	80	B	Left
2–	32	90	B	
3–	42	127	C	Tandem
4–	53	126	C	Tandem
5–	37	86	B	
6–	37	86	B	Left

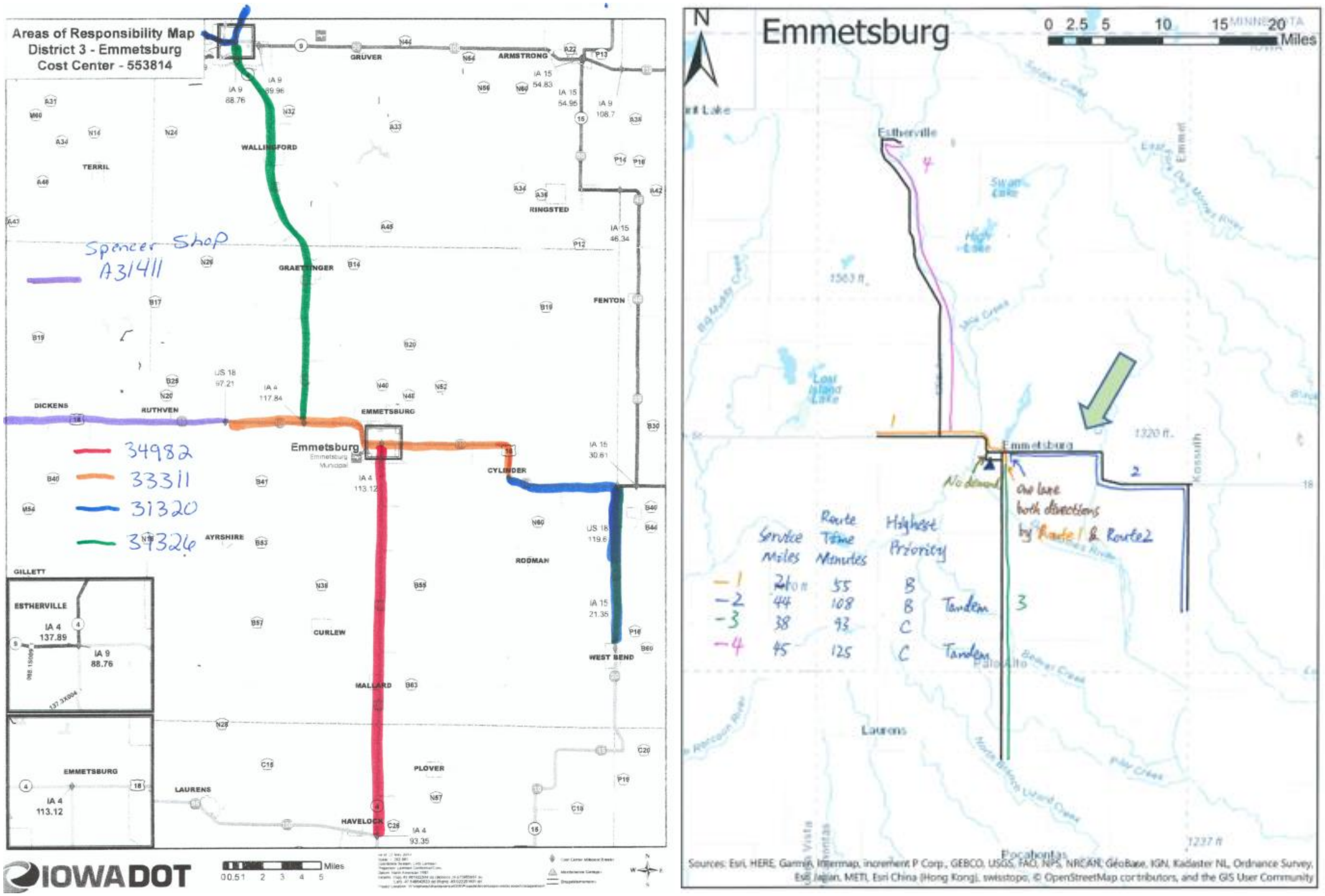
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 7.4. Correctionville routes – current (left), optimized (right)



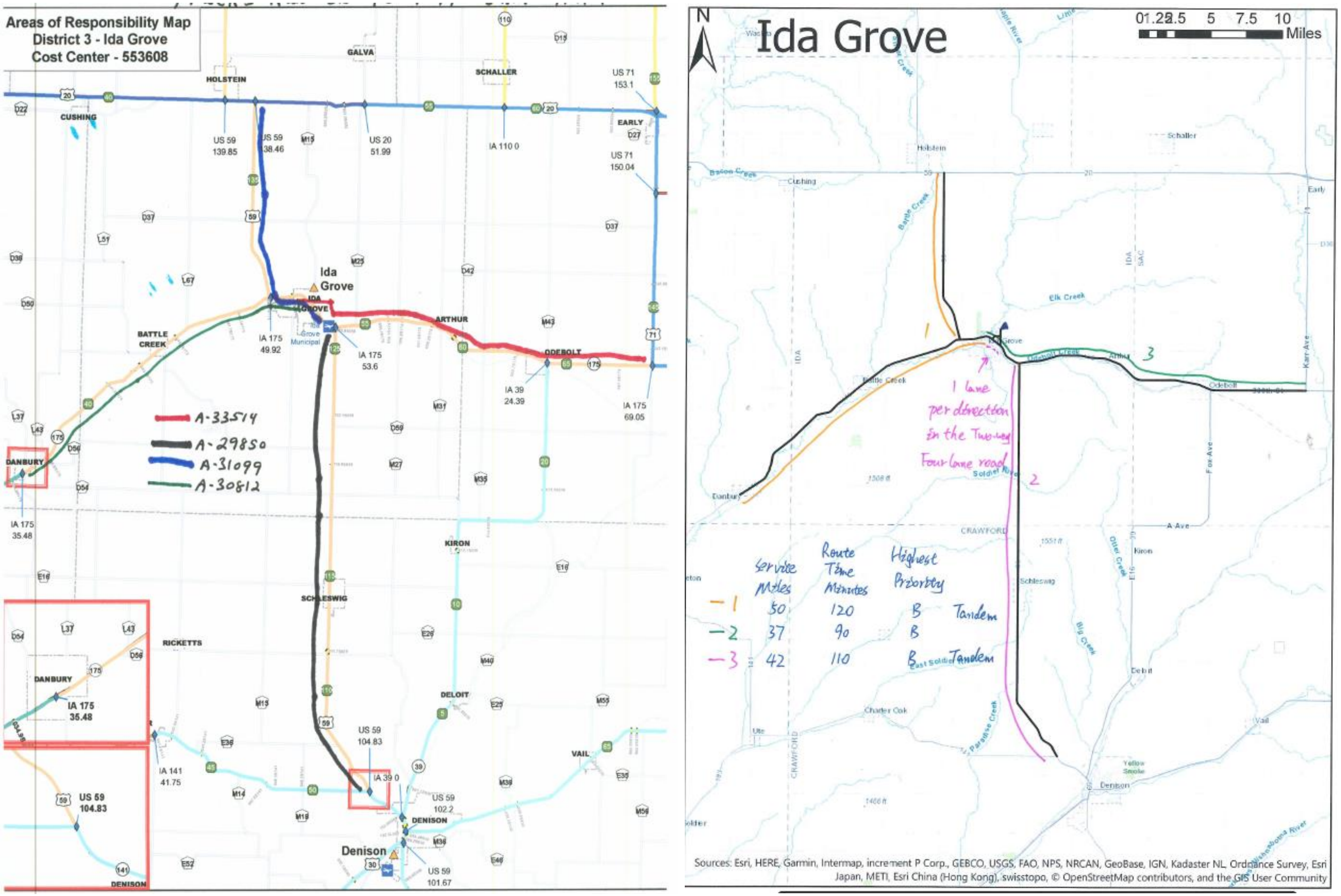
	Service Miles	Route Time Minutes	Highest Priority	
—1	35	89	B	
—2	38	96	B	
—3	34	82	B	
—4	49	123	C	Tandem
—5	29	93	C	
—6	33	87	B	

Figure 7.5. Denison routes – current (left), optimized (right)



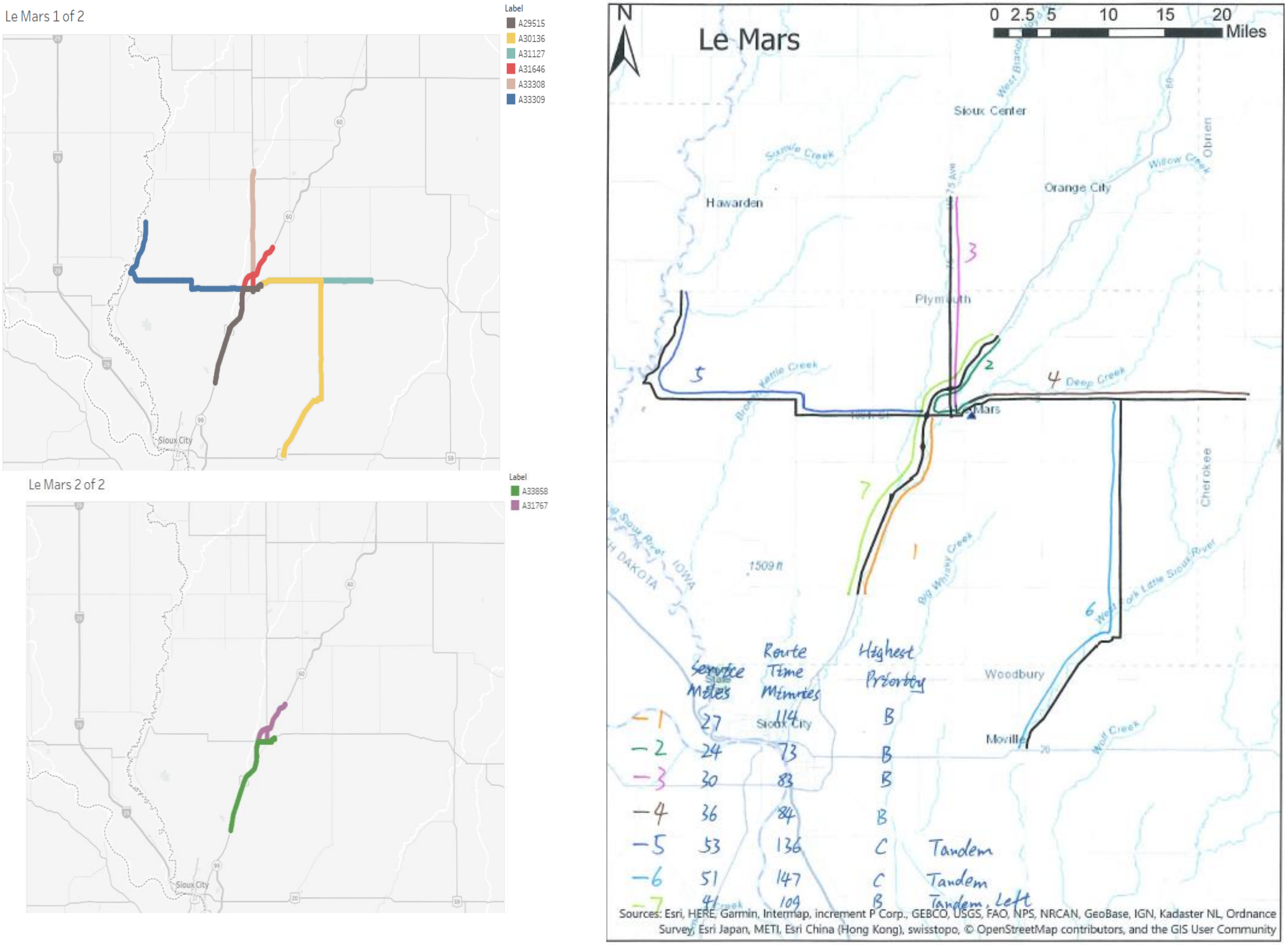
	Service Miles	Route Time Minutes	Highest Priority	
—1	21	55	B	
—2	44	108	B	Tandem
—3	38	93	C	
—4	45	125	C	Tandem

Figure 7.6. Emmetsburg routes – current (left), optimized (right)



	Service Miles	Route Time Minutes	Highest Priority	
—1	50	120	B	Tandem
—2	37	90	B	
—3	42	110	B	Tandem

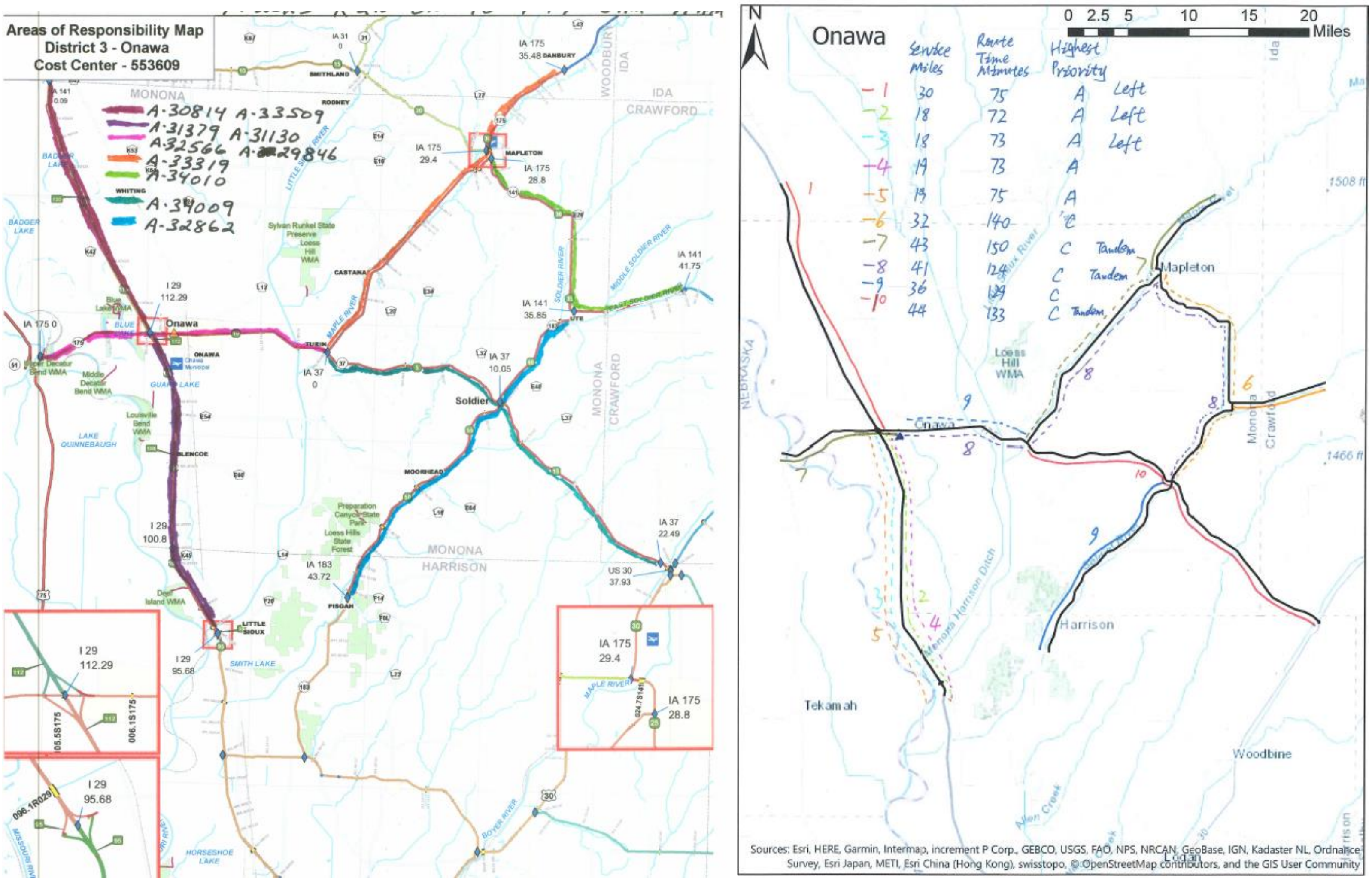
Figure 7.7. Ida Grove routes – current (left), optimized (right)



	Service Miles	Route Time Minutes	Highest Priority	
1	27	114	B	
2	24	73	B	
3	30	83	B	
4	36	84	B	
5	53	136	C	Tandem
6	51	147	C	Tandem
7	41	109	B	Tandem, Left

