Optimal Placement of Iowa DOT Maintenance Garages: Muscatine and Dubuque Case Studies

Final Report
March 2017

Center for Transportation Research and Education

IOWA STATE UNIVERSITY
Institute for Transportation

Sponsored by
Iowa Department of Transportation
(InTrans Project 15-534)
Federal Highway Administration

About CTRE

The mission of the Center for Transportation Research and Education (CTRE) at Iowa State University is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, and reliability while improving the learning environment of students, faculty, and staff in transportation-related fields.

About InTrans

The mission of the Institute for Transportation (InTrans) at Iowa State University is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, reliability, and sustainability while improving the learning environment of students, faculty, and staff in transportation-related fields.

Disclaimer Notice

ISU Non-Discrimination Statement

Iowa DOT Statements

The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
InTrans Project 15-534		

4. Title and Subtitle	5. Report Date
Optimal Placement of Iowa DOT Maintenance Garages: Muscatine and Dubuque Case Studies	March 2017
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
Jing Dong (orcid.org/0000-0002-7304-8430) and Luning Zhang (orcid.org/0000-0001-7764-0047)	InTrans Project 15-534
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Institute for Transportation Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664	**11. Contract or Grant No.**
12. Sponsoring Organization Name and Address	**13. Type of Report and Period Covered**
Iowa Department of Transportation 800 Lincoln Way Ames, IA 50010 Federal Highway Administration U.S. Department of Transportation 1200 New Jersey Avenue SE Washington, DC 20590	Final Report **14. Sponsoring Agency Code** SPR RB26-015

15. Supplementary Notes

Visit www.intrans.iastate.edu for color pdfs of this and other research reports.

16. Abstract

Winter road maintenance operations involve complex operational strategies and long-term planning decisions. The objective of this project was to develop an optimization-based approach to sustainable replacement, improvement, and relocation of maintenance garages. In particular, an arc routing problem was formulated to design efficient routes for salting, pre-wetting, and plowing, considering the operational characteristics of winter road maintenance.

The researchers conducted two case studies—for the Muscatine and Dubuque areas in Iowa. In both case studies, heuristic solution algorithms were developed to find the optimal snow routes that satisfy maintenance service level requirements.

Alternative garage locations were compared in terms of number of snow routes, deadhead times, and distances. New garage locations were recommended to replace the existing Muscatine and Dubuque garages.

17. Key Words	18. Distribution Statement
arc routing problem—automatic vehicle location (AVL) data—optimal garage location—road maintenance operations—winter road maintenance	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	101	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

OPTIMAL PLACEMENT OF IOWA DOT MAINTENANCE GARAGES: MUSCATINE AND DUBUQUE CASE STUDIES

Final Report
March 2017

Principal Investigator
Jing Dong, Transportation Engineer
Center for Transportation Research and Education, Iowa State University

Research Assistant
Luning Zhang

Authors
Jing Dong and Luning Zhang

Sponsored by
Iowa Department of Transportation
and Federal Highway Administration

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement with the
Institute for Transportation
(InTrans Project 15-534)

A report from
Institute for Transportation
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
www.intrans.iastate.edu

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The research team would like to acknowledge the Iowa Department of Transportation (DOT) for sponsoring this research and the Federal Highway Administration for state planning and research (SPR) funds used for this project.

EXECUTIVE SUMMARY

Winter road maintenance operations involve complex operational strategies and long-term planning decisions. During the 2014 garage review, the Iowa Department of Transportation (DOT) District Maintenance Manager group evaluated the existing garages in each district in terms of operational efficiency, building considerations, and site characteristics.

Based on the repair/replacement urgency, the group recommended replacement of the Dubuque garage and the Muscatine garage as the highest replacement priorities. The objective of this project was to develop optimization-based approaches to sustainable replacement, improvement, and relocation of maintenance garages.

This final report documents the data, methodologies, and findings from the case studies conducted for the Muscatine and Dubuque, Iowa areas. To reduce operational costs, improve mobility, and reduce environmental and societal impacts, an optimization-based approach was proposed to locate winter maintenance garages by leveraging existing data and models.

The Iowa DOT's geographic information management system (GIMS) database and snowplow automatic vehicle location (AVL) databases were the two major datasets used in this study.

Two heuristic algorithms were developed to support the winter road maintenance planning decisions in terms of garage location, vehicle route design, and fleet configuration.

An arc routing problem was formulated to design efficient routes for salting, pre-wetting, and plowing, considering the operational characteristics of winter road maintenance. Two case studies were conducted for the Muscatine and Dubuque areas, respectively.

In both case studies, the researchers developed heuristic solution algorithms to find the optimal snow routes that satisfy maintenance service level requirements. Alternative garage locations were compared in terms of number of snow routes, deadhead times, and distance. New garage locations were recommended to replace the existing Muscatine and Dubuque, Iowa garages.

INTRODUCTION

Winter road maintenance is important to road safety and efficiency for road users (Haghani and Qiao 2001). From October 2014 to April 2015, 23 states spent a total of $1.1 billion on plowing and spreading materials on roadways according to a recent survey by the American Association of State Highway and Transportation Officials (AASHTO 2015).

In spring 2013, the Center for Transportation Research and Education (CTRE) at Iowa State University conducted a study on service-level assignment for snowplow operations. Alternative scenarios were developed in an effort to align winter maintenance resources with priorities, as in, higher volume roads and Interstates. During the 2014 garage review, the Iowa Department of Transportation (DOT) District Maintenance Manager group evaluated the existing garages in each district in terms of operational efficiency, building considerations, and site characteristics. Based on the repair/replacement urgency, the group recommended replacement of the Dubuque garage and the Muscatine garage as the highest replacement priorities.

To reduce operational costs, improve mobility, and reduce environmental and societal impacts, an optimization-based approach was proposed to locate winter maintenance garages by leveraging existing datasets and models. The maintenance trucks are mainly used in winter for plowing and material spreading. Satisfying the winter road maintenance level of service requirement is the main concern of the garage location issue.

This research developed heuristic-based optimization approaches to support the winter road maintenance planning decisions in terms of depot location, vehicle route design, and fleet configuration. The first approach was applied to a case study focusing on maintenance operations and planning for Muscatine County and Louisa County, Iowa, and the second approach was applied to a case study focusing on maintenance operations and planning for Dubuque County, Iowa.

LITERATURE REVIEW

Winter road maintenance involves a variety of strategic and operational planning decisions, including depot placement, sector design, route design and fleet scheduling. Real world constraints, such as vehicle capacity, workload balance, service frequency, and synchronized service requirement, may be imposed when solving these problems.

Considering these constraints in the decision-making process often makes the problem unique and calls for problem-specific formulation and solution methods. In general, snowplowing and salt spreading operations involve two types of problems: (1) the arc routing problem (ARP), where the depot locations and sectors are given, and routes need to be decided and (2) the location routing problem (LRP), where the depot locations, sector allocations, and routes need to be solved simultaneously.

Perrier et al. (2006a, 2006b, 2007a, 2007b) conducted a four part survey of models and algorithms for winter road maintenance. In the third part, vehicle routing and depot location problems were reviewed. Later, Perrier et al. (2010) conducted another survey on vehicle routing models and algorithms for winter road spreading operations, in which related papers were classified by problem character, model structure, and solution method.

Arc Routing Problems

Most of the existing ARP studies solved capacitated arc routing problems (CARPs) (Haghani and Qiao 2001, 2002, Omer 2007, Liu et al. 2014). In particular, Haghani and Qiao (2001, 2002) and Omer (2007) considered truck capacity constraints; Haghani and Qiao (2001), Omer (2007), and Liu et al. (2014) considered maximum travel time constraints. In addition to these constraints, Haghani and Qiao (2001) also added a time window to deal with network hierarchy. Haghani and Qiao (2002) introduced continuity constraints. The continuity constraints require links that are serviced by one truck to be connected, and the deadhead of one route may only exist from the depot to the beginning node of the first service link and from the end node of the last service link back to the depot.

Mathematical programming and heuristics have been used to solve the CARP. Haghani and Qiao (2001) proposed a “merge, delete, insert, exchange” method to build and improve routes. To account for service continuity constraints in the ARP formulation, Haghani and Qiao (2002) represented the network in a from-link to-link matrix and solved the problem as a capacitated minimum spanning tree (CMST). Omer (2007) proposed a greedy randomized adaptive search procedure (GRASP) method to build and improve routes.

GRASP consists of iterations made up from constructions of a greedy randomized step and improvement through a local searches step. The route is initialized by sequentially adding arcs to the last node of this route. Starting from the beginning node, all arcs that connected to this node are considered as possible incremental arcs if adding the arc will not violate capacity constraint. From the possible incremental arcs set, one arc is chosen randomly to be the next arc for the route, and the end node of this arc will be the last node of this route. This procedure ends when the route cannot add more arcs or all arcs are serviced. Then, routes are improved by local search methods similar to Haghani and Qiao (2001). Simulated annealing (SA) is used to guide the local search.

Liu et al. (2014) used the memetic algorithm with extended neighborhood search (MAENS) to solve the CARP problem. The memetic algorithm (MA) is analogous to the genetic algorithm (GA), with each arc represented by genotype. The local search in the MA replaces the mutation operators in the GA. In MAENS, the extended neighborhood search uses a large step size and, thus, is capable of searching within a large neighborhood.

Some research focuses on special concerns of winter maintenance operations. Perrier et al. (2008) addressed hierarchical routing problems for plowing operations where service order is determined by road segment priority. Mathematical programming has been used to solve the hierarchical routing problems.

Salazar-Aguilar et al. (2012) considered the synchronized arc routing problem (SyARP) for snowplowing operations, where road segments with more than one lane must be plowed simultaneously by multiple vehicles. Adaptive large neighborhood heuristics were used to construct and improve route design. Sullivan et al. (2015) examined the use of satellite salt facilities to minimize travel time. The use of satellite salt facilities could reduce the deadhead time that plow trucks travel to reload. Finding the best location for satellite salt facilities is a facility location problem and was solved using the built-in algorithm in TransCAD transportation planning software.

In summary, four of the seven ARP papers on winter maintenance operation optimization problems addressed CARP (i.e., Haghani and Qiao 2001, 2002, Omer 2007, Liu et al. 2014) and the other three dealt with special concerns. In most cases, the objective function was to minimize deadhead distance or deadhead time. Four of the seven papers used heuristic based approaches and implemented a local search (i.e., Haghani and Qiao 2001, Omer 2007, Salazar-Aguilar et al. 2012, Liu et al. 2014). Two of the seven used IBM’s ILOG CPLEX Optimization Studio (CPLEX) to solve mathematical programming (i.e., Haghani and Qiao 2002, Perrier et al. 2008), and one used TransCAD’s built-in solution method (i.e., Sullivan et al. 2015).

Location Routing Problems

Fewer studies focused on LRPs for winter maintenance operations. This could be because that LRPs are more complicated than ARPs. LRPs include multi-level decision making, which makes it difficult to find high quality solutions in a reasonable time. Existing approaches solve LRPs using heuristic algorithms and iterating between location decisions and routing.

For example, Cai et al. (2009) applied a two-stage Tabu search algorithm with the objective of minimizing the total cost of vehicle routing and depot construction. The Tabu search for depot location was initialized by randomly selecting a depot, then moving or adding a depot to construct a new solution. Every time the depot location changes, the vehicle routing problem is solved. Drawbacks to this approach include the following: sector design is neglected; the search of routing procedures is not included; and the algorithm terminates with a certain number of iterations, which does not guarantee convergence.

Jang et al. (2010) developed an integrated model for locating depots, partition sectors, and design routes, and scheduling fleets. The model is solved by finding feasible solutions at three levels iteratively: starts from the depot location and sector selection, then route design, and finally fleet configuration and scheduling. If the solution generated from the upper level cannot generate feasible solutions in the lower level, the procedure returns to the upper level to find a new solution.

In the depot location and sector selection level, a greedy heuristic was used to locate depots and determine sectors. In the route design level, routes are first initialized by route-first, cluster-second procedure, then improved by one arc movement and exchange, which can be seen as a local search. The arc movement removes one arc in a sector’s route and then inserts it into a neighbor sector’s route, while the one-arc exchange attempts to moves arcs between routes in the same sector.

Truck capacity and service frequency constraints are taken into account in this level. Fleet configuration is formulated as a mathematical program with the objective of minimizing the number of trucks used. Overall, global optimal is not guaranteed, because problems are solved separately, and the method only finds feasible solutions.

Summary of the Literature

Table 1 provides a summary of the research studies to date.

Table 1. Summary of the literature

Problem Category	Authors	Problem type	Problem characteristics	Objective function	Solution method
Arc Routing	Haghani and Qiao 2001	CARP	Time window for hierarchy	Minimize deadhead distance	Constructed, local search
	Haghani and Qiao 2001	CARP	Service continuity	1. Minimize number of trucks used 2. Minimize total deadhead distance	Network transformation, CMST, linear approximation, CPLEX
	Omer 2007	CARP		Minimize total travel distance	GRASP
	Perrier et al. 2010	Hierarchical routing problems	High priority roads must be serviced as soon as possible	1. Minimize class service time 2. Minimize sum of shortest paths lengths	CPLEX
	Salazar-Aguilar et al. 2012	Synchronized arc routing	Multiple lanes in the same direction must be plowed simultaneously	Minimize duration of longest route	Adaptive large neighborhood
	Liu et al. 2014	CARP		Minimize total travel time	MAENS
	Sullivan et al. 2015	Facility location	Satellite salt facility	Minimize total service time	TransCAD
Location Routing	Cai et al. 2009	Locating depots and route design	Multiple depots	Minimize total cost of vehicle routing and depot construction	Two-stage Tabu
	Jang et al. 2010	Locating depots, sector and route design, configuring and scheduling vehicles	Multiple depots, service cycle time constraint	Minimize number of trucks used	Iterative among three problems: greedy type solution for depots and sector; route first cluster second for route initialization, then, local search; integer programming for fleet scheduling

CARP=capacitated arc routing problem; CMST=capacitated minimum spanning tree; CPLEX=IBM's ILOG CPLEX Optimization Studio; GRASP=greedy randomized adaptive search; MAENS=memetic algorithm with extended neighborhood search

DATA PREPARATION

Geographic Information Management System and Automatic Vehicle Location Data

The Iowa DOT's geographic information management system (GIMS) database and the snowplow automatic vehicle location (AVL) database are the two major data sources used in this study. The GIMS provides the geographic characteristics, speed limits, and annual average daily traffic (AADT) of each roadway segment. For example, Figure 1 plots the speed limits of the road segments in the Muscatine and Wapello network.

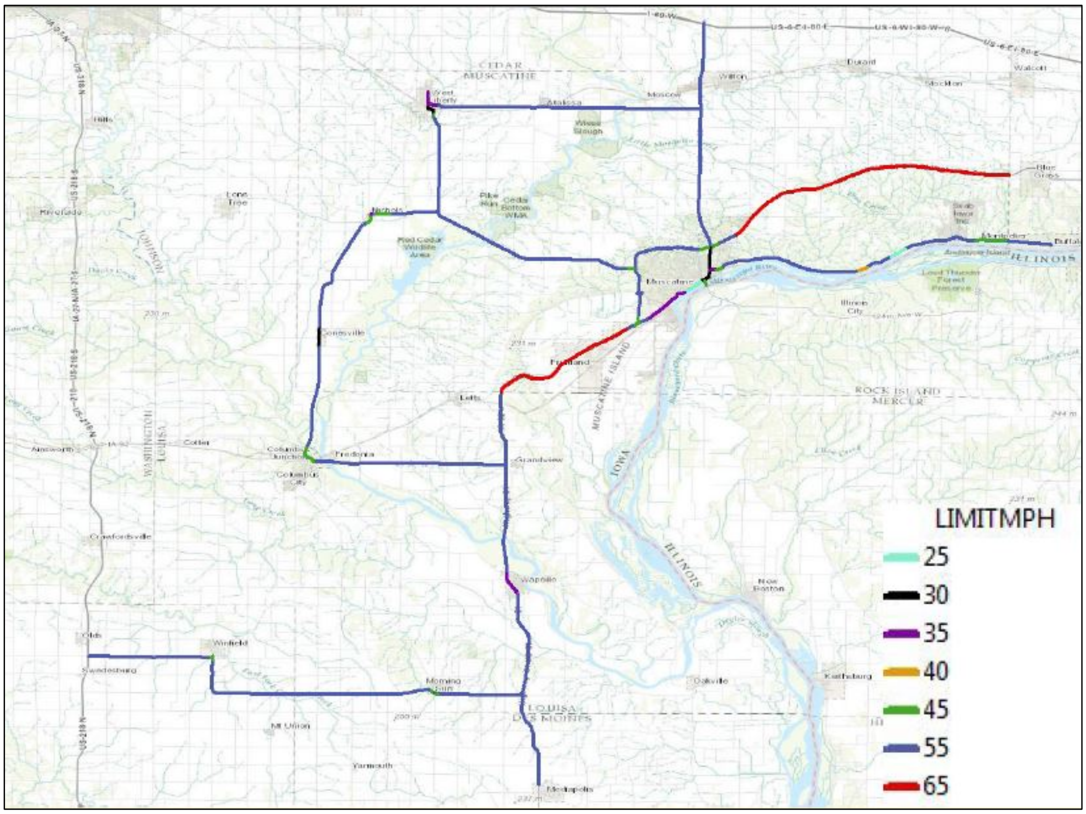


Figure 1. Speed limits of roadways in the Muscatine and Wapello, Iowa service network

For most of the roadways in the study area, the speed limits are 55 or 65 mph.

The snowplow AVL records the date and time, longitude and latitude, traveling speed, plow position (up/down), and spreading rate at a one-minute refresh rate for each vehicle. Note that because the plow position sensor is not reliable, the plow position information was disregarded in this study.

The six snowiest days in winter 2014–2015 were selected from the AVL database to examine the snowplow operations, including vehicle routing and scheduling plans. The information was used to generate input for designing snow routes. The six snowiest days were November 24, 2014; January 4, 2015; January 6, 2015; February 1, 2015; February 24, 2015; and February 25, 2015.

When spreading and plowing, vehicle speeds tend to be much slower than normal driving speeds. Thus, two types of vehicle speeds were considered: service speed (or the plow speed) and traverse speed (assumed to be the speed limit). Figure 2 shows the distributions of vehicle speeds when the spreading rate is greater than 0 for pre-wet, liquid, and solid materials.

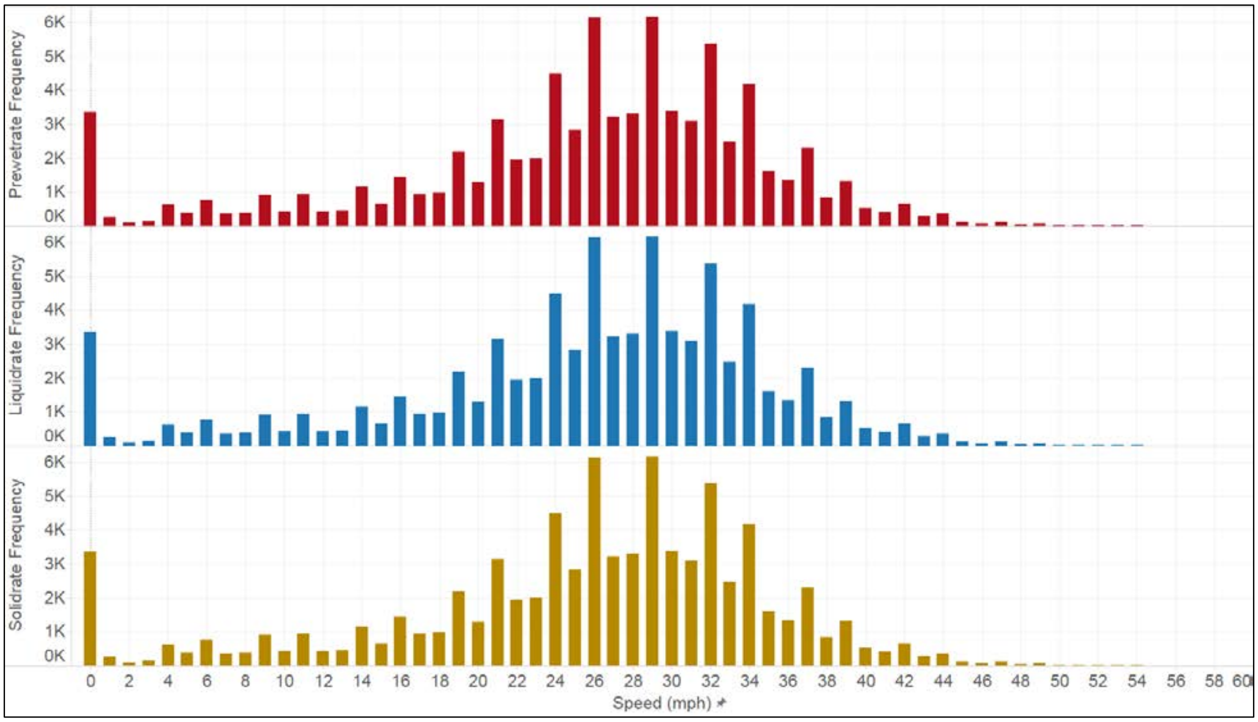


Figure 2. Spreading vehicle speed distributions for the Muscatine and Wapello, Iowa service network: pre-wet (top), liquid (middle), and solid (bottom)

Vehicle speeds while spreading are mostly between 20 and 40 mph. This is much lower than the speed limits of most of the roadways (as shown in Figure 1).

Figure 3 plots the distribution of the speed data collected from the six snowiest days.

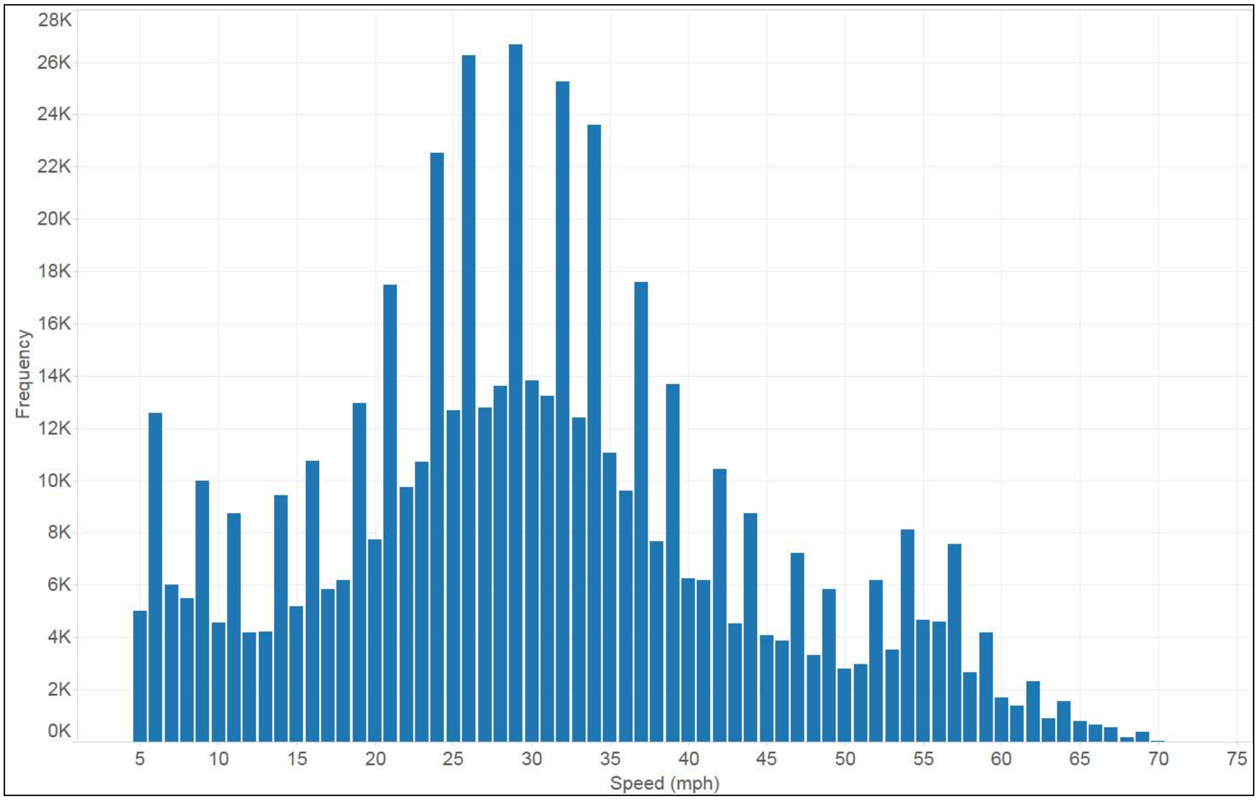


Figure 3. Vehicle speed distribution for the Muscatine and Wapello, Iowa service network on the six snowiest days of winter 2014–2015

In this plot, we disregarded speeds that were less than 5 mph. These records were likely collected when drivers stopped at a turnaround site or were parked at the garage. The first peak occurs between 20 and 40 mph, which indicates the service speed. This is consistent with the observation from the spreading speed distribution shown in Figure 2. The second peak occurs between 50 and 60 mph, which is close to the speed limits.

CASE STUDY 1: MUSCATINE GARAGE LOCATION

Service Network

The Muscatine and Louisa County roadway network and existing garage locations (depots) are shown in Figure 4.

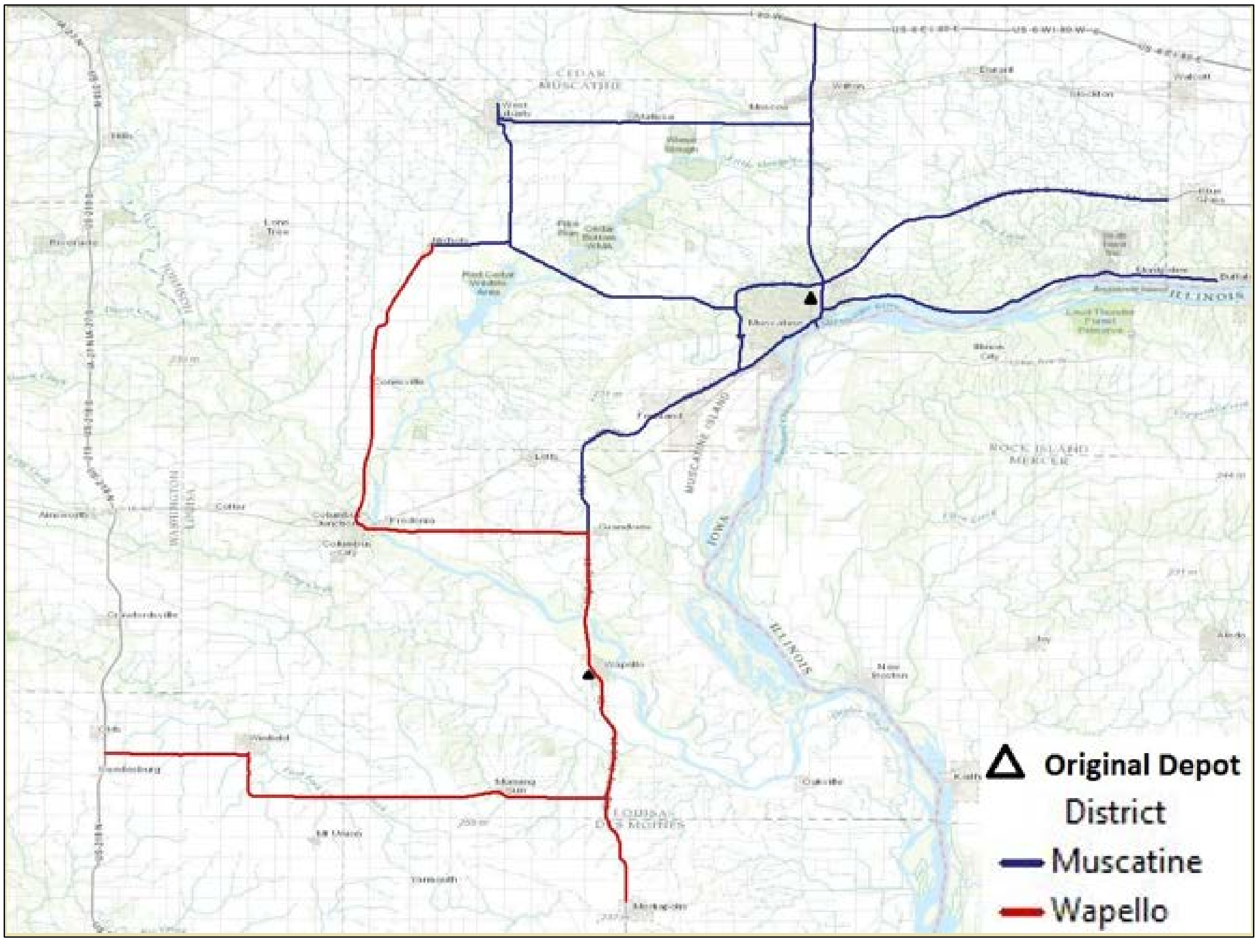


Figure 4. Service area covered by Iowa DOT Muscatine and Wapello garages

The garages are shown with black triangles. Blue lines indicate road segments maintained by Muscatine County with the current garage located in Muscatine. Red lines indicate road segments maintained by Louisa County with the current garage located in Wapello.

All road segments on the network are maintained by Iowa DOT snowplow trucks in winter. The Iowa DOT plans to close the garages in Wapello and Muscatine and merge Louisa and Muscatine County road maintenance operations. A new garage in Muscatine along the US 61 corridor will be built to serve both counties.

Candidate Garage Locations

Based on the discussion with the technical advisory committee (TAC), three sites were selected as candidate locations of the new Muscatine garage. As shown in Figure 5, one candidate site is located near the existing garage and is labeled as the Old position.

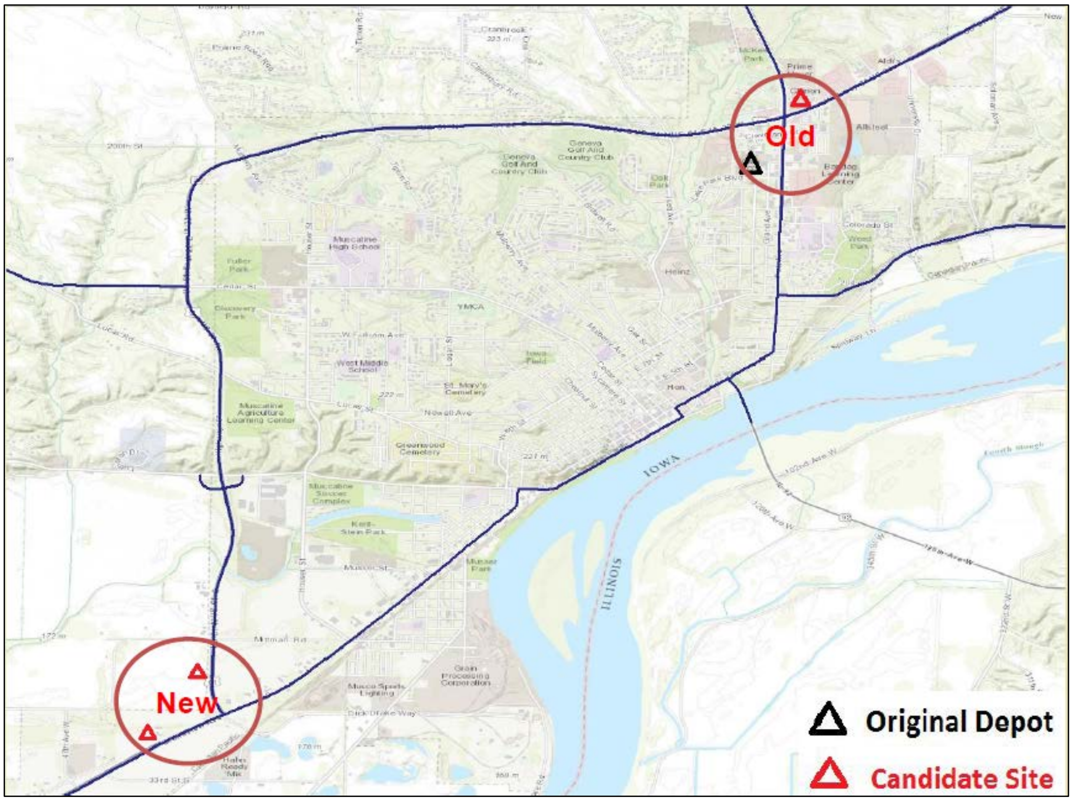


Figure 5. Candidate garage locations for Muscatine and Wapello, Iowa service network

The other two candidate sites are located in the southwest of the city. Because these two sites are one mile apart, no significant difference can be found in terms of snow routes and deadhead distances. Therefore, these two sites are considered as one location, called the New position for this study. The distance between the Old and New positions is approximately five miles.

Maintenance Service Level

Maintenance service levels can be found in the GIMS database. As illustrated in Figure 6, the road segments in the Muscatine and Wapello study area are classified as service levels B and C.

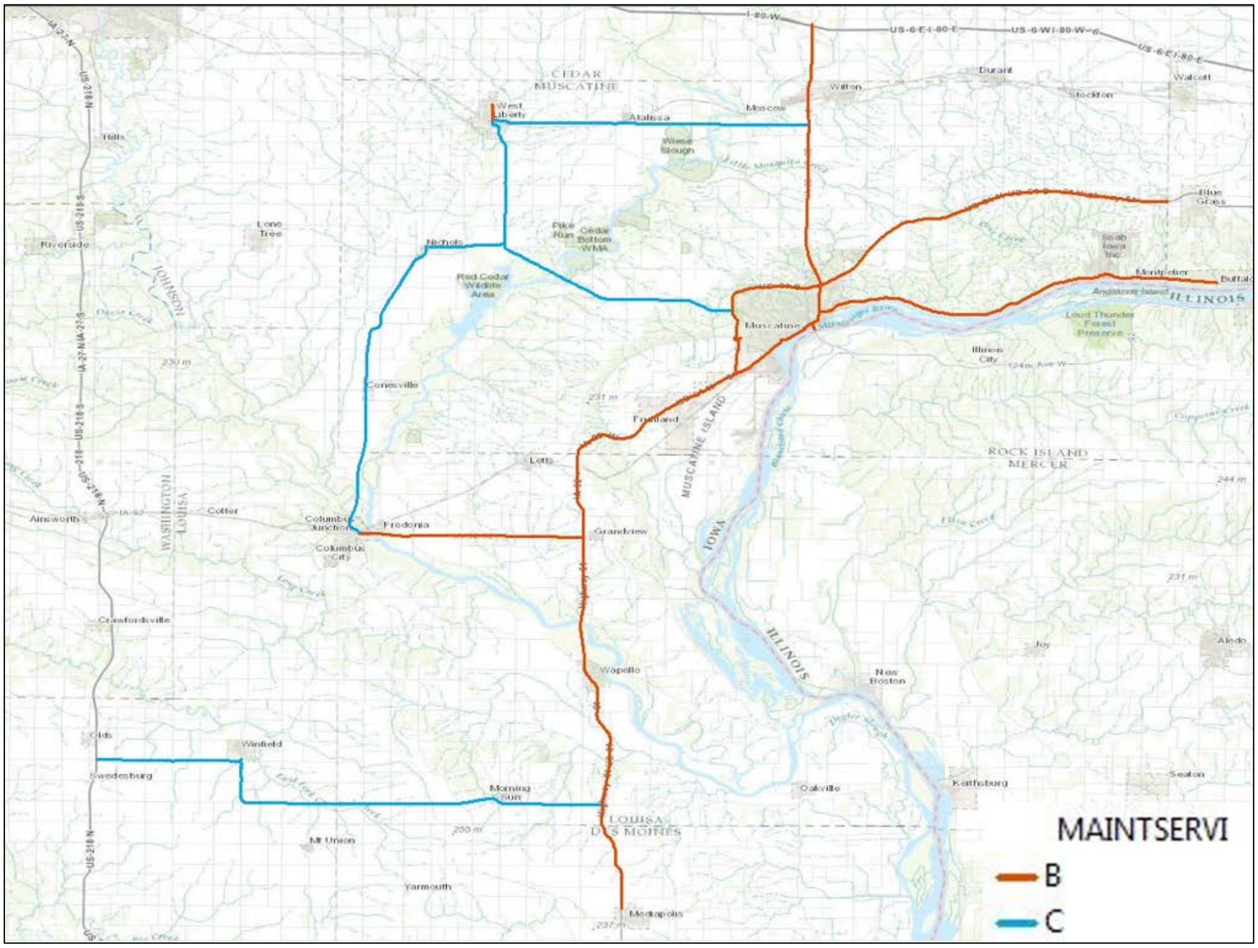


Figure 6. Maintenance service levels of the Muscatine and Wapello, Iowa network

According to the Iowa DOT Office of Maintenance, the service level is defined largely based on AADT. Table 2 lists the AADT range and the expected turnaround time for each maintenance service level. The turnaround time represents how frequent a roadway segment is expected to be serviced. For example, Level A road with AADT above 100,000 vehicle per day is expected to be plowed every 1 to 1.5 hours during a snowstorm.

Table 2. Expected turnaround times by maintenance service level and AADT

Service Level	Turnaround Time (hrs)	AADT
A	1.5–1.75	0–100,000
A	1–1.5	100,001–125,000
B	2–2.5	0–24,000
B	1.5–2	24,001–40,000
C	2.5–3	0–14,300

Turnaround times are described later in the Solution Algorithm section of this chapter (under the steps listed).

Network Representation

Based on the vehicle trajectories extracted from the AVL database, the researchers built the Muscatine and Wapello service network as follows. Nodes are at the same locations as cost center milepost breaks, which are intersections of two roadways maintained by the Iowa DOT or turnaround locations for trucks observed in real-world operations. The researchers defined an arc for this study as the segment connecting two nodes and each arc is directional. As a result, the network consists of 20 nodes, as shown in Figure 7, and 42 arcs.

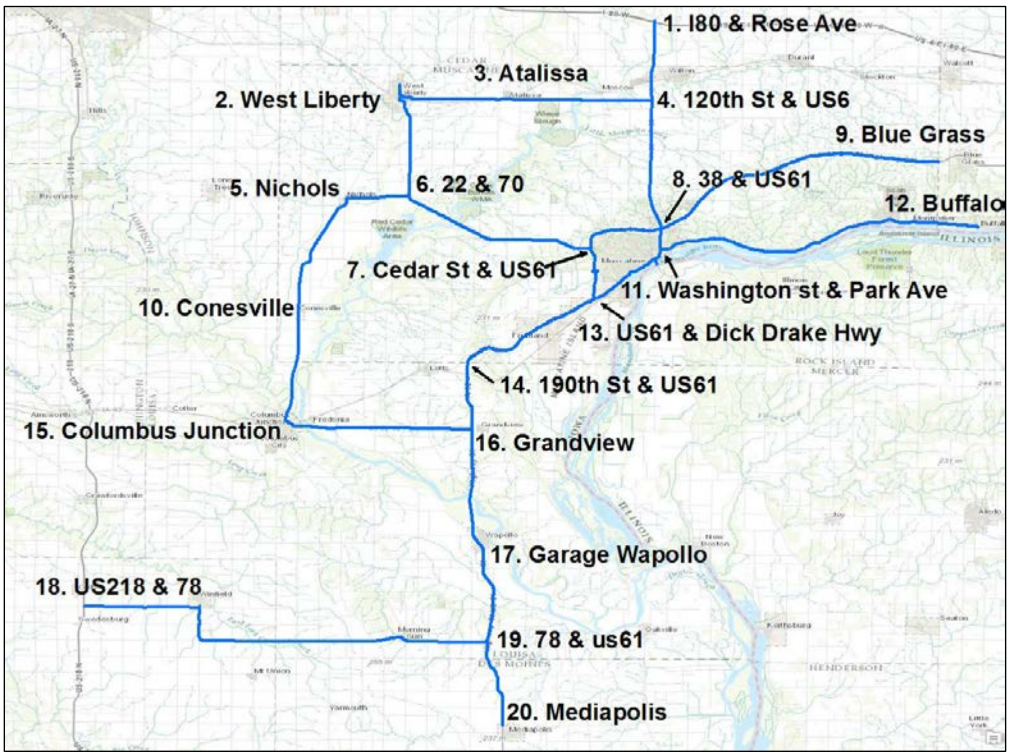


Figure 7. Muscatine and Wapello, Iowa service network with 20 nodes and 42 arcs

Arc characteristics were computed and are listed in Table 3.