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

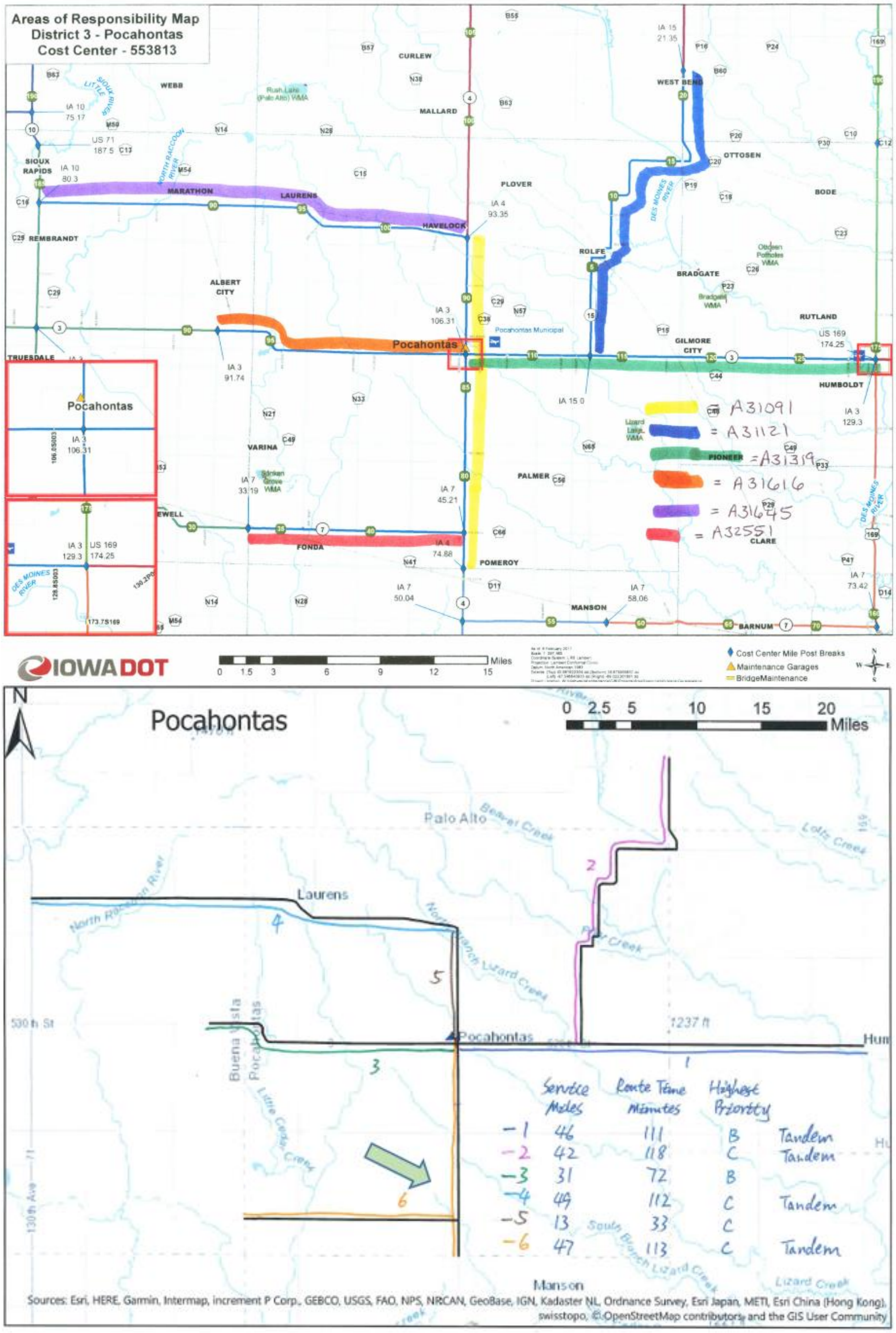
Figure 7.8. Le Mars routes – current (left), optimized (right)



	Service Miles	Route Time Minutes	Highest Priority	
1	30	75	A	Left
2	18	72	A	Left
3	18	73	A	Left
4	19	73	A	
5	19	75	A	
6	32	140	C	
7	43	150	C	Tandem
8	41	124	C	Tandem
9	36	129	C	
10	44	133	C	Tandem

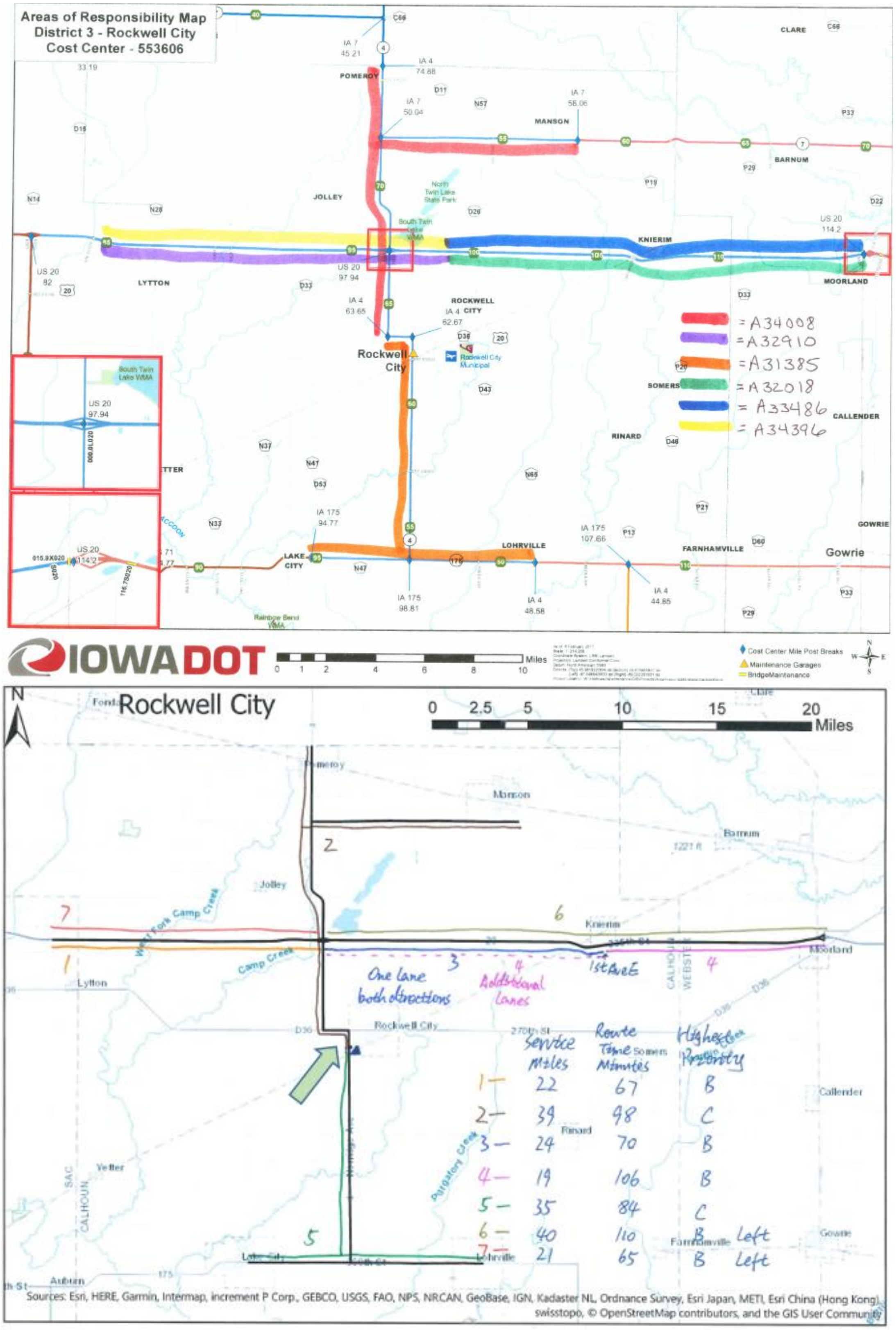
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 7.9. Onawa routes – current (left), optimized (right)



	Service Miles	Route Time Minutes	Highest Priority	
—1	46	111	B	Tandem
—2	42	118	C	Tandem
—3	31	72	B	
—4	49	112	C	Tandem
—5	13	33	C	
—6	47	113	C	Tandem

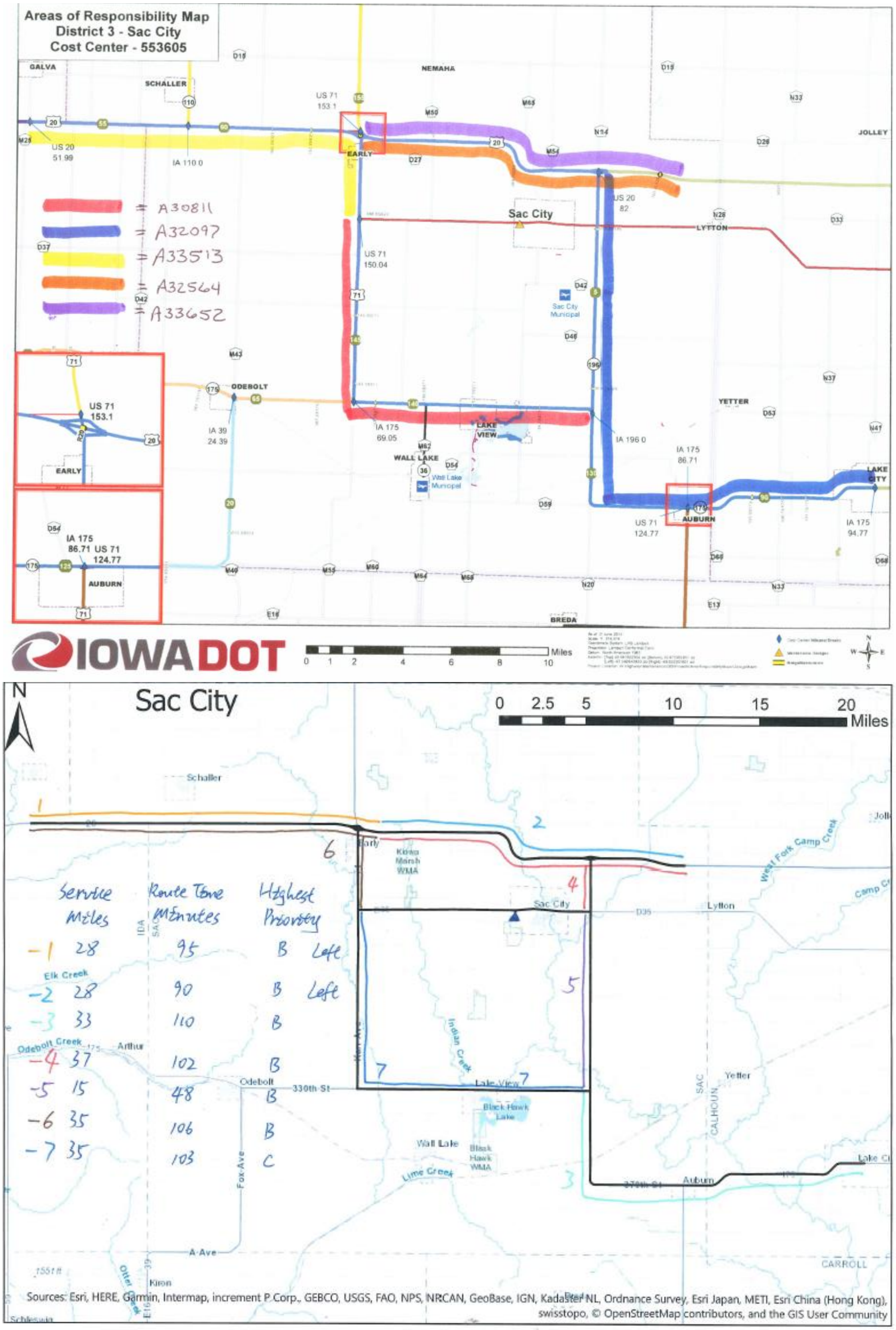
Figure 7.10. Pocahontas routes – current (top), optimized (bottom)



	Service Miles	Route Time Minutes	Highest Priority	
1—	22	67	B	
2—	39	98	C	
3—	24	70	B	
4—	19	106	B	
5—	35	84	C	
6—	40	110	B	Left
7—	21	65	B	Left

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 7.11. Rockwell City routes – current (top), optimized (bottom)



	Service Miles	Route Time Minutes	Highest Priority	
–1	28	95	B	Left
–2	28	90	B	Left
–3	33	110	B	
–4	37	102	B	
–5	15	48	B	
–6	35	106	B	
–7	35	103	C	

Figure 7.12. Sac City routes – current (top), optimized (bottom)

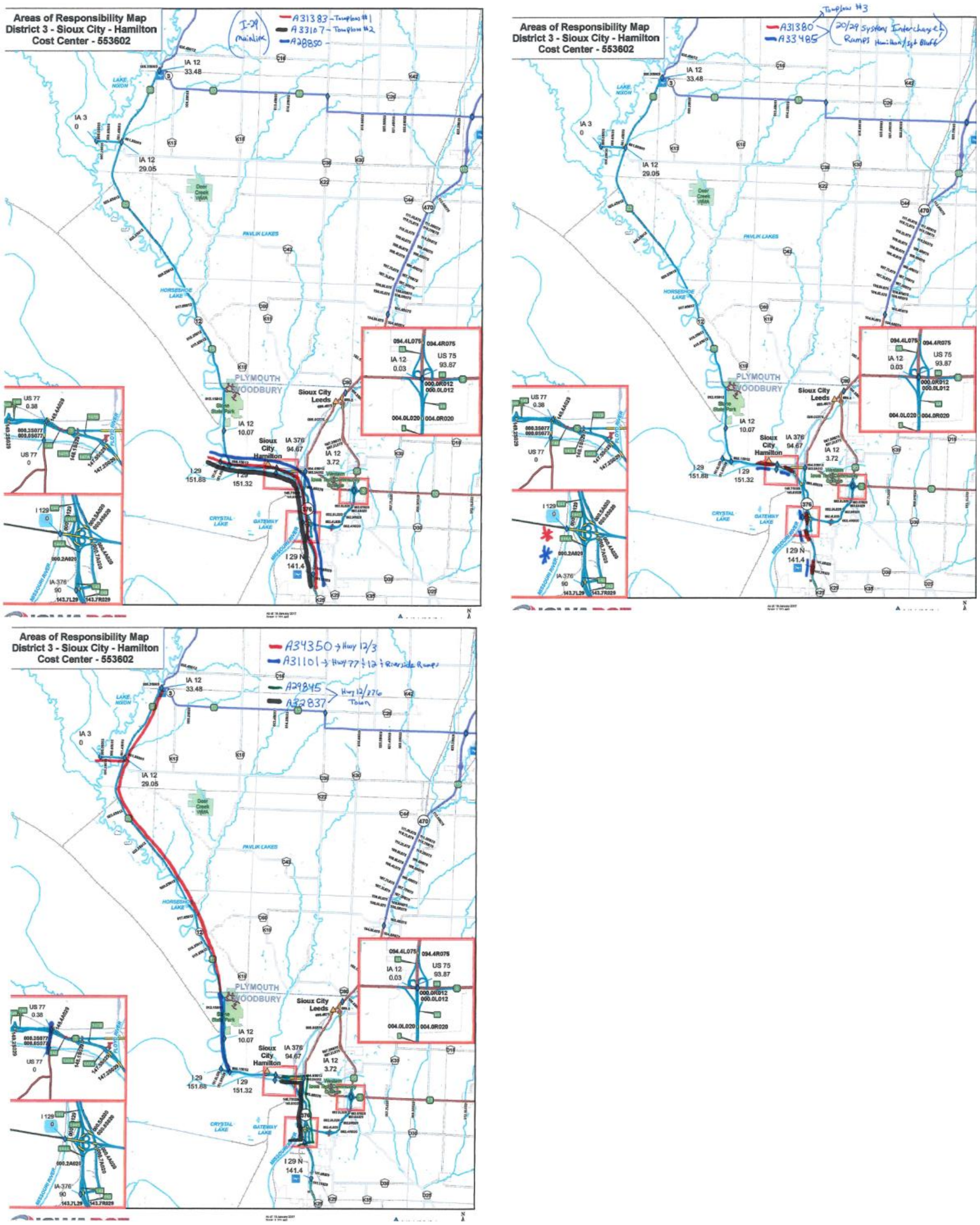
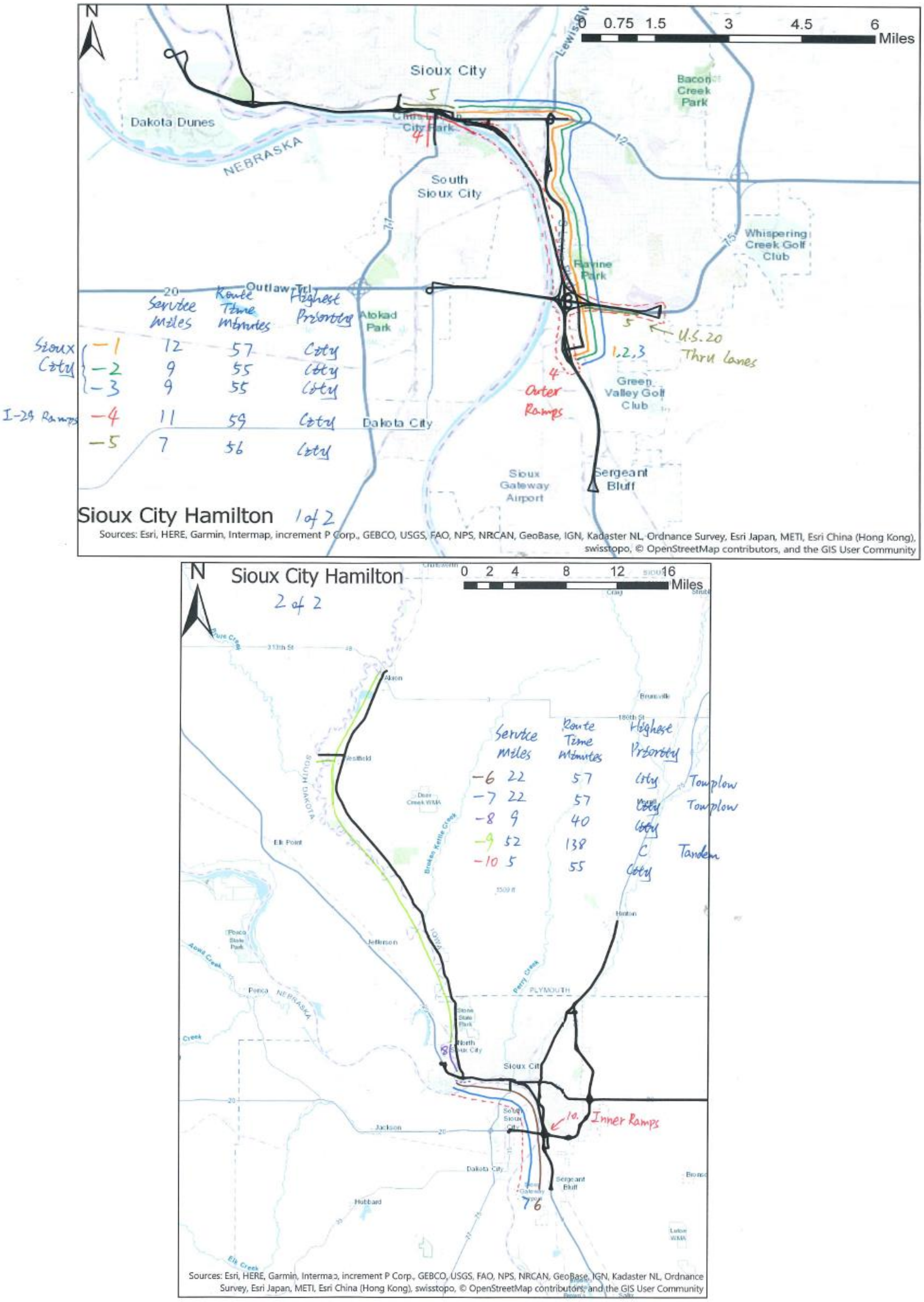


Figure 7.13. Sioux City Hamilton routes – current



Sioux City Hamilton 1 of 2

		Service Miles	Route Time Minutes	Highest Priority
Sioux City	-1	12	57	City
	-2	9	55	City
	-3	9	55	City
I-29 Ramps	-4	11	59	City
	-5	7	56	City

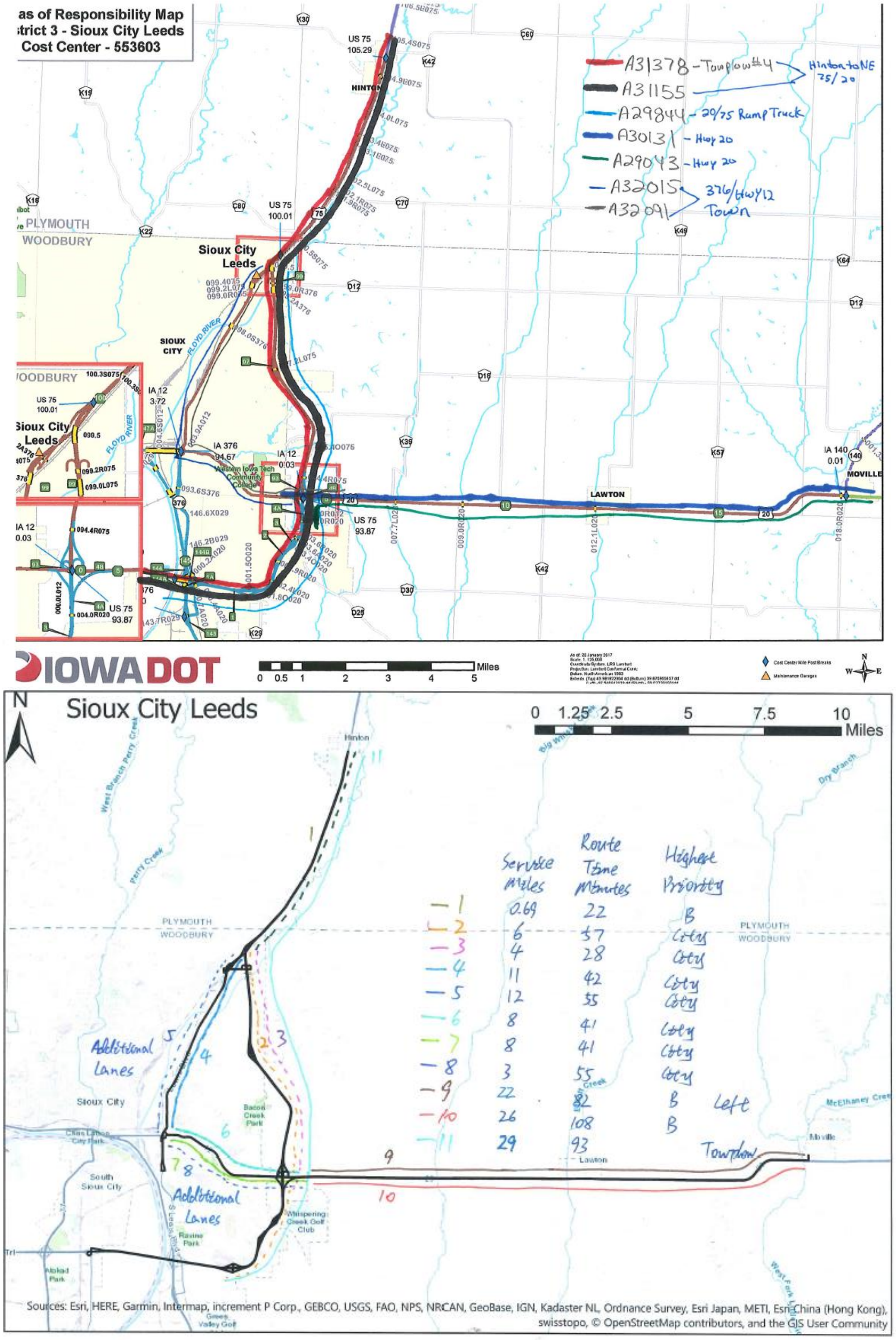
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Sioux City Hamilton 2 of 2

	Service Miles	Route Time Minutes	Highest Priority	
-6	22	57	City	Towplow
-7	22	57	City	Towplow
-8	9	40	City	
-9	52	138	C	Tandem
-10	5	55	City	

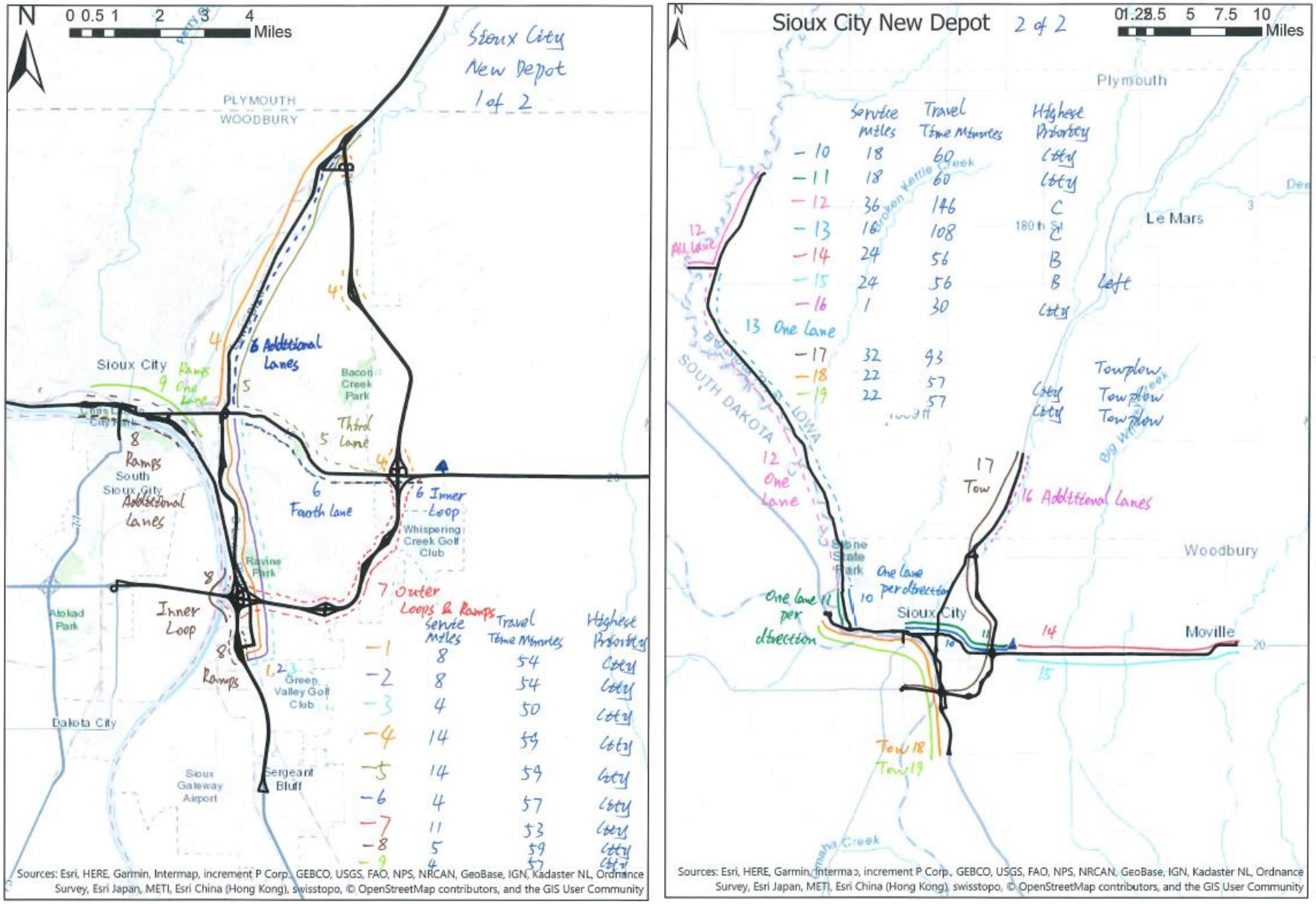
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 7.14. Sioux City Hamilton routes – optimized



	Service Miles	Route Time Minutes	Highest Priority
1	0.69	22	B
2	6	57	City
3	4	28	City
4	11	42	City
5	12	55	City
6	8	41	City
7	8	41	City
8	3	55	City
9	22	82	B
10	26	108	B
11	29	93	

Figure 7.15. Sioux City Leeds routes – current (top), optimized (bottom)



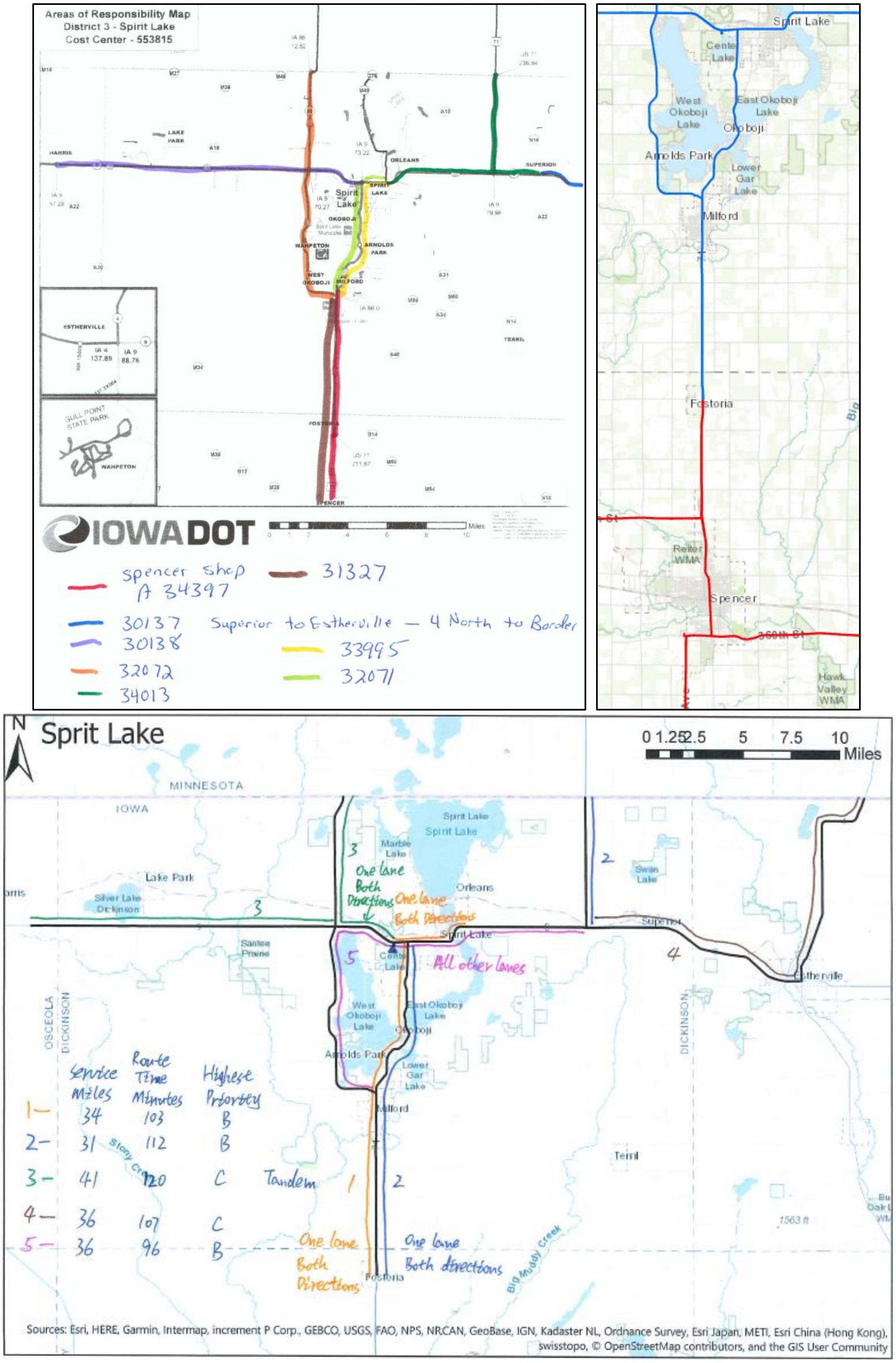
	Service Miles	Travel Time Minutes	Highest Priority
1	8	54	City
2	8	54	City
3	4	50	City
4	14	59	City
5	14	59	City
6	4	57	City
7	11	53	City
8	5	59	City
9	4	57	City

	Service Miles	Travel Time Minutes	Highest Priority	
10	18	60	City	
11	18	60	City	
12	36	146	C	
13	16	108	C	
14	24	56	B	
15	24	56	B	
16	1	30	City	
17	32	93		Towplow
18	22	57	City	Towplow
19	22	57	City	Towplow