Table 3. Arc characteristics of Muscatine and Wapello, Iowa service network

Arc ID	From Node	To Node	Service TT (minutes)	Speed Limit TT (minutes)	Maintenance Service Level	Number of Lanes	Mileage (miles)	Speed Limit (mph)
1	1	4	10.8	5.1	B	1	4.7	55
2	2	3	11.8	5.3	C	1	4.9	55
3	2	6	12.2	6.9	C	1	6.3	55
4	3	2	11.8	5.3	C	1	4.9	55
5	3	4	15.5	7.3	C	1	6.7	55
6	4	1	10.8	5.1	B	1	4.7	55
7	4	3	15.5	7.3	C	1	6.7	55
8	4	8	16.3	8.6	B	1	7.9	55
9	5	6	6.7	3.2	C	1	2.9	55
10	5	10	17.1	8.4	C	1	7.7	55
11	6	2	12.2	6.9	C	1	6.3	55
12	6	5	6.7	3.2	C	1	2.9	55
13	6	7	23.6	12	C	1	11	55
14	7	6	23.6	12	C	1	11	55
15	7	8	8.9	4.7	B	2	4.3	55
16	7	13	6.6	3.4	B	2	3.1	55
17	8	4	16.3	8.6	B	1	7.9	55
18	8	7	8.9	4.7	B	2	4.3	55
19	8	9	27.8	12.8	B	2	13.9	65
20	8	11	4.3	1.4	B	1	1.3	55
21	9	8	27.8	12.8	B	2	13.9	65
22	10	5	17.1	8.4	C	1	7.7	55
23	10	15	17.3	7.9	C	1	7.2	55
24	11	8	4.3	1.4	B	1	1.3	55
25	11	12	38.8	18.3	B	1	16.8	55
26	12	11	38.8	18.3	B	1	16.8	55
27	13	7	6.6	3.4	B	2	3.1	55
28	13	14	16.6	7.4	B	2	8	65
29	14	13	16.6	7.4	B	2	8	65
30	14	16	8.2	4.5	B	2	4.1	55
31	15	10	17.3	7.9	C	1	7.2	55
32	15	16	18.9	8.9	B	1	8.2	55
33	16	14	8.2	4.5	B	2	4.1	55
34	16	15	18.9	8.9	B	1	8.2	55
35	16	17	12.8	7.4	B	1	6.8	55
36	17	16	12.8	7.4	B	1	6.8	55
37	17	19	13.4	7.1	B	1	6.5	55
38	18	19	43.9	22.4	C	1	20.5	55
39	19	17	13.4	7.1	B	1	6.5	55
40	19	18	43.9	22.4	C	1	20.5	55
41	19	20	10.8	5.9	B	1	5.4	55
42	20	19	10.8	5.9	B	1	5.4	55

TT=travel time

The service travel time (TT) on an arc was calculated based on the difference between two time stamps when the truck arrived at two end nodes. The speed limit TT on an arc was calculated as the division of the arc length by the speed limit. Speed limit TT was used as traverse travel time. In addition, because trucks servicing this area can only plow one lane each run, the number of lanes determines how many runs are needed to service the arc. For example, a four-lane road needs to be serviced by two roundtrip snow runs.

The segment between nodes 14 and 16, from 190th Street to Grandview Avenue, is currently a two-lane road and will be broadened to four lanes in the near future. The researchers incorporated this change into the optimal route design.

The segment between nodes 11 and 13 (Figure 8) is seldom visited by trucks.

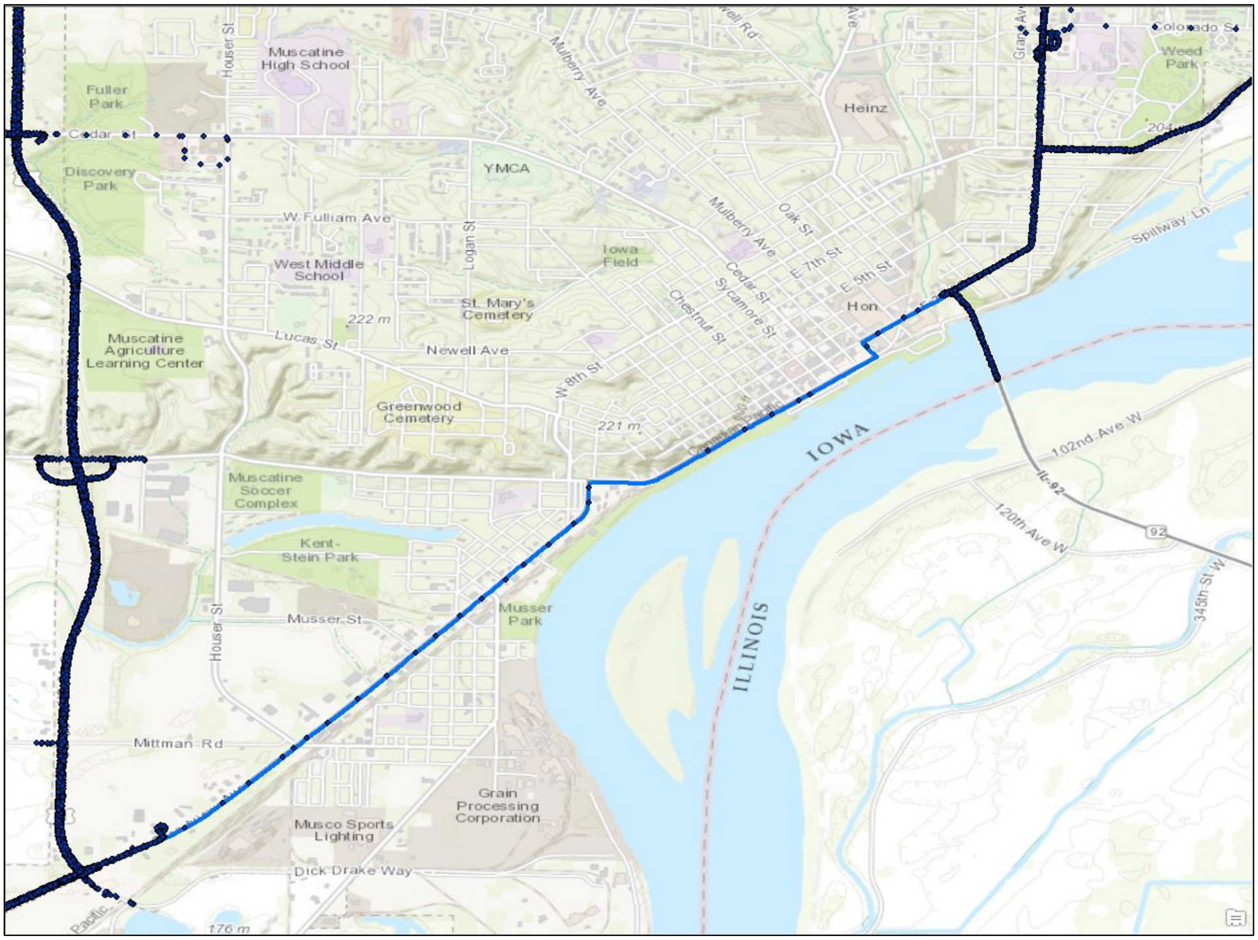


Figure 8. Node 11 to 13 AVL data coverage

Over the six snowiest days, this segment was only visited once by one truck, on November 24, 2014, traveling from southwest to northeast, as illustrated by the sparse dots on this arc in Figure 8. Therefore, no data were available to calculate the service travel time and turnaround time. This arc was excluded from the network when finding the optimal routes.

Solution Algorithm

The garage location problem involves the comparison of the two candidate sites with an objective of minimizing the deadhead travel time and the total number of runs. The researchers incorporated a maintenance service-level requirement by imposing a maximum turnaround time constraint for each route.

The researchers implemented a heuristic algorithm (adopted from Haghani and Qiao 2001) to solve for the optimal snow truck routes on the service network. All trucks were assumed to start from the garage with a full load of spreading material at the beginning of their runs. If an arc had more than one lane in one direction, trucks were assumed to service the lanes that had not been treated or plowed. If all lanes had been serviced, trucks were assumed to travel at the speed limit, in which case deadhead miles and deadhead time were recorded. A maximum turnaround time was imposed to ensure that the maintenance service level was met. Note that rest time and truck reload time were not considered in calculating the turnaround time.

The optimal routing solution algorithm entails the following steps:

- **Step 1**. Calculate turnaround time for each arc. Find the shortest path from the garage to the starting node of an arc and from the end node of that arc to the garage. The turnaround time of this arc is calculated as the total travel from and to the garage.

- **Step 2**. For all arcs that have not been serviced and for which the turnaround time is less than the maximum turnaround time, establish an initial route from the garage to that arc.

- **Step 3**. Find the nearest arc to the current route. Add this arc to the route if the time constraint is not violated.

- **Step 4**. Repeat Step 3 until the time constraint is violated.

- **Step 5**. Arcs for which all lanes have been serviced are traversed at the speed limit. Repeat Step 1 through Step 4 until no arc can be serviced within the time constraint.

- **Step 6**. Repeat Step 2 through Step 5 without the time constraint until all arcs are serviced.

Results and Discussion

The procedure was applied to the Iowa DOT maintenance network in Muscatine and Louisa counties to compare the routing results for the old and new garage locations. Maximum turnaround times of 1.5 hours, 1.75 hours, and 2 hours were considered. The summary results, including total deadhead time and number of runs for each scenario, are listed in Table 4. Detailed results for each route are provided in Appendix A. The corresponding routes are plotted in Appendix B.

Table 4. Comparison of the old and new garage locations

	Maximum Turnaround Time					
	1.5 Hours		1.75 Hours		2 Hours	
Garage Location	**Old**	**New**	**Old**	**New**	**Old**	**New**
Deadhead Time (minutes)	445.4	255.4	321.2	**249**	238.4	193.8
Number of Runs	16	12	12	**11**	9	9
No. of Runs Violating the Maximum Turnaround Time	3	2	1	**1**	1	1
Total Violation Time (minutes)	68.6	57.2	51.8	**35.6**	36.8	20.6

New=Recommended location, from a routing and scheduling perspective, with a 1.75-hour turnaround time

In Table 4, the deadhead time is the total time spent for trucks to travel from the garage to the work location. The number of runs is the number of trucks needed to service the entire network. The number of violated runs is the number of routes that exceed the maximum turnaround time. The total violation time is the sum of excess time in the violation runs.

As expected, when the maximum turnaround time constraint increases, deadhead time, number of runs, and violation time decrease. For all scenarios, the new garage location performs better than the old position in that there is less deadhead time (and fewer runs for the 1.5- and 1.75-hour maximums). From a routing and scheduling perspective, the new positon with a 1.75-hour turnaround time is recommended. Adding half an hour of rest and reload time to each route, the actual turnaround time is about 2 to 2.5 hours.

Appendix A lists the operational performance measures for each route. The spreading mile is the distance that a truck travels while spreading or plowing (the length of the route minus the deadhead distance). The material weight is calculated by assuming a 200 lb/lane-mile spreading rate. Among all the scenarios and routes, the maximum load weight is 11,120 lbs., which is about 5.6 tons. Because single-axle trucks typically hold 6 to 7 tons and tandem-axle trucks hold 11 to 12 tons, the existing Iowa DOT trucks should be able to carry enough material to spread along the entire route under normal operations.

The maps in Appendix B show the optimal operation routes for each scenario. Black lines indicate the servicing segments, while red lines indicate the deadhead segments.

CASE STUDY 2: DUBUQUE GARAGE LOCATION

Service Network

The Dubuque County network with the existing garage location (depot) is shown in Figure 9.

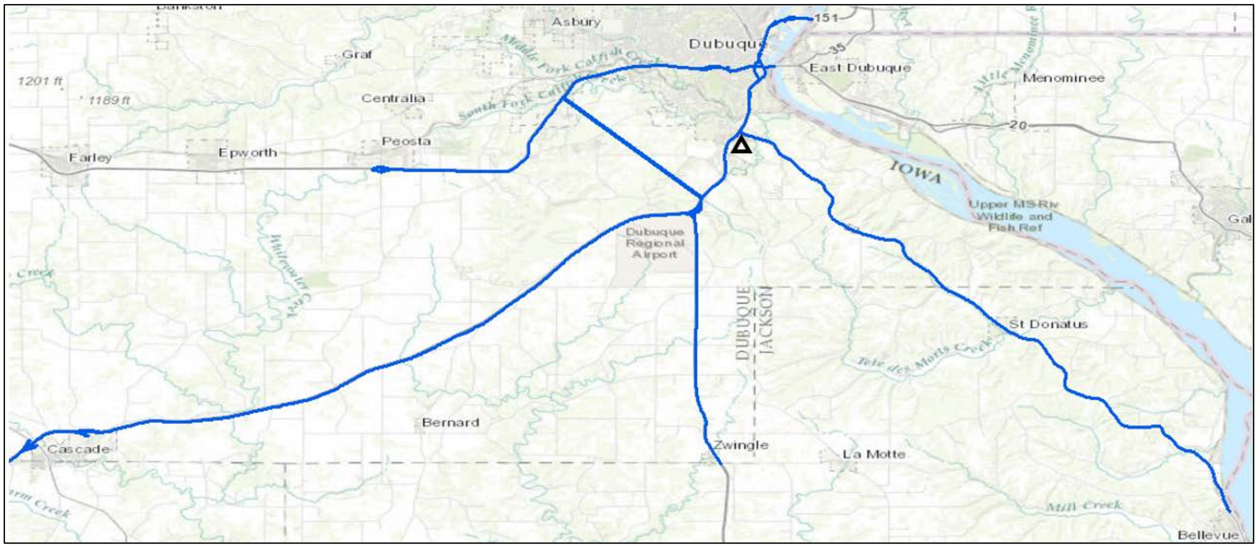


Figure 9. Service area covered by Iowa DOT Dubuque garage

The current garage location is shown with a black triangle. Blue lines indicate road segments maintained by the Dubuque area garage. The researchers included a projected road (US 52) from Seippel Road and US 20 to US 61 at US 151 in the network. This 6.2-mile, 4-lane arterial was currently under construction (and is shown with the straight diagonal blue line on the map). IA 3 north of Dubuque is currently serviced by the Dubuque garage. However, the TAC decided to assign it to the Dyersville garage, so the road segment was not included in the Dubuque service network in the subsequent analysis.

Candidate Garage Locations

The TAC did not provide specific candidate locations for a new Dubuque garage for this case study. Instead, various practical considerations were discussed, which constrained the selection of candidate sites. For example, the downtown area including the region near the old garage is not available because of unavailable land.

As shown in Figure 10, hilly areas, within the green rectangle, were not considered, because it would be difficult for trucks to make U-turns. In addition, candidate sites should be located around state highways and also have easy access to state highways.

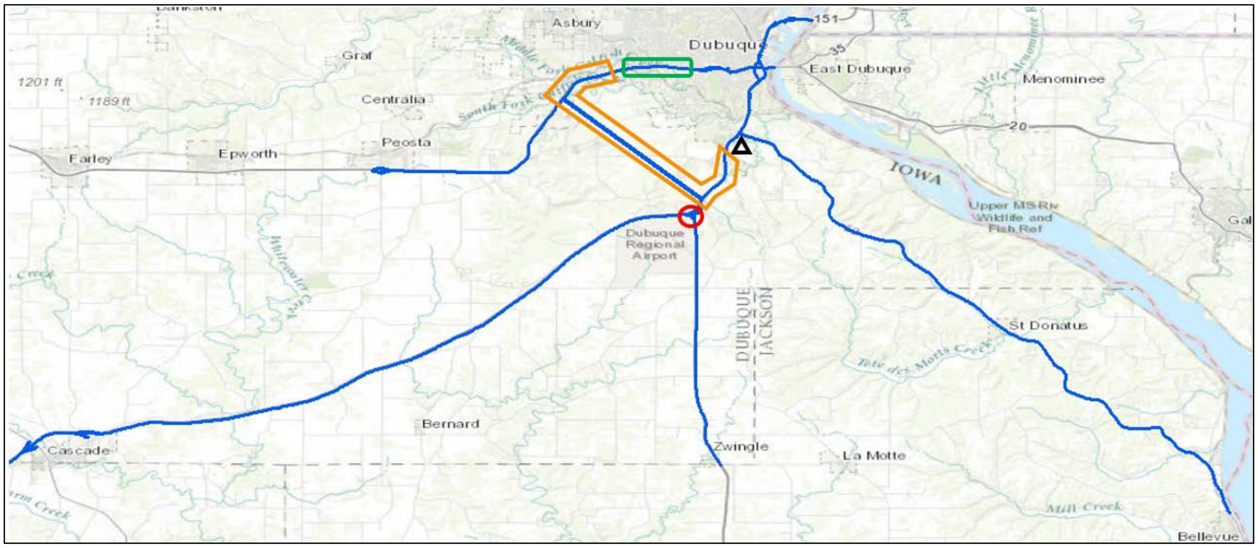


Figure 10. Candidate garage locations for Dubuque, Iowa service network

The red circled region is an overpass and does not provide easy access to the highways. The region outlined in orange indicates the preferred region for a new garage. Note that most of this region is located on the 6.2-mile, 4-lane arterial (US 52) that was currently under construction.

Maintenance Service Level

The quality of winter maintenance level of service (LOS) can be defined by service frequency, which the researchers used for this case study. Roadways with higher traffic demands require a greater number of services per day. The Iowa DOT requires that roadways classified as service level I have a target service number of 12 or 13 times during a full-day (24-hour) storm. That means these roadways need to be serviced at least once every 2 hours during a continuous storm. As shown in Table 5, service frequency requirements are defined for roadways based on vehicles per lane per day, which is the sum of the number of passenger vehicles plus 1.8 times the number heavy trucks.

Table 5. Number of services per day by maintenance service level

Service Level	Number of services per day	Vehicles per lane per day
I	12 or 13	>8,000
II	10 or 11	5,001–8,000
III	9	2,501–5,000
IV	7	1,501–2,500
V	5	801–1,500
VI	3 or 4	0–800

As illustrated in Figure 11, the road segments in the Dubuque study area are classified as service levels I, II, III, and IV.

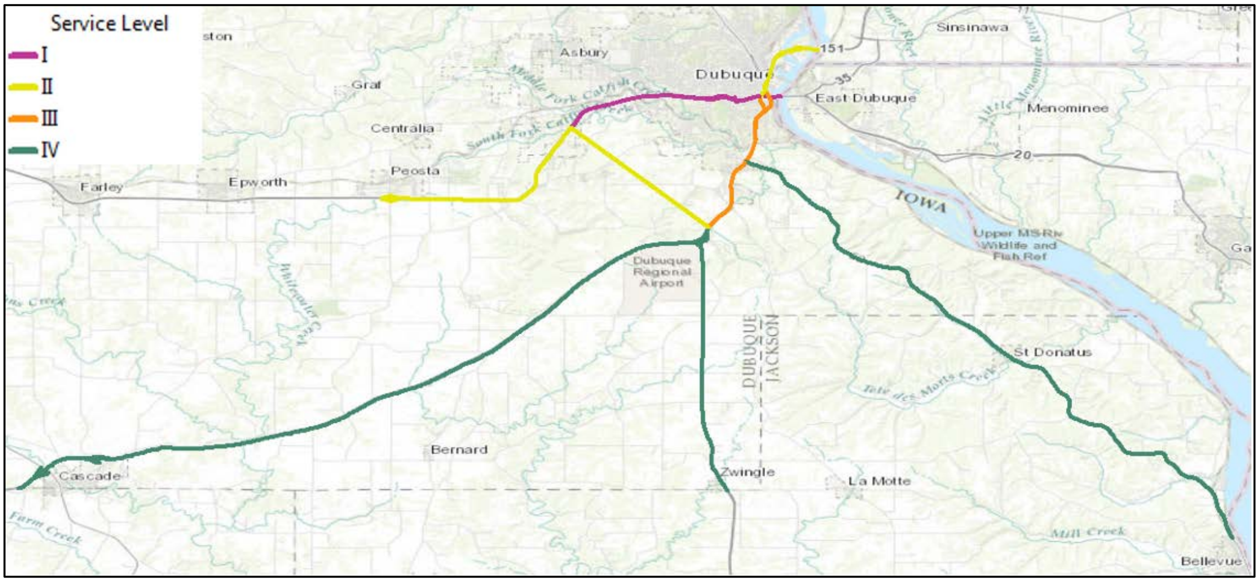


Figure 11. Maintenance service levels of the Dubuque, Iowa network

Network Representation

In the Dubuque service network, nodes and arcs have the same definition as in the Muscatine garage case study; the network is shown in Figure 12.

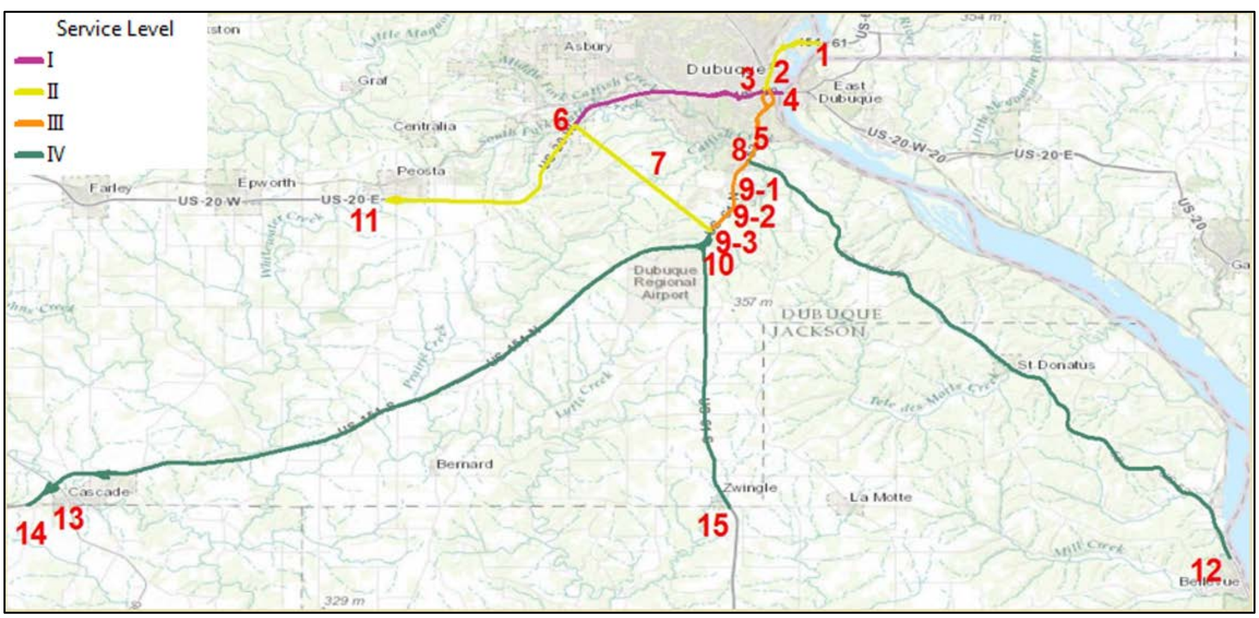


Figure 12. Dubuque, Iowa service network with 15 nodes and 32 arcs

The southwest arterial under construction (US 52) is represented by the arc connecting Nodes 6 and 9-3. There will be an access point in the middle of arc 6 to 9-3, which is labeled as Node 7. Thus, Nodes 6, 7, 9-1, 9-2, and 9-3 are in the region (as shown in Figure 10) to consider for candidate garage sites. Node 9-1 or 9-2 will be added into the networks if, and only if, the garage site would be located at 9-1 or 9-2, respectively. That is to say, turning around at Node 9-1 and 9-2 is not allowed unless they are selected as the garage location. As a result, the network consists of 15 nodes and 32 arcs (or 16 nodes and 34 arcs if the New garage is located at Node 9-1 or 9-2).

Arc characteristics are listed in Table 6.

In particular, service TT on an arc was calculated as the division of the arc length by the service speed (30 mph). Speed limit TT on an arc was calculated as the division of the arc length by the speed limit and was used as traverse travel time.

Assuming a truck spreads material at a rate of 200 lbs. per lane mile, the material tonnage was calculated as the length of the arc multiplied by 200 lb/lane mile. To compare the performance of different candidate locations, the network in use for candidate sites at Nodes 6, 7, and 9-3 are the same. In Table 6, this basic network is labeled as Garage Site 6, 7, or 9-3. The network for candidate sites at Node 9-1 or 9-2 are slightly different from the basic network. Arcs 20 and 31 in the basic network were modified for this part of the analysis, and Arcs 33 and 34 were added, generating the network of garage sites 9-1 and 9-2, respectively.

Table 6. Arc characteristics of Dubuque, Iowa service network

Garage Site	From Node	To Node	Service TT (minutes)	Speed Limit TT (minutes)	LOS	No. of Lanes	Length (miles)	Speed Limit (mph)	Tonnage (lbs/lane)	Arc ID
6, 7, or 9-3	1	2	3.8	3.3	II	2	1.9	35	380	1
	2	1	3.8	3.3	II	2	1.9	35	380	2
	2	3	0.4	0.3	II	2	0.2	35	40	3
	2	5	2.6	2.0	III	2	1.3	40	260	4
	3	2	0.4	0.3	II	2	0.2	35	40	5
	3	4	1	0.9	I	1	0.5	35	100	6
	3	5	2	1.7	III	2	1	35	200	7
	3	6	10.6	8.0	I	2	5.3	40	1,060	8
	4	3	1	0.9	I	1	0.5	35	100	9
	5	2	2.6	2.0	III	2	1.3	40	260	10
	5	3	2	1.7	III	2	1	35	200	11
	5	8	2.6	1.7	III	2	1.3	45	260	12
	6	3	10.6	8.0	I	2	5.3	40	1,060	13
	6	7	6.2	3.4	II	2	3.1	55	620	14
	6	11	12	6.0	II	2	6	60	1,200	15
	7	6	6.2	3.4	II	2	3.1	55	620	16
	7	9-3	6.2	3.4	II	2	3.1	55	620	17
	8	5	2.6	1.7	III	2	1.3	45	260	18
	8	12	41.2	24.7	IV	1	20.6	50	4,120	19
	8	9-3	5	3.0	III	2	2.5	50	500	20
	10	13	47.4	25.9	IV	2	23.7	55	4,740	21
	10	15	17.6	8.8	IV	2	8.8	60	1,760	22
	10	9-3	1.2	0.7	IV	2	0.6	50	120	23
	11	6	12	6.0	II	2	6	60	1,200	24
	12	8	41.2	24.7	IV	1	20.6	50	4,120	25
	13	10	47.4	25.9	IV	2	23.7	55	4,740	26
	13	14	2.6	1.4	IV	2	1.3	55	260	27
	14	13	2.6	1.4	IV	2	1.3	55	260	28
	15	10	17.6	8.8	IV	2	8.8	60	1,760	29
	9-3	7	6.2	3.4	II	2	3.1	55	620	30
	9-3	8	5	3.0	III	2	2.5	50	500	31
	9-3	10	1.2	0.7	IV	2	0.6	50	120	32
9-1	8	9-1	2	1.2	III	2	1	50	200	20
	9-1	8	2	1.2	III	2	1	50	200	31
	9-1	9-3	3	1.8	III	2	1.5	50	300	33
	9-3	9-1	3	1.8	III	2	1.5	50	300	34
9-2	8	9-2	3.4	2.0	III	2	1.7	50	340	20
	9-2	8	3.4	2.0	III	2	1.7	50	340	31
	9-2	9-3	1.6	1.0	III	2	0.8	50	160	33
	9-3	9-2	1.6	1.0	III	2	0.8	50	160	34

TT= travel time

Service Network Schedule

Road segments of different maintenance LOS were integrated into a service network schedule, as shown in Table 7.

Table 7. Network service schedule

	Number of plows per day						
	VI	V	IV	III	II	I	Service
Hour	3	5	7	9	11	12	Levels
00:00	Y	Y	Y	Y	Y	Y	I, II, III, IV, V, VI
01:00							
02:00						Y	I, II, III
03:00				Y	Y		
04:00			Y	Y		Y	I, II, III, IV, V
05:00		Y			Y		
06:00				Y		Y	I, II, III, IV
07:00			Y		Y		
08:00	Y					Y	I, II, III, VI
09:00				Y	Y		
10:00		Y				Y	I, II, IV, V
11:00			Y		Y		
12:00				Y		Y	I, III
13:00							
14:00			Y		Y	Y	I, II, III, IV, V
15:00		Y		Y			
16:00	Y				Y	Y	I, II, VI
17:00							
18:00			Y	Y	Y	Y	I, II, III, IV
19:00							
20:00		Y			Y	Y	I, II, III, IV, V
21:00			Y	Y			
22:00					Y	Y	I, II
23:00							

The service frequency for service I through VI are 12, 11, 9, 7, 5, and 3 times per day, respectively. Service networks are generated in 2-hour timeslots, which is the most frequent service cycle.

The road segments of each LOS that need service for each 2-hour timeslot are listed in the last column of Table 7 as Service Levels. In each timeslot, the network needing service was considered as connected, and route optimization was implemented on the network. For instance, optimal routes were created for a combined network of I, II, III, and IV for the 6:00–7:00 timeslot, while road segments with LOSs that did not require service (V and VI) in that timeslot were still accessible (i.e., could be traveled while deadheading). Therefore, service routes were created integrally and simultaneously for all LOS levels that needed service in that timeslot.

The schedule of the service network was as follows. Letter Y in Table 7 indicates that the corresponding network would be serviced in the corresponding hour. For roadway segments requiring service levels I and VI, the equivalent service cycles were every 2 and 8 hours, respectively. For service levels II, III, IV, and V, an arithmetic progression on the number of plows per day was used to determine the service hours, so the required number of plows per day were met.

Solution Algorithm

The depot location problem involves the comparison among all candidate sites within a region with an objective of minimizing the deadhead travel distance. Five candidate sites were determined previously, at Nodes 6, 7, 9-1, 9-2, and 9-3. The researchers incorporated truck capacity as a constraint. Thus, a CARP was formulated to optimize the route design. Operational efficiency was evaluated by the total deadhead distance. Minimized deadhead distances for the candidate sites were compared to find the optimal garage location as follows.

Let $G = (V, A)$ be a directed graph where $V = \{v_0, v_1, \ldots, v_n\}$ is a set of nodes, and $A = \{(v_i, v_j): v_i, v_j \in V \text{ and } i \neq j\}$ is a set of arcs. The garage location is represented by node v_0. Define $R \subseteq$ A as the set of arcs needing service. Each arc $(v_i, v_j) \in R$ is associated with a demand q_{ij}, expressed as the total amount of material needed to service the arc, a distance d_{ij} corresponding to the length of the road segment. Every arc $(v_i, v_j) \in A$ is associated with a deadhead time t'_{ij}. Define n_{ij} as the number of times arc $(v_i, v_j) \in R$ should be serviced in a service timeslot (i.e., number of lanes). Let K be the set of vehicles. For every arc $(v_i, v_j) \in A$, let x_{ijk} and y_{ijk} be binary variables, which equal to 1 if, and only if, arc (v_i, v_j) is serviced or traversed as deadhead from i to j in Route K, respectively. Let W be the maximum capacity of all vehicles. The CARP is formulated as follows.

Minimize $\sum_{k \in K} \sum_{(v_i, v_j) \in A} d_{ij}\, y_{ijk}$ **(1)**

Subject to:

$\sum_{\{v_j:(v_j, v_i) \in A\}} (y_{jik} + x_{jik}) - \sum_{\{v_j:(v_j, v_i) \in A\}} (y_{ijk} + x_{ijk}) = 0$ $(v_i \in V, k \in K)$ **(2)**

$\sum_{k \in K} x_{ijk} = n_{ij}$ $((v_i, v_j) \in R)$ **(3)**

$$\sum_{(v_i,v_j)\in R} q_{ij}x_{ijk} \leq W \qquad (k \in K) \textbf{ (4)}$$

$$\sum_{k\in K} y_{ijk} = 0 \qquad ((v_i, v_j) \in R, \sum_{k\in K} x_{ijk} < n_{ij}) \textbf{ (5)}$$

$$\sum_{\{v_i:(v_i,v_0)\in A\}}(x_{i0k} + y_{i0k}) = 1 \qquad (k \in K) \textbf{ (6)}$$

$$\sum_{\{v_j:(v_0,v_j)\in A\}}(x_{0jk} + y_{0jk}) = 1 \qquad (k \in K) \textbf{ (7)}$$

$$\sum_{(v_i,v_j)\in S}(x_{ijk} + y_{ijk}) \leq |S| - 1 + |V|^2 u_k^S \qquad (S \subseteq \mathrm{V}\backslash\{v_0\}, \mathrm{S} \neq \emptyset, k \in K) \textbf{ (8)}$$

$$\sum_{v_i\in S}\sum_{v_j\in S}(x_{ijk} + y_{ijk}) \geq 1 - w_k^S \qquad (S \subseteq \mathrm{V}\backslash\{v_0\}, \mathrm{S} \neq \emptyset, k \in K) \textbf{ (9)}$$

$$u_k^S + w_k^S \leq 1 \qquad (S \subseteq \mathrm{V}\backslash\{v_0\}, \mathrm{S} \neq \emptyset, k \in K) \textbf{ (10)}$$

$$u_k^S, w_k^S \in \{0,1\} \qquad (S \subseteq \mathrm{V}\backslash\{v_0\}, \mathrm{S} \neq \emptyset, k \in K) \textbf{ (11)}$$

$$x_{ijk}, y_{ijk} \in \{0,1\} \qquad ((v_i, v_j) \in A, k \in K) \textbf{ (12)}$$

The objective function minimizes the total deadheading distance. Constraints (2) are flow conservation equations for each vehicle. Constraints (3) state that each arc is serviced the required number of times in that service timeslot. Constraints (4) are the capacity constraint. Constraints (5) state that trucks cannot traverse on an unplowed road segment as deadhead, which is explained in the route connectivity constraint section. Constraints (6) and (7) require all routes to start and end at the depot. Constraints (8) through (11) prohibit the formation of disconnected sub tours (as explained in detail by Golden and Wong 1981). Finally, constraint (12) restricts x_{ijk}, y_{ijk} to be binary.

Route Connectivity Constraint

Route continuity requires that unplowed road segments should not be traversed as deadhead segments. This is a practical concern. Traveling on snowy roads but not plowing is much slower and not efficient. Haghani and Qiao (2002) first introduced the service route continuity constraint. In their definition, arcs that need service in a route must be connected to each other, which is referred to as strong continuity in this study. The top route in Figure 13 satisfies strong continuity.

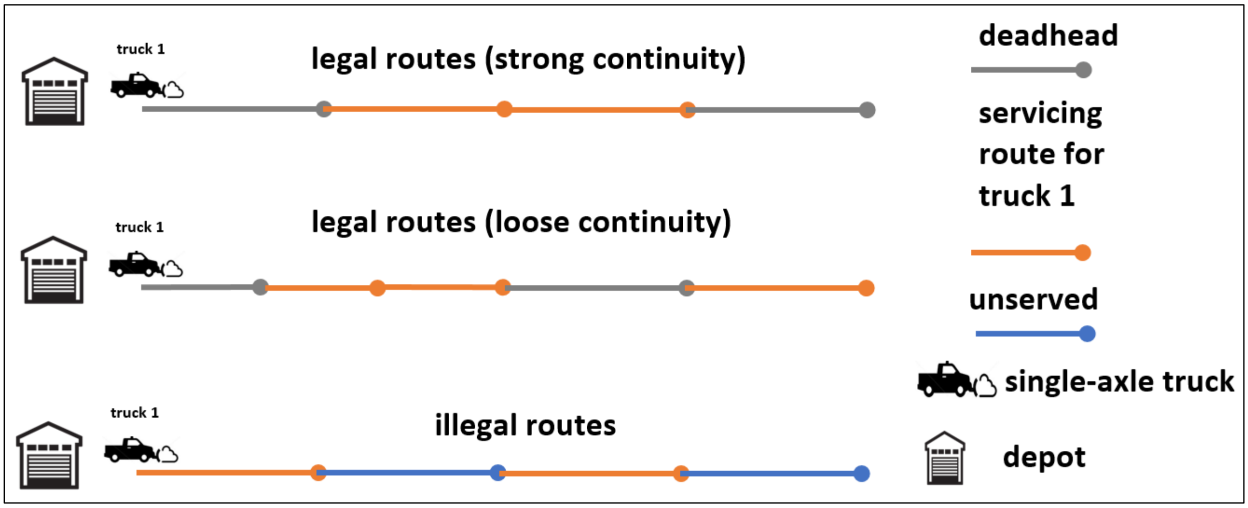


Figure 13. Service continuity

If arcs needing service can be connected by deadhead arcs, the route is referred to satisfy loose continuity (in the middle). Both the top route and the middle route in Figure 13 satisfy loose continuity, although the middle route has a deadhead segment (already plowed) between service arcs.

Because loose continuity constraints allow service segments to be connected by deadheads, they tend to make full usage of truck capacity. The total deadhead distance could be reduced given that less commute time would be needed between the garage and separate service segments. Fleet size could also be reduced with fewer runs needed. Thus, in this study, loose continuity constraints were considered.

Since CARP is NP-hard (non-deterministic polynomial-time hard) (Golden and Wong 1981), the exact method can only solve small size instances. This study used memetic algorithms (MAs) (Lacomme et al. 2004) to solve the proposed model for snowplow routing. MAs combine the genetic algorithm (GA) with a local search. A genotype encoding scheme is employed. A solution is represented by a sequence of tasks, which are the arcs that demand service. Deadhead arcs between two tasks are omitted in the sequence.

First, they build a solution ignoring all constraints; then, they apply Ulusoy's heuristic to separate the sequence into a number of routes. Local search is analogous to but better than mutation operators in GA (Lacomme et al. 2002).

In this case study, the initial task sequence was generated by a random sequence of all service arcs. Single insertion, double insertion, and swap methods (Tang et al. 2009) were used as local search move operators. To account for the route continuity constraint, after initialization and after each local search movement, the solution sequence were adjusted to guarantee "legal" routes.

Results and Discussion

The procedure was applied to the Iowa DOT maintenance network in Dubuque County to compare the routes for five candidate garage locations. The Dubuque district fleet consists of single-axle trucks and tandem-axle trucks. Currently, the district had nine single-axle trucks and eight tandem-axle trucks.

The single-axle trucks have a capacity of 12,000 lbs. of materials, whereas the tandem-axle trucks have a capacity of 24,000 lbs. Given trucks spread materials at a rate of approximately 200 lbs. per lane mile, a single-axle truck has a maximum service distance of 60 miles, while a tandem-axle truck can service up to 120 miles. Also, assuming the average service speed is 30 mph, a single-axle truck has a maximum service time of 2 hours, while a tandem-axle truck can service up to 4 hours. The reload time is assumed to be 30 minutes.

Because four levels of service are used in the study area, each candidate site involves five different service networks: I+II, I+III, I+II+III, I+II+IV, and I+II+III+IV. The network service schedule is listed in Appendix C. For all 5 candidate sites, the number of trucks required are the same. For all candidate sites, the network of I+II+III+IV requires five trucks and all trucks would need almost 2 hours servicing time.

The total travel time and reload time for each truck is greater than 2 hours, but less than 4 hours. According to the scheduling table, the third and fourth time slot both service the I+II+III+IV network; thus, the minimum number of trucks needed for each candidate site is 10 single-axle trucks.

Routes are developed by solving the CARP for every service network in the service schedule. The deadhead time and distance for all candidate sites can be compared. Parallel computing is used to speed up computation. Each service network is solved five times for each candidate site, and the best result is recorded. The deadhead of five networks is summed as the total deadhead time and miles and the results are shown in Table 8.