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

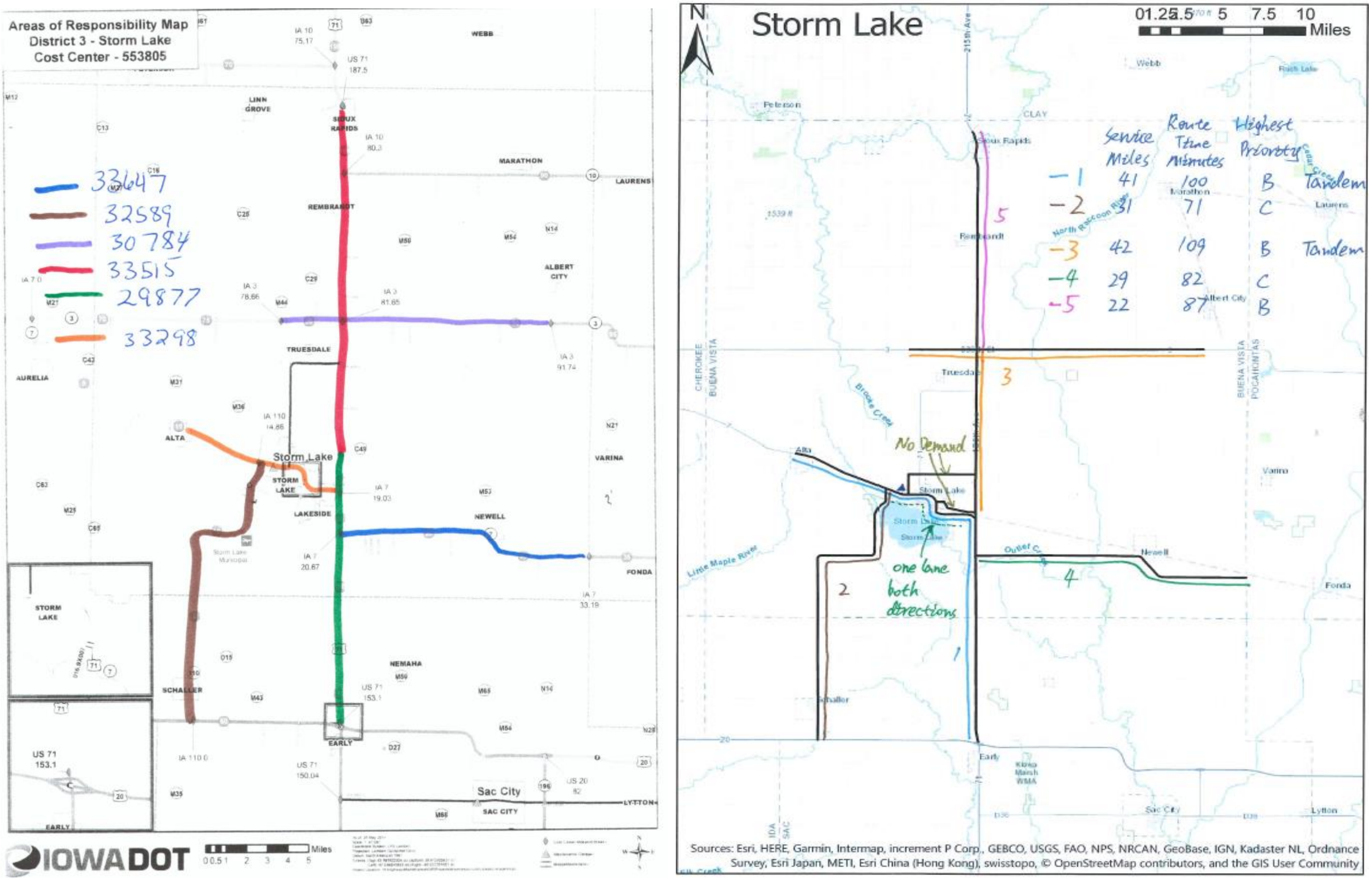
Figure 7.16. Sioux City new depot routes – current (left), optimized (right)



	Service Miles	Route Time Minutes	Highest Priority	
1—	34	103	B	
2—	31	112	B	
3—	41	120	C	Tandem
4—	36	107	C	
5—	36	96	B	

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 7.17. Spirit Lake depot routes – current (above left), optimized (below)



	Service Miles	Route Time Minutes	Highest Priority	
–1	41	100	B	Tandem
–2	31	71	C	
–3	42	109	B	Tandem
–4	29	82	C	
–5	22	87	B	

Figure 7.18. Storm Lake depot routes – current (left), optimized (right)

In the optimized route maps for all depots, the service miles for each route indicate the total running distance for that route. Since the spreading rate is set at 300 lbs per lane mile, a single-axle truck with a capacity of 12,000 lbs has a maximum service distance of 40 miles, and a tandem-axle truck with a capacity of 16,000 lbs has a maximum service distance of 53.3 miles. The route time minutes for each route indicate the total travel time for that route. The road segments with the highest priority in a route dictate the required cycle time for all of the road segments in that route. That is, if a route includes both Service Level B and Service Level C road segments, the required cycle time for a Service Level B road segment is met for the entire route. If a left-wing plow or a tandem truck is needed for the route, it is noted next to the priority index. A solid colored line indicates that the truck will service all lanes in both directions if no other colored line overlaps the same streets. A dashed colored line indicates that the truck will service ramps, additional turning lanes, or one lane of a multilane road.

The current and optimized routes for the Ashton depot are shown in Figure 7.1. For this depot, the current service routes along US 18 end at Hull, whereas the optimized routes would extend to the US 75 intersection at Perkins, as per the request from this project's technical advisory committee (TAC). However, this change would make the route too long to be serviced by truck A34012, as shown in Figure 7.1. Similarly, truck A32897 would exceed the cycle time constraint of two hours.

The optimized routes are shown in the right-hand map in Figure 7.1. Routes 2 and 3 share the segment of US 59 between Iowa 9 and US 18, with each truck servicing only one direction. Route 2 also includes ramps on Iowa 60. Route 5 services the entirety of Iowa 9. Routes 6 and 7 share a segment of Iowa 60 South. Route 8 services the area from Sheldon to Perkins. Route 9 services ramps that are not covered by Routes 6 and 7 and services Sheldon to the intersection of US 18 and Iowa 60.

Figure 7.2 shows the current and optimized routes for the Carroll depot. In the optimized map, Routes 2 and 3 both service US 30: Route 2 services one lane in both directions and Route 3 services all locations with additional lanes. This could reduce deadhead distance, since in current practice truck A32552 deadheads from the depot to the junction of US 71 and US 30. Similarly, deadhead distance is reduced by assigning Routes 1 and 5 to service US 71.

The current and optimized routes for the Cherokee depot are shown in Figure 7.3. The only change is within the metropolitan area. To achieve a one-hour cycle time, the optimized solution includes two routes to cover the urban area of Cherokee, which is currently serviced by one route, i.e., truck A32016. The other routes remain the same.

The current and optimized routes for the Correctionville depot are shown in Figure 7.4. For this depot, since US 20 has been expanded to a four-lane divided roadway, a left-wing truck is added for both the eastbound and westbound directions. Route 2 services additional turning lanes near Correctionville, resulting in longer travel times. In current practice, truck A30442 exceeds the cycle time constraint. Therefore, the optimized solution assigns the road segment between Anthon and Correctionville to Route 4 instead of Route 3. This leads to additional deadhead for Route 3. However, if operational staff decide to allow the truck on Route 3 to drive slightly faster than the average service speed, they can maintain the current practice and save deadhead distance.

The current and optimized routes for the Denison depot are shown in Figure 7.5. Based on the suggestion of the TAC, the Denison depot now services US 59 only to the intersection with Iowa 37. The optimized routes are almost the same as the current routes. Routes 1 and 2 service US 59 in the Denison urban area.

The current and optimized routes for the Emmetsburg depot are shown in Figure 7.6. The Emmetsburg depot had previously used a different service responsibility map than the one it currently uses. The current service routes shown in Figure 7.6 (left) were designed mostly based on the outdated service area map. In this map, the route serviced by truck A31320 in particular generates unnecessary deadhead distance. In the optimized route map, the road segments from Emmetsburg to East US 18 can be serviced by one route.

The current and optimized routes for the Ida Grove depot are shown in Figure 7.7. The current routes serviced by trucks A31099 and A30812 can be serviced by Route 1 in the optimized map. Routes 1 and 2 both service the four-lane road in the Ida Grove urban area. Thus, one less truck is needed.

The current and optimized routes for the Le Mars depot are shown in Figure 7.8. The current map uses four trucks on US 75 and Iowa 60 (the routes shown in red, black, purple, and green). The optimized solution needs only three trucks to service these roads. The other routes stay the same.

The current and optimized routes for the Onawa depot are shown in Figure 7.9. The optimized routes for the Service Level C roads have almost the same travel distance as the comparable current routes. Therefore, no change is needed for this part of the network. However, the current routes servicing Interstate 29 south of Onawa have a cycle time of about 85 minutes, which exceeds the desired cycle time. If the operational staff allow the trucks on these routes to drive slightly faster than the average service speed, the trucks might be able to traverse the route in 75 minutes. Otherwise, an additional truck is needed, as shown in the optimized route map.

The current and optimized routes for the Pocahontas depot are shown in Figure 7.10. The optimized solution reduces deadhead by using Route 6 to service Iowa 4 south of Pocahontas. During the TAC meeting, District 3 representatives mentioned that in current practice truck A32551 services Iowa 7 because of drifting snow. Therefore, if drifting snow is a concern during a specific storm, the current route map can be applied. Otherwise, the optimized routes can reduce some deadhead distance.

The current and optimized routes for the Rockwell City depot are shown in Figure 7.11. In current practice, the travel time of truck A32018 exceeds the desired cycle time. In the optimized routes, Route 3 services one lane in each direction of part of US 20. Route 4 services the additional turning lanes that are not serviced by Route 3 and the eastern portion of US 20. In addition, Route 2 starts from the depot and services Iowa 4, thereby reducing deadhead distance compared to the current practice.

The current and optimized routes for the Sac City depot are shown in Figure 7.12. Because US 20 has been expanded to a four-lane divided road, one additional truck is needed to supplement A33513, the truck currently used to service that road. In addition, in current practice the route serviced by truck A32097 exceeds the desired cycle time and is therefore split into Routes 3 and 5 in the optimized map.

The current service routes of the Sioux City Hamilton depot are shown in Figure 7.13, and the optimized service routes for this depot are shown in Figure 7.14. In the optimized solution, one additional truck is needed to service the urban area in Sioux City Hamilton due to the cycle time constraint. The urban area would be serviced by Routes 1 to 3.

The current and optimized routes for the Sioux City Leeds depot are shown in Figure 7.15. In the optimized map, the Sioux City urban area needs more trucks because of the one-hour cycle time constraint. The current routes are sufficient for a two-hour cycle time in the Sioux City urban area.

A new Sioux City depot has been created at the intersection of US 75 and US 20, as shown in Figure 7.16. When operational, this new depot will service the entire Sioux City area, with the Hamilton and Leeds depots being closed. The optimized solution for the new depot includes 19 routes, compared to a combined total of 21 routes for the Hamilton and Leeds depots. The total travel distance of all routes for the new depot is 636.9 miles, compared to a combined total of 659.3 miles for the Hamilton and Leeds depots. The mileage savings mainly come from two changes: Routes 10 and 11 from the new depot would cover the road segments on US 20 that previously were covered by the Hamilton and Leeds depots, and Routes 4, 5, and 6 would cover the road segments on US 75 that previously were covered by the Hamilton and Leeds depots. Since Routes 10 and 11 would service the through lanes on US 20, the additional turning lanes on US 20 would be serviced by Routes 5 and 6.

The current and optimized routes for the Spirit Lake depot are shown in Figure 7.17. Since the Spencer depot is currently efficient, the service boundary between the Spencer and Spirit Lake depots is at Fostoria, as shown in Figure 7.17. Many road segments in the Spirit Lake area are multilane road segments. These are mostly serviced by more than one route in the optimized solution.

The current and optimized routes for the Storm Lake depot are shown in Figure 7.18. The deadhead savings come from Route 1 and 4 servicing Iowa 7 in the area around the town of Storm Lake.

Sensitivity Analysis of Spreading Rates

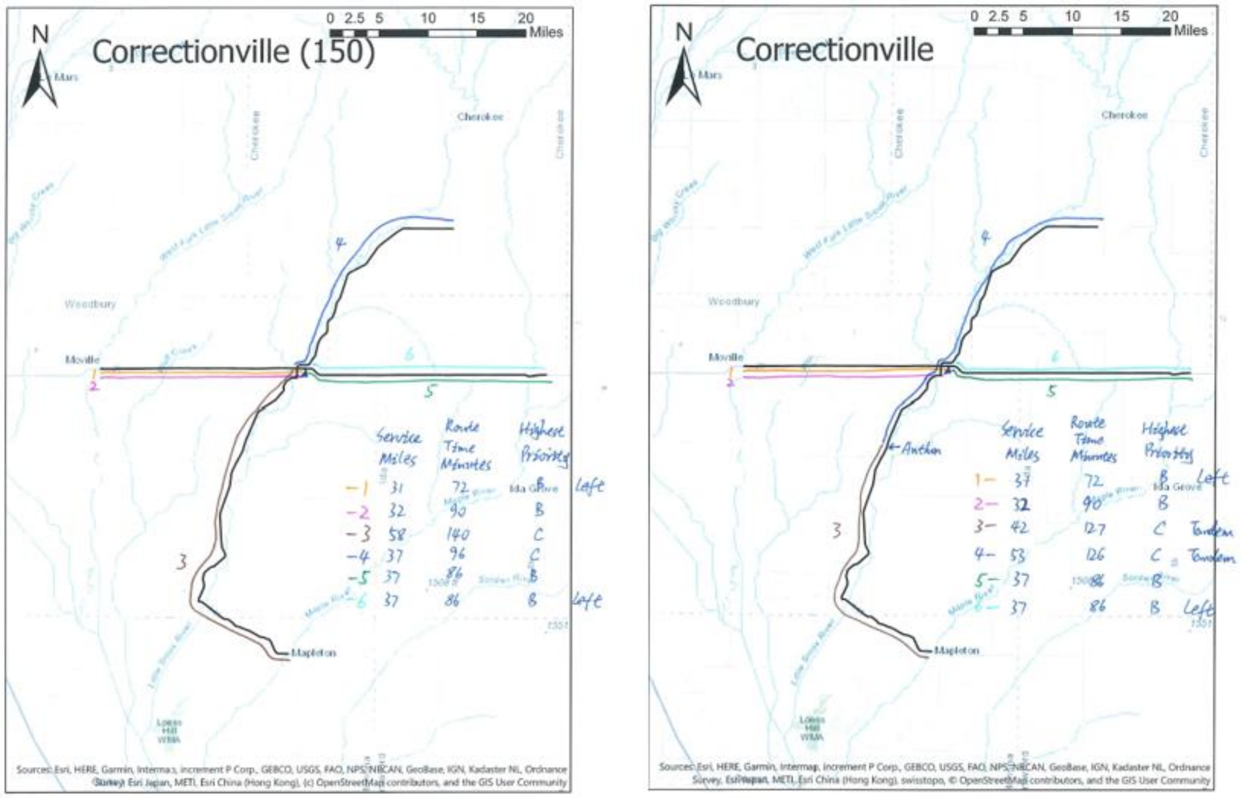
To explore how the spreading rate might change the optimized routes, a sensitivity analysis with regard to the spreading rate was conducted. The spreading rate was set at 150, 200, 250, and 300 lbs per lane mile to solve the SDWMRP for all depots. Table 7.2 presents the total travel distances under different spreading rates.

Table 7.2. Sensitivity analysis summary of travel distance under different spreading rates

Depot	150 lbs/lane mile	200 lbs/lane mile	250 lbs/lane mile	300 lbs/lane mile
Ashton	500.3	499.6	499.6	**499.6**
Carroll	205.4	205.4	205.4	**205.4**
Cherokee	213.6	212.0	213.6	**212.0**
Correctionville	237.9	237.9	237.9	**254.7**
Denison	253.1	253.1	252.3	**252.4**
Emmetsburg	169.5	169.5	169.5	**169.5**
Ida Grove	139.3	139.3	139.3	**139.3**
Le Mars	335.1	335.1	335.1	**335.1**
Onawa	475.7	475.7	475.7	**475.7**
Pocahontas	247.0	247.0	247.0	**259.6**
Rockwell City	276.2	276.2	276.2	**276.2**
Sac City	313.8	314.2	313.8	**313.8**
Sioux City Hamilton	332.5	332.6	332.4	**332.6**
Sioux City Leeds	251.3	251.1	251.1	**251.1**
Sloan	162.9	162.9	162.9	**162.9**
Spencer	207.0	207.0	207.0	**207.0**
Spirit Lake	223.8	223.7	223.7	**223.8**
Storm Lake	231.7	231.7	231.7	**231.7**

With spreading rates less than 300 lbs per lane mile, the Correctionville and Pocahontas depots can significantly reduce their deadhead distances. The routes for the Correctionville and Pocahontas depots that result in deadhead savings have a desired cycle time of 2.5 hours. This result shows that only the Service Level C routes, which include Iowa roads with a service cycle time of 2.5 hours, are sensitive to spreading rates. The reason is that the other road levels are more strongly bound by the cycle time constraint than the capacity constraint.

Figure 7.19 compares the optimized route maps for the Correctionville depot with a spreading rates of 150 lbs per lane mile (left) and 300 lbs per lane mile (right).