Table 8. Comparison of candidate sites

Garage at	Deadhead Time (minutes)	Deadhead Length (miles)	Number of Single-Axle Trucks
6	54.4	43	10
7	39.6	30.6	10
9-1	44.8	32.4	10
9-2	32	23.8	10
9-3	17.8	13.6	10

Table 8 shows the deadhead sums for five service schedule networks counted only once for each of the five candidate sites. Node 9-3 has the smallest deadhead length and deadhead time. Note that truck capacity was assumed to be 12,000 lbs. (i.e., single-axle trucks).

Table 9 lists route performance measures of the best candidate site, 9-3.

Table 9. Performance measures of best candidate site, 9-3

No. of Occurrences in 24 hours	Service Network	Route Number	Service Time (min)	Traverse Time (min)	Service Length (miles)	Traverse Length (miles)	Tonnage (lbs.)	Total Travel Time (min)
2	9-3 I+II	1	112.8	0	56.4	0	11,280	112.8
		2	46	0	23	0	4,600	46
2	9-3 I+II+III	1	116.2	0	58.1	0	11,620	116.2
		2	91.4	0	45.7	0	9,140	91.4
6	9-3 I+II+III+IV	1	103.6	0	51.8	0	10,360	103.6
		2	117.6	0	58.8	0	11,760	117.6
		3	119.6	0.5	59.8	0.2	11,960	**120.1**
		4	112.4	1.4	56.2	1.2	11,240	113.8
		5	112	1.7	56	1.4	11,200	113.7
1	9-3 I+II+IV	1	102.4	0	51.2	0	10,240	102.4
		2	113.8	6.4	56.9	**4.8**	11,380	**120.2**
		3	114.8	0	57.4	0	11,480	114.8
		4	115	6.4	57.5	**4.8**	11,500	**121.4**
		5	70.4	1.4	35.2	1.2	7,040	71.8
1	9-3 I+III	1	93.2	0	46.6	0	9,320	93.2

Boldface in right-most column indicates total travel time exceeds 2 hours

The number of occurrence of each service network in 24 hours is based on the service schedule, as shown in Appendix C. For example, service network I+II occurred twice in the 24-hour schedule, i.e., time slot 9 (16:00 and 17:00) and time slot 12 (22:00 and 23:00). For each service network, the performance measures of each truck route include service time, deadhead traverse time, service distance, deadhead traverse distance, and tonnage requirements. The total travel time is the sum of service time and traverse time. The research confirmed that, for most routes, the total travel time with reload time was greater than 2 hours but less than 4 hours.

In service network 9-3 I+II+IV, Routes 2 and 4 had the longest deadhead traverse distance (4.8 miles). This is because these routes have connection arcs in LOS III between their service arcs; however, LOS III segments do not require service in this particular service schedule. Other than these routes, deadhead distance is a result of traversing already serviced arcs, which is relatively short compared to service distance.

The maps in Appendix D show the optimal routes for site 9-3. Blue lines indicate the servicing segments, while black lines indicate the deadhead segments.

The single-axle trucks have a maximum of 2 hours servicing time, calculated from truck capacity, spreading rate, and servicing speed. If tandem-axle trucks are used, and the maximum servicing time would be 4 hours. Note that the total travel time might exceed the 2-hour constraint if deadheading were involved. For example, in Table 8, three routes have total travel times that exceed 120 minutes, but their service times are less than 120 minutes.

CONCLUSIONS

This report presents a data-driven optimization-based approach to support the winter road maintenance planning decisions in terms of garage location, vehicle route design, and fleet configuration. An arc routing problem was formulated to design efficient routes for salting, pre-wetting, and plowing, considering the operational characteristics of winter road maintenance.

Two ARP approaches were developed to account for two types of maintenance service level requirements. Alternative garage locations were compared in terms of number of snow routes, deadhead times, and distances. New garage locations were recommended to replace the existing Muscatine and Dubuque, Iowa garages.

Limitations and Future Research

In future research, the following issues should be addressed:

- Incorporating the route continuity constraint in the CARP significantly increases computational time. Solving the CARP on the Dubuque network takes 2–4 hours for each candidate site. Parallel computing cannot speed up the MA process, since the algorithm builds up solutions from the previous generation to the next generation. A more efficient algorithm is desired to solve the CARP while guaranteeing route continuity.

- This study dealt with the static routing problem for planning purposes. In the context of real-time operations, a dynamic route optimization model considering weather forecasts would be of great interest for practitioners.

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.

Cai, W. P., G. Liu, and W. S. Cao. 2009. A Study of Vehicle and Materials Depot Location Problems for Winter Road Maintenance. Ninth International Conference of Chinese Transportation Professionals (ICCTP), August 5–9, 2009, Harbin, China. *ICCTP 2009 Critical Issues In Transportation Systems Planning, Development, and Management*, pp. 1530–1535. doi:10.1061/41064(358)215.

Golden B. L. and R. T. Wong. 1981. Capacitated Arc Routing Problems. *Networks*. Vol. 11, No. 3, pp. 305–315.

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. doi:10.3141/1771-22.

———. 2002. Snow Emergency Vehicle Routing with Route Continuity Constraints. *Transportation Research Record: Journal of the Transportation Research Board.* No.1783, pp. 119–124. doi:10.3141/1783-15.

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. doi:10.1080/07408171003705375.

Lacomme, P., C. Prins, and W. Ramdane-Cherif. 2004. Competitive Memetic Algorithms for Arc Routing Problems. *Annals of Operations Research*. Vol. 131, No. 1, pp. 159–185.

Liu, G., Y. Ge, T. Z. Qiu, and H. R. Soleymani. 2014. Optimization of Snowplowing Cost and Time in an Urban Environment: A Case Study for the City of Edmonton. *Canadian Journal of Civil Engineering*. Vol. 41, No. 7, pp. 667–675. doi:10.1139/cjce-2013-0409.

Omer, M. 2007. *Efficient Routing of Snow Removal Vehicles: A Study of Capacitated Arc Routing Problem*. VDM Verlag Dr. Müller, Saarbrücken, Germany.

Perrier, N., J. F. Campbell, M. Gendreau, and A. Langevin. 2010. *Vehicle Routing Models and Algorithms for Winter Road Spreading Operations*. Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation, Montreal, Quebec, Canada. Last accessed February 13, 2017 at https://www.cirrelt.ca/DocumentsTravail/CIRRELT-2010-53.pdf.

Perrier, N., A. Langevin, and C.-A. Amaya. 2008. Vehicle Routing for Urban Snowplowing Operations. *Transportation Science*. Vol. 42, No. 1, pp. 44–56. doi:10.1287/trsc.1070.0195.

Perrier, N., A. Langevin, and J. F Campbell. 2006a. A Survey of Models and Algorithms for Winter Road Maintenance. Part I: System Design for Spreading and Plowing. *Computers and Operations Research*. Vol. 3, No. 1, pp. 209–238. doi:10.1016/j.cor.2004.07.006.

———. 2006b. A Survey of Models and Algorithms for Winter Road Maintenance. Part II : System Design for Snow Disposal. *Computers and Operations Research*. Vol. 33, No. 1, pp. 239–262. doi:10.1016/j.cor.2004.07.007.

———. 2007a. A Survey of Models and Algorithms for Winter Road Maintenance. Part III: Vehicle Routing and Depot Location for Spreading. *Computers and Operations Research*. Vol. 34, No. 1, pp. 211–257.

———. 2007b. A Survey of Models and Algorithms for Winter Road Maintenance. Part IV : Vehicle Routing and Fleet Sizing for Plowing and Snow Disposal. *Computers and Operations Research*. Vol. 34, No. 1, pp. 258–294.

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. doi:10.1016/j.cor.2011.08.014.

Sullivan, J. L, J. Dowds, D. C. Novak, and D. M. Scott. 2015. Strategic Location of Satellite Salt Facilities for Roadway Snow and Ice Control. *Transportation Research Record: Journal of the Transportation Research Board*. No. 2482, pp. 32–40. doi:10.3141/2482-05.

Tang K., Y. Mei, and X. Yao. 2009. Memetic Algorithm With Extended Neighborhood Search for Capacitated Arc Routing Problems. *IEEE Transactions on Evolutionary Computation*. Vol. 13, No. 5, pp. 1151–1166. doi:10.1109/TEVC.2009.2023449.

APPENDIX A. OPERATIONAL PERFORMANCE MEASURES FOR MUSCATINE GARAGE

This appendix lists the operational performance measures for each route. The spreading mile is the distance that a truck travels while spreading or plowing (the length of the route minus the deadhead distance). The material weight is calculated by assuming a 200 lb/lane-mile spreading rate. Among all the scenarios and routes, the maximum load weight is 11,120 lbs., which is about 5.6 tons. Because single-axle trucks typically hold 6 to 7 tons and tandem-axle trucks hold 11 to 12 tons, the existing Iowa DOT trucks should be able to carry enough material to spread along the entire route under normal operations.

Table A.1. Maximum turnaround time of 1.5 hours

Garage Location	Route #	Turnaround Time (minutes)	Deadhead Time (minutes)	Spreading Miles	Material Used (lbs.)	Maximum Turnaround Violated?
Old	1	87.2	0	39	7800	No
	2	86.2	0	36.2	7240	No
	3	80.6	0	39	7800	No
	4	70	9.4	27.8	5560	No
	5	74	39.8	15.4	3080	No
	6	65.8	16.2	24.2	4840	No
	7	77.8	40	16.4	3280	No
	8	65.6	40	13.6	2720	No
	9	81.6	54.8	13	2600	No
	10	57.8	33.4	12.6	2520	No
	11	55.6	0	27.8	5560	No
	12	55.6	0	27.8	5560	No
	13	38.8	17.2	9.4	1880	No
	14	91.2	56.6	14.4	2880	Yes
	15	90.6	69	10.8	2160	Yes
	16	156.8	69	41	8200	Yes
New	1	87.4	0	40.6	8120	No
	2	85.2	0	40	8000	No
	3	78.4	6.8	34.6	6920	No
	4	75.2	0	37.8	7560	No
	5	87	38.6	23.8	4760	No
	6	76.2	41.6	14.4	2880	No
	7	80.4	16.2	30.4	6080	No
	8	71.8	16.2	27.8	5560	No
	9	88	33.4	23.2	4640	No
	10	78.4	30.8	21.2	4240	No
	11	96.6	19	33.6	6720	Yes
	12	140.6	52.8	41	8200	Yes

Table A.2. Maximum turnaround time of 1.75 hours

Garage Location	Route #	Turnaround Time (minutes)	Deadhead Time (minutes)	Spreading Miles	Material Used (lbs.)	Maximum Turnaround Violated?
Old	1	95.8	0	41.6	8320	No
	2	80.6	0	39	7800	No
	3	103.6	16.2	40.6	8120	No
	4	92.4	40	26.6	5320	No
	5	92.4	57.8	14.4	2880	No
	6	90.6	69	10.8	2160	No
	7	80.4	2.8	33.6	6720	No
	8	94.4	9.4	40.4	8080	No
	9	74	39.8	15.4	3080	No
	10	94.4	17.2	37.2	7440	No
	11	55.6	0	27.8	5560	No
	12	156.8	69	41	8200	Yes
New	1	102	0	50.8	10160	No
	2	100.2	29	35	7000	No
	3	96.2	23.8	30.8	6160	No
	4	103.2	0	46.6	9320	No
	5	71.8	16.2	27.8	5560	No
	6	71.8	16.2	27.8	5560	No
	7	93.2	48	19.2	3840	No
	8	91.8	6.8	40.4	8080	No
	9	71.4	37.2	15.4	3080	No
	10	96.6	19	33.6	6720	No
	11	140.6	52.8	41	8200	Yes

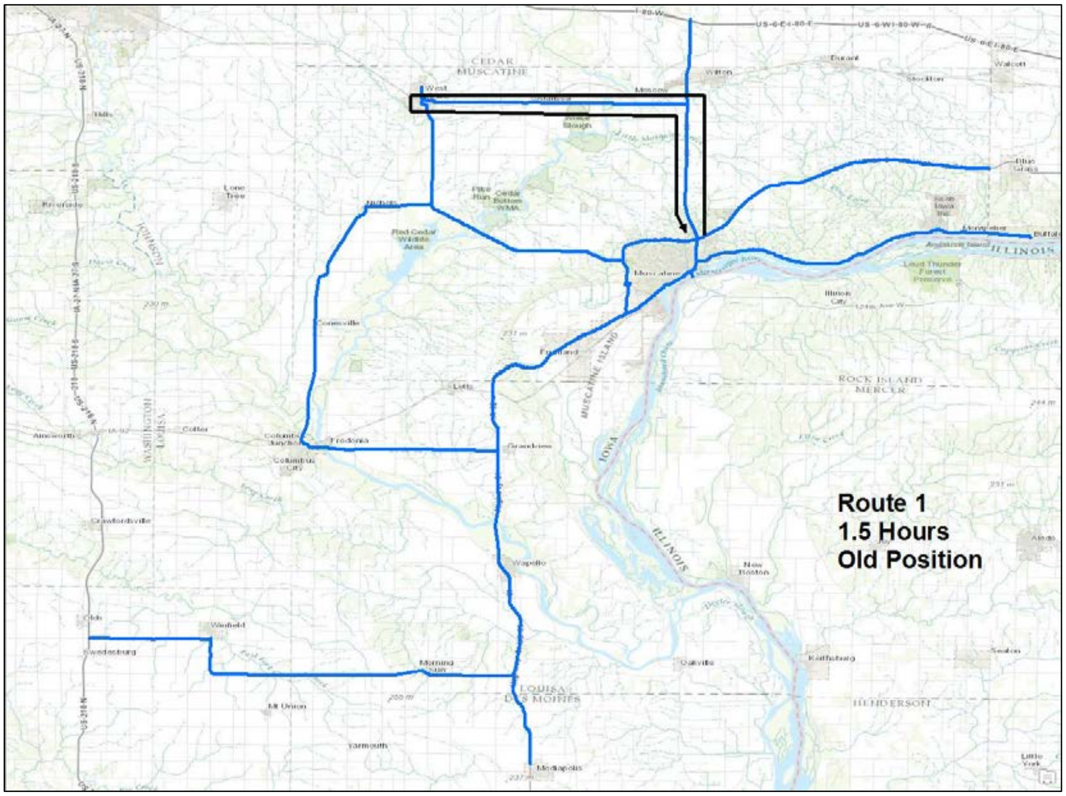
Table A.3. Maximum turnaround time of 2 hours

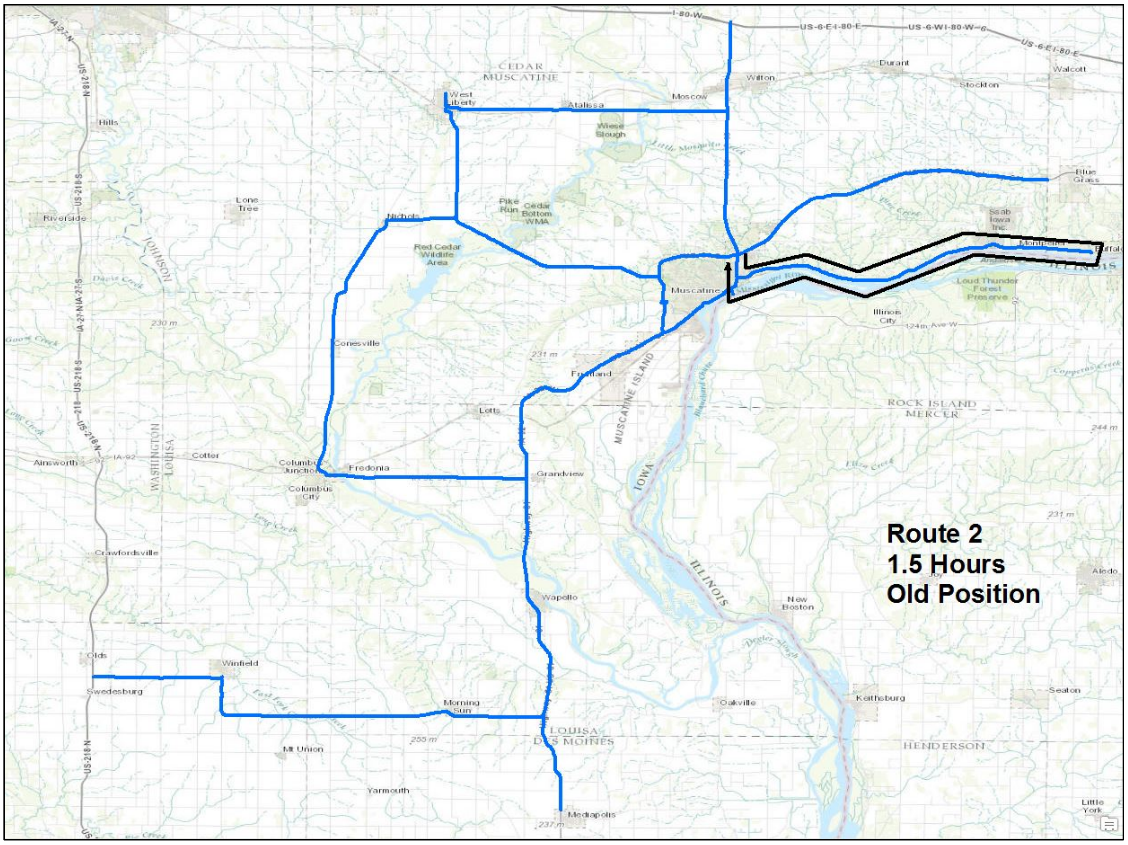
Garage Location	Route #	Turnaround Time (minutes)	Deadhead Time (minutes)	Spreading Miles	Material Used (lbs.)	Maximum Turnaround Violated?
Old	1	118.4	0	51.8	10360	No
	2	106.4	9.4	46.6	9320	No
	3	107.4	31	37.2	7440	No
	4	90.6	69	10.8	2160	No
	5	112.4	40	30.8	6160	No
	6	113	2.8	49.4	9880	No
	7	117.8	17.2	45.2	9040	No
	8	111.2	0	55.6	11120	No
	9	156.8	69	41	8200	Yes
New	1	117.2	0	51	10200	No
	2	102	0	50.8	10160	No
	3	101.6	7.8	43.2	8640	No
	4	100.2	29	35	7000	No
	5	96.2	23.8	30.8	6160	No
	6	109.8	30.8	35.8	7160	No
	7	104.4	16.2	43.6	8720	No
	8	110.6	33.4	37.2	7440	No
	9	140.6	52.8	41	8200	Yes

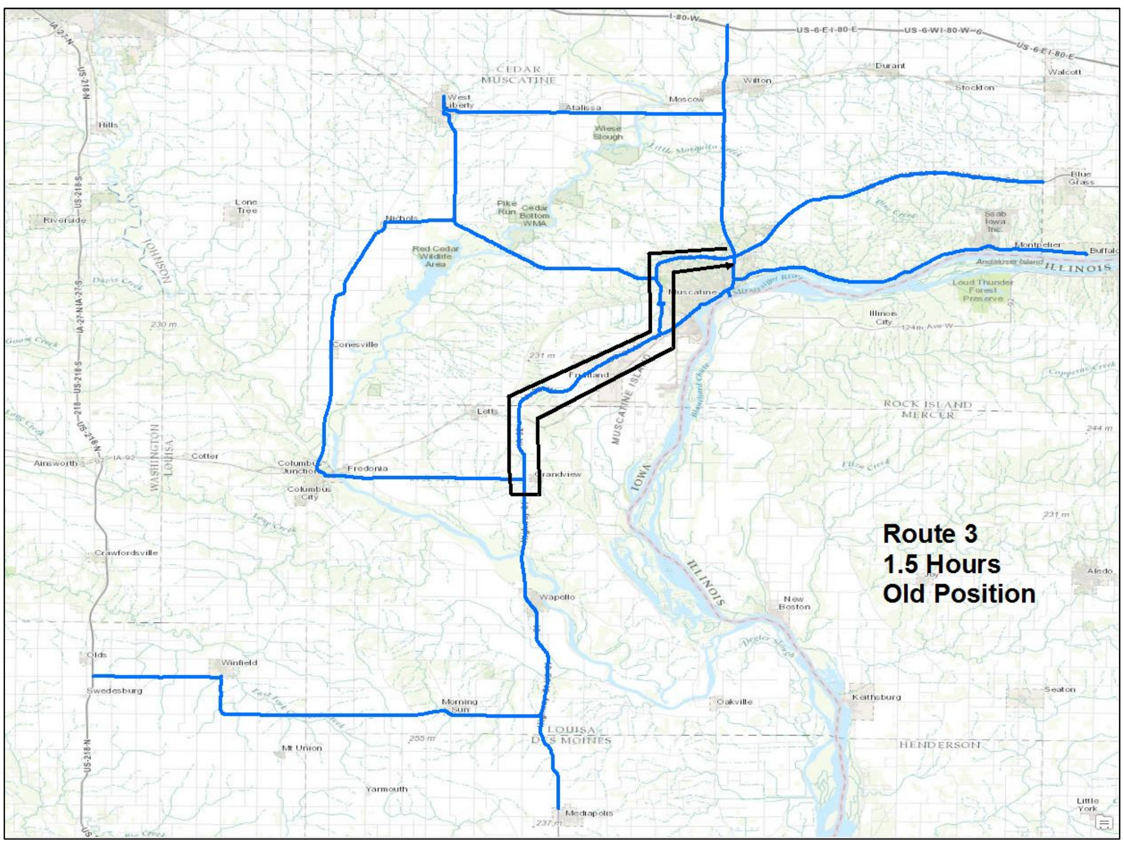
APPENDIX B. OPTIMAL SNOW ROUTES FOR MUSCATINE GARAGE

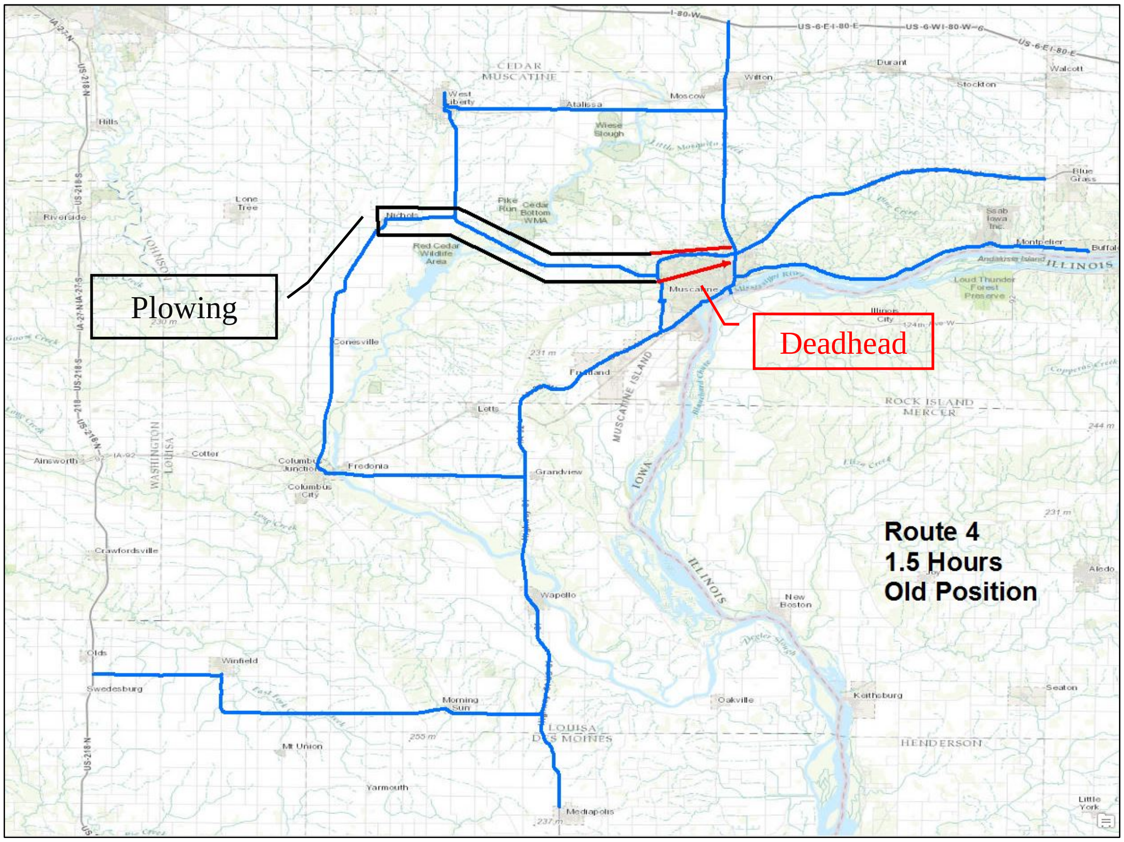
The maps in this appendix show the optimal operation routes for each scenario (i.e., with 1.5-, 1.75, and 2-hour maximum turnaround times). Black lines indicate the servicing segments, while red lines indicate the deadhead segments.