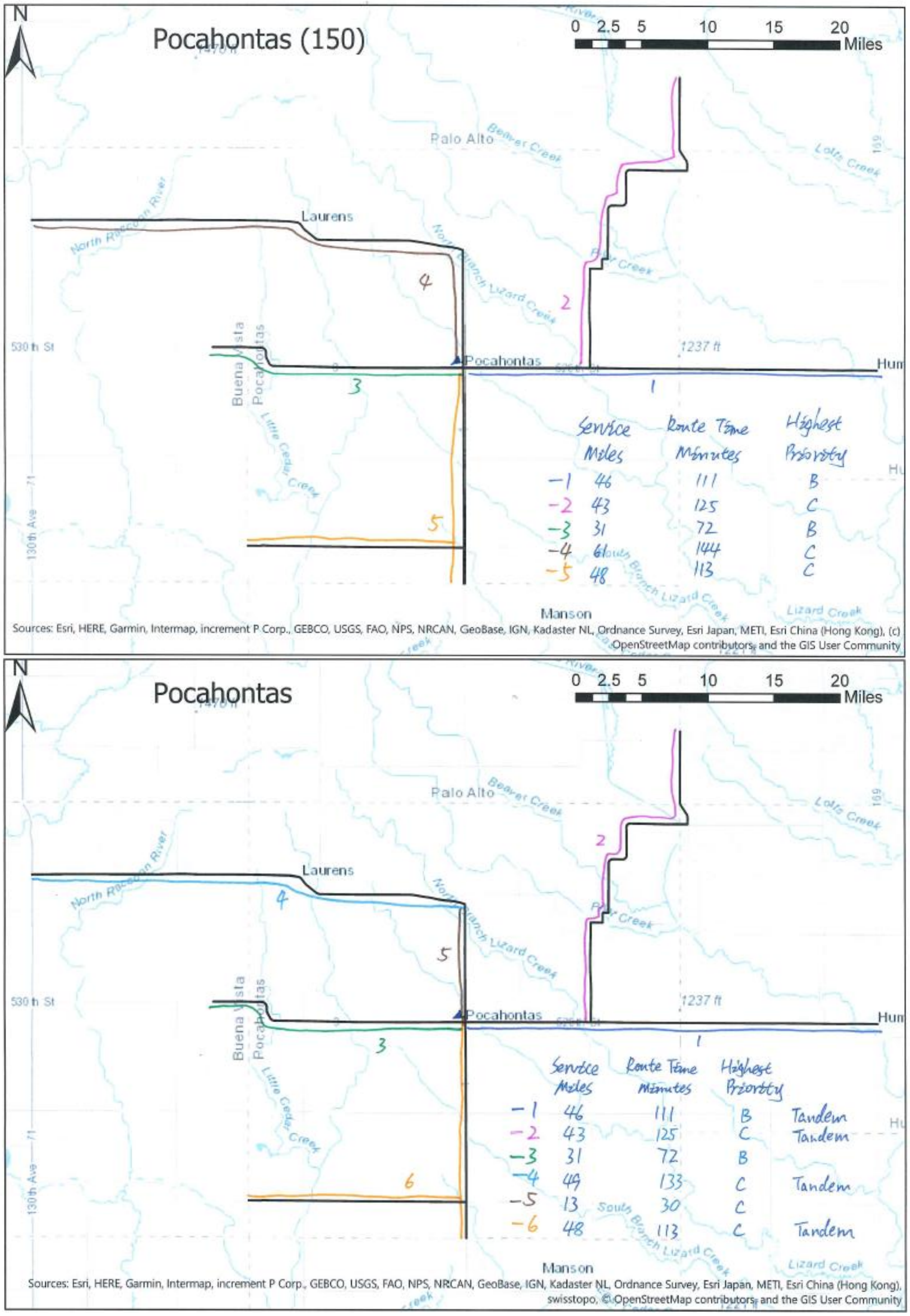
	Service Miles	Route Time Minutes	Highest Priority	
-1	31	72	B	Left
-2	32	90	B	
-3	58	140	C	
-4	37	96	C	
-5	37	86	B	
-6	37	86	B	Left

	Service Miles	Route Time Minutes	Highest Priority	
1-	37	72	B	Left
2-	32	90	B	
3-	42	127	C	Tandem
4-	53	126	C	Tandem
5-	37	86	B	
6-	37	86	B	Left

Figure 7.19. Optimized Correctionville routes with a spreading rate of 150 lbs/lane mile (left) and 300 lbs/lane mile (right)

The current practice uses the same routes as shown in the left-hand map, where Routes 3 and 4 both start from the depot. However, if the spreading rate is set at 300 lbs per lane mile, Route 3 is not feasible. The total distance from the depot to Mapleton is about 58 lane miles. At 300 lbs per lane mile, this road needs 17,400 pounds of material, which exceeds the capacity of a tandem truck.

For the Pocahontas depot, if a lower spreading rate is used, a new set of routes can be created to reduce the deadhead distance. Figure 7.20 shows the optimized routes for this depot with a spreading rate of 150 lbs per lane mile (top) and 300 lbs per lane mile (bottom).



	Service Miles	Route Time Minutes	Highest Priority
-1	46	111	B
-2	43	125	C
-3	31	72	B
-4	61	144	C
-5	48	113	C

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

	Service Miles	Route Time Minutes	Highest Priority	
-1	46	111	B	Tandem
-2	43	125	C	Tandem
-3	31	72	B	
-4	49	133	C	Tandem
-5	13	30	C	
-6	48	113	C	Tandem

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 7.20. Optimized Pocahontas routes with a spreading rate of 150 lbs/lane mile (top) and 300 lbs/lane mile (bottom)

Route 4 on the top map services 61 lane miles. At a spreading rate of 300 lbs per lane mile, this route would exceed the capacity of a tandem truck. But at lower spreading rates (e.g., 150, 200, or 250 lbs per lane mile), this route can be serviced by only one truck.

Multiple-Depot Winter Maintenance Routing Problem with Reload/Intermediate Facilities

This section presents the optimized routes generated for each sector in District 3 by solving the multiple-depot winter maintenance routing problem with reload/intermediate facilities. The depot sector boundaries are shown in Figure 3.2. The reload time, t_R, was set at 15 minutes, and the work span was set at 8 hours.

The MA was used to solve the MDWMRP for each sector using the same algorithm parameters as those described in Chapter 6. Table 7.3 summarizes the total distances and fleet sizes required for the optimized routes in each sector.

Table 7.3. Total travel distance and fleet size comparison: single depot versus multiple depot

Sector	Garage Name	Total Optimized Single-Depot Distance	Optimized Sector Distance	Optimized Single-Depot Fleet Size	Optimized Sector Fleet Size
Ashton	Ashton	717.2	712.2	10	10
	Rock Rapids			4	4
	Rock Valley (for Rock Rapids)			1	2
Le Mars	Alton	1,072.7	1,061.1	9	10
	Rock Valley (for Alton)			1	0
	Correctionville			6	6
	Le Mars			7	7
Onawa	Denison	1,030.3	1,016.3	6	7
	Ida Grove			3	4
	Onawa			10	9
	Sloan			5	5
Sac City	Carroll	1,054.9	1,053.5	4	4
	Pocahontas			6	7
	Rockwell City			6	6
	Sac City			7	6
Storm Lake	Cherokee	1,043.9	1,016.7	6	6
	Emmetsburg			4	3
	Spencer			5	6
	Spirit Lake			5	4
	Storm Lake			5	5

For each of the five sectors, the “Total Optimized Single-Depot Distance” column lists the sum of the optimized route distances generated by solving the SDWMRP for each depot. The “Optimized Sector Distance” column lists the optimized route distance generated by solving the MDWMRP for the sector. The last two columns list the optimized fleet sizes assigned to each depot for the SDWMRP and MDWMRP scenarios, respectively. Because Rock Valley acts as a depot in the Alton and Rock Rapids network, the routing problems for the Alton and Rock Rapids depots are solved as multiple-depot problems, and the results for those depots are presented under the SDWMRP section above.

It can be observed from Table 7.3 that the optimized route distance generated by the MDWMRP for each sector is less than the sum of the distances found by the SDWMRP. Additionally, in the MDWMRP scenario some depots require smaller or larger fleets than in the SDWMRP scenario. The reason is that the road segment service responsibilities for these depots have changed, and the routes are optimized under new circumstances.

The total optimized travel distance for all sectors under the MDWMRP scenario is 4,859.8 miles, slightly lower than the total distance under the SDWMRP scenario (i.e., 4,919 miles). The deadhead distance savings in the MDWMRP scenario compared to the SDWMRP scenario are 1.2%.

As an example, Figure 7.21 illustrates the current responsibility map for the Onawa sector, and Figure 7.22 illustrates the optimized routes for that sector.

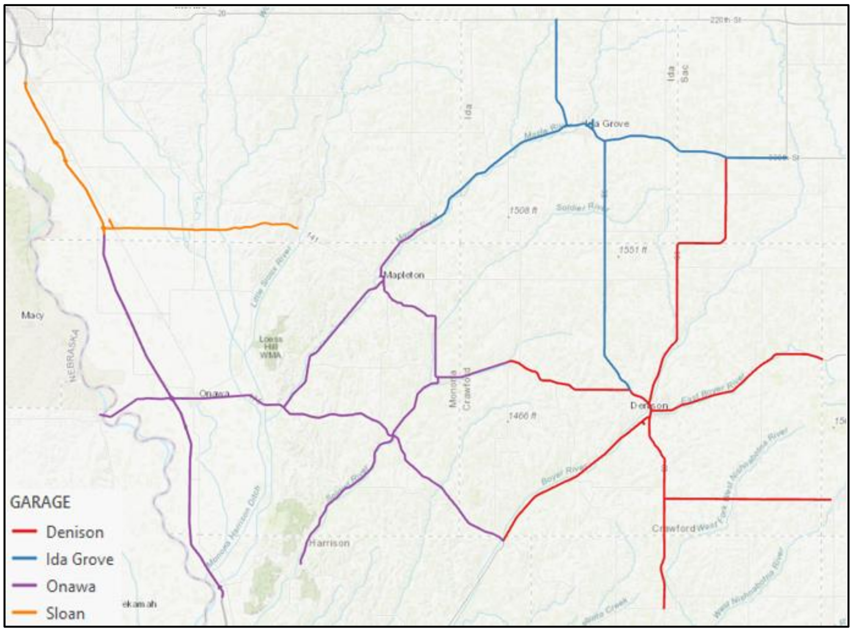


Figure 7.21. Current responsibility map of the Onawa sector

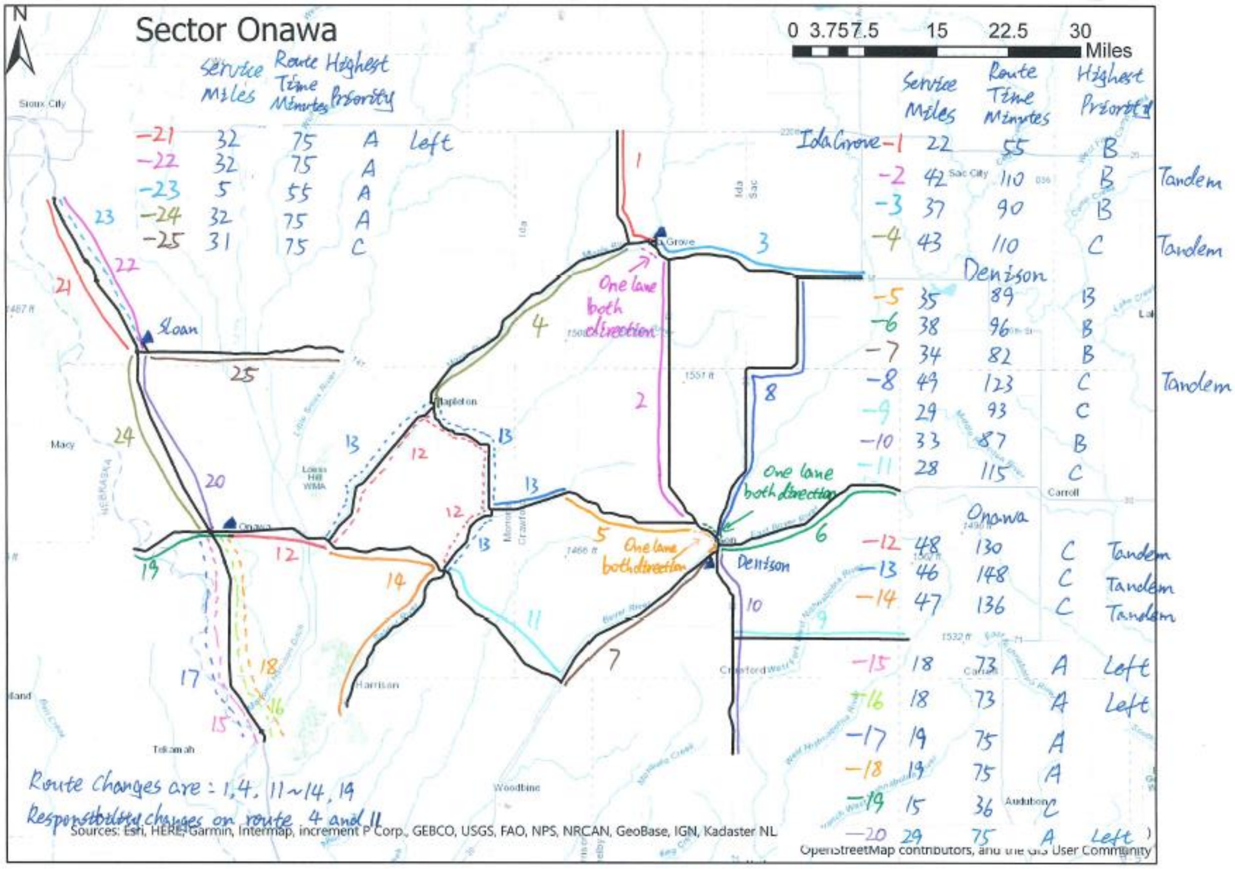


Figure 7.22. Optimized routes for the Onawa sector

The road segment covered by Route 11 is closer to Denison than to Onawa. Therefore, in the optimized solution Route 11 is assigned to the Denison depot. Similarly, the road segment serviced by Route 4 is assigned to the Ida Grove depot. Optimized routes for the other parts of the new Onawa network are changed accordingly. The other routes are the same as those in the SDWMRP scenario. This example shows that the MDWMRP algorithm can find better sector partitions than those in the current route plans.

As shown in Table 7.2, the MDWMRP does not significantly reduce travel distance compared to the SDWMRP. This could be due to the network structure of the depots tested in this study. To explain, Figure 7.23 illustrates three different situations in which a reload is needed.

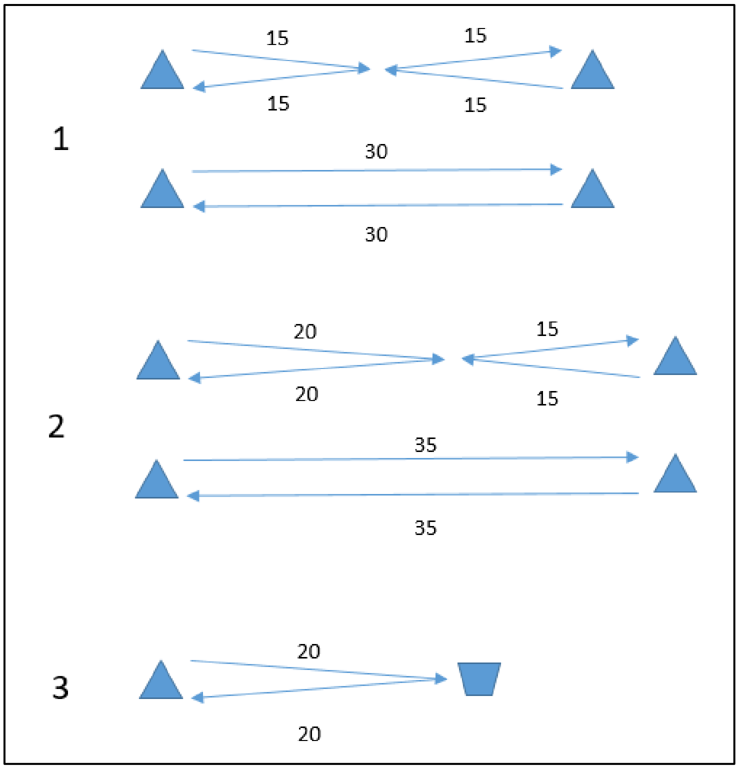


Figure 7.23. Three reload situations

In the figure, the triangles represent depots, and the trapezoid represents a reload station. Each arc has a specific demand for material. For simplicity, let the length of all the arcs be the same. Assume that each truck has a capacity of 30 units of material.

The first diagram in Figure 7.23 illustrates that for a route that requires less than 30 units of material, combining two depots into one sector (so that a truck from depot A can reload at depot B, and vice versa) will not change the total travel distance because the deadhead distance is 0 in both scenarios. The second diagram in Figure 7.23 illustrates that for a route that requires more than 30 units of material, combining two depots will not reduce deadhead. The recommended solution is to add a reload station, as illustrated in the third diagram in Figure 7.23.

The current network structure and depot locations do not require a long haul between any two depots. Since the current operation needs to make the SDWMRP work for any single depot, the whole district network was partitioned into individual depots under the scenario where no reload is required. Therefore, the depots are placed near the center of their responsibility map and such that no road segment is too far to be serviced in a single haul.

8. CONCLUSIONS

Summary

This study developed methods to design optimized routes for winter road maintenance operations. Two types of winter road maintenance routing problems were studied, considering practical constraints. The proposed solution algorithms were applied to real-world networks. The results show that the proposed methods can reduce deadhead distance.

The SDWMRP incorporated real-world winter road maintenance constraints, including road segment service cycle time, heterogeneous vehicle capacities, fleet size, and road-vehicle dependency. The problem was solved using an MA approach. In addition, a parallel metaheuristic algorithm was proposed to enhance the quality and computational efficiency of the solution. The results show that the optimized routes reduced deadhead distance by a total of 13.2% compared to current operations. The deadhead savings percentage could be even larger because while the optimized routes strictly satisfy all constraints, the current operations might not.

The results of the sensitivity analysis of the spreading rate parameter show that this parameter only impacts routes that service roadways with a service level of C, which have a service cycle time of 2.5 hours. This is because roadways with service levels of A or B or those in metropolitan areas are more strongly bound by the cycle time constraint. Trucks that service these roadways will exceed the operation time constraint before using up their material. Meanwhile, the trucks that service roadways with a service level of C will use up their material before they exceed the operation time constraint if the deadhead time of the route is relatively short compared to the service time. Since the spreading rate is highly related to the snowfall amount, the agency can choose the best plan to execute for the network based on the storm severity.

The MDWMRP considered a work duration constraint of eight hours in addition to the constraints of road segment service cycle time, heterogeneous vehicle capacities, fleet size, and road-vehicle dependency. Due to the current network structure and depot locations, the difference between the optimized routes based on the MDWMRP and SDWMRP is insignificant.

This study proposed methods for agencies to optimize their winter maintenance routes. The results can be used to guide route designs and sector partitions. Inefficiencies in current operations can be discovered by comparing current plans with the optimized plans generated by the methods proposed in this study. Note that the optimized routes are calculated based on the assumed speed and spreading rate under the fleet sizes, truck capacities, service cycle times, and plow directions of the current network. If any of these factors change, the agency should recalculate the optimized routes. Otherwise, the optimized routes can be used as a static plan.

Limitations and Future Research

The present study formulated and solved winter maintenance routing problems based on fixed speeds and spreading rates and under current fleet size, truck capacity, service cycle time, and plow direction constraints. There are several caveats and limitations regarding this approach.

First, the service cycle time is treated as a hard constraint in this study, whereas in reality the cycle time is a guideline set by the Iowa DOT. In practice, the cycle time is not strictly enforced. For some routes, exceeding the cycle time by a few minutes might result in significantly improved operational efficiency. Therefore, in future studies the cycle time constraint can be incorporated as a penalty in the objective function or as a soft constraint.

Second, this study assumed a fixed service speed and deadhead speed. However, in real-world operations, these speeds could vary depending on driving habits, road conditions, and traffic conditions. Therefore, speed could be incorporated in the model as a random parameter that follows a probability distribution. A stochastic programming approach can be explored in future research to capture speed.

Third, the optimized routes were designed by assuming the maximum spreading rate. However, as shown in Table 1.1, different spreading rates should be applied for different temperatures, precipitation amounts, and road surface conditions. The sensitivity analysis with regard to spreading rates suggests that the optimized routes could be different if a lower spreading rate is used on certain networks. Using a conservative estimate for the spreading rate might result in longer deadhead distances for such networks and inefficient use of resources.

Fourth, the mathematical models may not represent all of the practical considerations in real-world operations. Although the optimized routes may reduce deadhead distance, a different plan might be used in real-world operations for practical reasons. For example, to address drifting snow on a certain road section, a particular truck may need to be assigned to the problematic road section. The district maintenance manager should be consulted regarding these practical concerns, and routes should be adjusted accordingly.

Lastly, since this study uses the metaheuristic algorithm approach, it is not guaranteed that the optimal result was found. The metaheuristic algorithm can solve a problem in a relatively short amount of computational time, but it usually only generates a locally optimal solution. An exact algorithm, in contrast, is guaranteed to find the global optimum, but it can only solve small-sized problems. By carefully tailoring the metaheuristic algorithm to the winter maintenance routing problem, the local optimal solution found through the metaheuristic algorithm could approach the global optimum in a statistical sense.

REFERENCES

AASHTO. 2015. *2014–2015 Winter Survey Summary*. American Association of State Highway and Transportation Officials, Washington, DC. http://sicop.transportation.org/Documents/SICOP-Survey%20Summaries/2014-15%20Winter%20Maintenance%20Survey%20Summary.pdf.

Dussault, B., B. Golden, C. Groer, and E. Wasil. 2013. Plowing with Precedence: A Variant of the Windy Postman Problem. *Computers and Operations Research*. Vol. 40, No. 4, pp. 1047–1059.

Gundersen A. H., M. Johansen, B. S. Kjær, H. Andersson, and M. Stålhane. 2017. Arc Routing with Precedence Constraints: An Application to Snow Plowing Operations. *ICCL 2017: Computational Logistics, Lecture Notes in Computer Science*. Vol. 10572, pp. 174–188.

Haghani, A. and H. Qiao. 2001. Decision Support System for Snow Emergency Vehicle Routing: Algorithms and Application. *Transportation Research Record: Journal of the Transportation Research Board*. No. 1771, pp. 172–178.

———. 2002. Snow Emergency Vehicle Routing with Route Continuity Constraints. *Transportation Research Record: Journal of the Transportation Research Board.* No.1783, pp. 119–124.

Hajibabai, L., S. M. Nourbakhsh, S., Y. Ouyang, Y., and F. Peng. 2014. Network Routing of Snowplow Trucks with Resource Replenishment and Plowing Priorities: Formulation, Algorithm, and Application. *Transportation Research Record: Journal of the Transportation Research Board*. No. 2440, pp. 16–25.

Hajibabai, L. and Y. Ouyang. 2016. Dynamic Snow Plow Fleet Management Under Uncertain Demand and Service Disruption. *IEEE Transactions on Intelligent Transportation Systems*. Vol. 17, No. 9, pp. 2574–2582.

Jang, W., J. S. Noble, and T. Hutsel. 2010. An Integrated Model to Solve the Winter Asset and Road Maintenance Problem. *IIE Transactions*. Vol. 42, No. 9, pp. 675–689.

Kinable, J., W.-J. van Hoeve, and S.F. Smith. 2016. Optimization Models for a Real-World Snow Plow Routing Problem. *Proceedings of the 13th International Conference on Integration of Artificial Intelligence and Operations Research Techniques in Constraint Programming (CPAIOR 2016)*. May 29–June 1, Banff, Alberta. pp. 229–245.

Knapp, K., B. Chandler, J. Atkinson, T. Welch, H. Rigdon, R. Retting, S. Meekins, E. Widstrand, and R. J. Porter. *Road Diet Informational Guide*. FHWA-SA-14-028. Federal Highway Administration, Office of Safety, Washington, DC.

Muyldermans L., D. Cattrysse, D. Van Oudheusden, and T. Lotan. 2002. Districting for Salt Spreading Operations. *European Journal of Operational Research*. Vol. 139, No. 3, pp. 521–532.

Muyldermans L., D. Cattrysse, and D. Van Oudheusden. 2003. District Design for Arc-Routing Applications. *Journal of Operational Research Society*. Vol. 54, No. 11, pp. 1209–1221.

NDDOT. n.d. *Snow Plow Truck*. North Dakota Department of Transportation, Maintenance Division. https://www.dot.nd.gov/divisions/maintenance/docs/plowtruck.pdf.

Perrier, N., A. Langevin, and C.-A. Amaya. 2008a. Vehicle Routing for Urban Snowplowing Operations. *Transportation Science*. Vol. 42, No. 1, pp. 44–56.

Perrier, N., A. Langevin, and J. F. Campbell. 2008b. The Sector Design and Assignment Problem for Snow Disposal Operations. *European Journal of Operational Research*. Vol. 189, No. 2, pp. 508–525.

Quirion-Blais, O., A. Langevin, and M. Trépanier. 2017. A Case Study of Combined Winter Road Snow Plowing and De-Icer Spreading. *Canadian Journal of Civil Engineering*. Vol. 44, No. 12, pp. 1005–1013.

Salazar-Aguilar, M. A., A. Langevin, and G. Laporte. 2012. Synchronized Arc Routing for Snowplowing Operations. *Computers and Operations Research.* Vol. 39, No. 7, pp. 1432–1440.

Salt Institute. 2013. *The Snowfighter's Handbook: A Practical Guide for Snow and Ice Control*. Salt Institute, Alexandria, VA.

Tagmouti, M., M. Gendreau, and J-Y. Potvin. 2007. Arc Routing Problems with Time-Dependent Service Costs. *European Journal of Operational Research*. Vol. 181, No. 1, pp. 30–39.

———. 2010. A Variable Neighborhood Descent Heuristic for Arc Routing Problems with Time-Dependent Service Costs. *Computers and Industrial Engineering*. Vol. 59, No. pp.954–963.

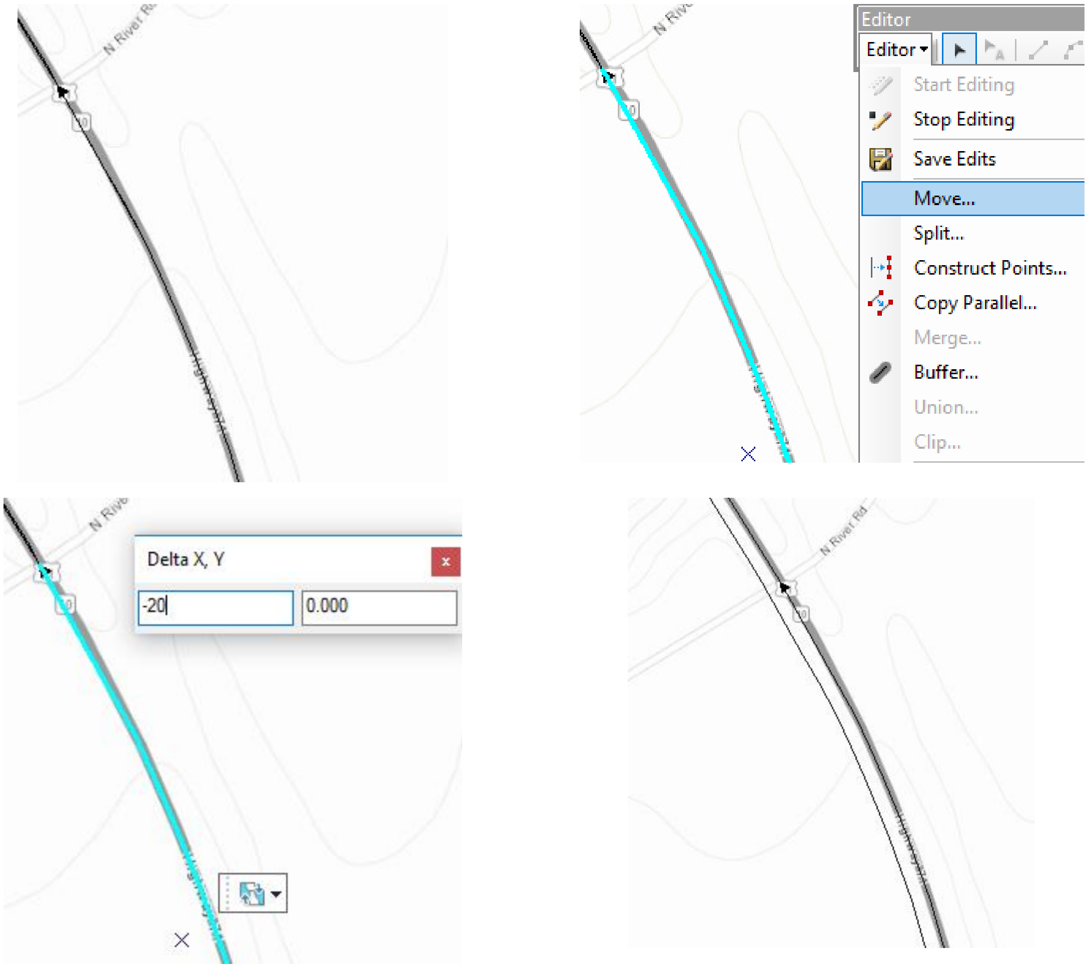
Usman, T., L. Fu, and L. F. Miaranda-Moreno. 2010. Quantifying Safety Benefit of Winter Road Maintenance: Accident Frequency Modeling. *Accident Analysis and Prevention*, Vol. 42, pp. 1878–1887.

APPENDIX: PROCEDURE FOR MANUALLY FIXING THE NETWORK

To ensure the accuracy of the transportation network data, the network of each depot was manually checked and edited in ArcGIS following the procedure summarized in this appendix.

Building Non-Inventory Polylines

First, segments were separated by direction so that roadways with opposing traffic flows did not share the same nodes. To be consistent, all inventory roads (northbound and eastbound) were left untouched, while the non-inventory roads (southbound and westbound) were offset using the "Move" command by (-20, 0) for southbound roads and (0, 20) for westbound roads (Figure A.1). Then the polyline was "Flipped".



Delta X, Y: -20 | 0.000

Figure A.1. Procedure for building a new polyline for one direction of a non-inventory road

Adding Non-Service Roads

Second, to distinguish between service and non-service roads, a “Service Flag” attribute was created. Service Flag = 1 was given to all service roads and 0 to all non-service roads. Non-service roads were drawn to connect the following (Figure A.2):

- The service boundary of each garage
- The garage to the service network
- Off-ramps to on-ramps

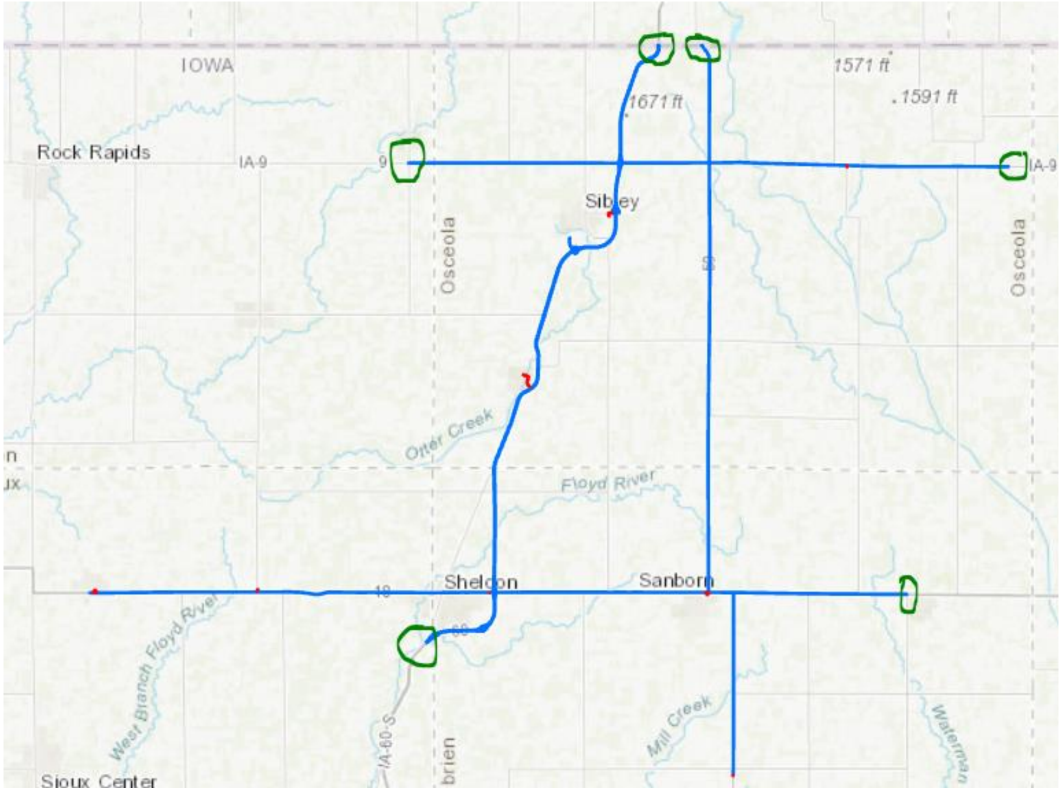


Figure A.2. Adding turnaround points at the service boundaries

For each location indicated by a green circle in Figure A2, a polyline was drawn to connect the end of an eastbound to a westbound roadway or a northbound to a southbound roadway (see Figure A.3).