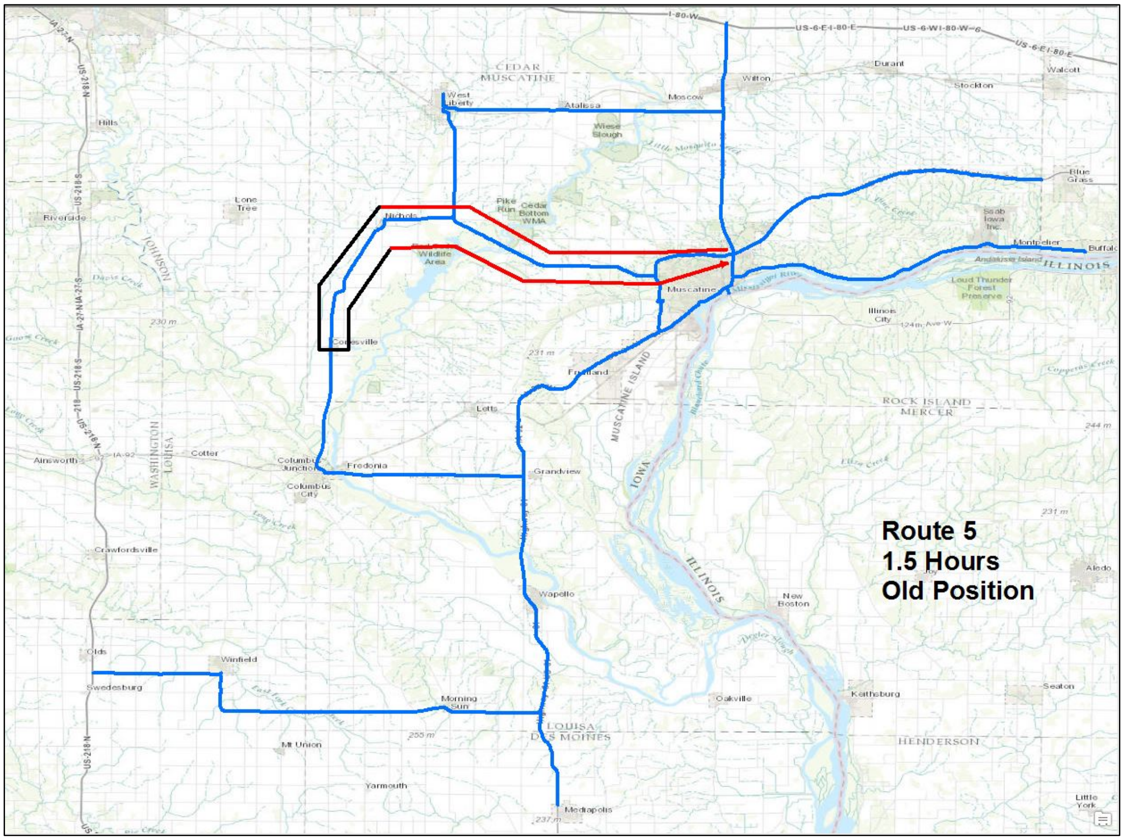
Old Position 1.5-Hour Routes

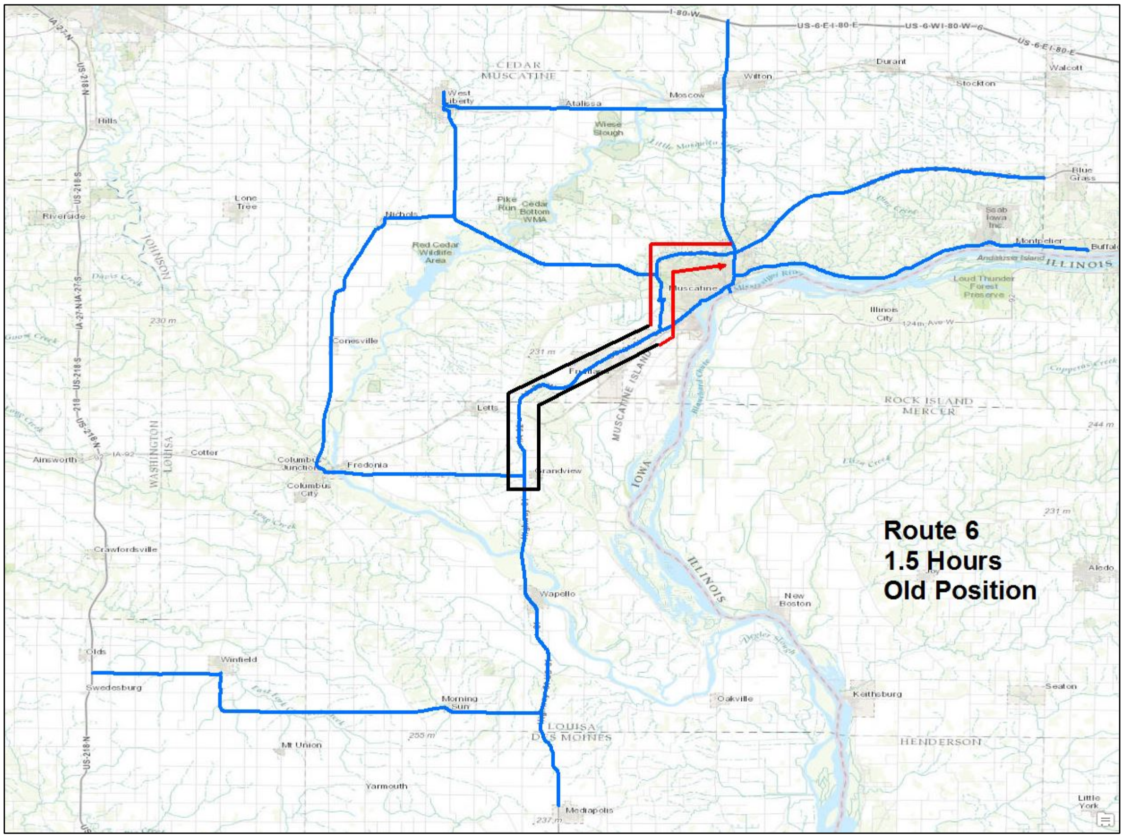


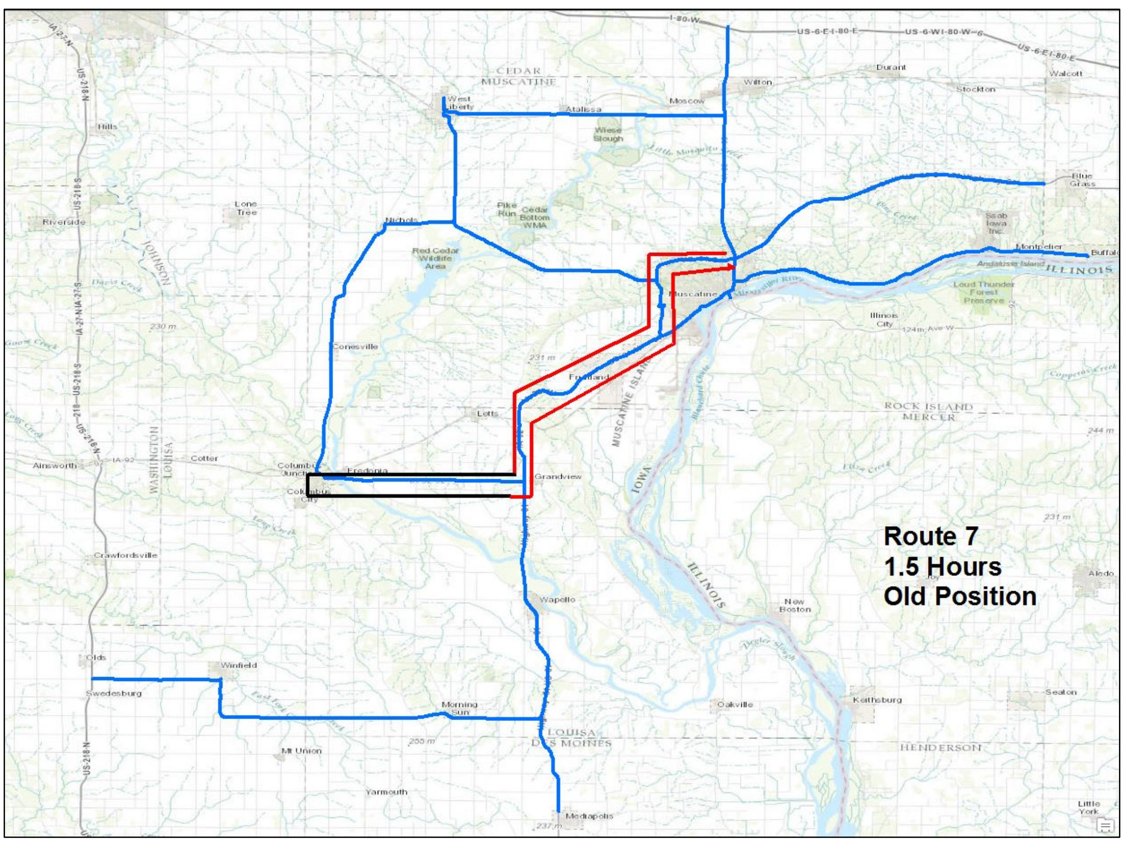

Route 2
1.5 Hours
Old Position

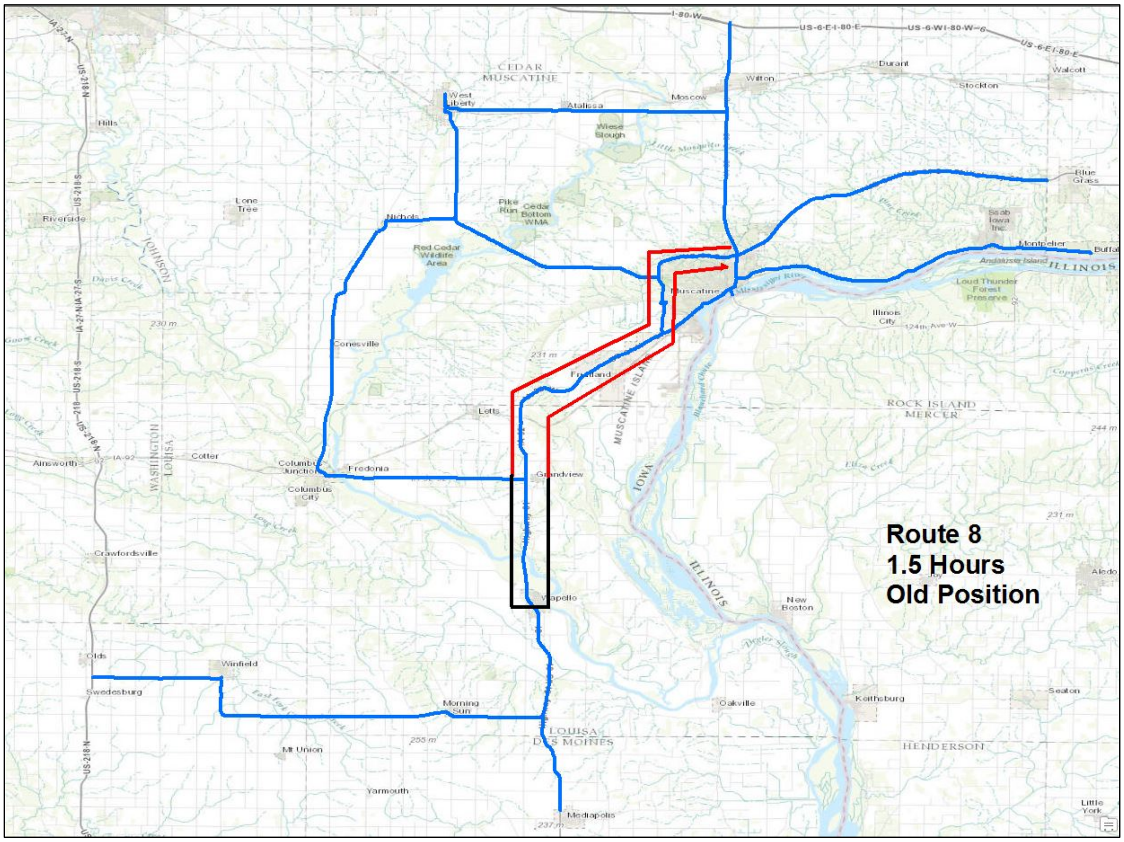

Route 3
1.5 Hours
Old Position

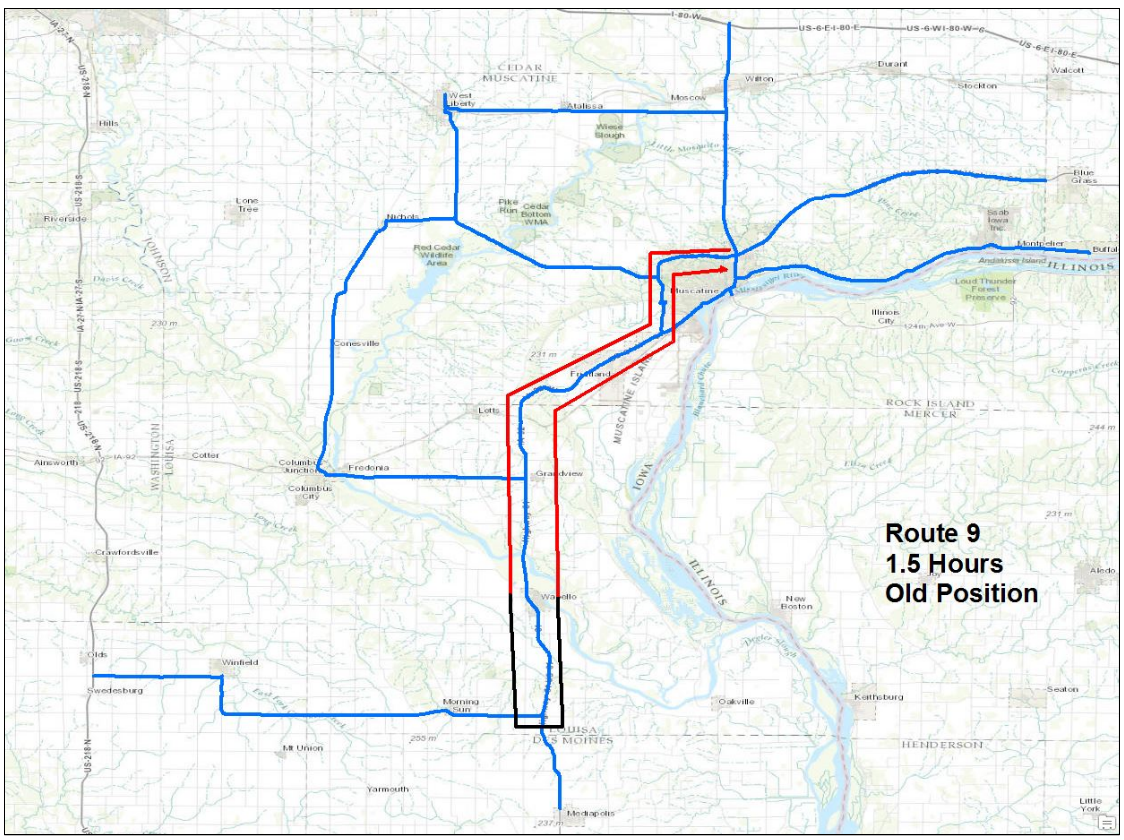

Plowing
Deadhead
Route 4
1.5 Hours
Old Position

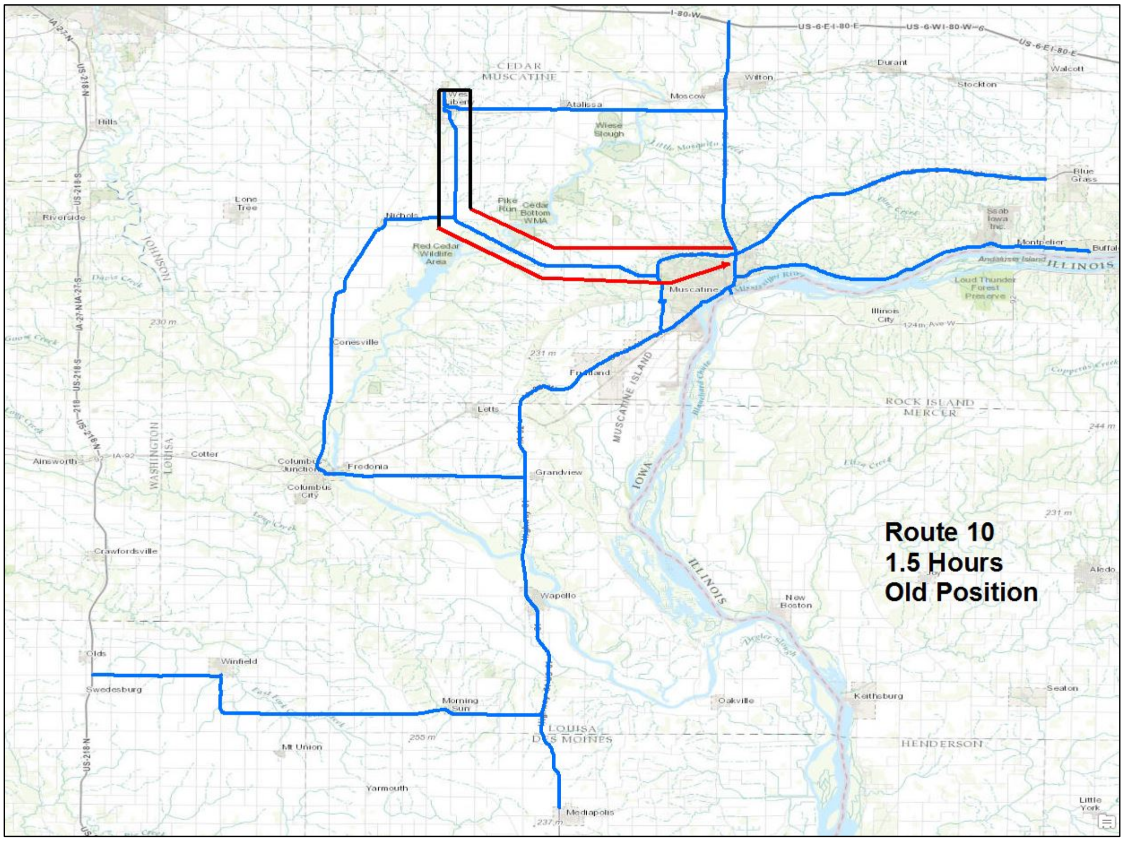

Route 5
1.5 Hours
Old Position

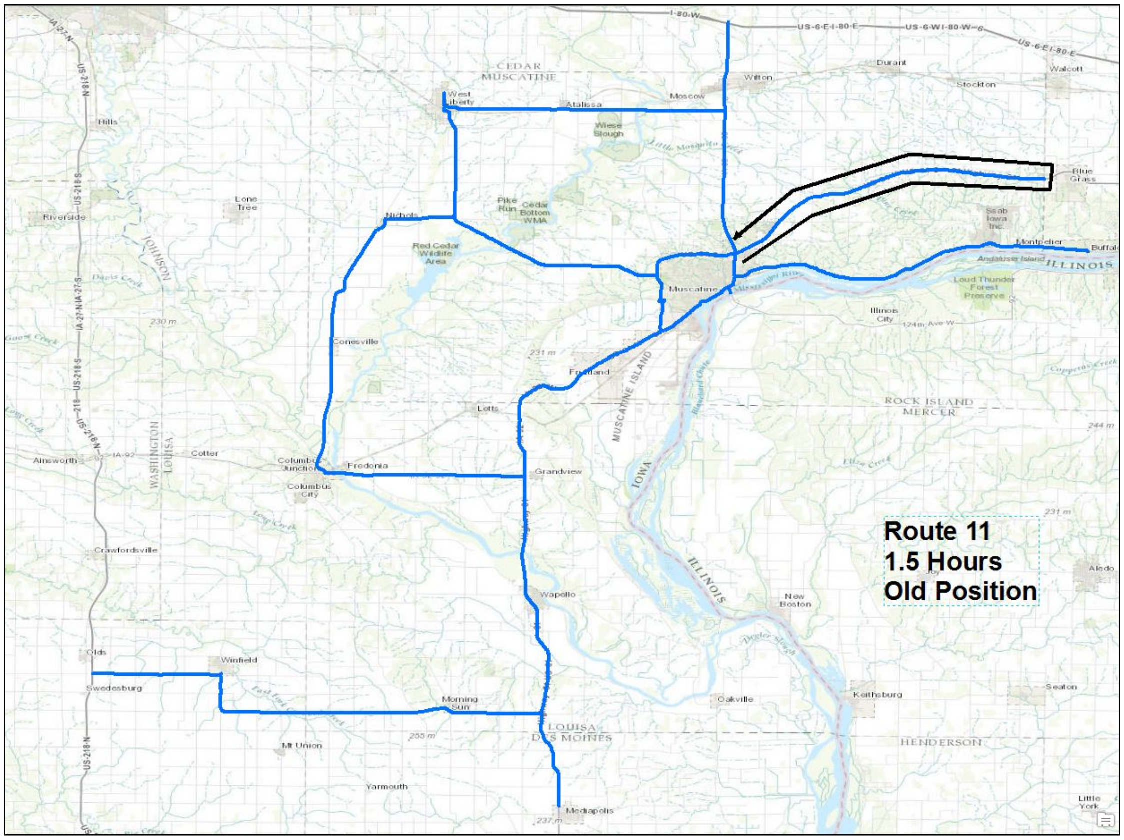

Route 6
1.5 Hours
Old Position
Muscatine
Letts
Grandview
Wapello
Conesville
Fredonia
Nichols
West Liberty
Atalissa
Wilton
Oakville
Keithsburg
Mediapolis
Morning Sun
Winfield
Columbus City
Columbus Junction

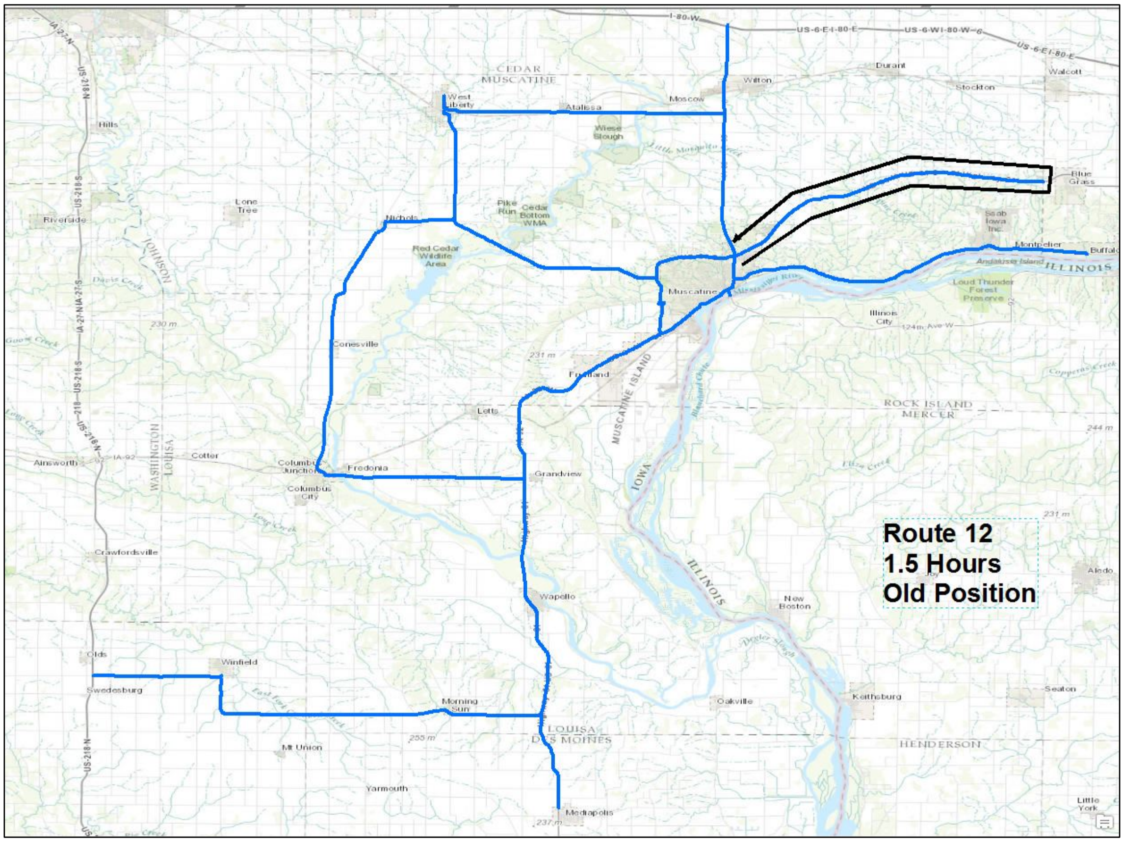

Route 7
1.5 Hours
Old Position
Muscatine
Letts
Grandview
Wapello
Conesville
Fredonia
Nichols
West Liberty
Atalissa
Wilton
Oakville
Keithsburg
Mediapolis
Morning Sun
Winfield

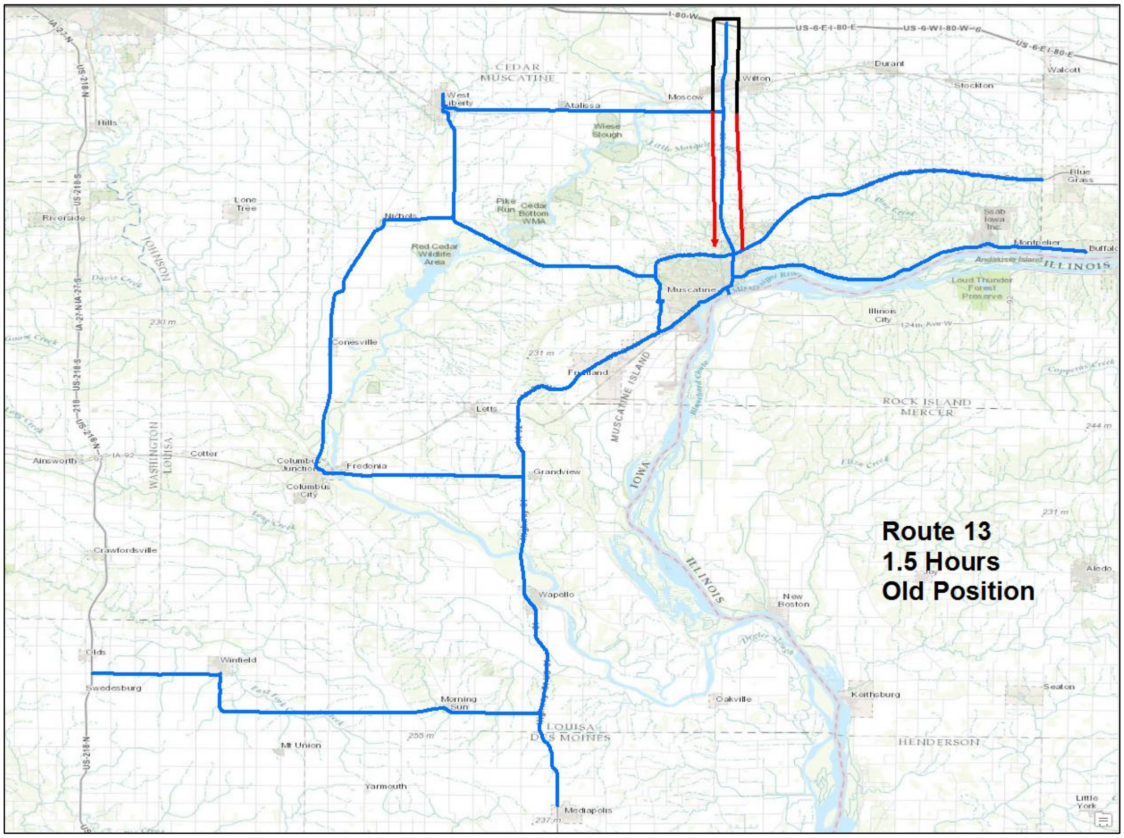

Route 8
1.5 Hours
Old Position

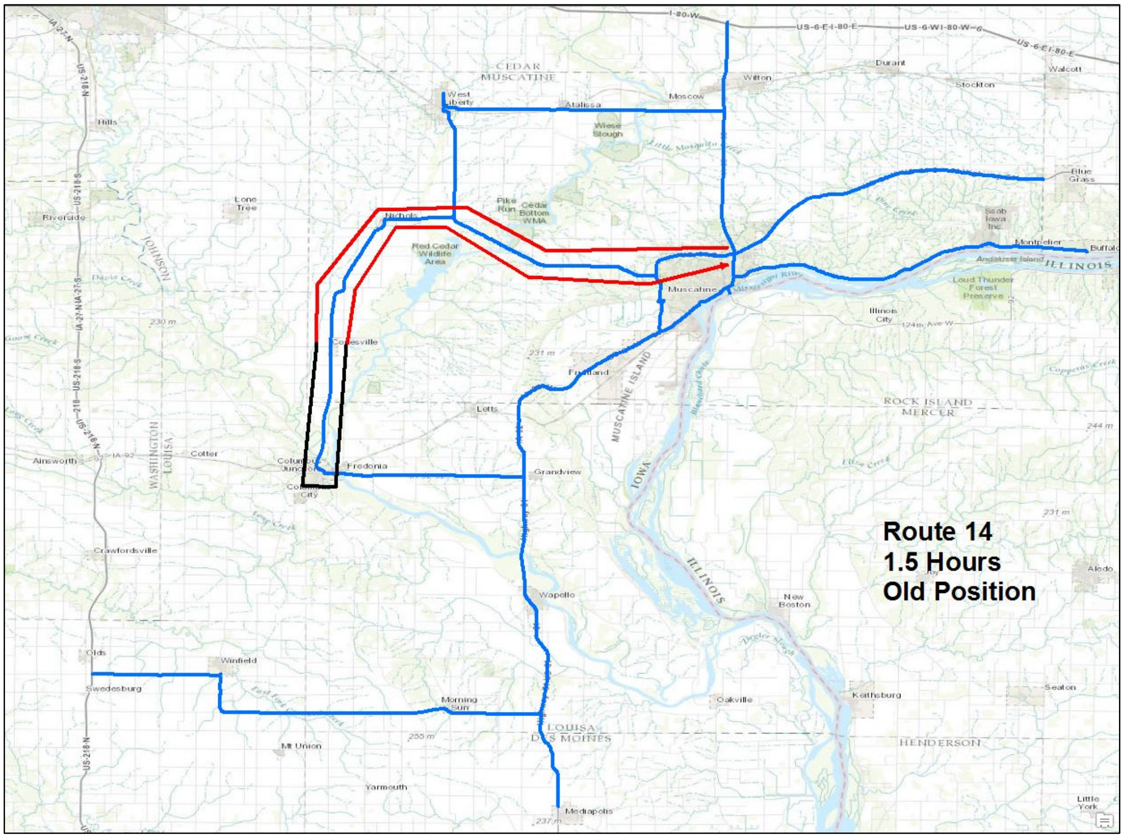

Route 9
1.5 Hours
Old Position

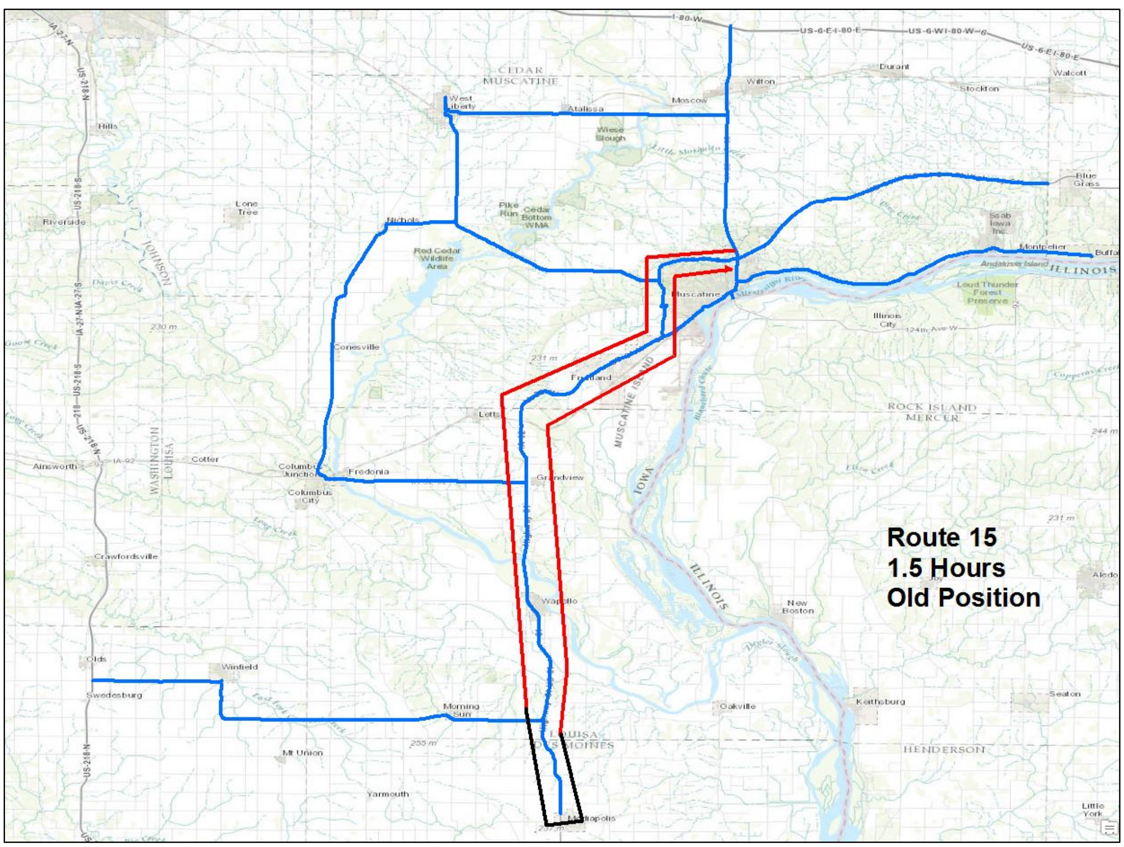

Route 10
1.5 Hours
Old Position

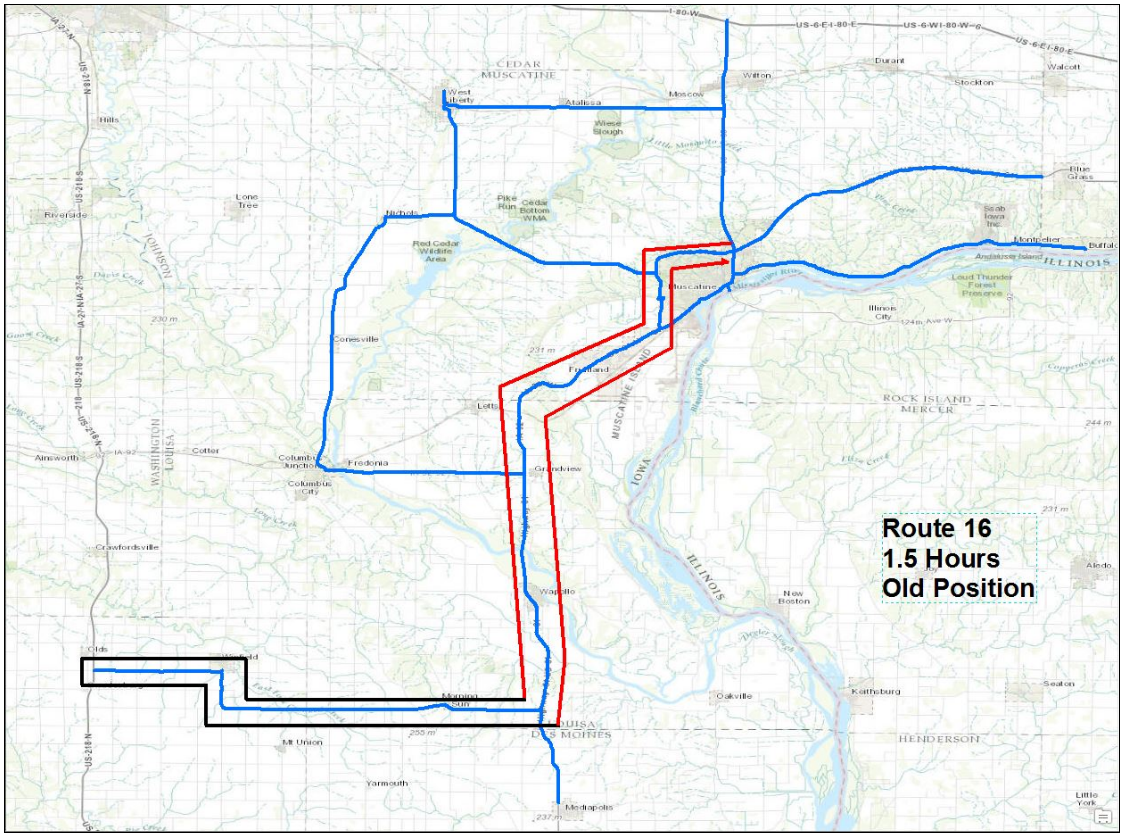

Route 11
1.5 Hours
Old Position


Route 12
1.5 Hours
Old Position

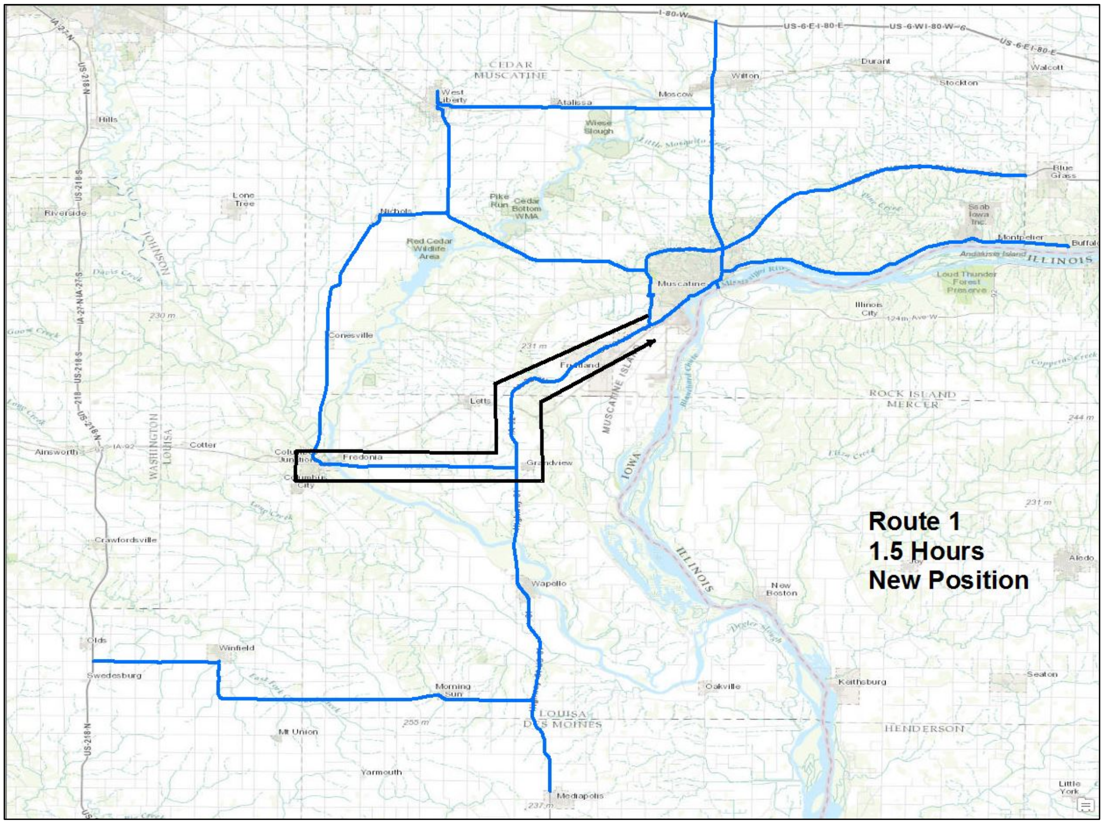

Route 13
1.5 Hours
Old Position

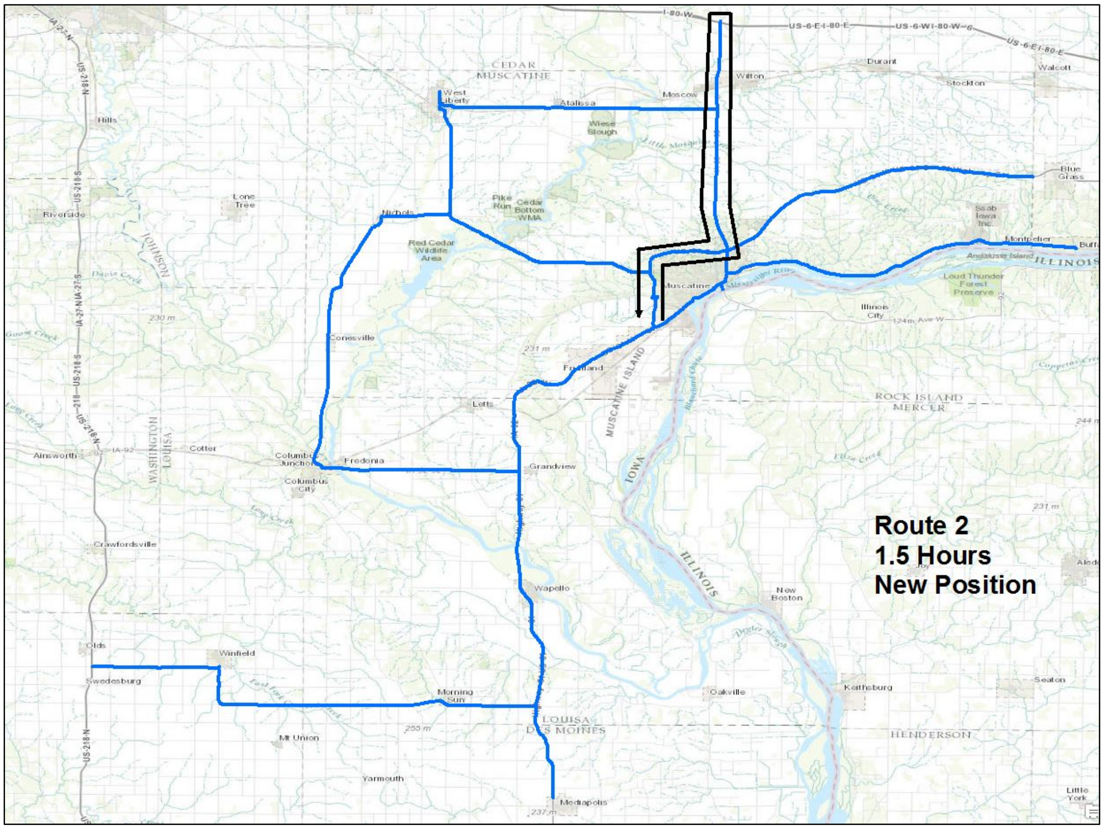

Route 14
1.5 Hours
Old Position
CEDAR
MUSCATINE
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Hills
Lone Tree
Riverside
Nichols
Pike Run
Cedar Bottom WMA
Red Cedar Wildlife Area
Muscatine
Conesville
Fruitland
Letts
Cotter
Ainsworth
Columbus Junction
Columbus City
Fredonia
Grandview
Crawfordsville
Wapello
Olds
Winfield
Swedesburg
Morning Sun
Mt Union
Yarmouth
Mediapolis
LOUISA
DES MOINES
Oakville
Keithsburg
New Boston
HENDERSON
ROCK ISLAND
MERCER
Illinois City
Aledo
Seaton
Little York
Blue Grass
Montpelier
Loud Thunder Forest Preserve
ILLINOIS
IOWA
MUSCATINE ISLAND
JOHNSON
WASHINGTON
LOUISA

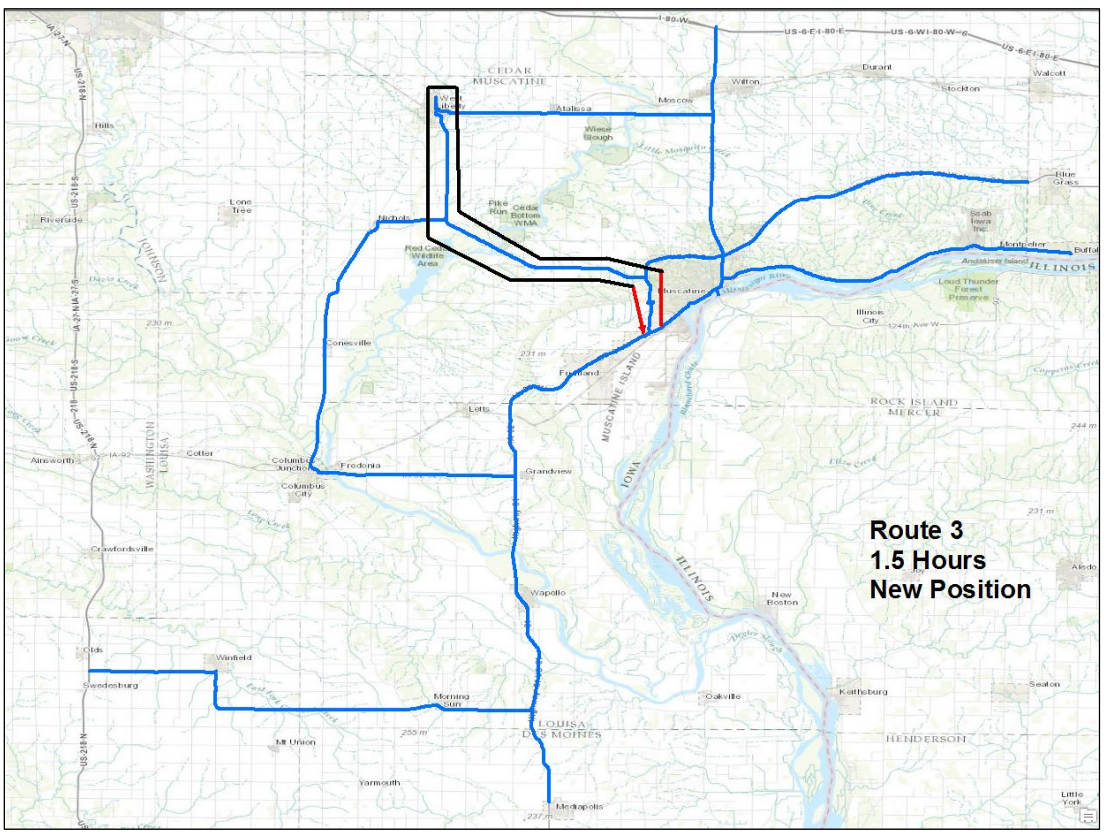

Route 15
1.5 Hours
Old Position
CEDAR
MUSCATINE
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Hills
Lone Tree
Riverside
Nichols
Pike Run
Cedar Bottom WMA
Red Cedar Wildlife Area
Muscatine
Conesville
Fruitland
Letts
Cotter
Ainsworth
Columbus Junction
Columbus City
Fredonia
Grandview
Crawfordsville
Wapello
Olds
Winfield
Swedesburg
Morning Sun
Mt Union
Yarmouth
Mediapolis
LOUISA
DES MOINES
Oakville
Keithsburg
New Boston
HENDERSON
ROCK ISLAND
MERCER
Illinois City
Aledo
Seaton
Little York
Blue Grass
Montpelier
Loud Thunder Forest Preserve
ILLINOIS
IOWA
MUSCATINE ISLAND
JOHNSON
WASHINGTON
LOUISA

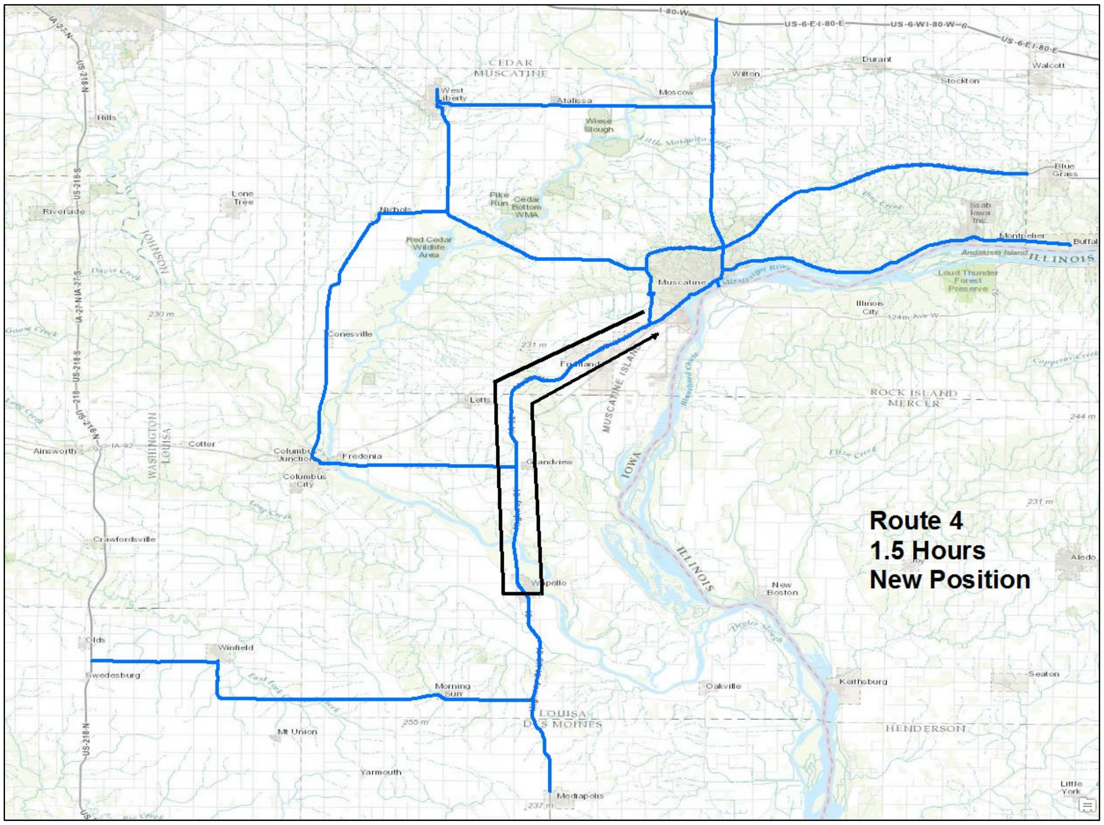

Route 16
1.5 Hours
Old Position

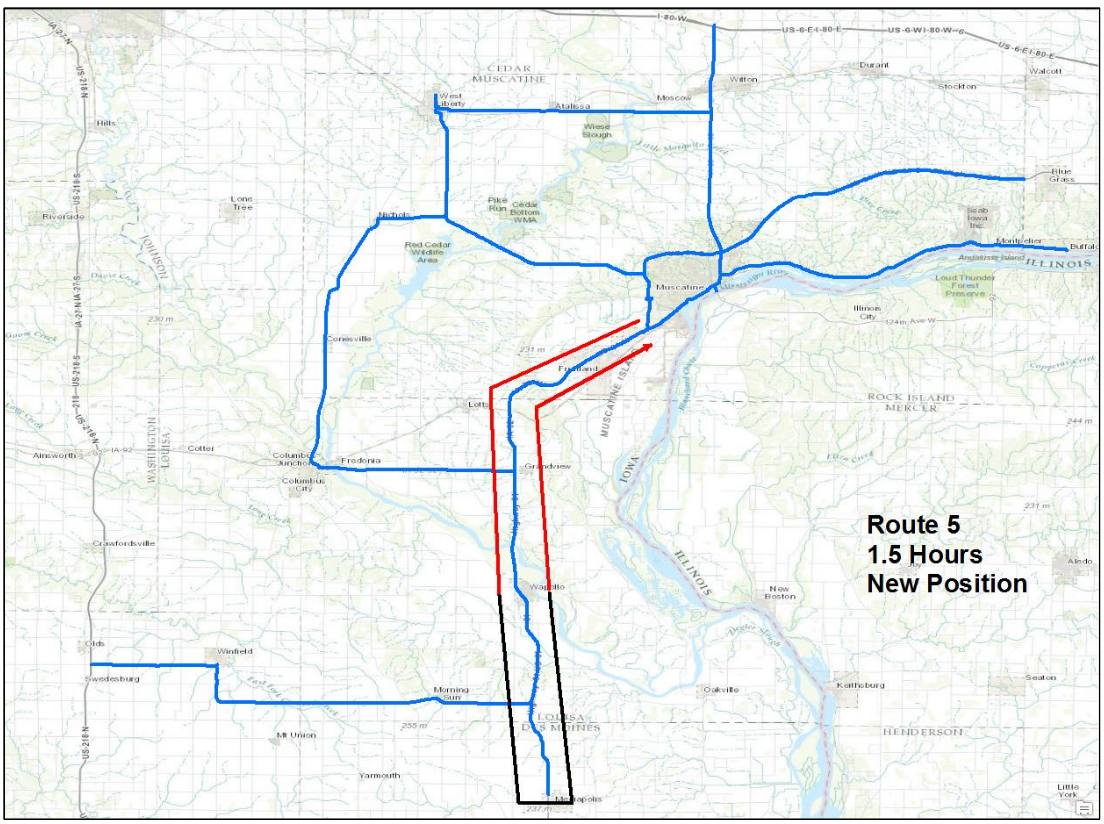
New Position 1.5-Hour Routes

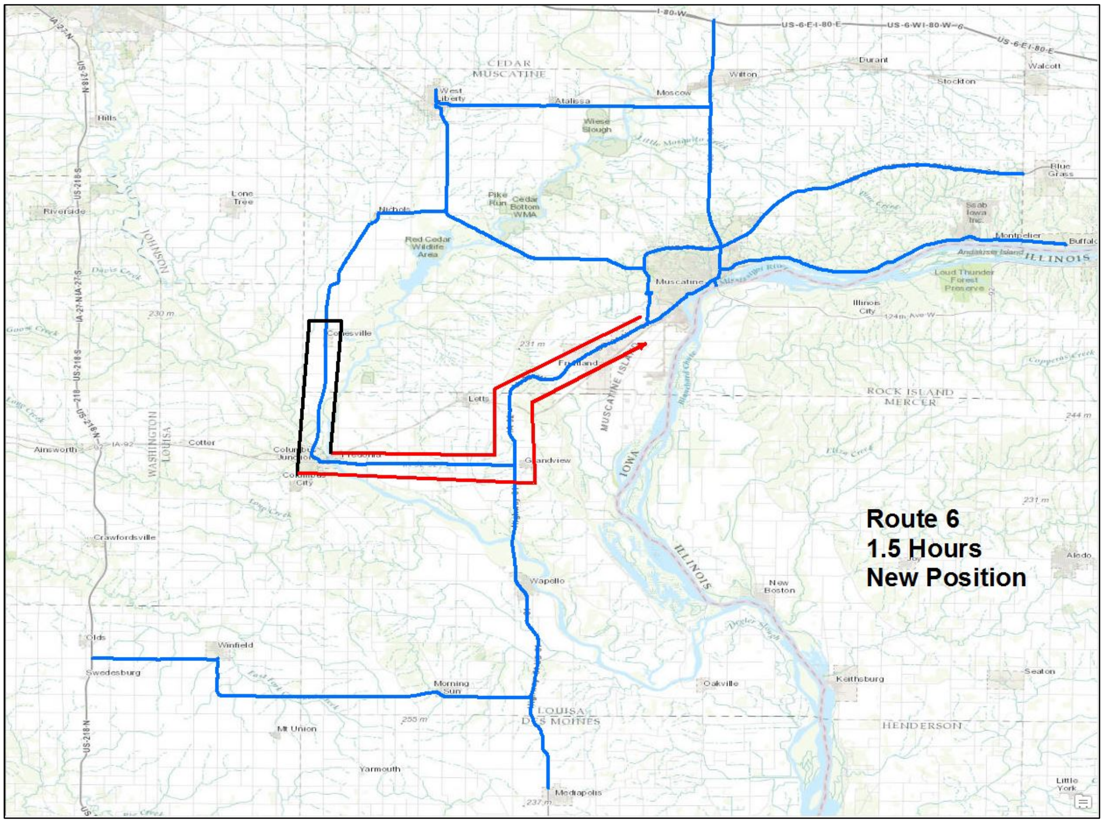


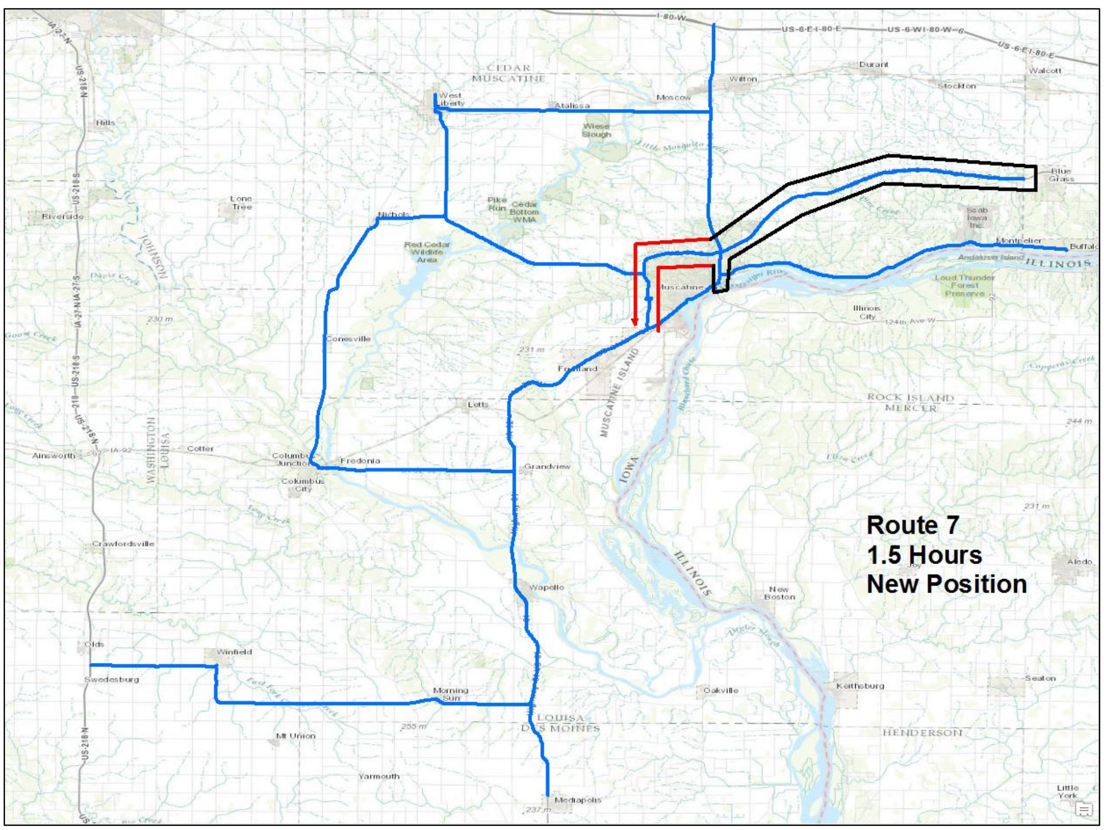

Route 2
1.5 Hours
New Position
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Blue Grass
Nichols
Muscatine
Fruitland
Letts
Conesville
Columbus Junction
Fredonia
Grandview
Wapello
Winfield
Swedesburg
Morning Sun
Mt Union
Yarmouth
Mediapolis
Oakville
Keithsburg
New Boston
Illinois City
Montpelier
ROCK ISLAND
MERCER
LOUISA
DES MOINES
HENDERSON
MUSCATINE ISLAND
IOWA
ILLINOIS
CEDAR
MUSCATINE
Hills
Riverside
Lone Tree
Ainsworth
Cotter
Crawfordsville
Olds
Red Cedar Wildlife Area
Pike Run
Cedar Bottom WMA
Wiese Slough
Loud Thunder Forest Preserve

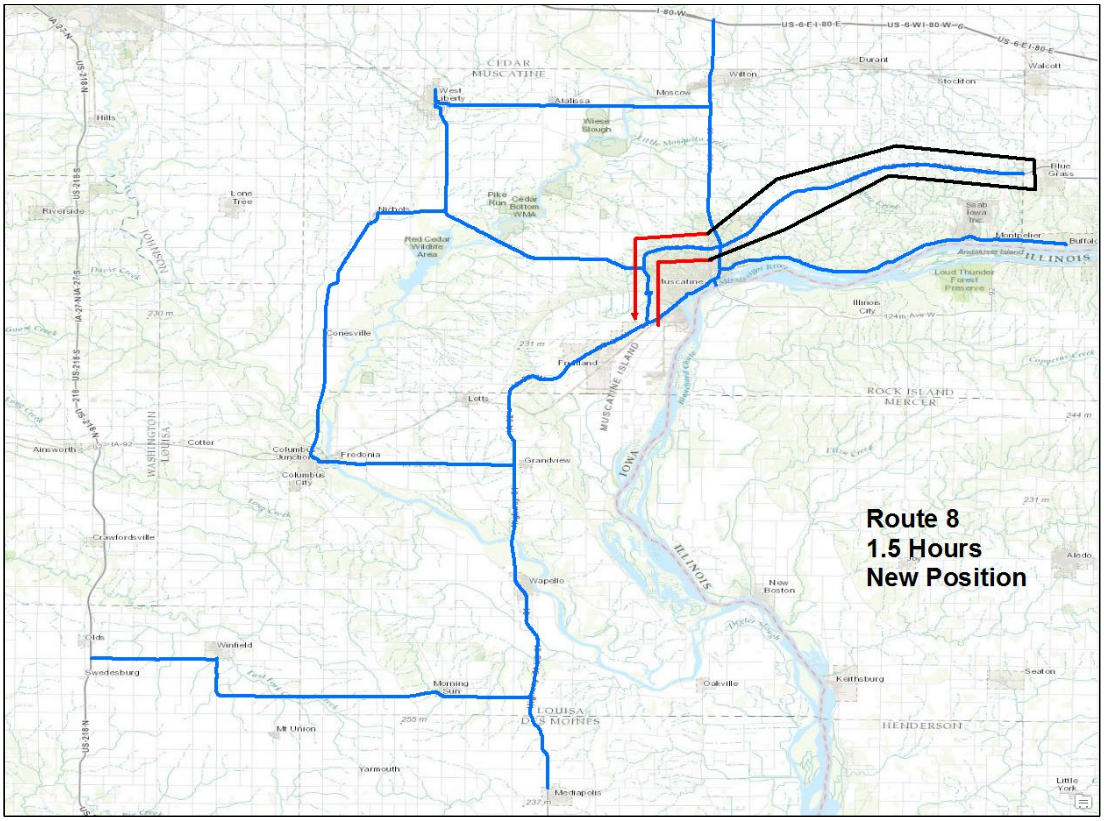

Route 3
1.5 Hours
New Position
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Blue Grass
Nichols
Muscatine
Fruitland
Letts
Conesville
Columbus Junction
Fredonia
Grandview
Wapello
Winfield
Swedesburg
Morning Sun
Mt Union
Yarmouth
Mediapolis
Oakville
Keithsburg
New Boston
Illinois City
Montpelier
ROCK ISLAND
MERCER
LOUISA
DES MOINES
HENDERSON
MUSCATINE ISLAND
IOWA
ILLINOIS
CEDAR
MUSCATINE
Hills
Riverside
Lone Tree
Ainsworth
Cotter
Crawfordsville
Olds
Red Cedar Wildlife Area
Pike Run
Cedar Bottom WMA
Wiese Slough
Loud Thunder Forest Preserve

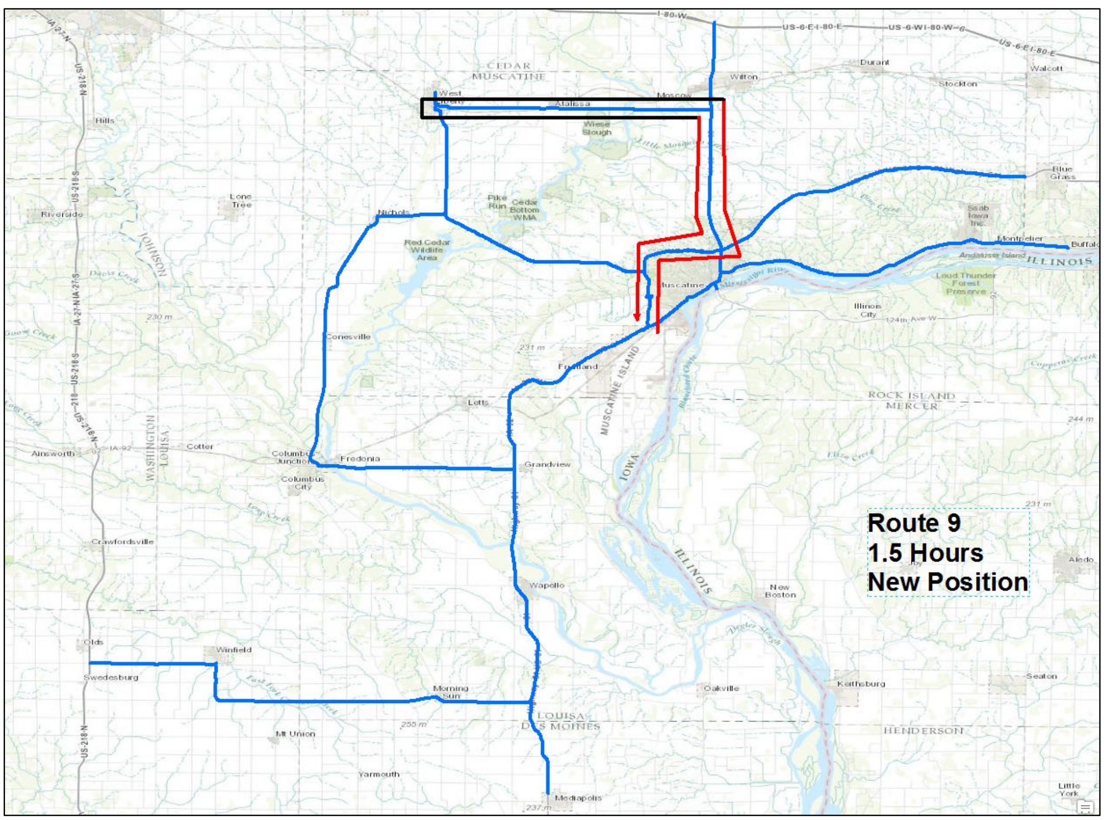

Route 4
1.5 Hours
New Position

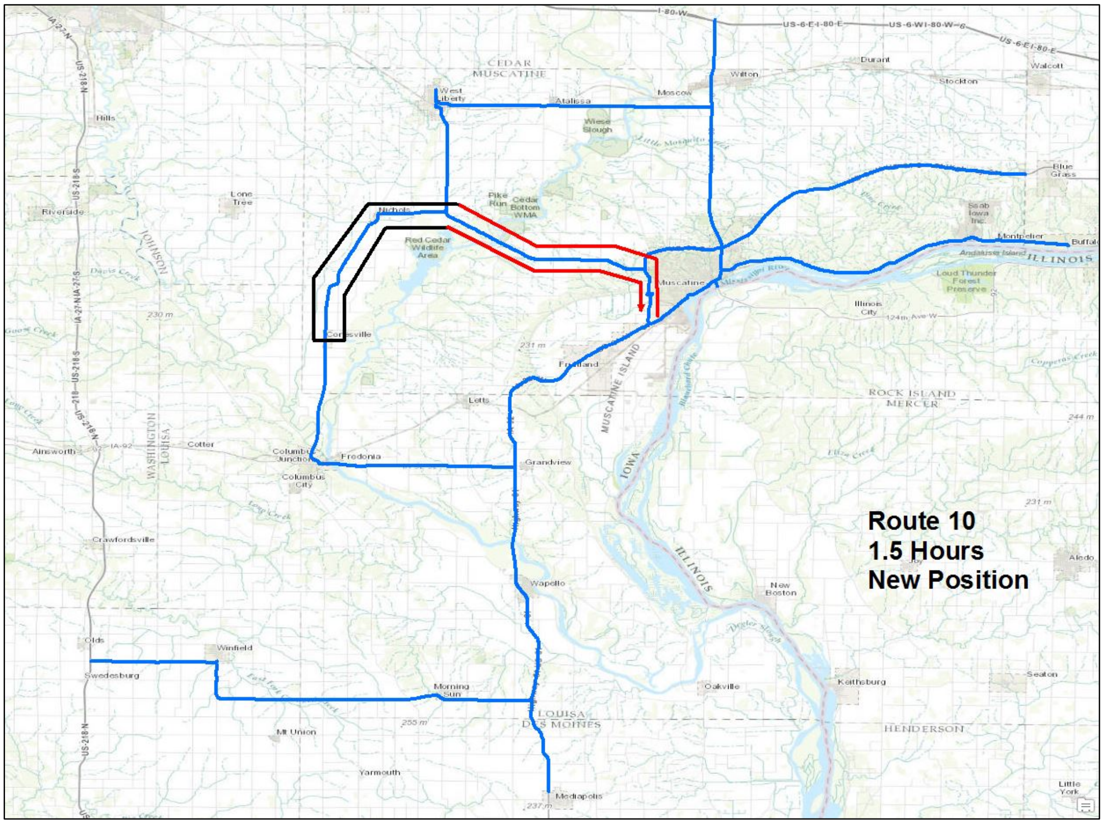

Route 5
1.5 Hours
New Position

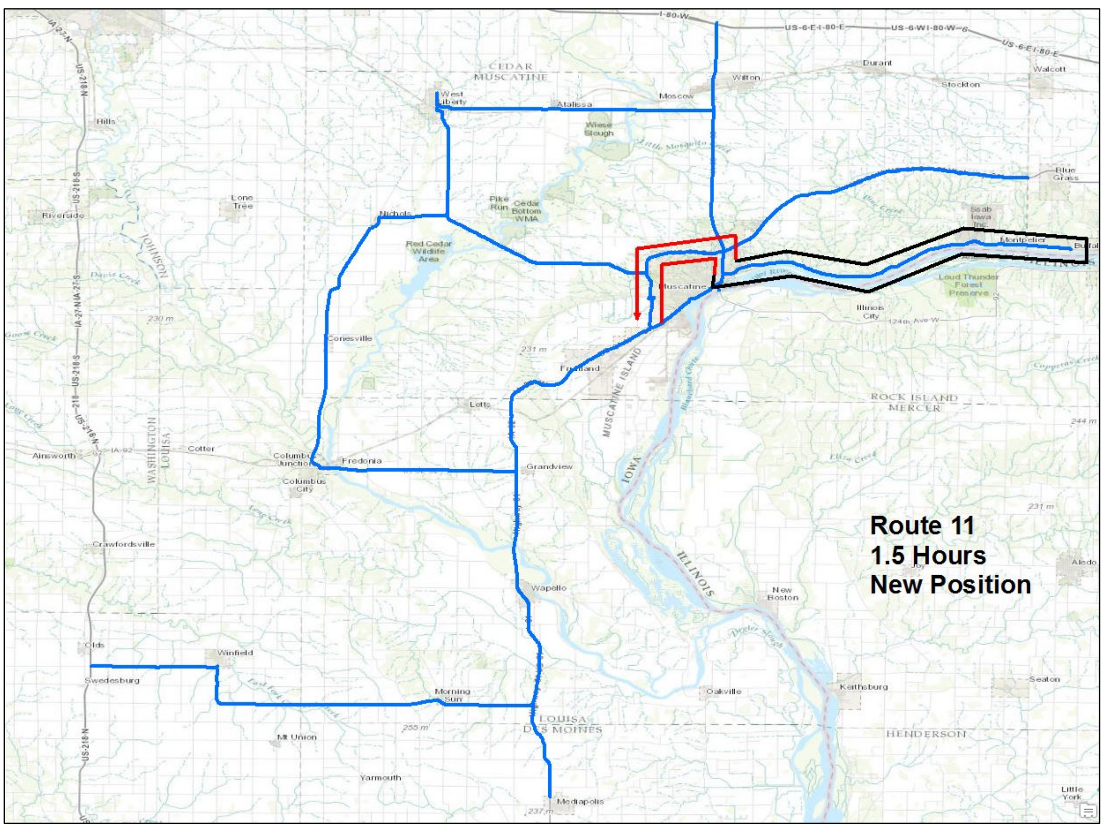

Route 6
1.5 Hours
New Position

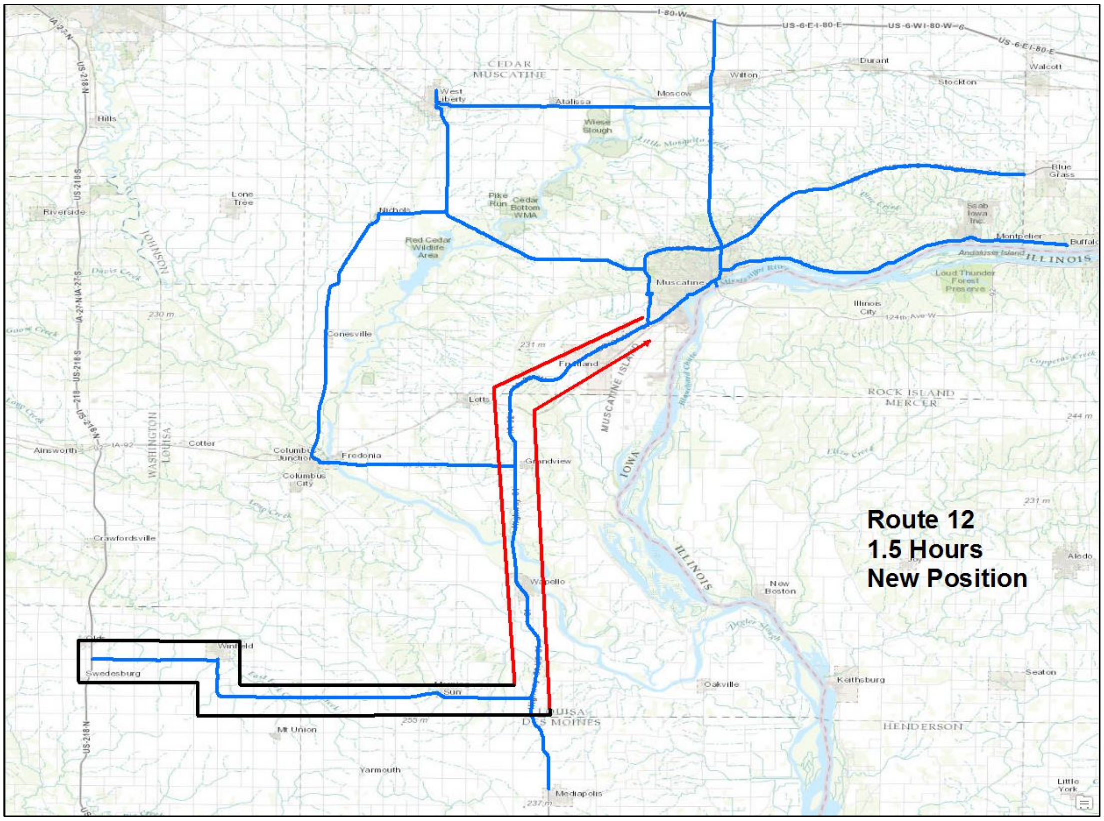

Route 7
1.5 Hours
New Position


Route 8
1.5 Hours
New Position

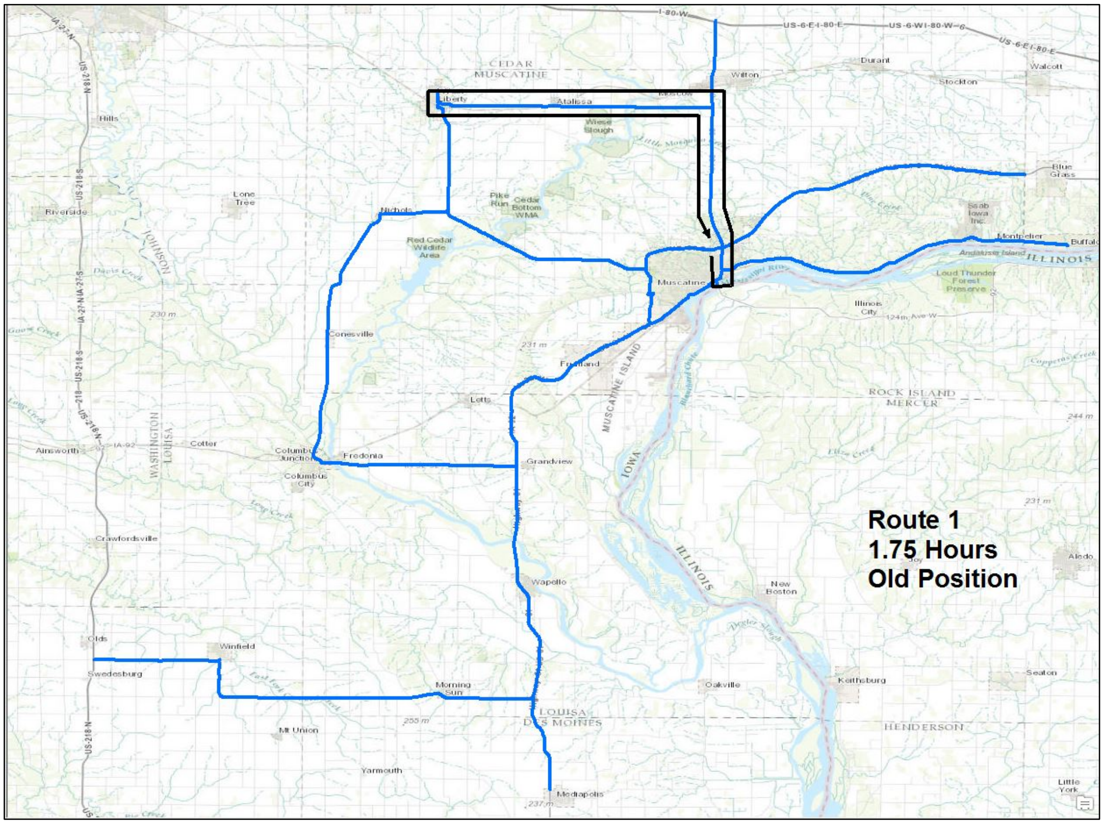

Route 9
1.5 Hours
New Position

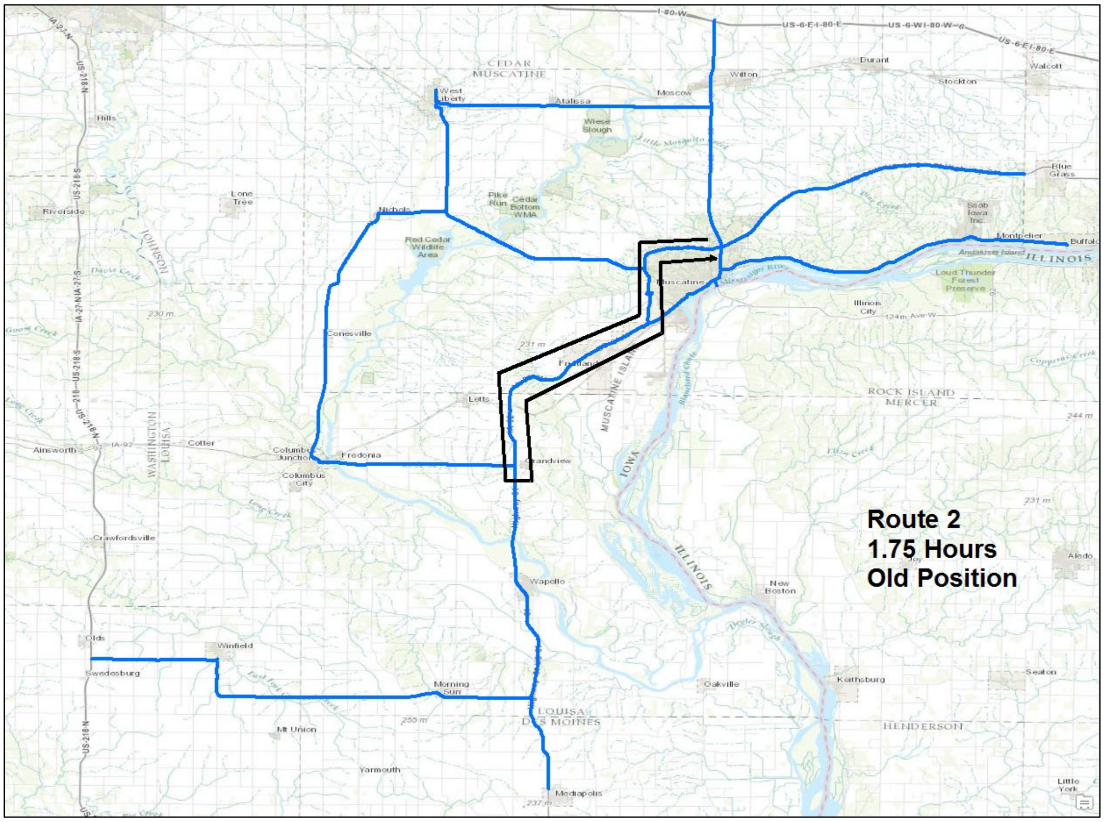

Route 10
1.5 Hours
New Position
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Blue Grass
Nichols
Red Cedar Wildlife Area
Conesville
Muscatine
Fruitland
Letts
Columbus Junction
Fredonia
Columbus City
Cotter
Grandview
Wapello
Winfield
Swedesburg
Morning Sun
Mt Union
Yarmouth
Mediapolis
Oakville
Keithsburg
New Boston
Aledo
Seaton
Montpelier
Illinois City
Riverside
Lone Tree
Hills
Ainsworth
Crawfordsville
Olds
CEDAR
MUSCATINE
ROCK ISLAND
MERCER
LOUISA
DES MOINES
HENDERSON
WASHINGTON
LOUISA
JOHNSON
IOWA
ILLINOIS

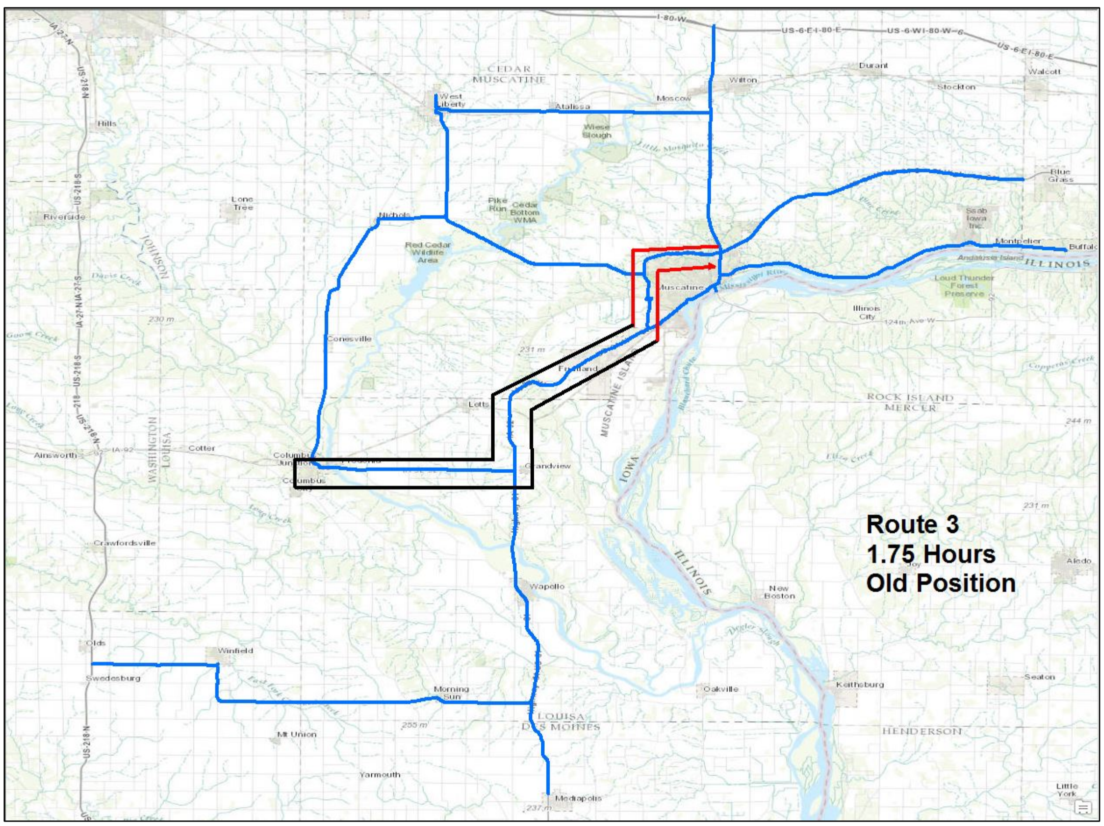

Route 11
1.5 Hours
New Position
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Blue Grass
Nichols
Red Cedar Wildlife Area
Conesville
Muscatine
Fruitland
Letts
Columbus Junction
Fredonia
Columbus City
Cotter
Grandview
Wapello
Winfield
Swedesburg
Morning Sun
Mt Union
Yarmouth
Mediapolis
Oakville
Keithsburg
New Boston
Aledo
Seaton
Montpelier
Illinois City
Riverside
Lone Tree
Hills
Ainsworth
Crawfordsville
Olds
CEDAR
MUSCATINE
ROCK ISLAND
MERCER
LOUISA
DES MOINES
HENDERSON
WASHINGTON
LOUISA
JOHNSON
IOWA
ILLINOIS

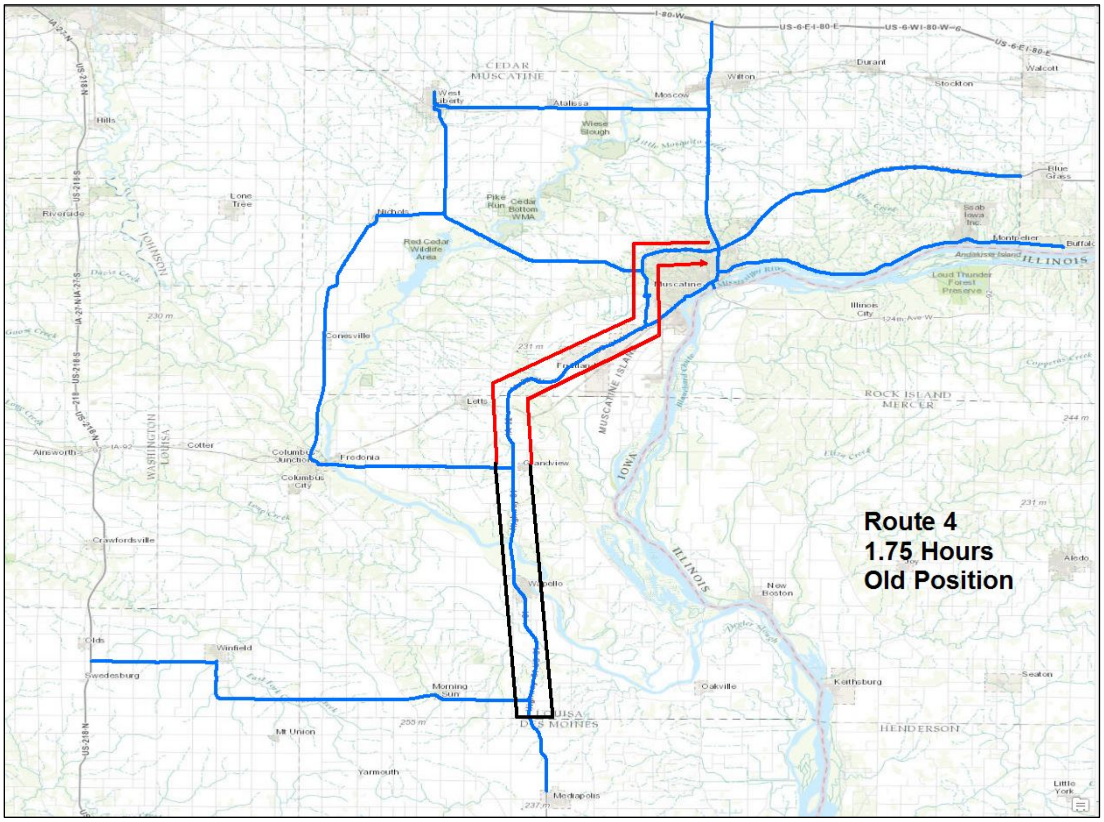

Route 12
1.5 Hours
New Position
West Liberty
Atalissa
Moscow
Wilton
Durant
Walcott
Stockton
Blue Grass
Nichols
Muscatine
Montpelier
Buffalo
Conesville
Fruitland
Letts
Columbus Junction
Fredonia
Columbus City
Grandview
Wapello
Winfield
Swedesburg
Oakville
Keithsburg
Seaton
New Boston
Mt Union
Yarmouth
Mediapolis
Aledo
Riverside
Lone Tree
Hills
Ainsworth
Cotter
Crawfordsville
Illinois City
Loud Thunder Forest Preserve
Red Cedar Wildlife Area
Wiese Slough
ROCK ISLAND
MERCER
HENDERSON
LOUISA
DES MOINES
CEDAR
MUSCATINE
JOHNSON
WASHINGTON
IOWA
ILLINOIS
MUSCATINE ISLAND
Little York