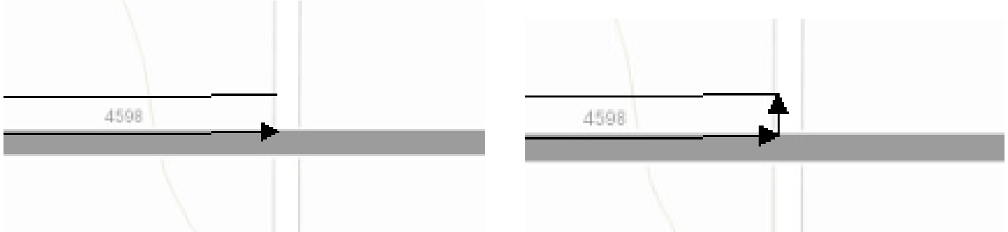


Figure A.3. Unconnected versus connected endpoint

In Figure A.4, the non-highlighted lines represent the service network.

Figure A.4. Connecting depot to service network

The highlighted portion in Figure A.4 was added to connect the route to the garage (i.e., the red triangle).

Additionally, polylines at intersections (Figure A.5, left) were added as service roads, and U-turns (Figure A.5, right) were added as non-service roads.

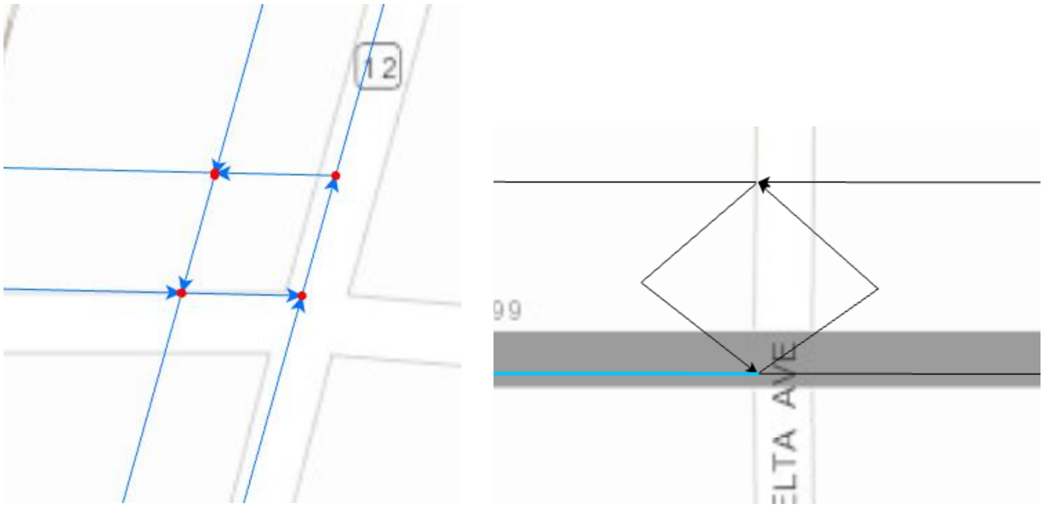


Figure A.5. Intersections (left) and U-turns (right)

The AVL data were used to locate garages, turnaround points, and U-turns.

As shown in Figure A.6, garage locations were determined by finding where all the maintenance trucks started and ended their routes.

Figure A.6. Garage location

These spots usually stood out because they diverged from the main roads. Turnaround points were also identified (Figure A.7).

Figure A.7. Turnaround point

Verifying Attributes

Third, each road segment's attributes, namely facility type, number of lanes, and direction, were examined (Figure A.8).

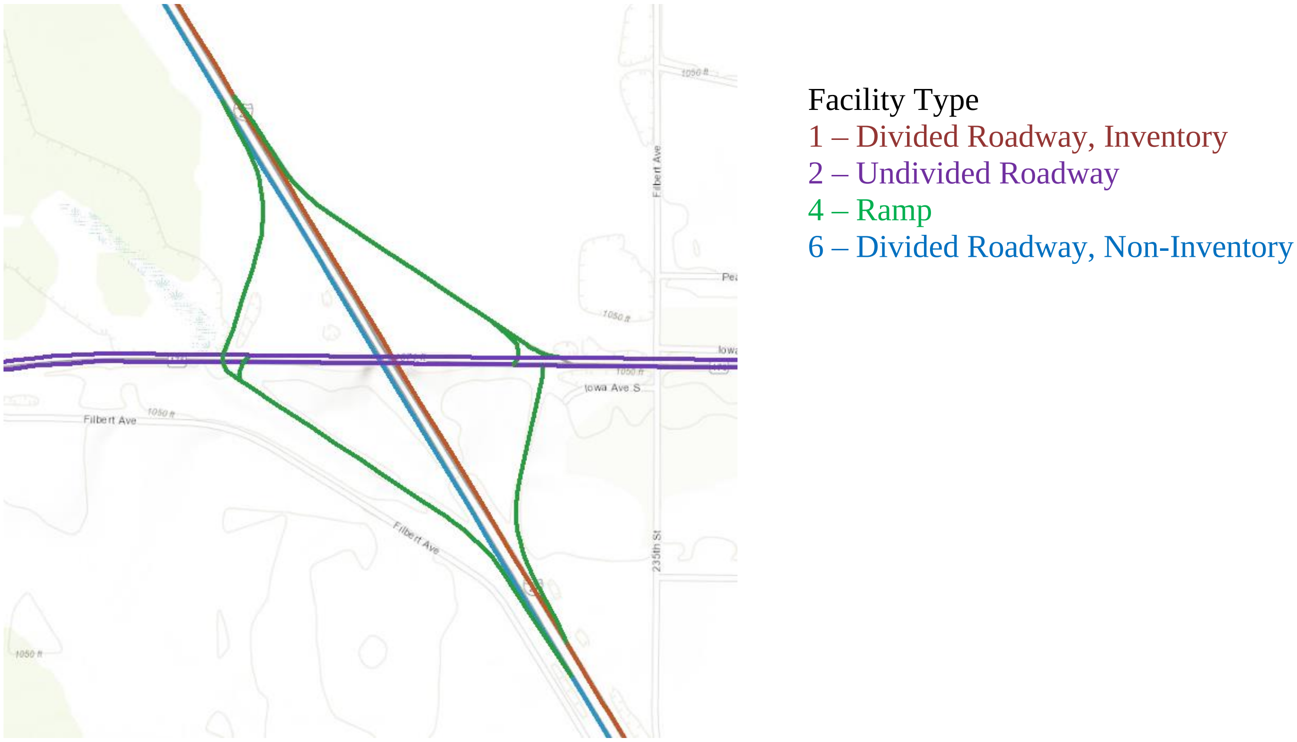


Figure A.8. Facility types identified in an of ArcGIS map

To represent the road-truck dependency constraint as described in Chapter 5, each roadway segment was assigned a facility type to indicate whether a left-wing truck or a right-wing truck is needed to service the roadway. In particular, all undivided roadways and their intersections, as well as all divided roadways spanning less than 16 miles, were given Facility Type = 2 (colored purple in Figure A.8). These roadways are serviced by right-wing trucks. Note that divided roadways spanning less than 16 miles can also be serviced by left-wing trucks, provided that the median is wide enough to hold the snow. However, if a left-wing truck were assigned to such roadways, the truck's full capacity would not be used. A single-axle truck with a capacity of 12,000 lbs can service 40 lane miles at a rate of 300 lbs/lane mile. For divided roadways longer than 16 miles, Facility Type = 1 was used to denote inventory roads (colored red in Figure A.8) and 6 to denote non-inventory roads (colored blue in Figure A.8). These roadways can be serviced by left-wing trucks because plowing the inner lanes in both directions covers 32 lane miles or more and can effectively use the truck's capacity. Facility Type = 4 was used for entrance and exit ramps (colored green in Figure A.8).

Each road segment's attributes were verified in Google Maps (Figure A.9).

Figure A.9. Corresponding Google map of facility types

Number of lanes ranged from 1 to 5, and direction was classified as E, N, S, or W, for eastbound, northbound, southbound, or westbound, respectively.

Finally, consecutive segments with the same facility type, number of lanes, direction, maintenance service level, garage, and service flag were merged in order to reduce the number of segments in the network (Figure A.10).

MAINT	GARAGE	FACILITY_TYPE	NUMBER_LANES	DIRECTION	Service_Flag
B	Pocahontas	2	1	E	1
B	Pocahontas	2	1	E	1

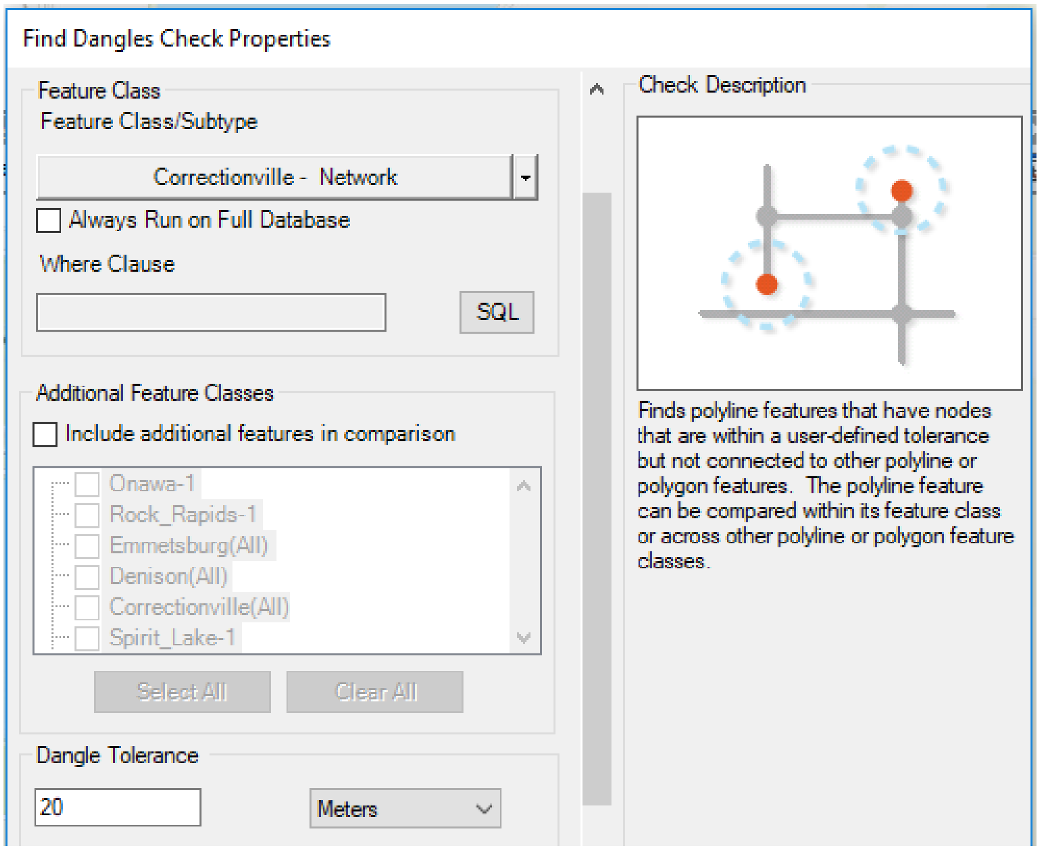
MAINT	GARAGE	FACILITY_TYPE	NUMBER_LANES	DIRECTION	Service_Flag
B	Pocahontas	2	1	E	1

Figure A.10. Merging segments

Using the ArcGIS Data Reviewer

The fourth step was to use the ArcGIS Data Reviewer for additional checks. In particular, “Find Dangles Check,” “Orphan Check,” “Polyline or Path Closes on Self Check,” “Multipart Line Check,” and “Evaluate Polyline Length Check” were run on the network.

The “Find Dangles Check” is shown in Figure A.11.


Find Dangles Check Properties

Feature Class

Feature Class/Subtype: Correctionville - Network

☐ Always Run on Full Database

Where Clause

SQL

Additional Feature Classes

☐ Include additional features in comparison

☐ Onawa-1
☐ Rock_Rapids-1
☐ Emmetsburg(All)
☐ Denison(All)
☐ Correctionville(All)
☐ Spirit_Lake-1

Select All | Clear All

Dangle Tolerance: 20 Meters

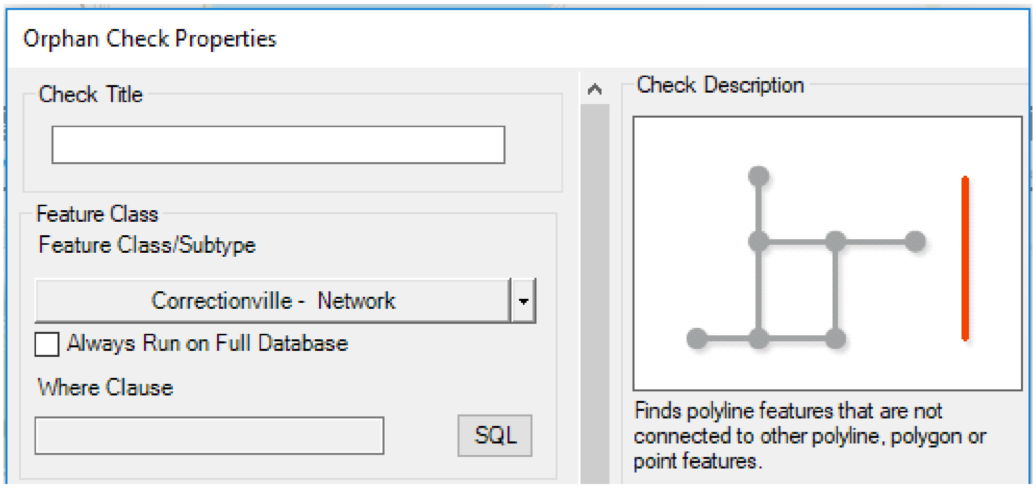
Check Description

Finds polyline features that have nodes that are within a user-defined tolerance but not connected to other polyline or polygon features. The polyline feature can be compared within its feature class or across other polyline or polygon feature classes.

Figure A.11. Find Dangles Check

A distance of 20 meters was input for the dangle tolerance. All dangles were deleted from the network.

The “Orphan Check” is shown in Figure A.12.


Orphan Check Properties

Check Title

Feature Class

Feature Class/Subtype: Correctionville - Network

☐ Always Run on Full Database

Where Clause

SQL

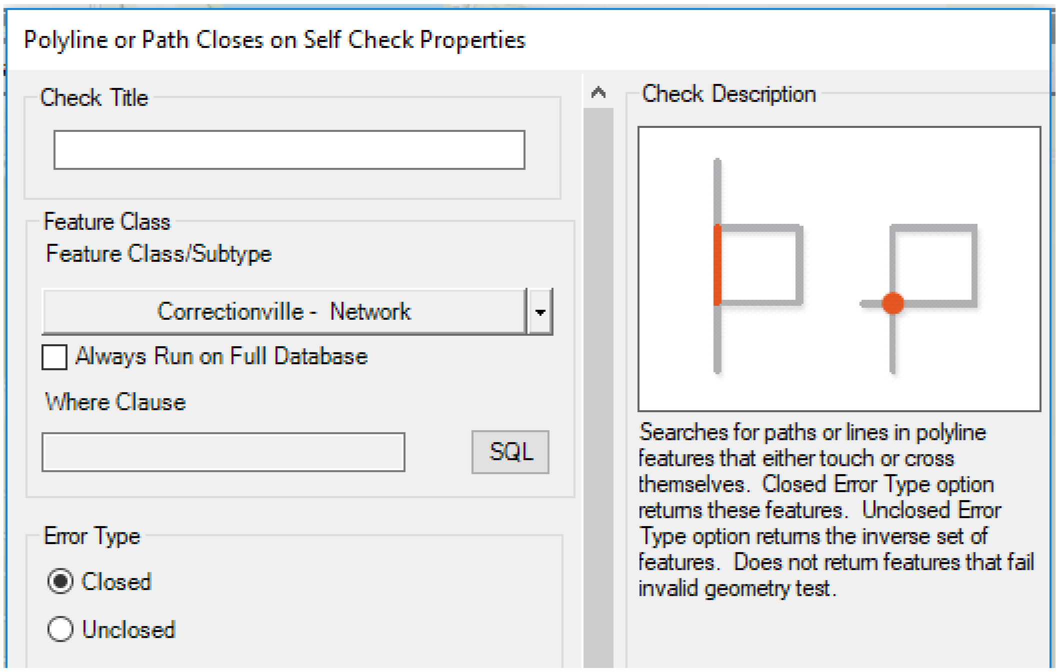
Check Description

Finds polyline features that are not connected to other polyline, polygon or point features.

Figure A.12. Orphan Check

Unconnected polylines found using this check were deleted.

The “Polyline or Path Closes on Self Check” is shown in Figure A.13.