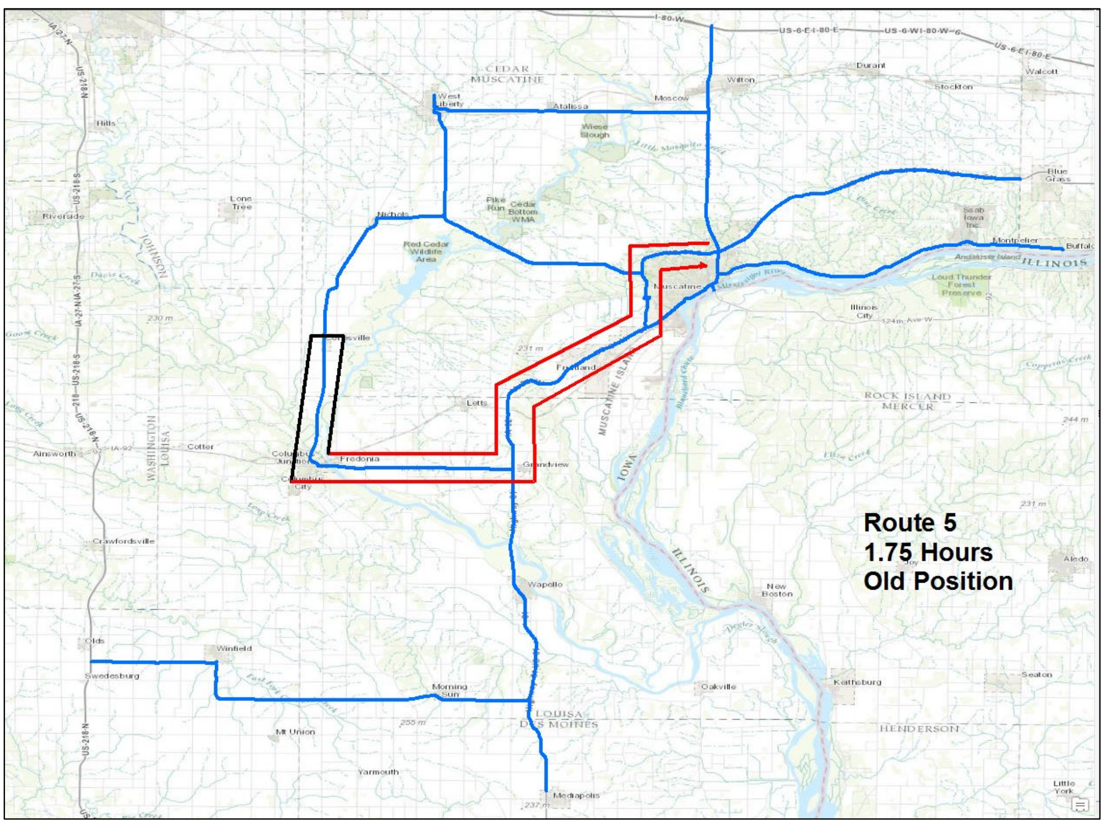
Old Position 1.75-Hour Routes

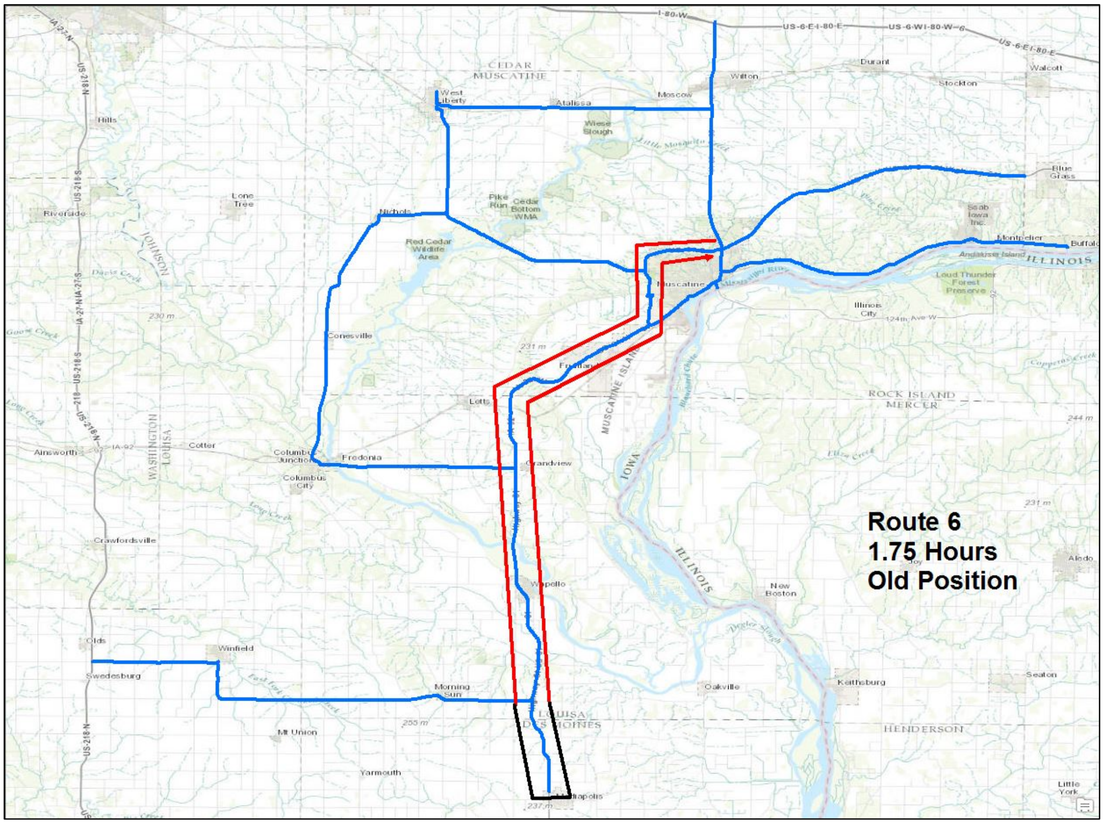


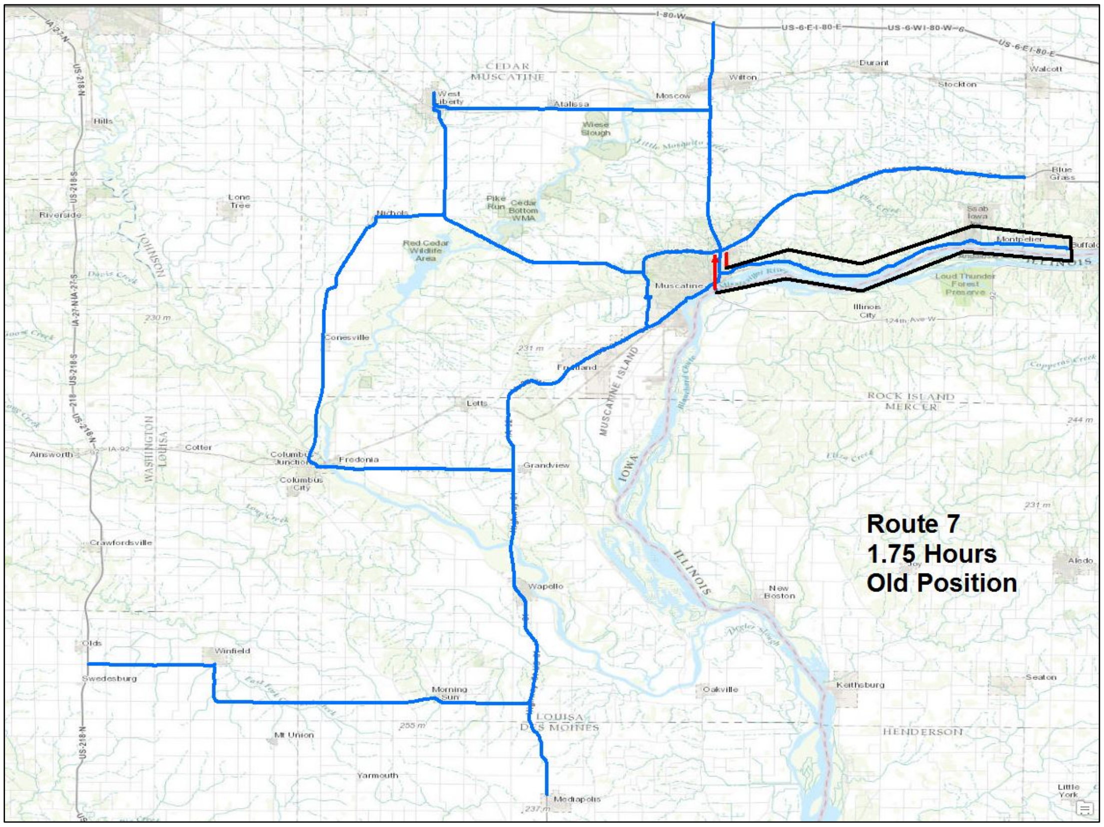

Route 2
1.75 Hours
Old Position

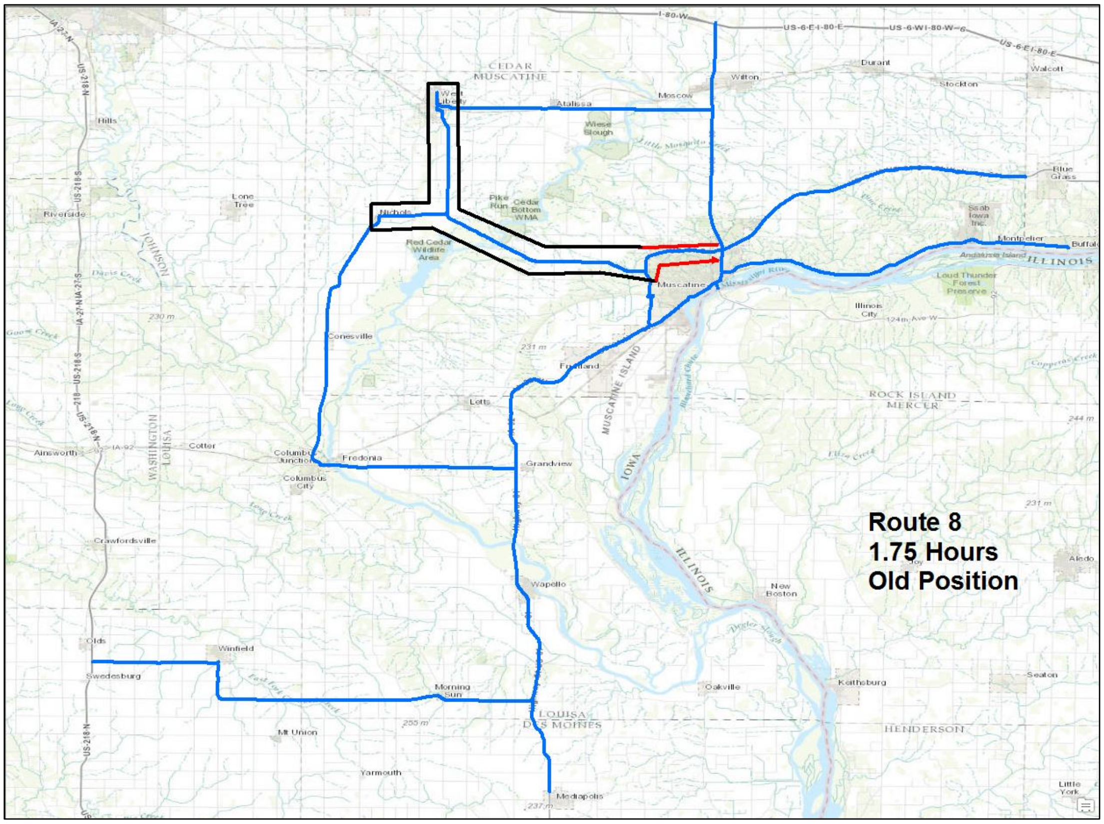

Route 3
1.75 Hours
Old Position

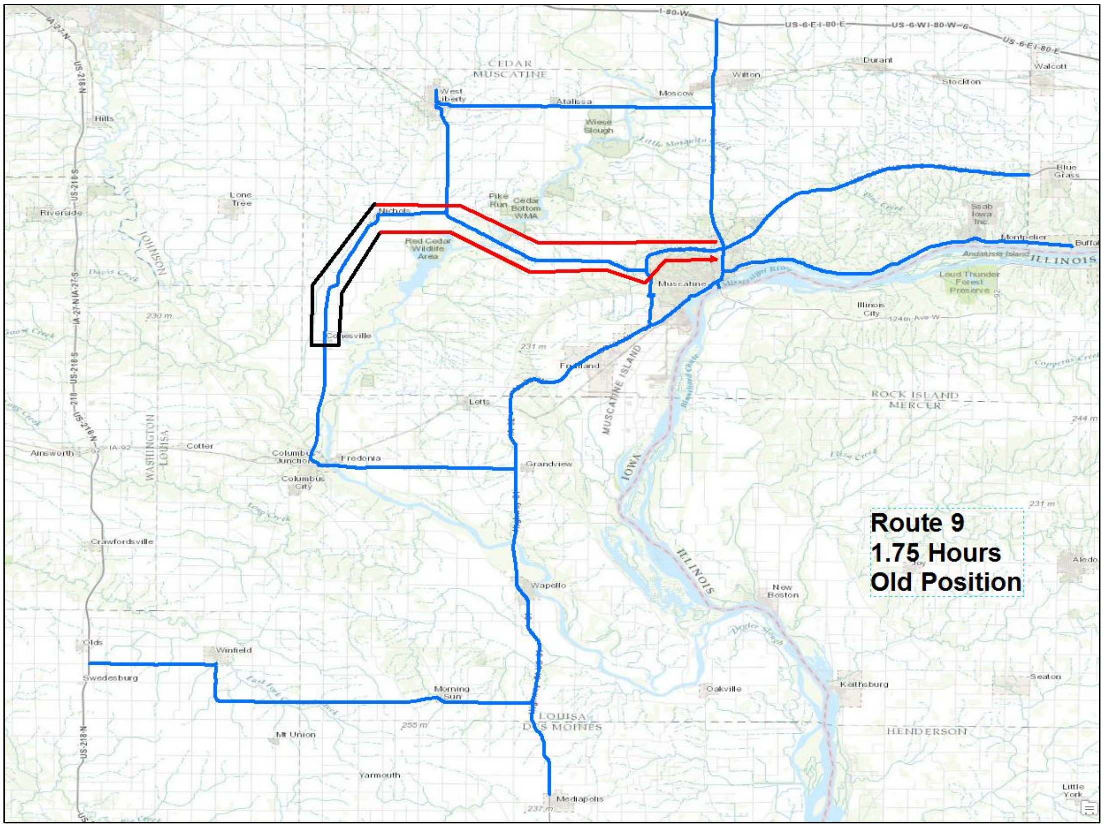

Route 4
1.75 Hours
Old Position

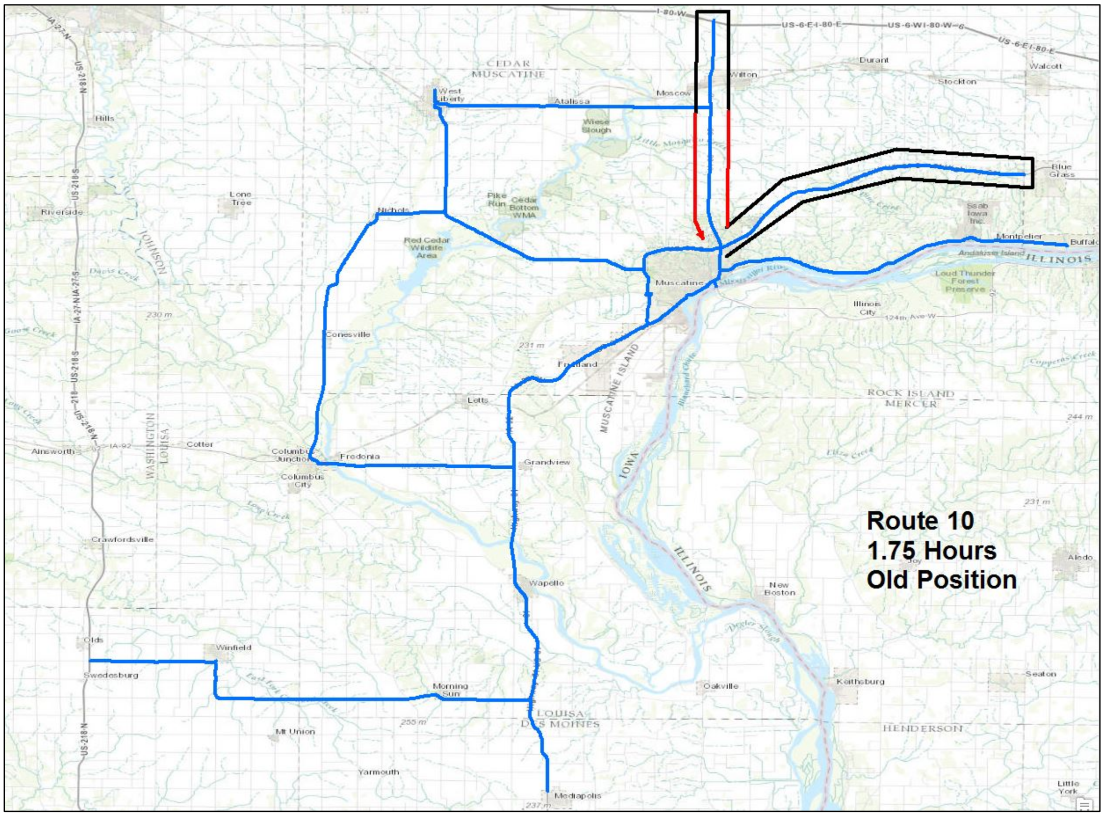

Route 5
1.75 Hours
Old Position

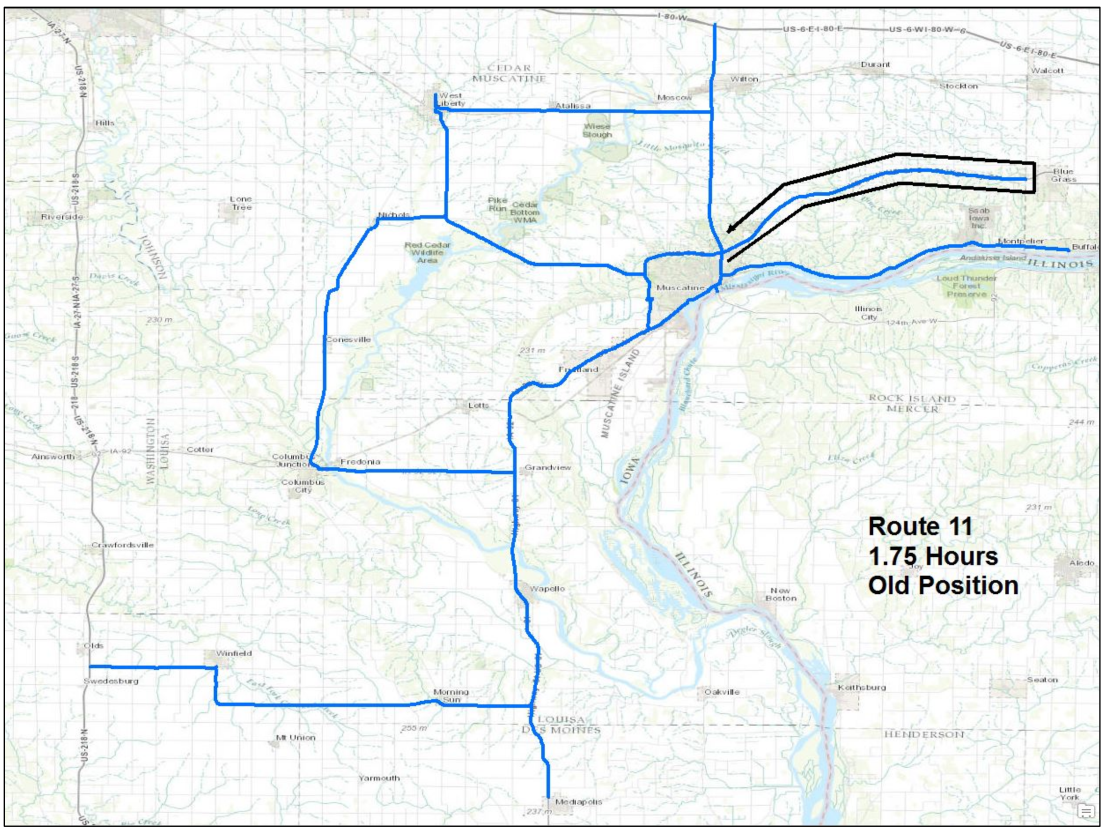

Route 6
1.75 Hours
Old Position

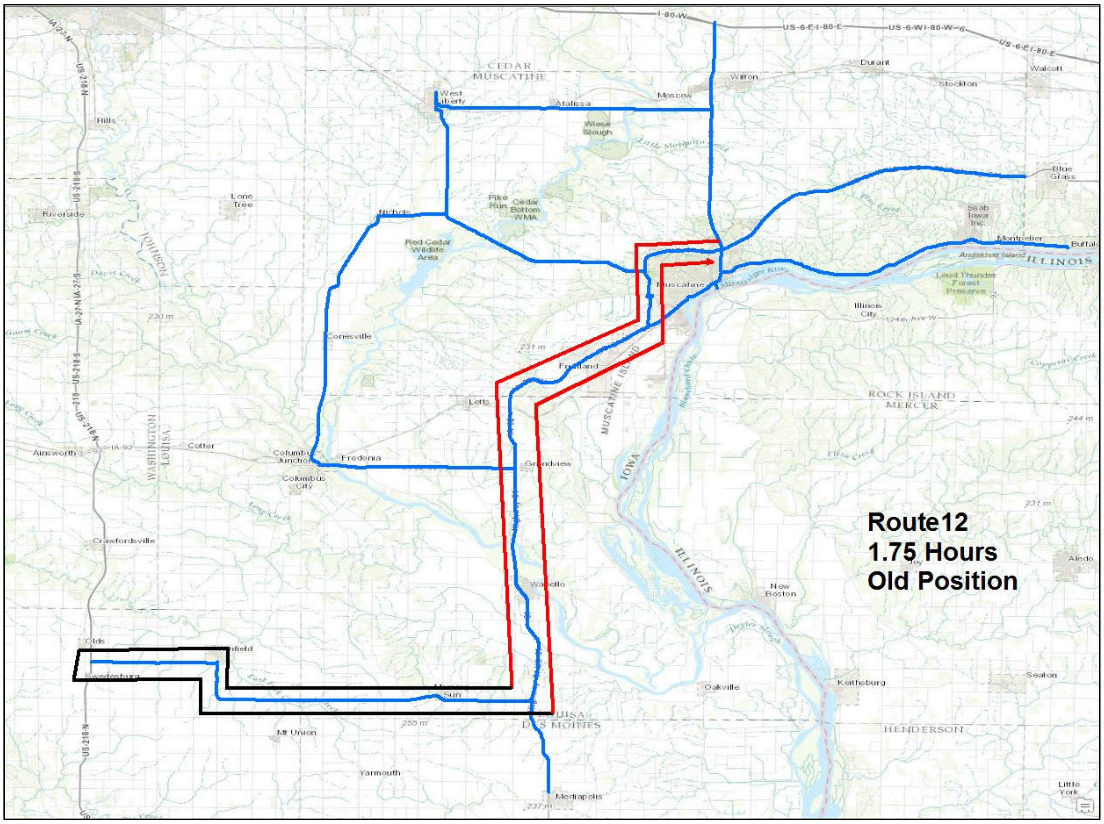

Route 7
1.75 Hours
Old Position


Route 8
1.75 Hours
Old Position

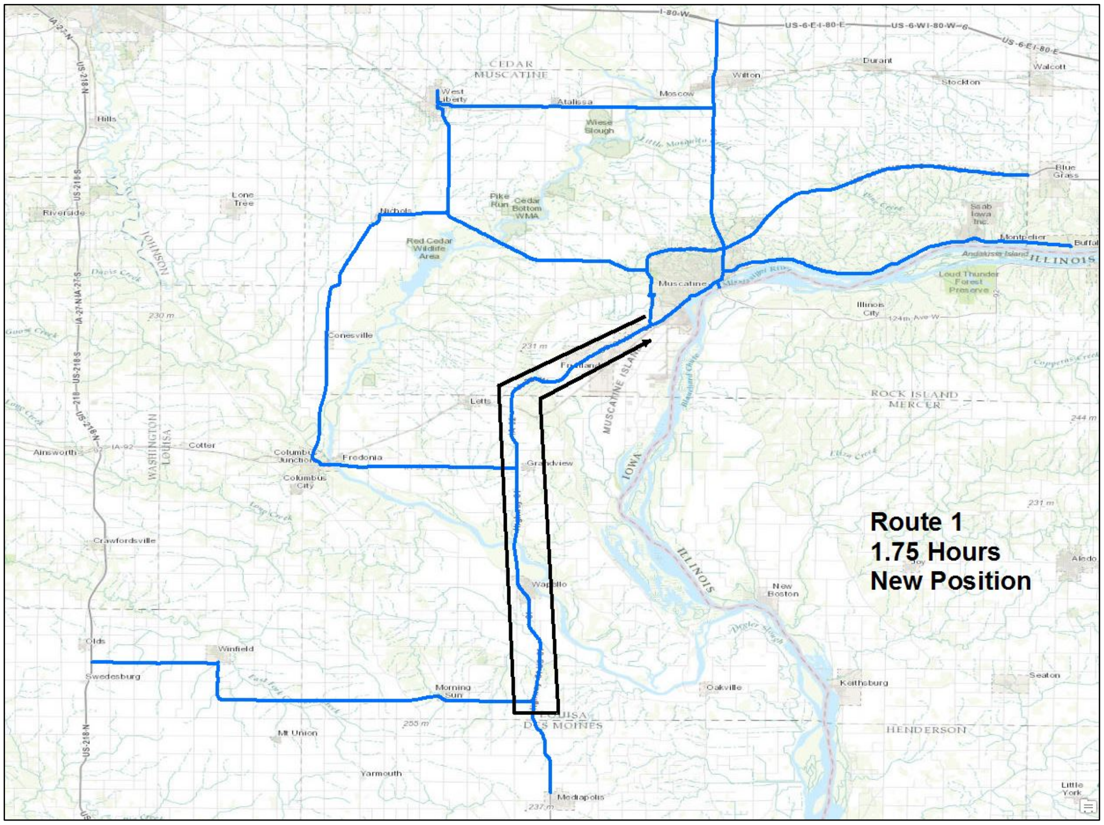

Route 9
1.75 Hours
Old Position

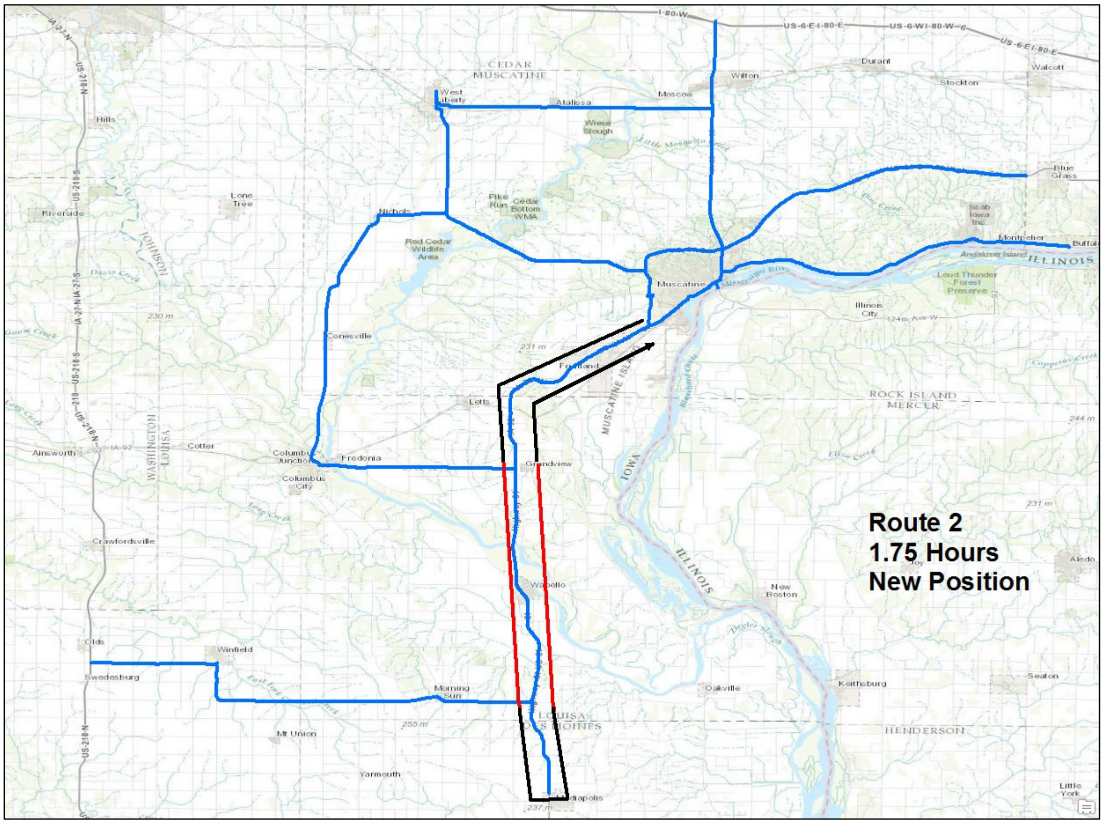

Route 10
1.75 Hours
Old Position

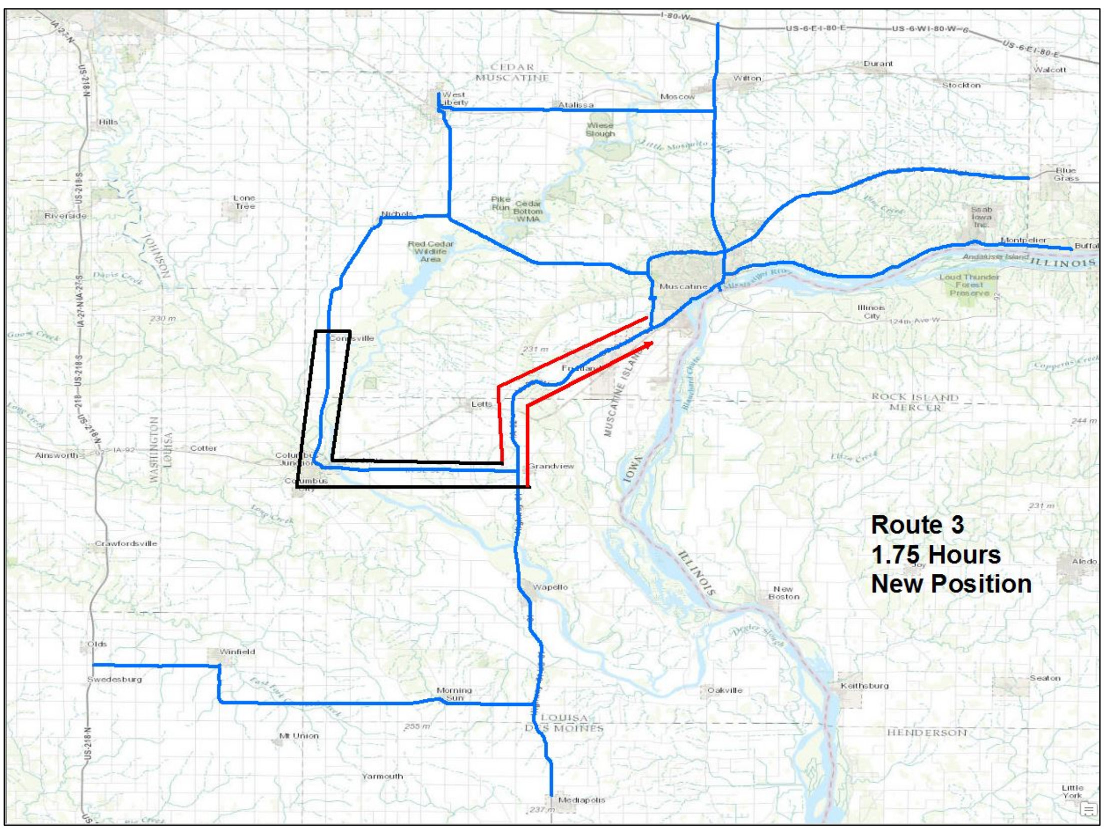

Route 11
1.75 Hours
Old Position

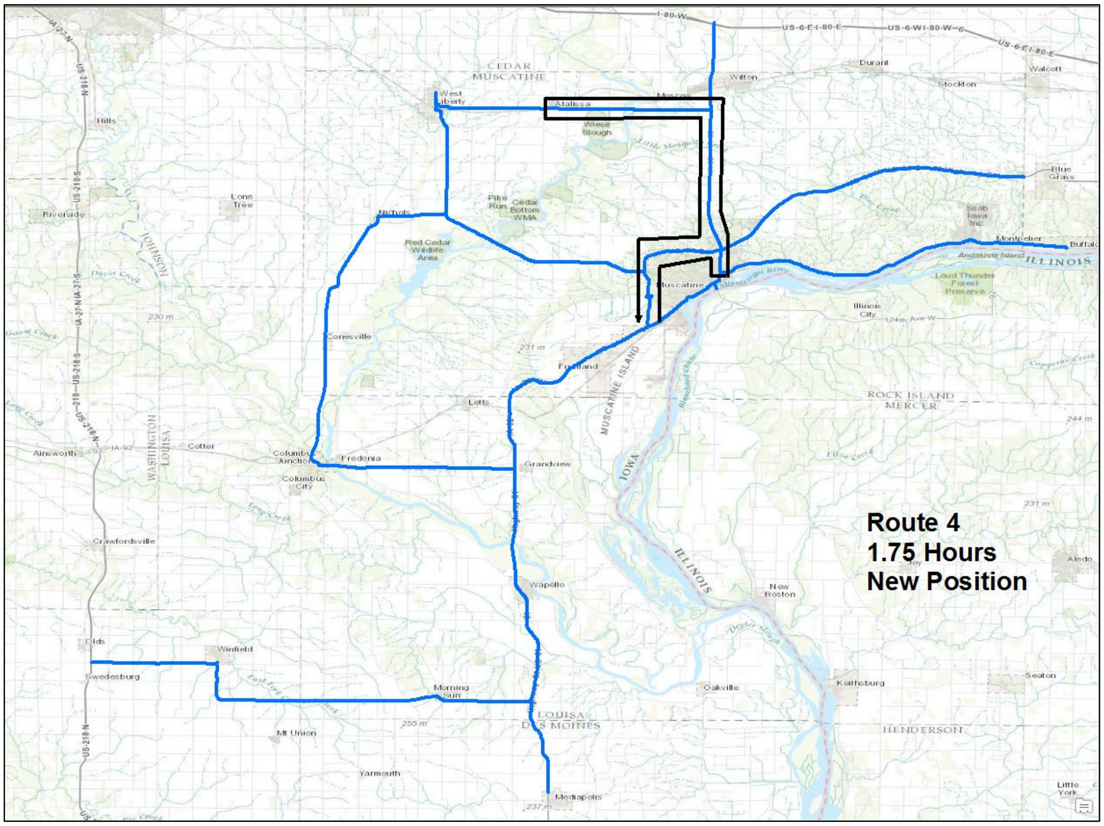

Route12
1.75 Hours
Old Position

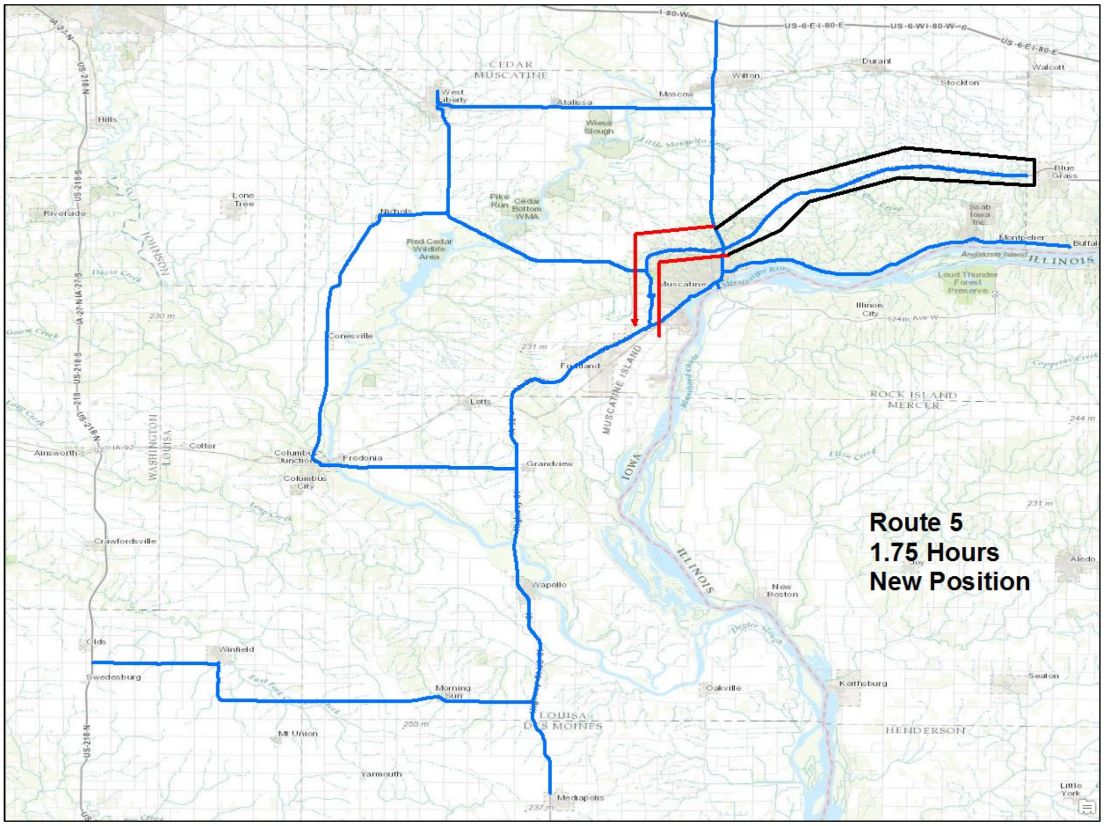
New Position 1.75-Hour Routes

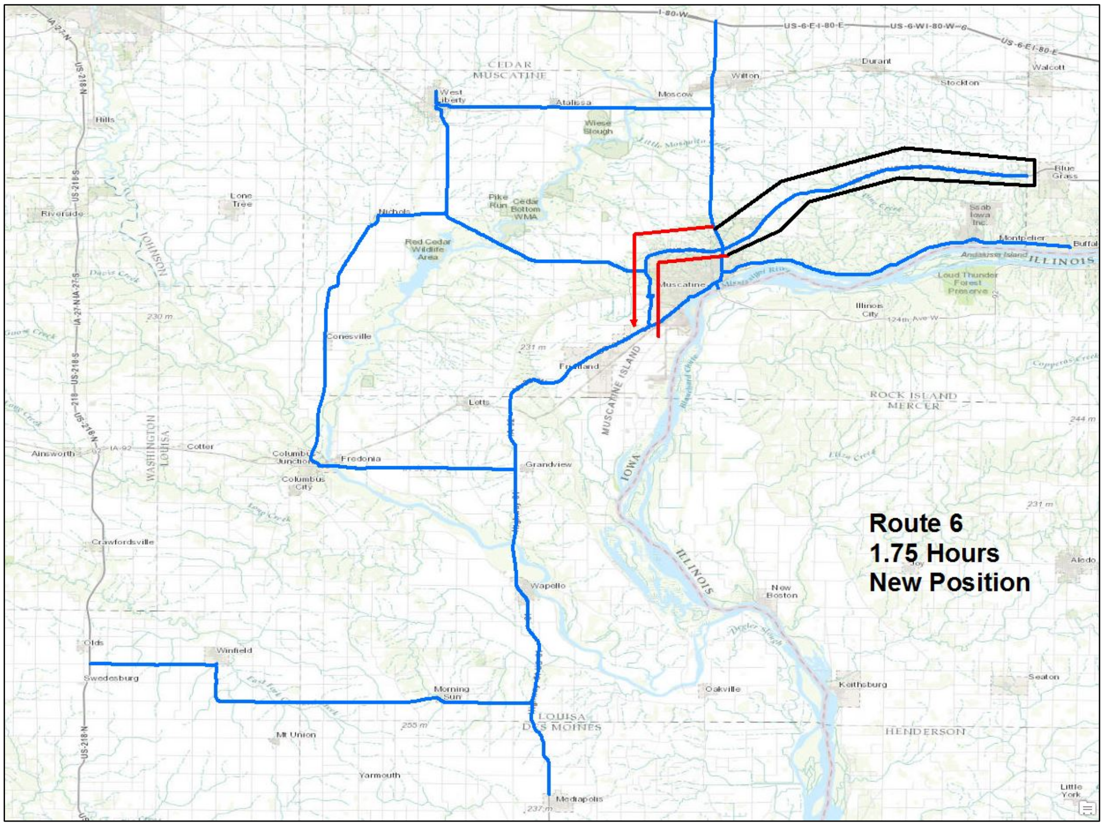


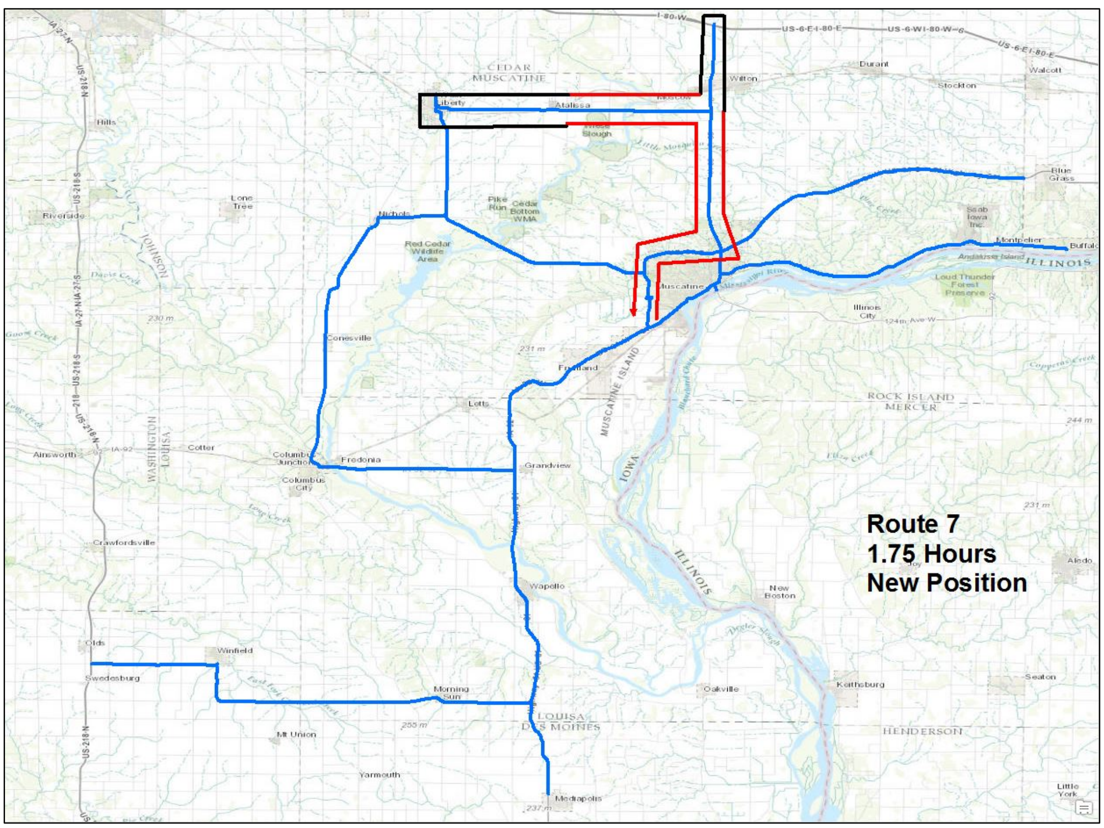

Route 2
1.75 Hours
New Position
CEDAR
MUSCATINE
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Wiese Slough
Blue Grass
Hills
Lone Tree
Riverside
Nichols
Pike Run
Cedar Bottom WMA
Red Cedar Wildlife Area
Montpelier
Buffalo
ILLINOIS
Muscatine
Loud Thunder Forest Preserve
Illinois City
Conesville
Fruitland
Letts
MUSCATINE ISLAND
ROCK ISLAND
MERCER
Ainsworth
Cotter
Columbus Junction
Fredonia
Grandview
Columbus City
WASHINGTON
LOUISA
JOHNSON
IOWA
Crawfordsville
Wapello
New Boston
Aledo
Olds
Winfield
Swedesburg
Morning Sun
Oakville
Keithsburg
Sealon
LOUISA
DES MOINES
HENDERSON
Mt Union
Yarmouth
Little York

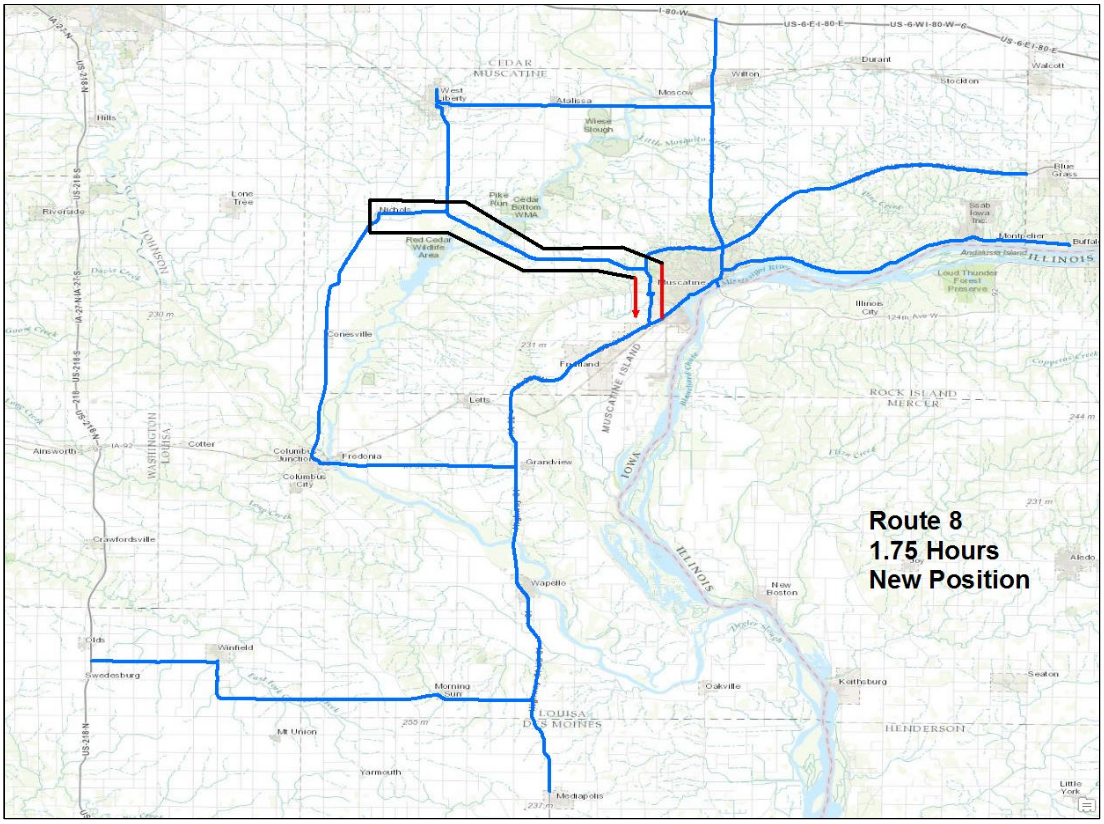

Route 3
1.75 Hours
New Position
CEDAR
MUSCATINE
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Wiese Slough
Blue Grass
Hills
Lone Tree
Riverside
Nichols
Pike Run
Cedar Bottom WMA
Red Cedar Wildlife Area
Montpelier
Buffalo
ILLINOIS
Muscatine
Loud Thunder Forest Preserve
Illinois City
Conesville
Fruitland
Letts
MUSCATINE ISLAND
ROCK ISLAND
MERCER
Ainsworth
Cotter
Columbus Junction
Grandview
Columbus City
WASHINGTON
LOUISA
JOHNSON
IOWA
Crawfordsville
Wapello
New Boston
Aledo
Olds
Winfield
Swedesburg
Morning Sun
Oakville
Keithsburg
Sealon
LOUISA
DES MOINES
HENDERSON
Mt Union
Yarmouth
Mediapolis
Little York

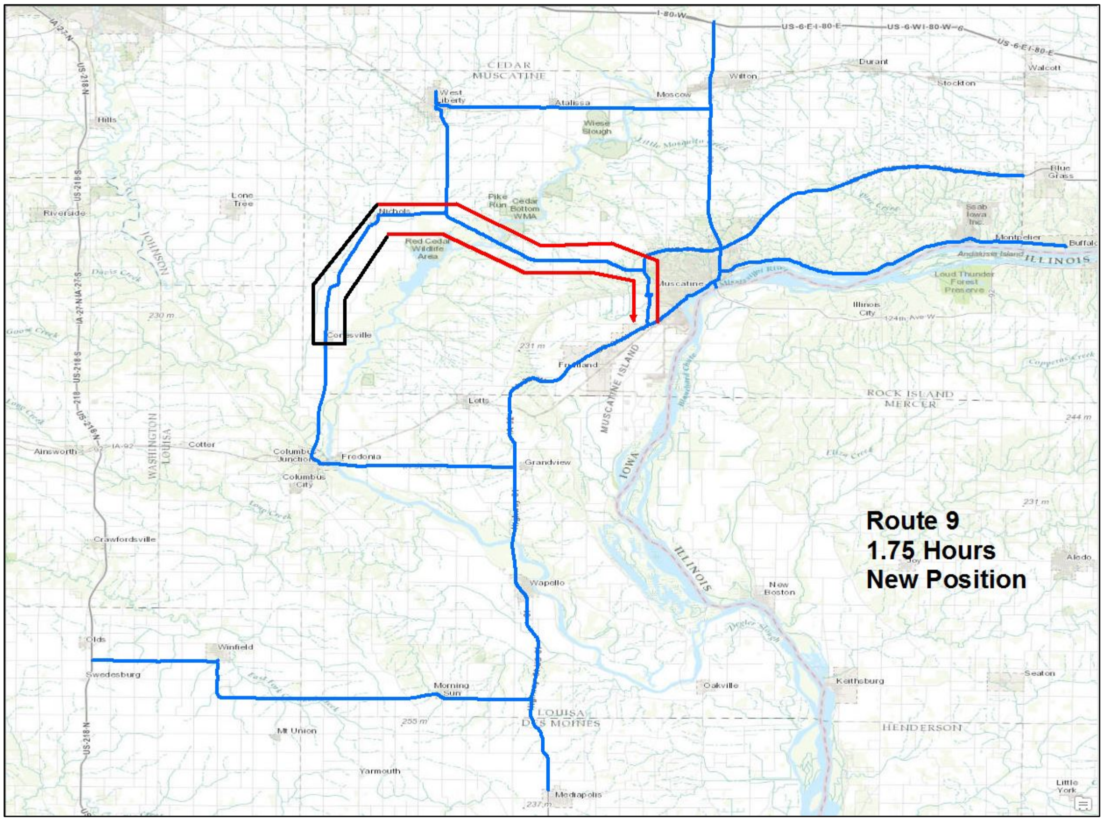

Route 4
1.75 Hours
New Position

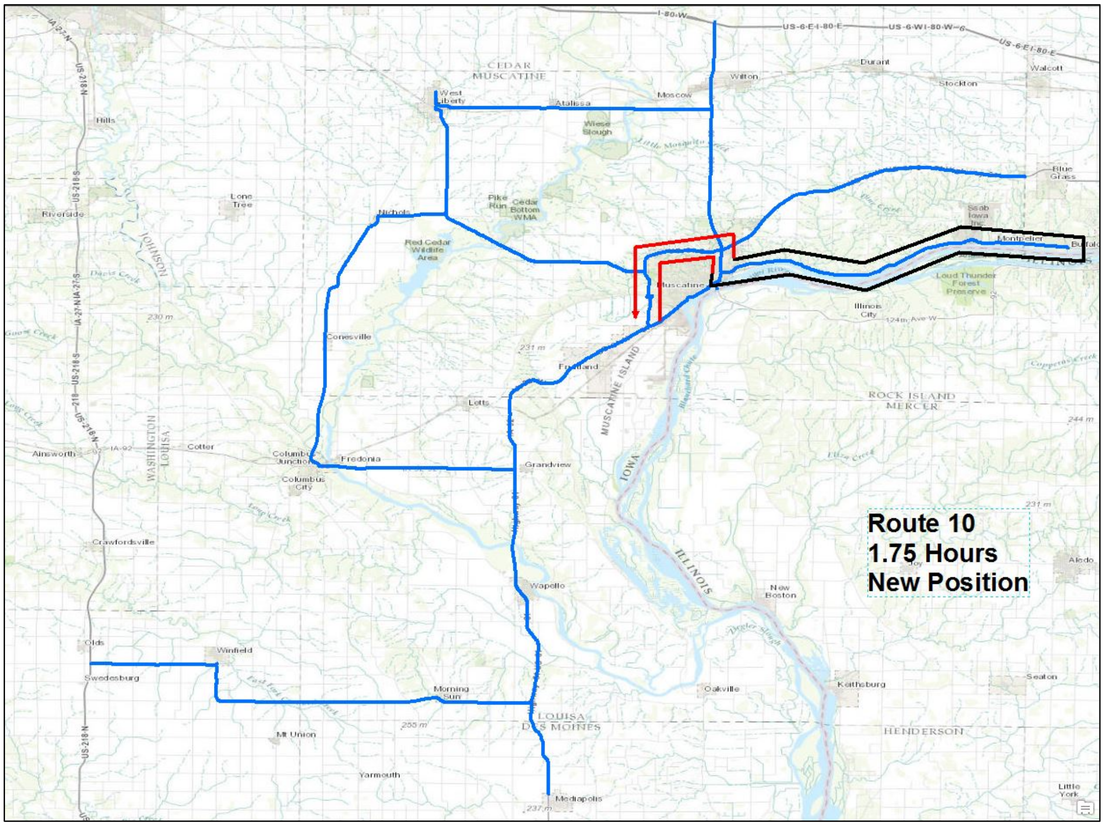

Route 5
1.75 Hours
New Position

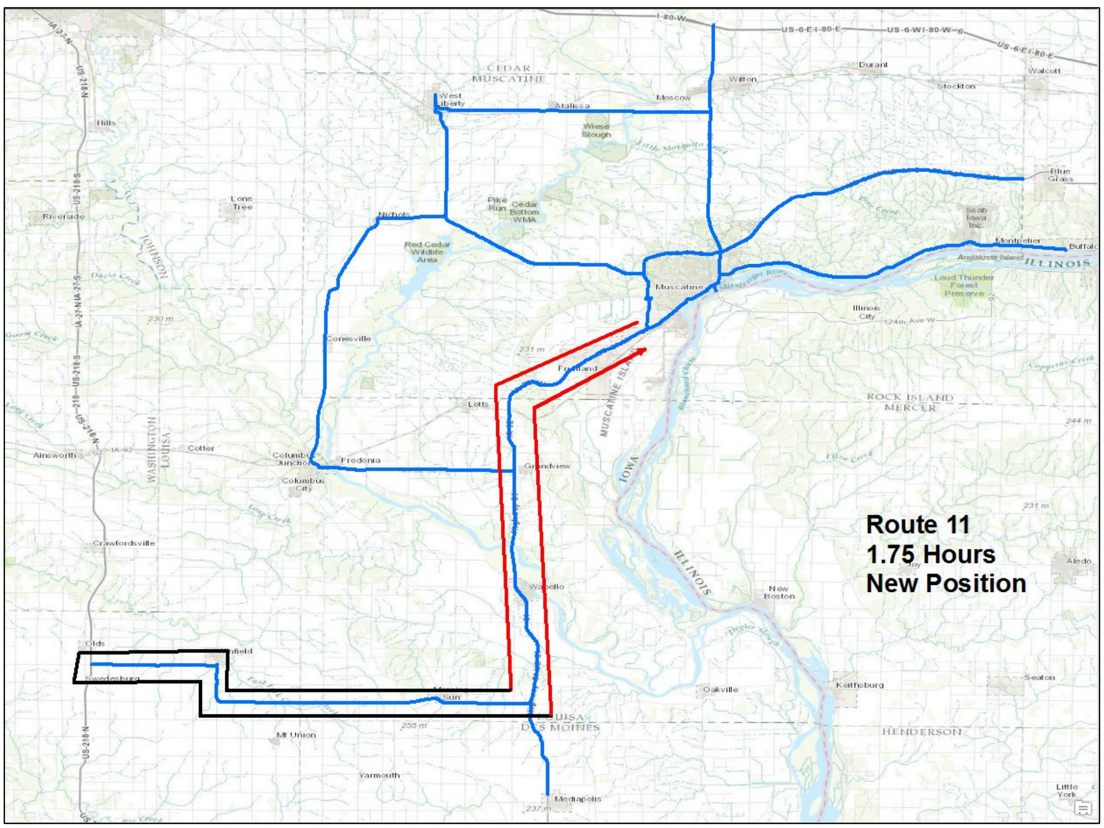

Route 6
1.75 Hours
New Position
CEDAR
MUSCATINE
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Blue Grass
Nichols
Muscatine
Montpelier
Buffalo
ILLINOIS
Illinois City
Conesville
Fruitland
Letts
MUSCATINE ISLAND
ROCK ISLAND
MERCER
Columbus Junction
Fredonia
Grandview
Columbus City
Cotter
Ainsworth
Riverside
Lone Tree
Hills
Crawfordsville
Wapello
IOWA
New Boston
Aledo
Olds
Winfield
Swedesburg
Morning Sun
Oakville
Keithsburg
Seaton
LOUISA
DES MOINES
HENDERSON
Mt Union
Yarmouth
Mediapolis
Little York


Route 7
1.75 Hours
New Position
CEDAR
MUSCATINE
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Blue Grass
Nichols
Muscatine
Montpelier
ILLINOIS
Illinois City
Conesville
Fruitland
Letts
MUSCATINE ISLAND
ROCK ISLAND
MERCER
Columbus Junction
Fredonia
Grandview
Columbus City
Cotter
Ainsworth
Riverside
Lone Tree
Hills
Crawfordsville
Wapello
IOWA
New Boston
Aledo
Olds
Winfield
Swedesburg
Morning Sun
Oakville
Keithsburg
Seaton
LOUISA
DES MOINES
HENDERSON
Mt Union
Yarmouth
Mediapolis
Little York

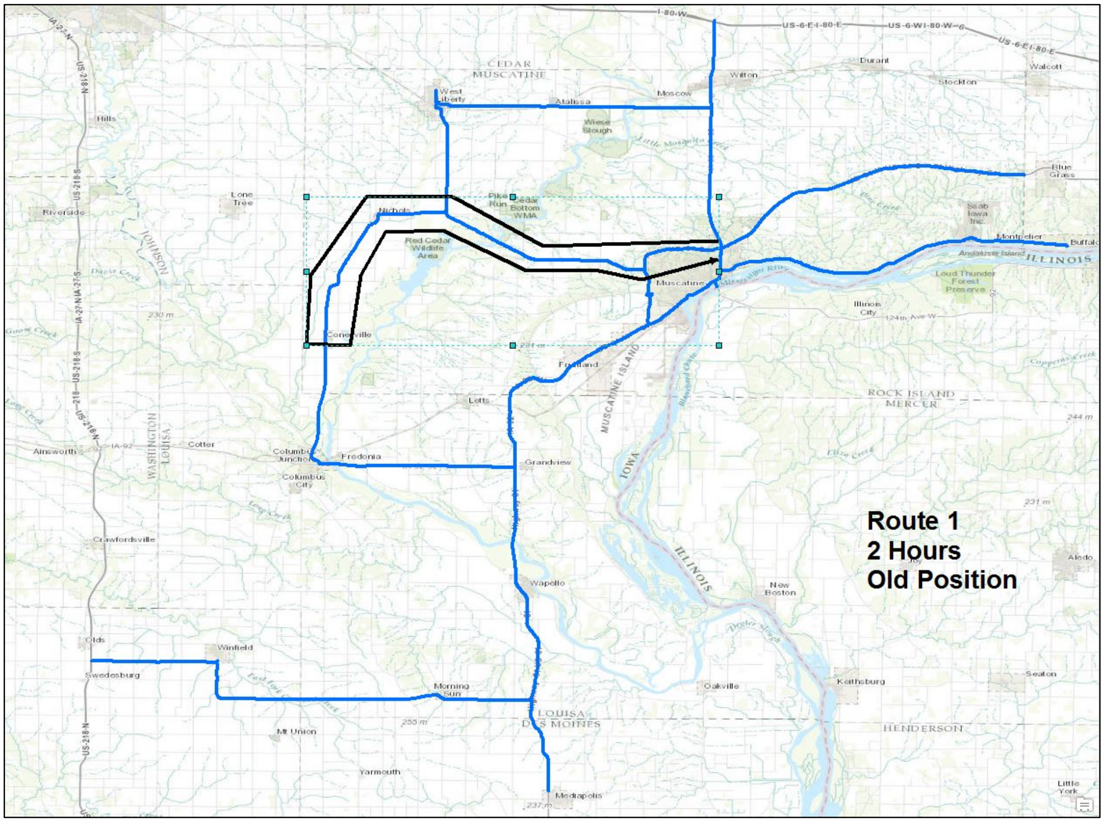

Route 8
1.75 Hours
New Position
CEDAR
MUSCATINE
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Hills
Lone Tree
Riverside
JOHNSON
Nichols
Pike Run
Cedar Bottom WMA
Red Cedar Wildlife Area
Muscatine
Montpelier
ILLINOIS
Loud Thunder Forest Preserve
Illinois City
Conesville
Fruitland
Letts
MUSCATINE ISLAND
ROCK ISLAND
MERCER
Ainsworth
Cotter
WASHINGTON
LOUISA
Columbus Junction
Fredonia
Columbus City
Grandview
IOWA
Crawfordsville
Wapello
New Boston
Aledo
Olds
Winfield
Swedesburg
Morning Sun
LOUISA
DES MOINES
Oakville
Keithsburg
Seaton
HENDERSON
Mt Union
Yarmouth
Mediapolis
Little York

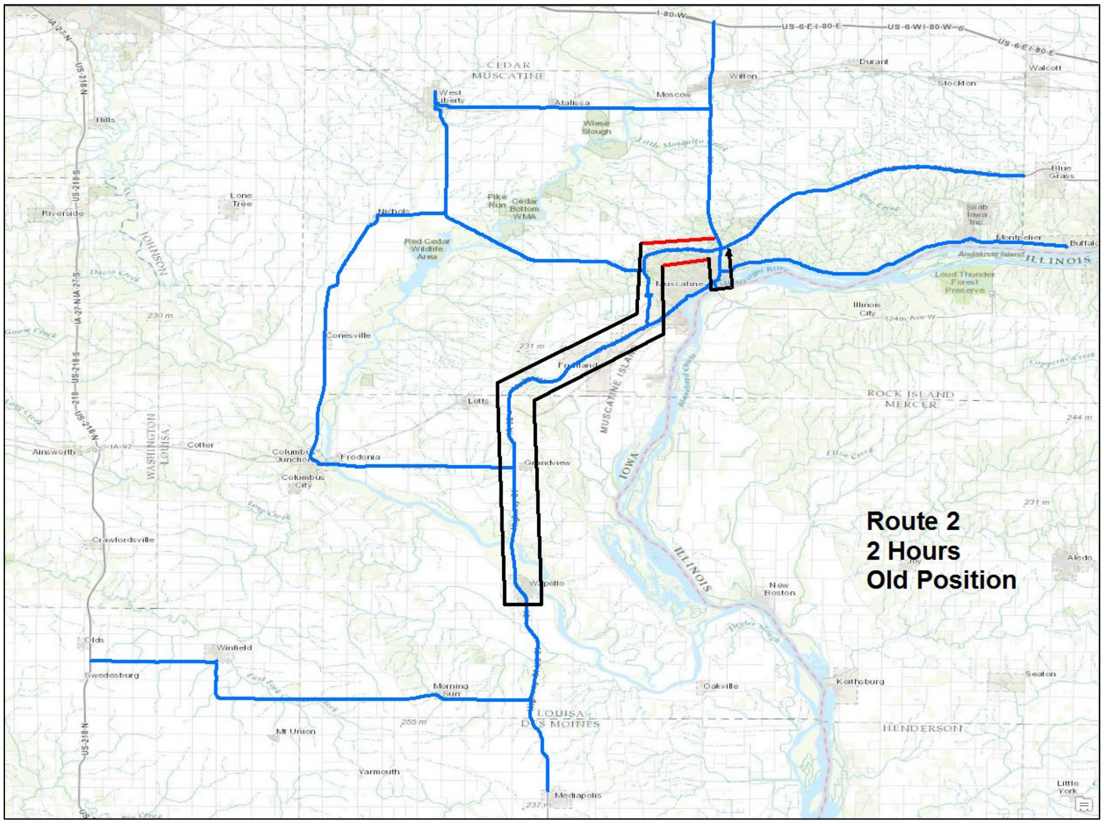

Route 9
1.75 Hours
New Position
CEDAR
MUSCATINE
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Hills
Lone Tree
Riverside
JOHNSON
Nichols
Pike Run
Cedar Bottom WMA
Red Cedar Wildlife Area
Muscatine
Montpelier
ILLINOIS
Loud Thunder Forest Preserve
Illinois City
Conesville
Fruitland
Letts
MUSCATINE ISLAND
ROCK ISLAND
MERCER
Ainsworth
Cotter
WASHINGTON
LOUISA
Columbus Junction
Fredonia
Columbus City
Grandview
IOWA
Crawfordsville
Wapello
New Boston
Aledo
Olds
Winfield
Swedesburg
Morning Sun
LOUISA
DES MOINES
Oakville
Keithsburg
Seaton
HENDERSON
Mt Union
Yarmouth
Mediapolis
Little York