Polyline or Path Closes on Self Check Properties

Check Title

Feature Class

Feature Class/Subtype

Correctionville - Network

☐ Always Run on Full Database

Where Clause

SQL

Error Type

● Closed

○ Unclosed

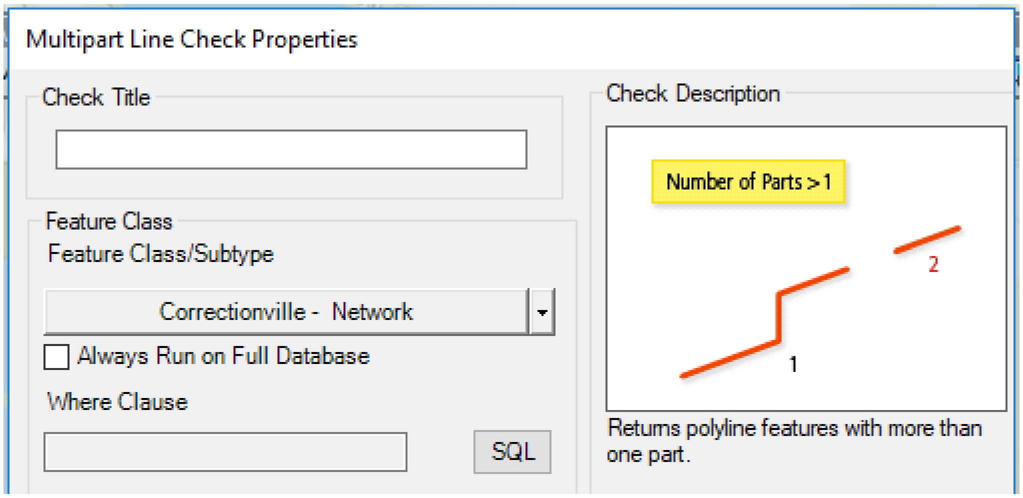
Check Description

Searches for paths or lines in polyline features that either touch or cross themselves. Closed Error Type option returns these features. Unclosed Error Type option returns the inverse set of features. Does not return features that fail invalid geometry test.

Figure A.13. Polyline or Path Closes on Self Check

This check used a “closed” error type. Polylines were split where they contacted themselves.

The “Multipart Line Check” is shown in Figure A.14.



Multipart Line Check Properties

Check Title

Feature Class

Feature Class/Subtype

Correctionville - Network

☐ Always Run on Full Database

Where Clause

SQL

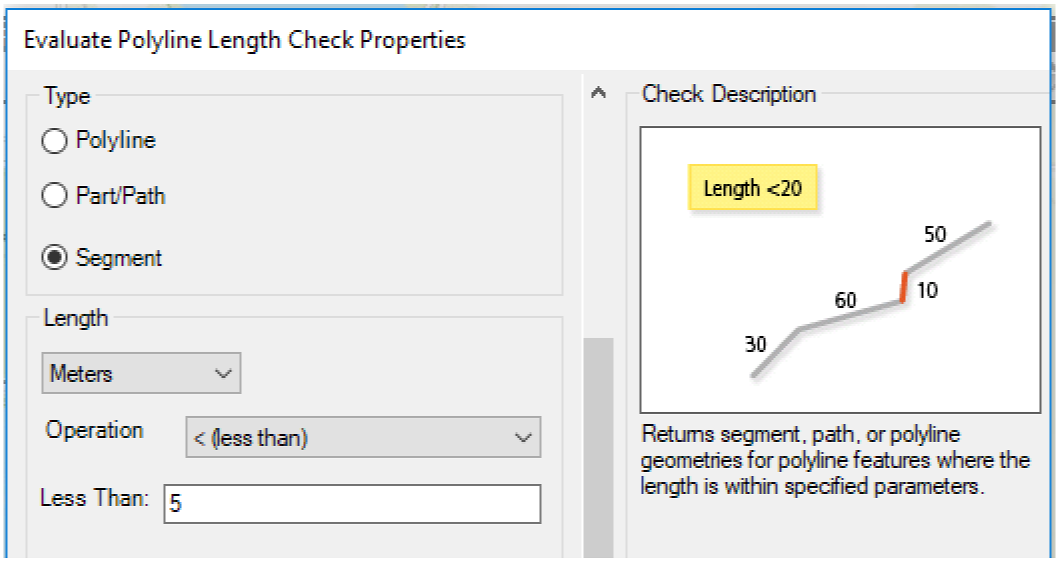
Check Description

Returns polyline features with more than one part.

Figure A.14. Multipart Line Check

To fix a multipart line, the line was split and the problem area was deleted. The remaining part of the line was then redrawn or stretched to connect the network.

The “Evaluate Polyline Length Check” is shown in Figure A.15.



Evaluate Polyline Length Check Properties

Type

○ Polyline

○ Part/Path

● Segment

Length

Meters

Operation: < (less than)

Less Than: 5

Check Description

Returns segment, path, or polyline geometries for polyline features where the length is within specified parameters.

Figure A.15. Evaluate Polyline Length Check

Segments less than 5 meters in length were examined. Corrections involved zooming to where two vertices were very close to each other and deleting one of them.

The network was edited until no records were returned by the checks. Intersection connectivity was also reviewed, because disconnects are common and difficult to see in these places (Figure A-16).

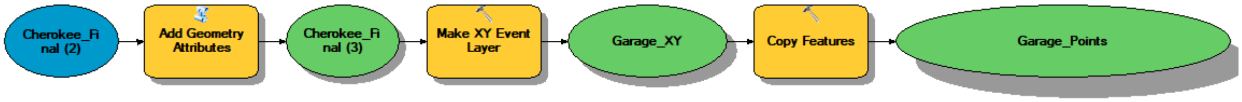
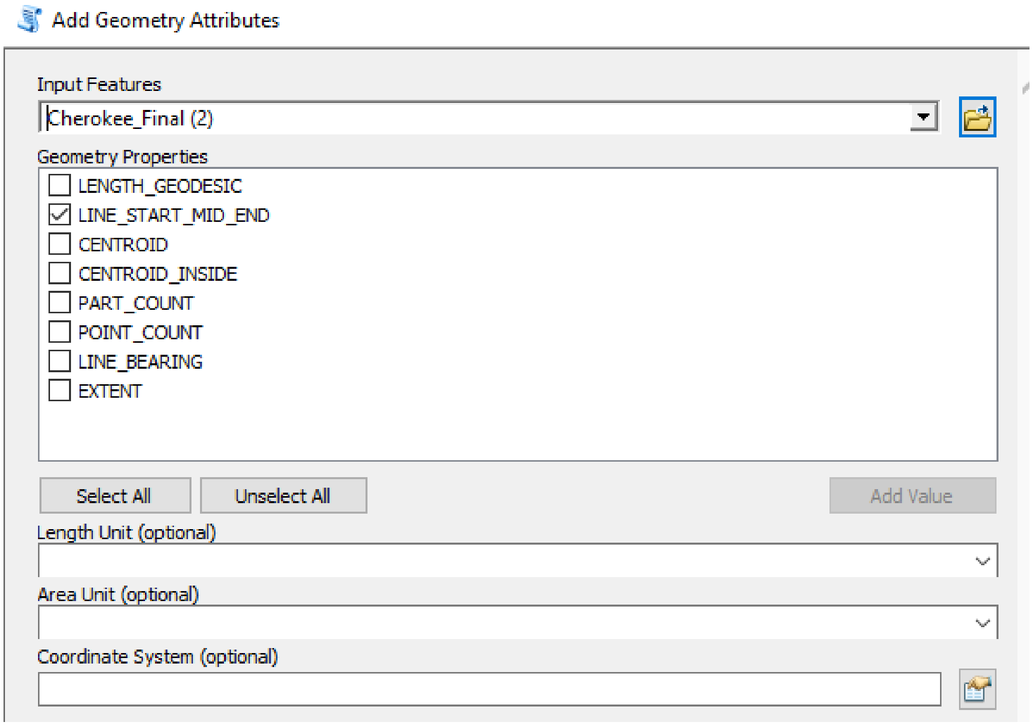


Figure A.16. Process for reviewing intersection connectivity

First, the endpoints of all polylines were created with the “Add Geometry Attributes” tool (Figure A.17).



Add Geometry Attributes

Input Features: Cherokee_Final (2)

Geometry Properties
- ☐ LENGTH_GEODESIC
- ☑ LINE_START_MID_END
- ☐ CENTROID
- ☐ CENTROID_INSIDE
- ☐ PART_COUNT
- ☐ POINT_COUNT
- ☐ LINE_BEARING
- ☐ EXTENT

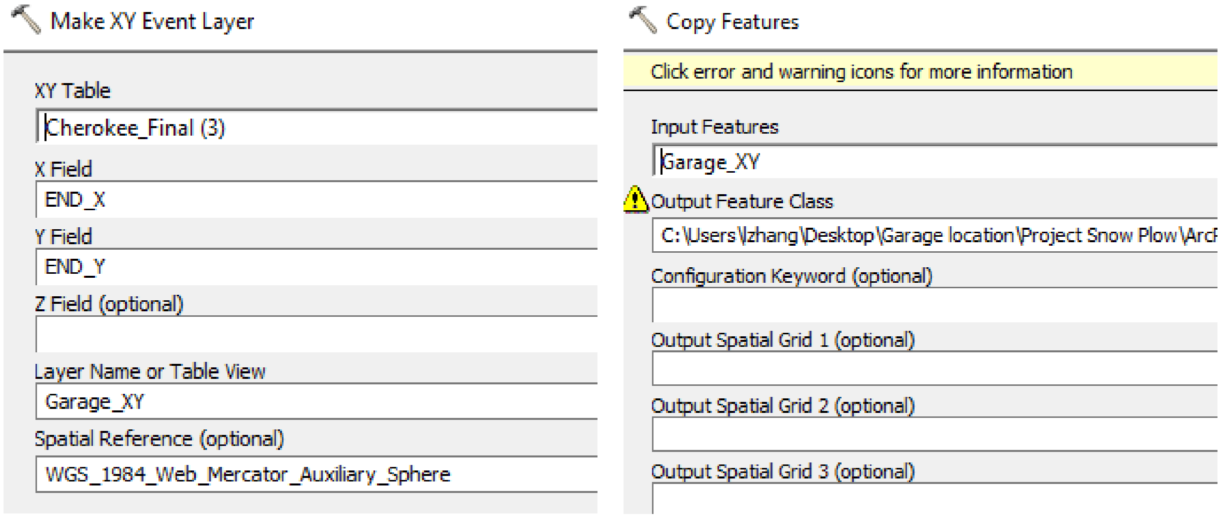
Length Unit (optional)

Area Unit (optional)

Coordinate System (optional)

Figure A.17. Add Geometry Attributes

Next, "Make XY Event Layer" and "Copy Features" were used to format these points as an independent layer (Figure A.18).



Make XY Event Layer

XY Table: Cherokee_Final (3)

X Field: END_X

Y Field: END_Y

Z Field (optional)

Layer Name or Table View: Garage_XY

Spatial Reference (optional): WGS_1984_Web_Mercator_Auxiliary_Sphere

Copy Features

Click error and warning icons for more information

Input Features: Garage_XY

Output Feature Class: C:\Users\lzhang\Desktop\Garage location\Project Snow Plow\Arc

Configuration Keyword (optional)

Output Spatial Grid 1 (optional)

Output Spatial Grid 2 (optional)

Output Spatial Grid 3 (optional)

Figure A.18. Make XY Event Layer (left) and Copy Features (right)

The second step was to find the point distance, or the distance between the points of two layers (Figure A.19).

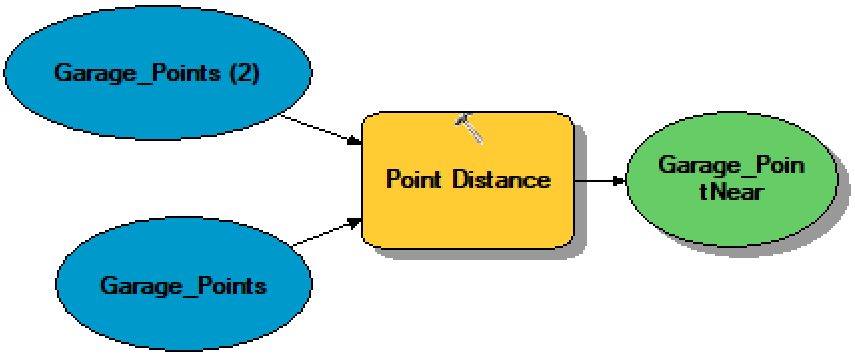
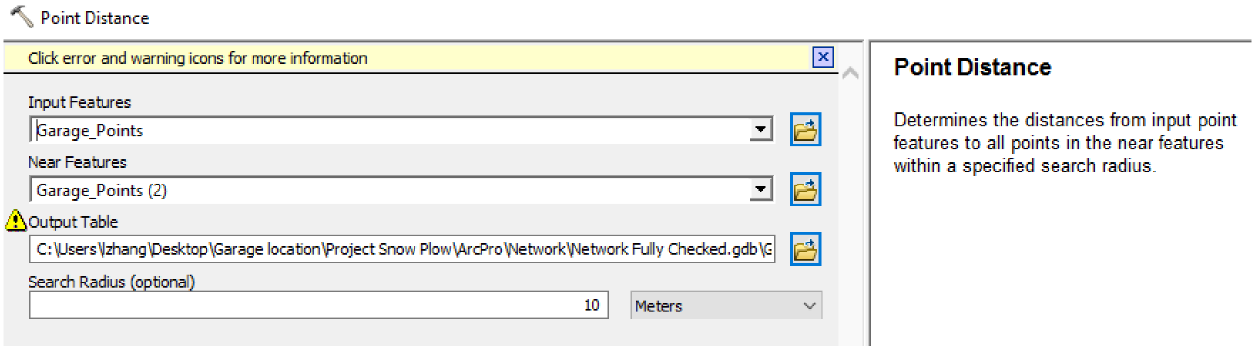


Figure A.19. Process for finding point distance

Both input layers were the "Garage Points" layers. A search radius of 10 meters was applied (Figure A.20).



Input Features: Garage_Points

Near Features: Garage_Points (2)

Output Table: C:\Users\lzhang\Desktop\Garage location\Project Snow Plow\ArcPro\Network\Network Fully Checked.gdb\

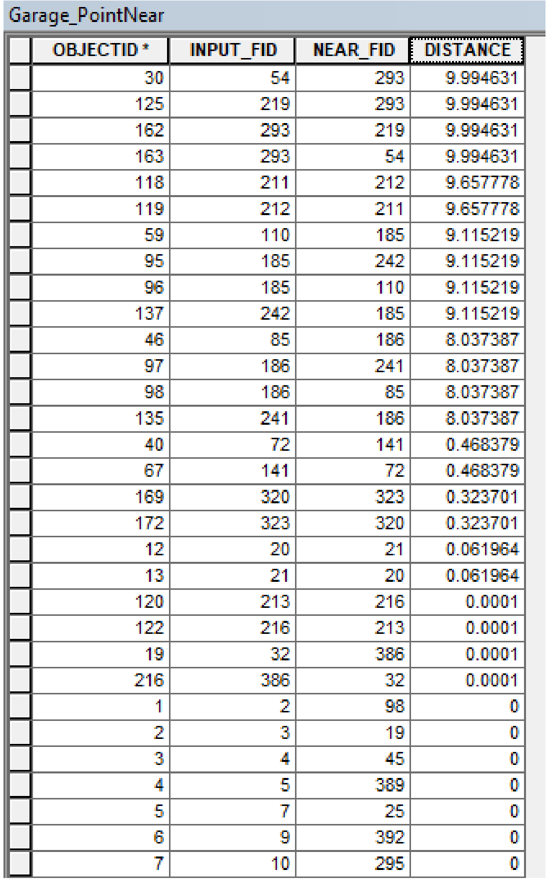
Search Radius (optional): 10 Meters

Point Distance

Determines the distances from input point features to all points in the near features within a specified search radius.

Figure A.20. Point Distance function in ArcGIS

A "Near" table was output (Figure A.21). A distance of zero indicated that the endpoints are identical. If the distance was slightly larger than zero, the corresponding points required examination.



Garage_PointNear

OBJECTID *	INPUT_FID	NEAR_FID	DISTANCE
30	54	293	9.994631
125	219	293	9.994631
162	293	219	9.994631
163	293	54	9.994631
118	211	212	9.657778
119	212	211	9.657778
59	110	185	9.115219
95	185	242	9.115219
96	185	110	9.115219
137	242	185	9.115219
46	85	186	8.037387
97	186	241	8.037387
98	186	85	8.037387
135	241	186	8.037387
40	72	141	0.468379
67	141	72	0.468379
169	320	323	0.323701
172	323	320	0.323701
12	20	21	0.061964
13	21	20	0.061964
120	213	216	0.0001
122	216	213	0.0001
19	32	386	0.0001
216	386	32	0.0001
1	2	98	0
2	3	19	0
3	4	45	0
4	5	389	0
5	7	25	0
6	9	392	0
7	10	295	0

Figure A.21. Near table in ArcGIS

Calculating Service and Deadhead Speed

Lastly, service speed, the speed at which a maintenance truck services the network, and deadhead speed, the speed at which a maintenance truck travels when it is not servicing the network, were added as attributes. The speeds differed for urban roadways (inside city limits) and rural roadways (outside city limits) (Table A.1).

Table A.1. Service and deadhead speeds

Speed (mph)	Service	Deadhead
Urban	22	32
Rural	26	40

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