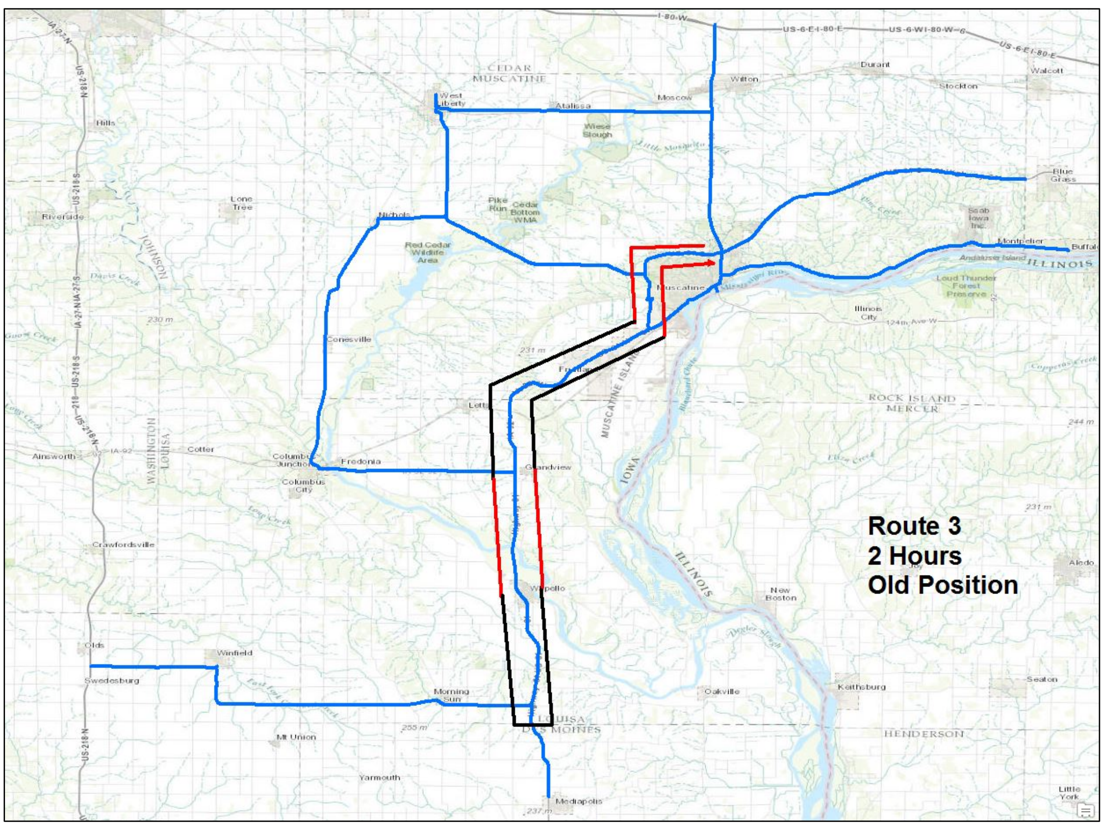

Route 10
1.75 Hours
New Position

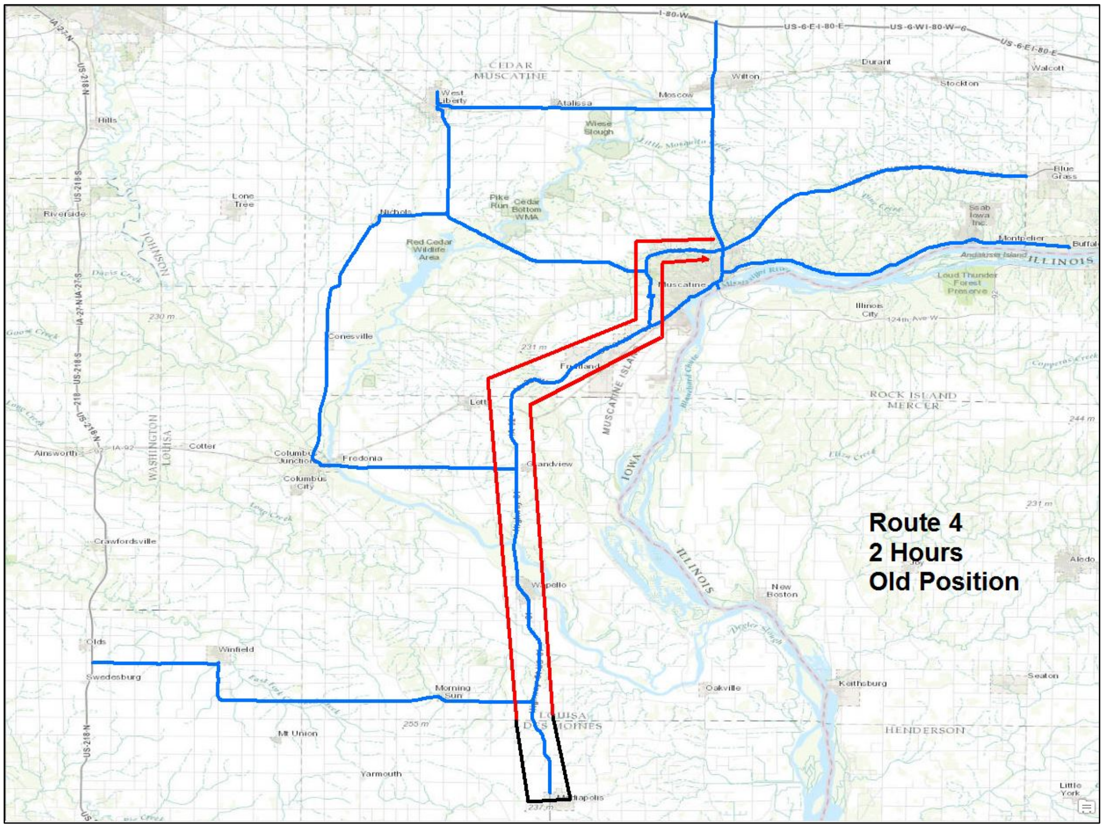

Route 11
1.75 Hours
New Position

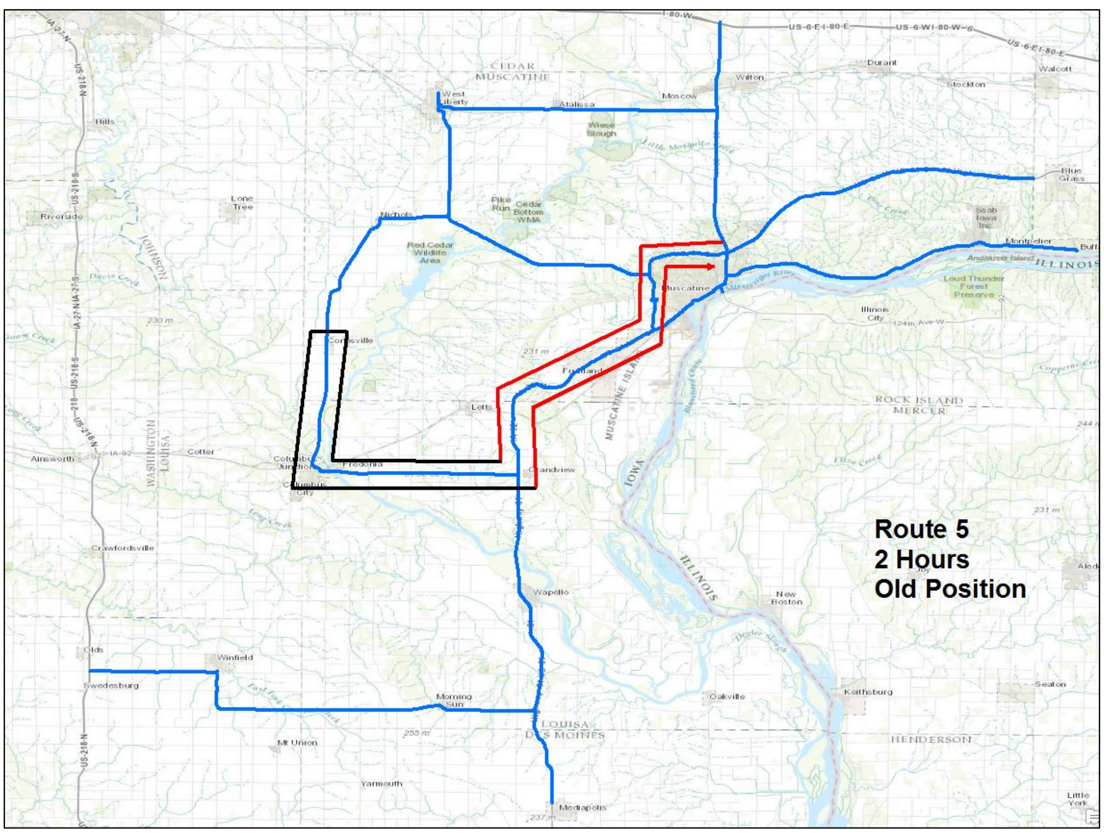
Old Position 2-Hour Routes

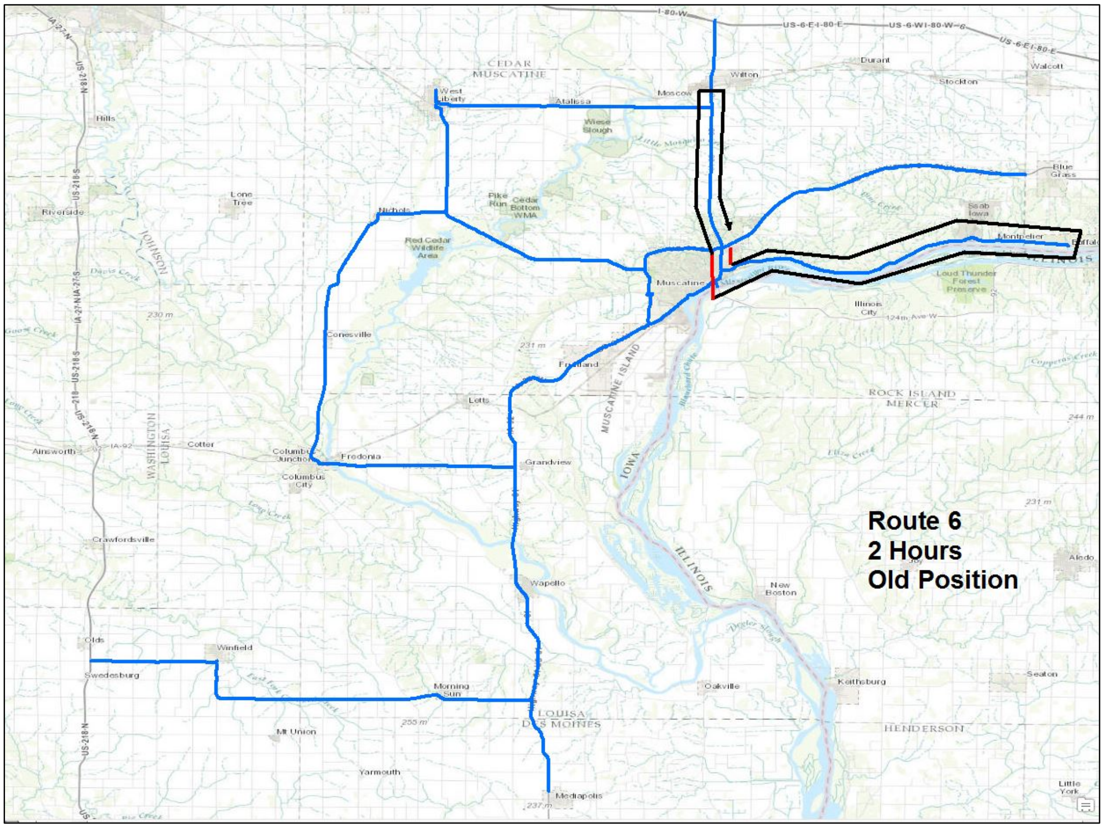


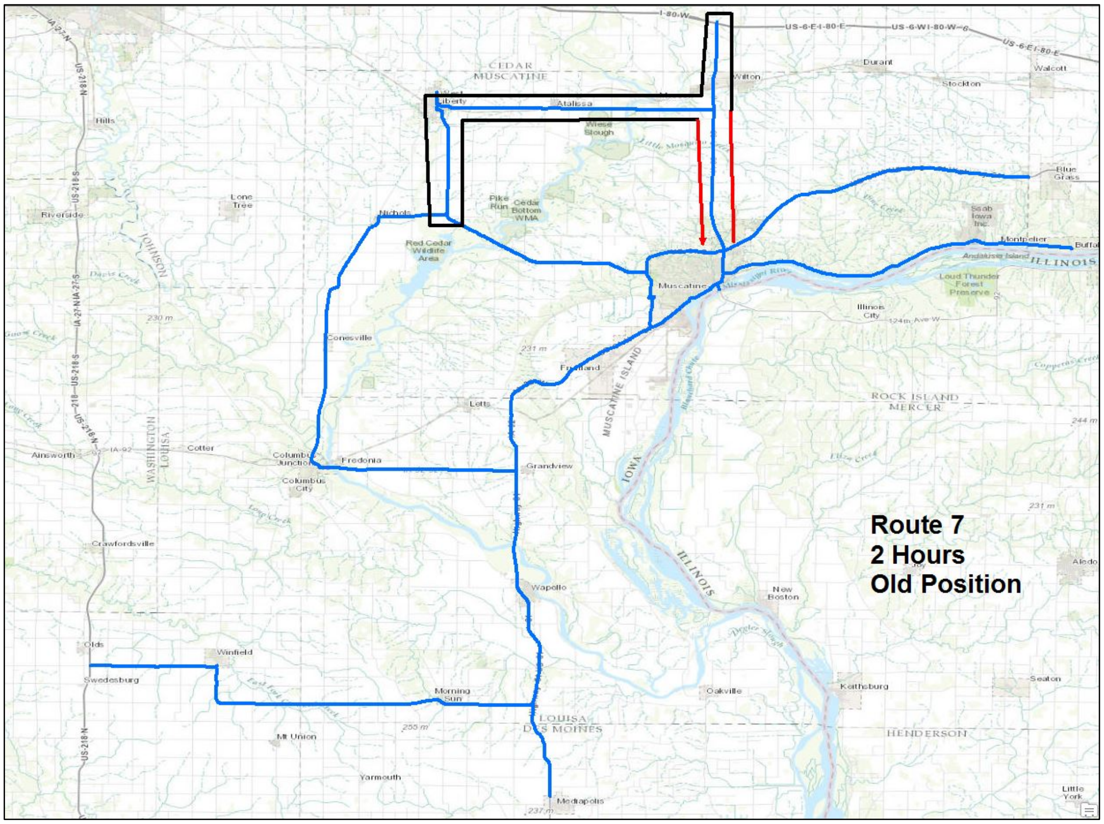

Route 2
2 Hours
Old Position

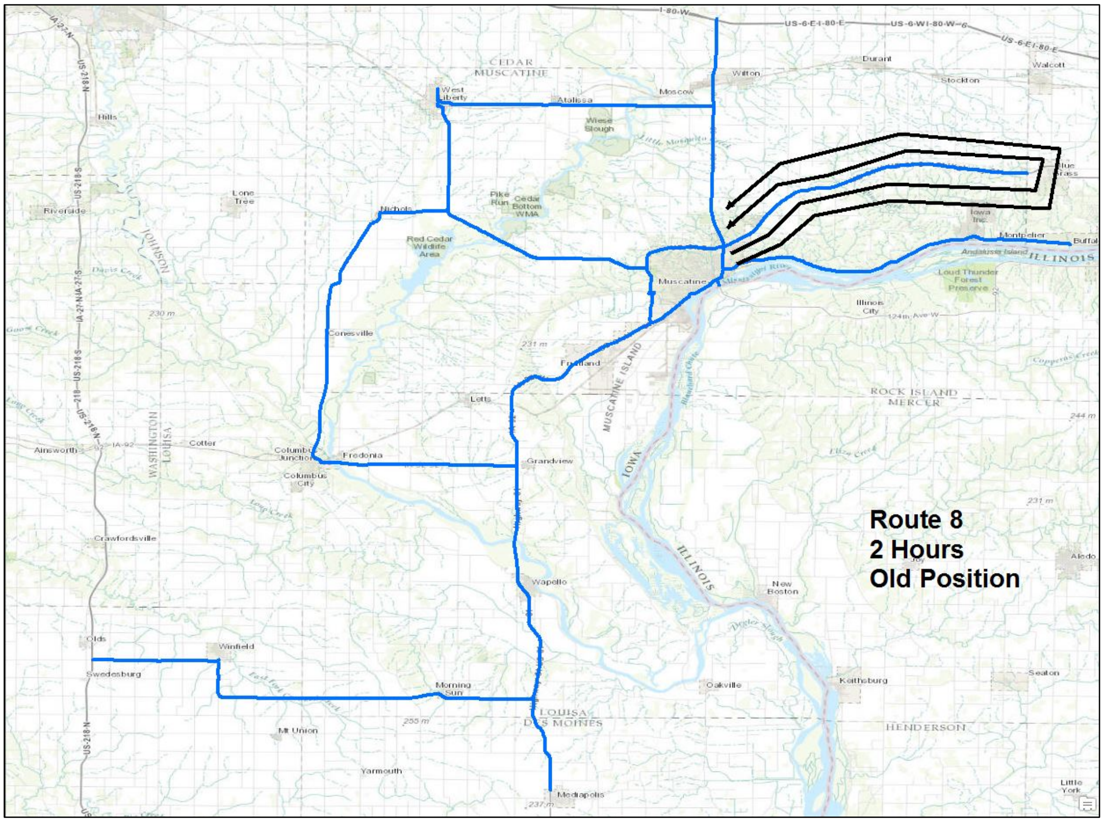

Route 3
2 Hours
Old Position

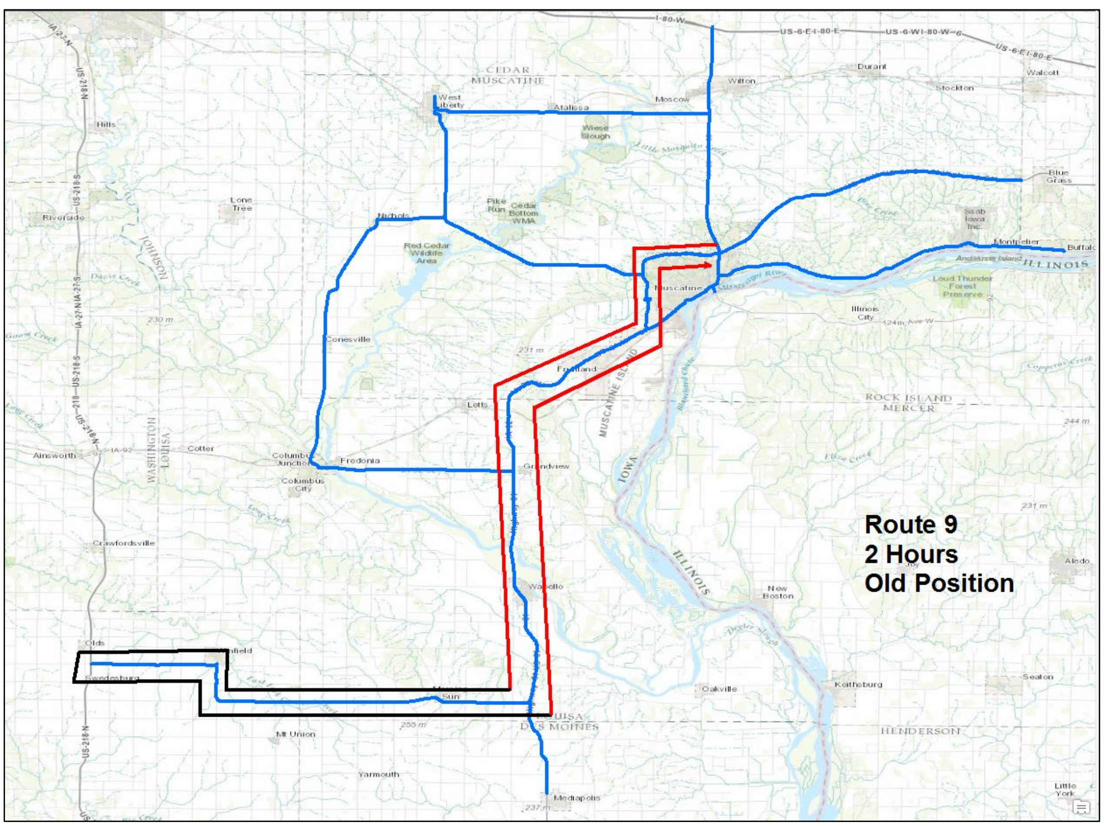

Route 4
2 Hours
Old Position


Route 5
2 Hours
Old Position

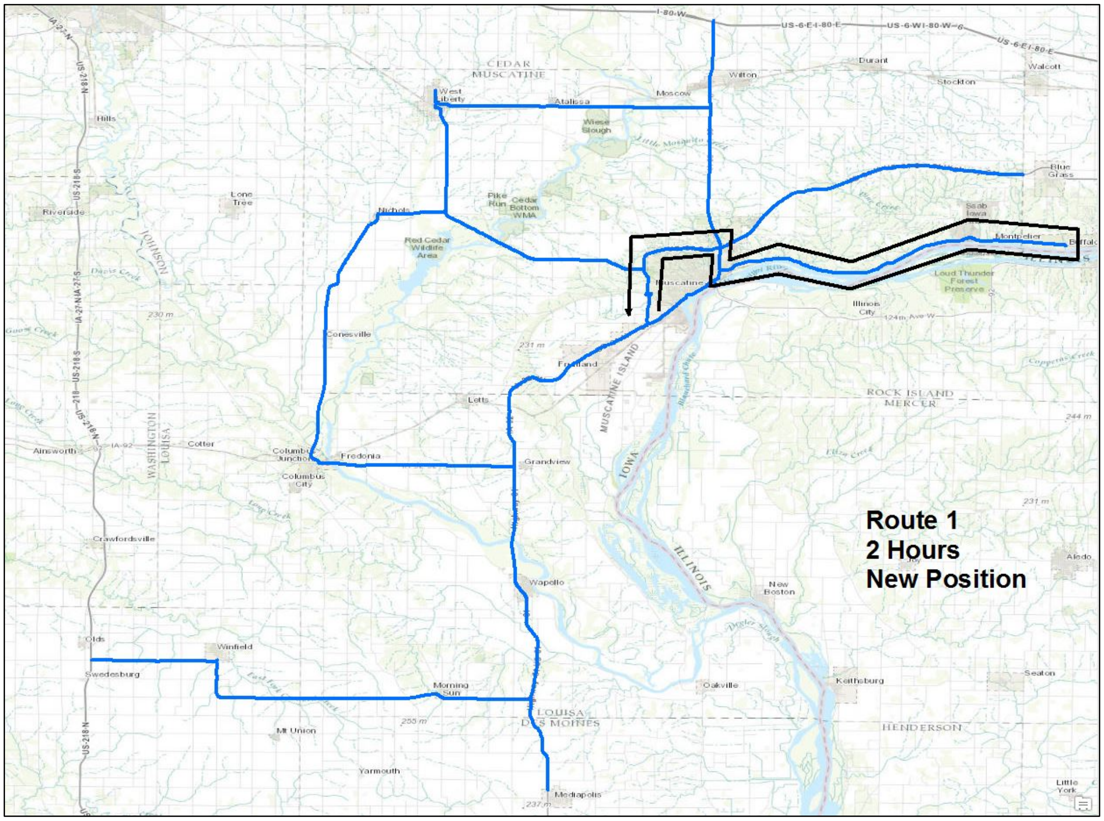

Route 6
2 Hours
Old Position

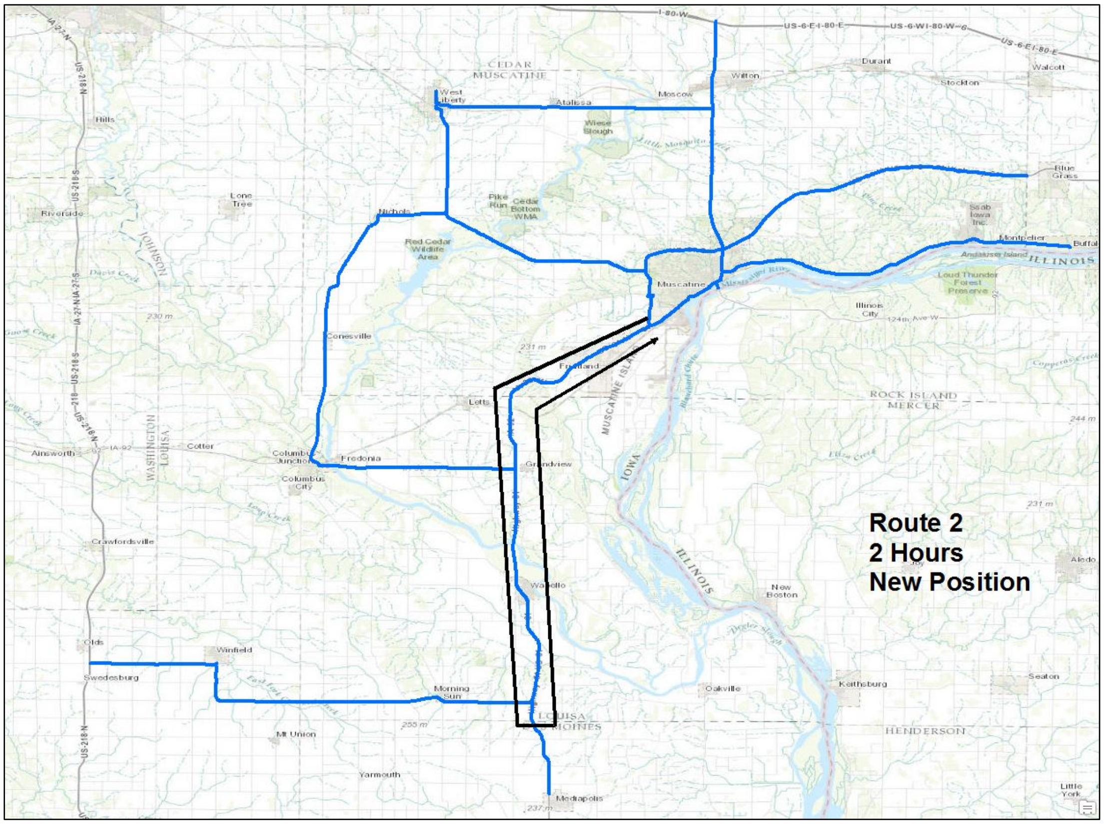

Route 7
2 Hours
Old Position

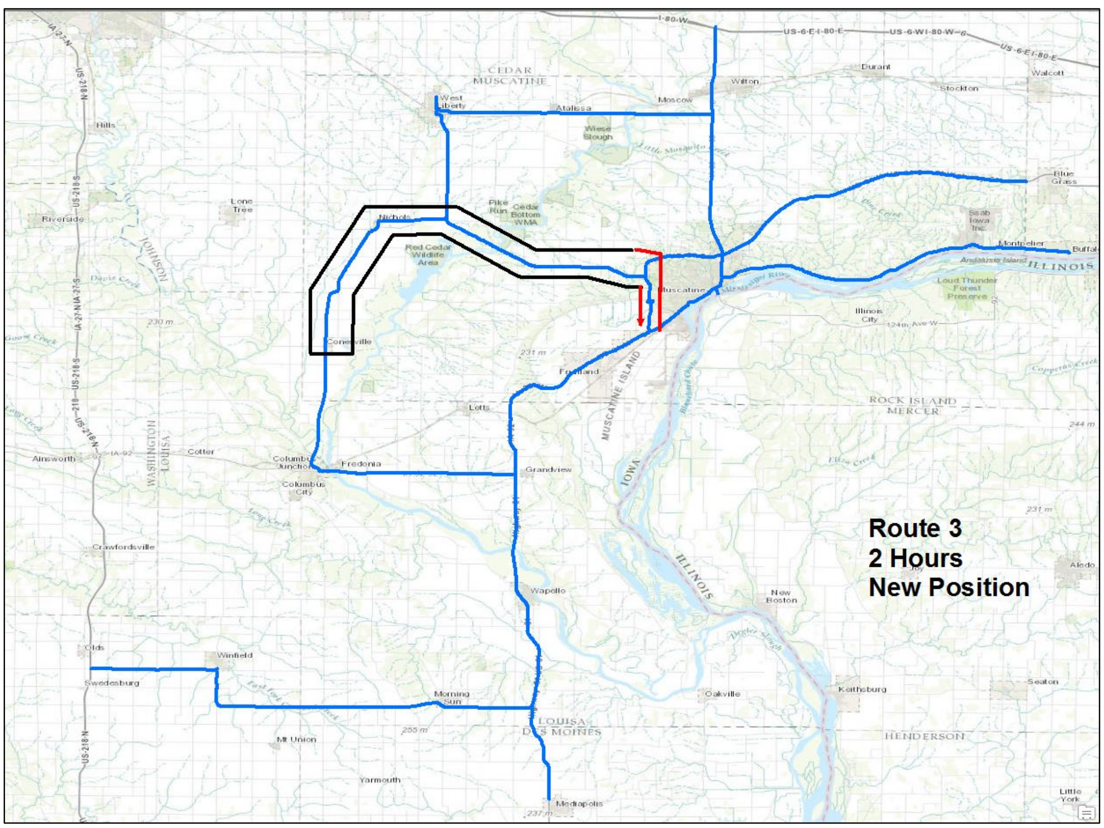

Route 8
2 Hours
Old Position

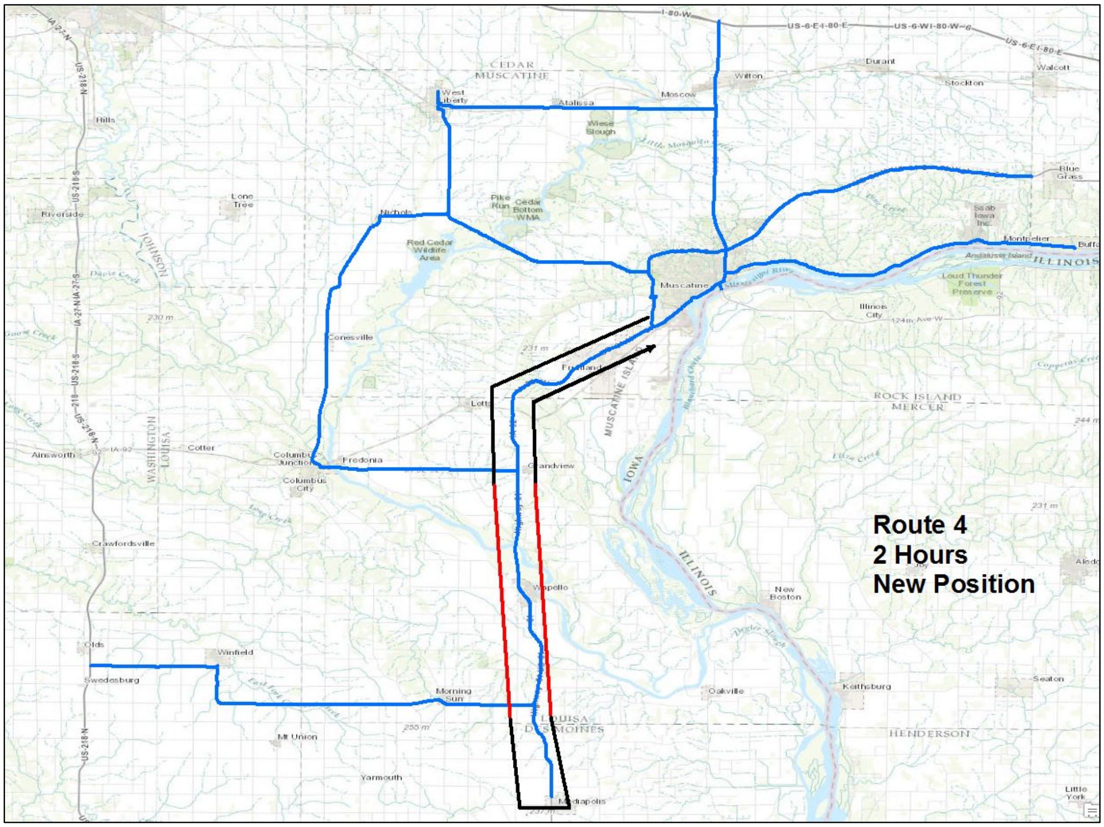

Route 9
2 Hours
Old Position

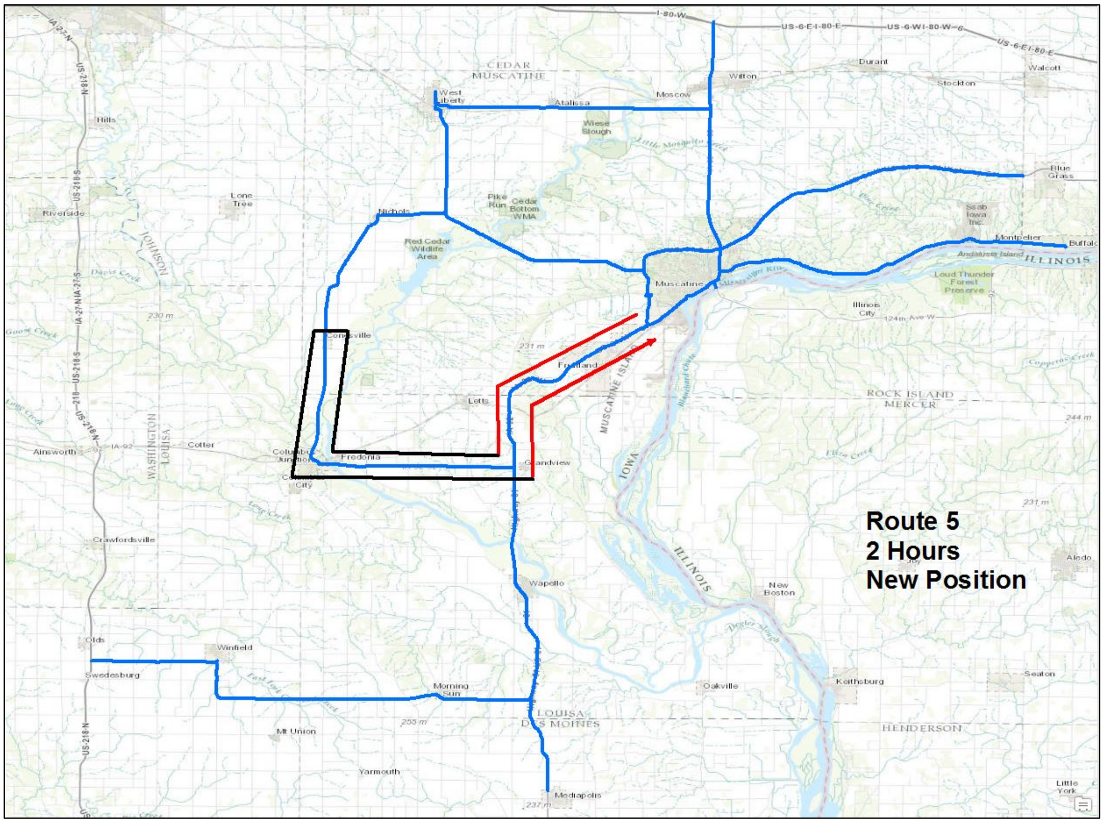
New Position 2-Hour Routes

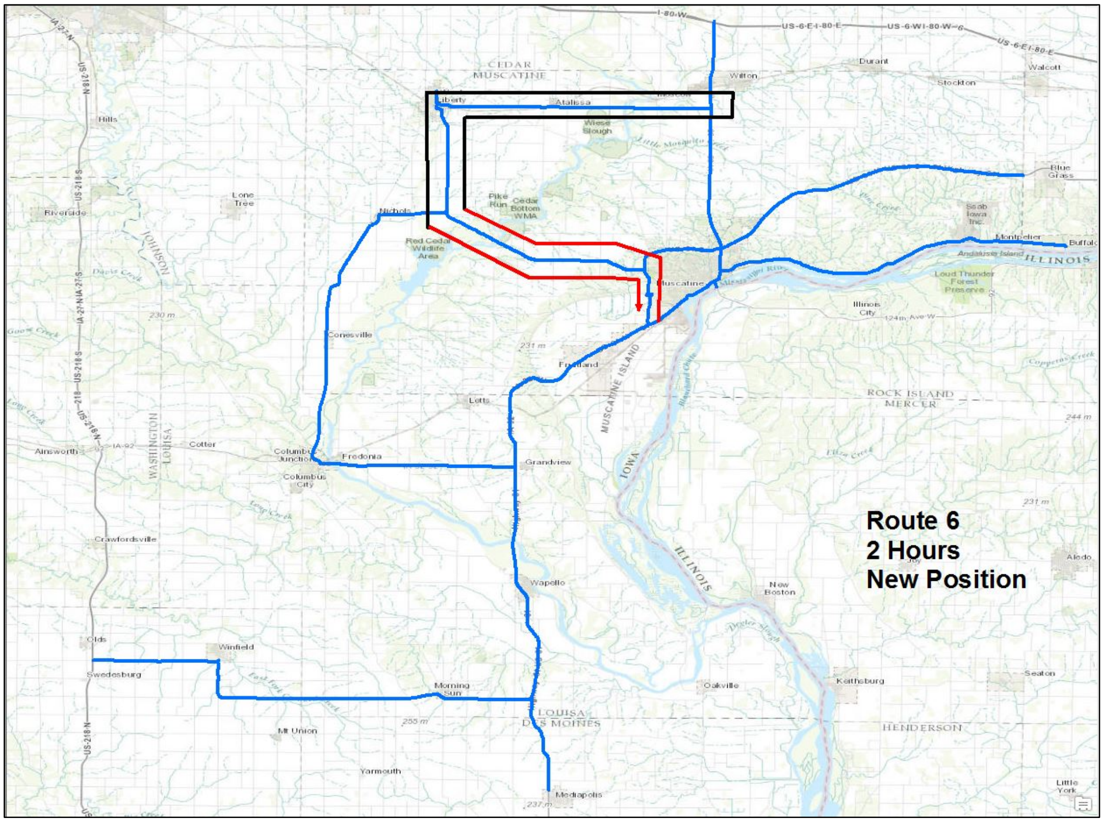


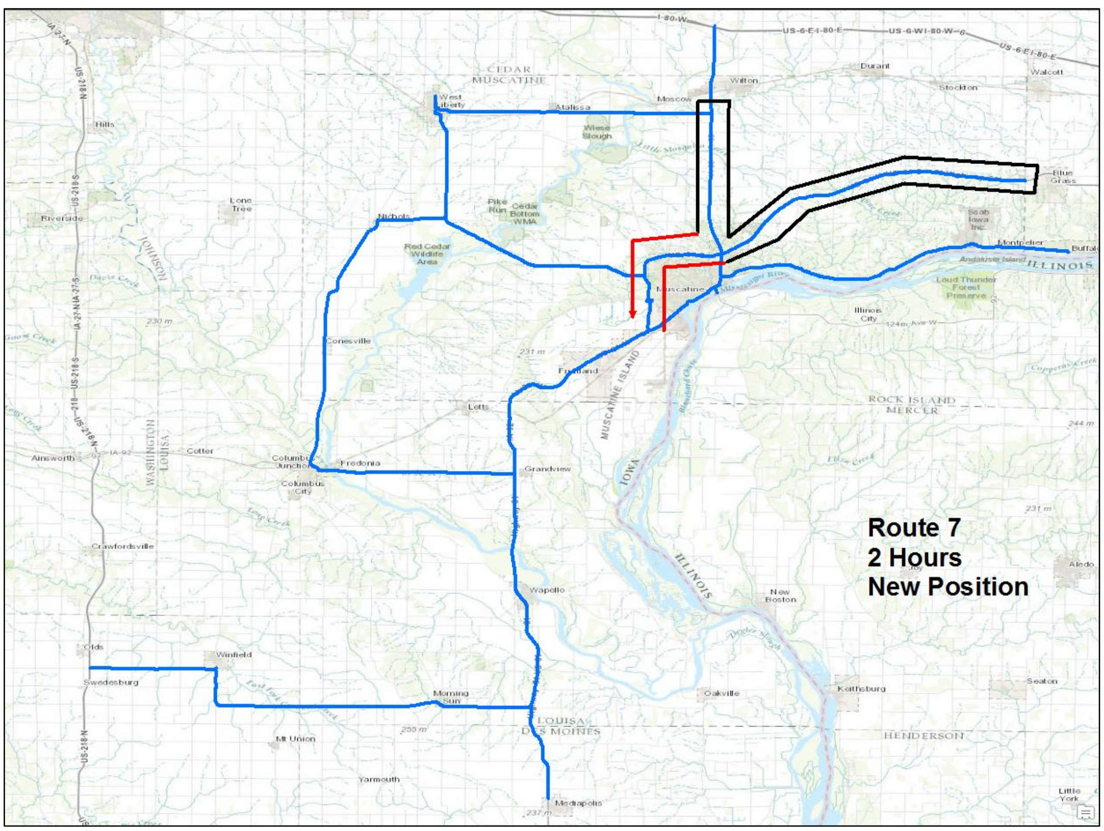

Route 2
2 Hours
New Position

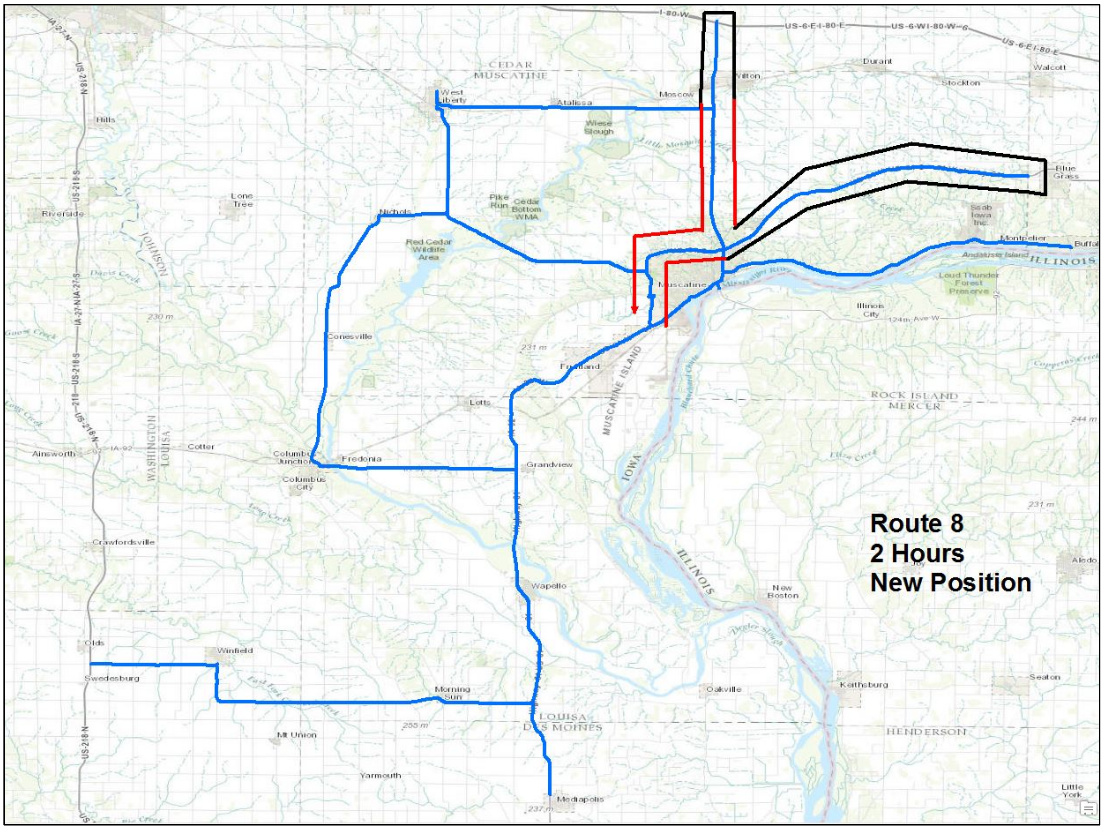

Route 3
2 Hours
New Position

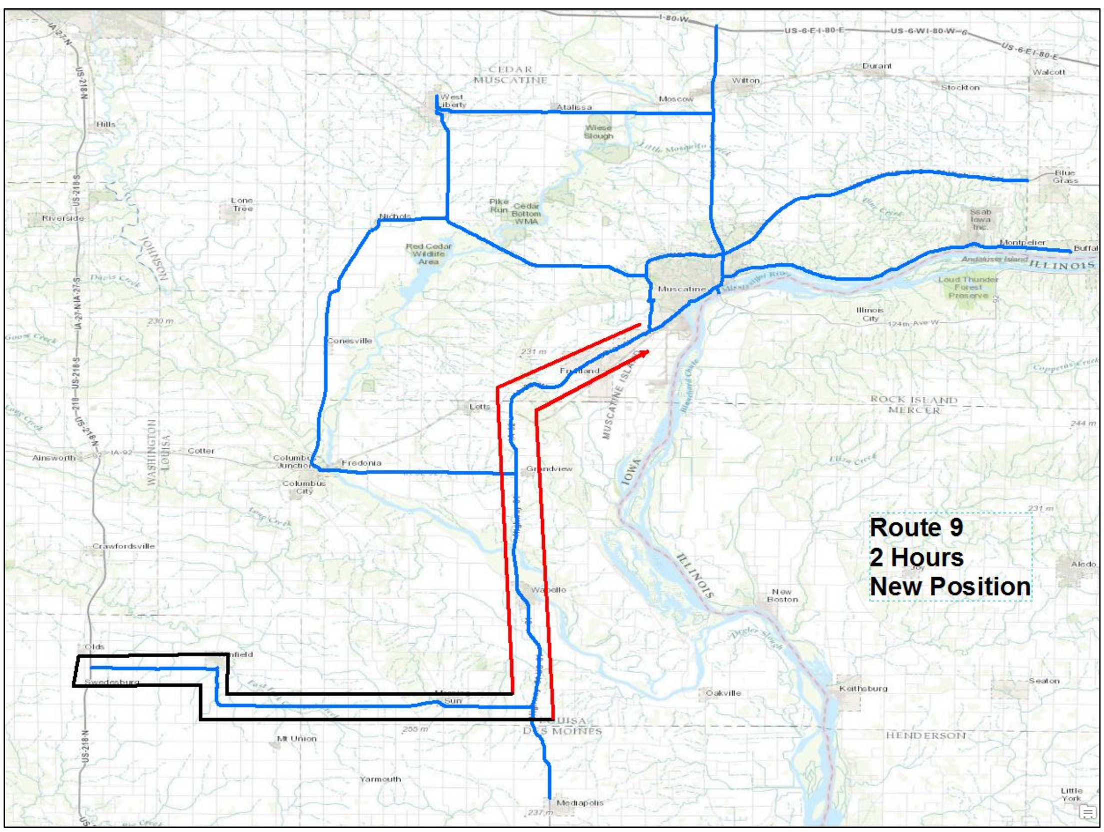

Route 4
2 Hours
New Position


Route 5
2 Hours
New Position


Route 6
2 Hours
New Position
CEDAR
MUSCATINE
Wilton
Durant
Stockton
Walcott
Liberty
Atalissa
Wiese Slough
Hills
Blue Grass
Lone Tree
Riverside
Pike Run
Cedar Bottom WMA
Nichols
Red Cedar Wildlife Area
Montpelier
Muscatine
ILLINOIS
Loud Thunder Forest Preserve
Illinois City
Conesville
Fruitland
MUSCATINE ISLAND
Letts
ROCK ISLAND
MERCER
Ainsworth
Cotter
Columbus Junction
Fredonia
Columbus City
Grandview
WASHINGTON
LOUISA
JOHNSON
IOWA
Crawfordsville
Wapello
New Boston
Aledo
Olds
Winfield
Swedesburg
Morning Sun
Oakville
Keithsburg
Seaton
LOUISA
DES MOINES
HENDERSON
Mt Union
Yarmouth
Mediapolis
Little York


Route 7
2 Hours
New Position
CEDAR
MUSCATINE
Wilton
Durant
Stockton
Walcott
West Liberty
Atalissa
Moscow
Wiese Slough
Hills
Blue Grass
Lone Tree
Riverside
Pike Run
Cedar Bottom WMA
Nichols
Red Cedar Wildlife Area
Montpelier
Muscatine
ILLINOIS
Loud Thunder Forest Preserve
Illinois City
Conesville
Fruitland
MUSCATINE ISLAND
Letts
ROCK ISLAND
MERCER
Ainsworth
Cotter
Columbus Junction
Fredonia
Columbus City
Grandview
WASHINGTON
LOUISA
JOHNSON
IOWA
Crawfordsville
Wapello
New Boston
Aledo
Olds
Winfield
Swedesburg
Morning Sun
Oakville
Keithsburg
Seaton
LOUISA
DES MOINES
HENDERSON
Mt Union
Yarmouth
Mediapolis
Little York


Route 8
2 Hours
New Position
CEDAR
MUSCATINE
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Blue Grass
Nichols
Muscatine
Conesville
Fruitland
Letts
Fredonia
Columbus Junction
Columbus City
Grandview
Wapello
Winfield
Swedesburg
Morning Sun
Mt Union
Yarmouth
Mediapolis
LOUISA
DES MOINES
ILLINOIS
IOWA
ROCK ISLAND
MERCER
HENDERSON
New Boston
Oakville
Keithsburg
Seaton
Aledo
Montpelier
Riverside
Lone Tree
Hills
Ainsworth
Cotter
Crawfordsville
Olds

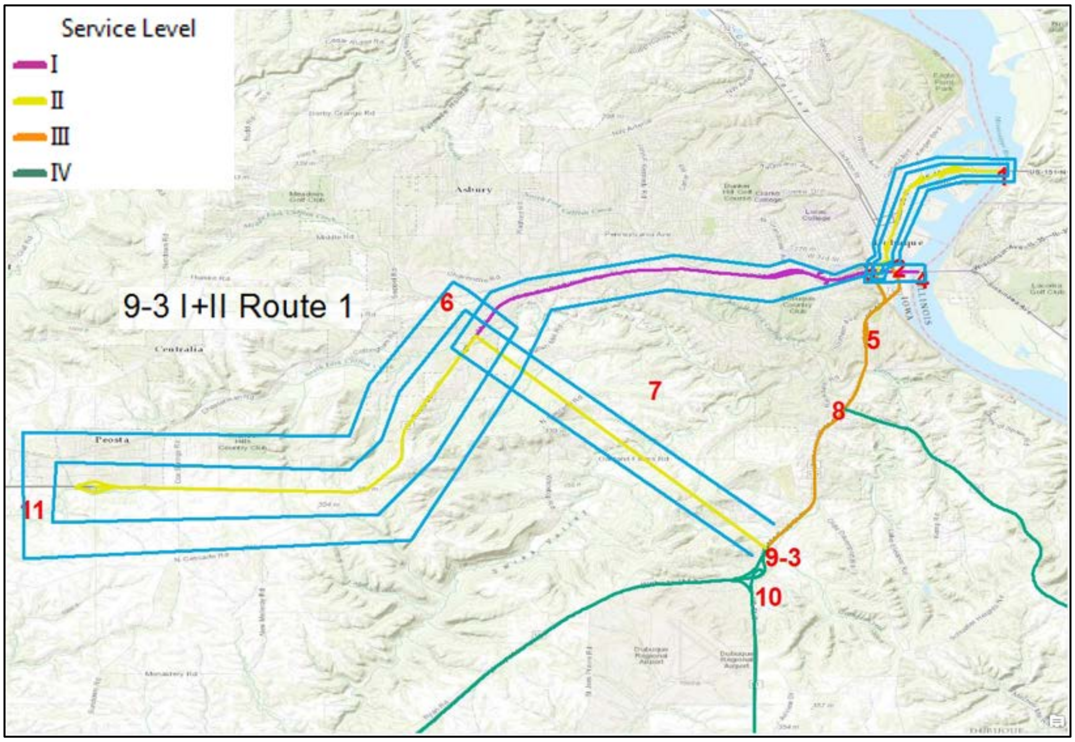

Route 9
2 Hours
New Position
CEDAR
MUSCATINE
West Liberty
Atalissa
Moscow
Wilton
Durant
Stockton
Walcott
Blue Grass
Nichols
Muscatine
Conesville
Fruitland
Letts
Fredonia
Columbus Junction
Columbus City
Grandview
Wapello
Swedesburg
Mt Union
Yarmouth
Mediapolis
DES MOINES
ILLINOIS
IOWA
ROCK ISLAND
MERCER
HENDERSON
New Boston
Oakville
Keithsburg
Seaton
Aledo
Montpelier
Riverside
Lone Tree
Hills
Ainsworth
Cotter
Crawfordsville
Olds

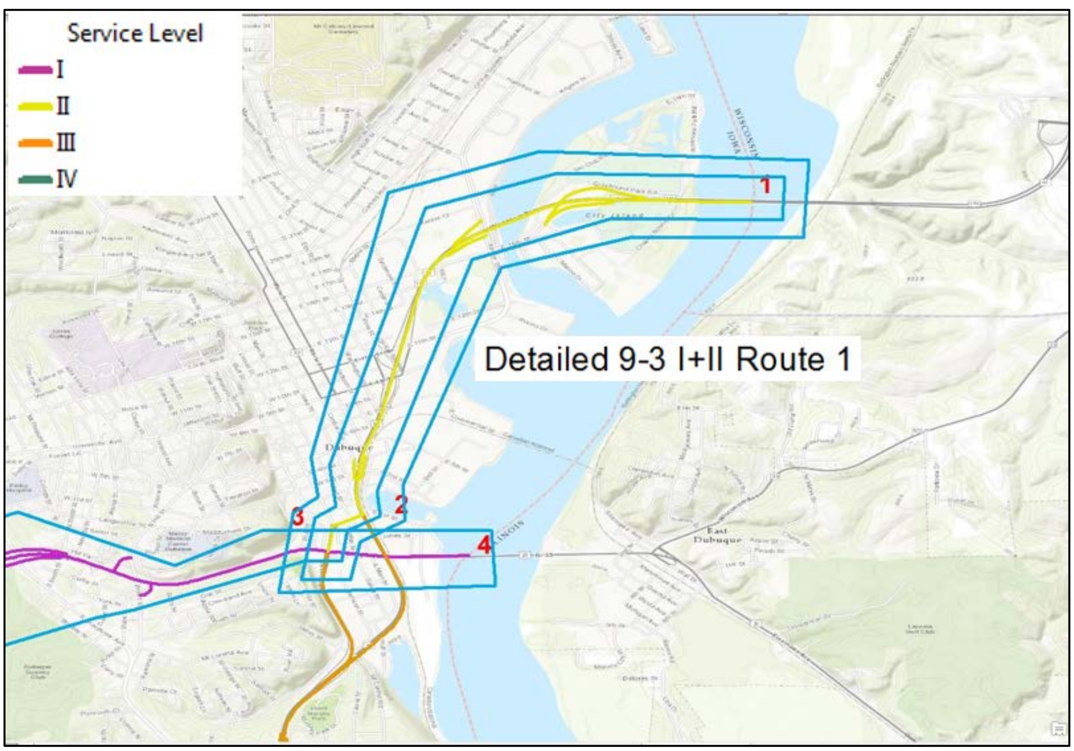
APPENDIX C. NETWORK SERVICE SCHEDULE FOR DUBUQUE GARAGE

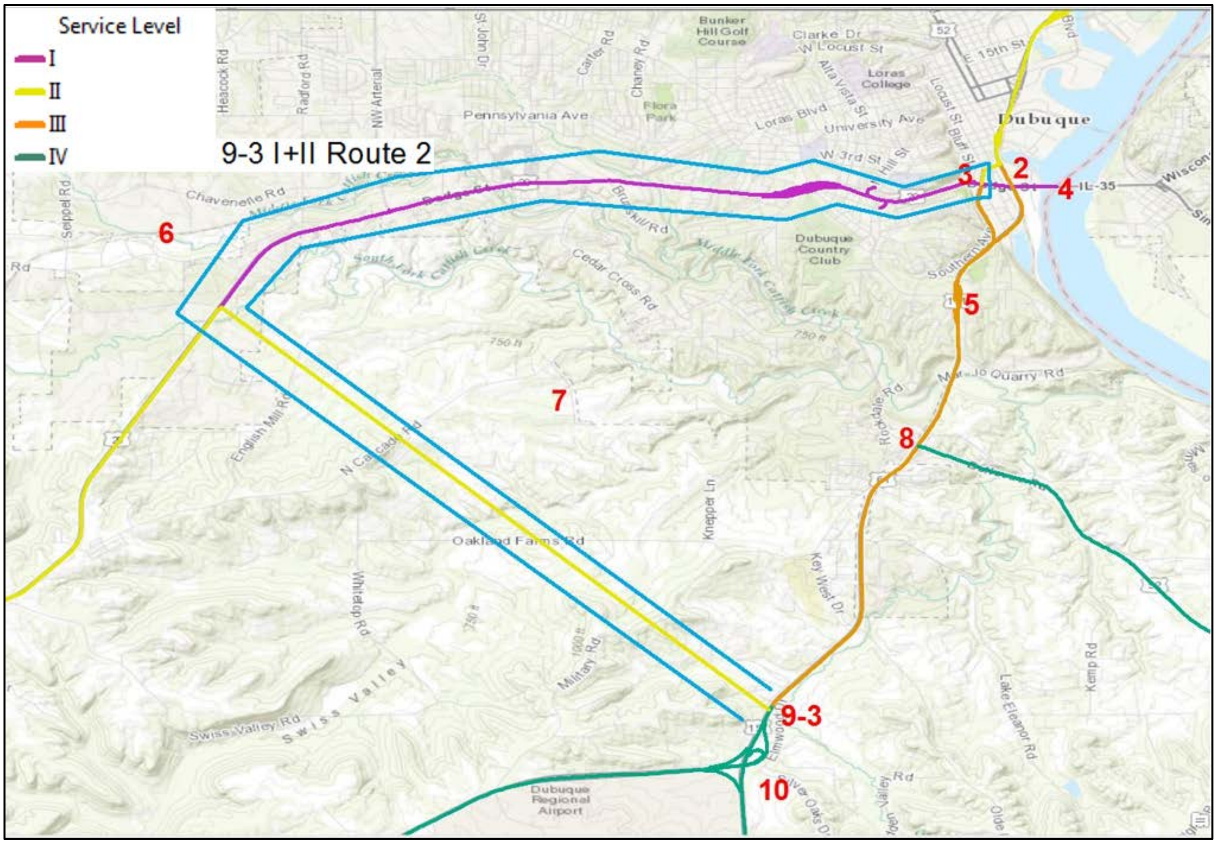
	Time slot	Category Times a day	IV 7	III 9	II 11	I 12	Network	Number of trucks
Hour	1	00:00	Y	Y	Y	Y	I,II,III,IV	5
		01:00						
	2	02:00				Y	I,II,III	2
		03:00		Y	Y			
	3	04:00	Y	Y		Y	I,II,III,IV	5
		05:00			Y			
	4	06:00		Y		Y	I,II,III,IV	5
		07:00	Y		Y			
	5	08:00				Y	I,II,III	2
		09:00		Y	Y			
	6	10:00				Y	I,II,IV	5
		11:00	Y		Y			
	7	12:00		Y		Y	I,III	1
		13:00						
	8	14:00	Y		Y	Y	I,II,III,IV	5
		15:00		Y				
	9	16:00			Y	Y	I,II	2
		17:00						
	10	18:00	Y	Y	Y	Y	I,II,III,IV	5
		19:00						
	11	20:00			Y	Y	I,II,III,IV	5
		21:00	Y	Y				
	12	22:00			Y	Y	I,II	2
		23:00						

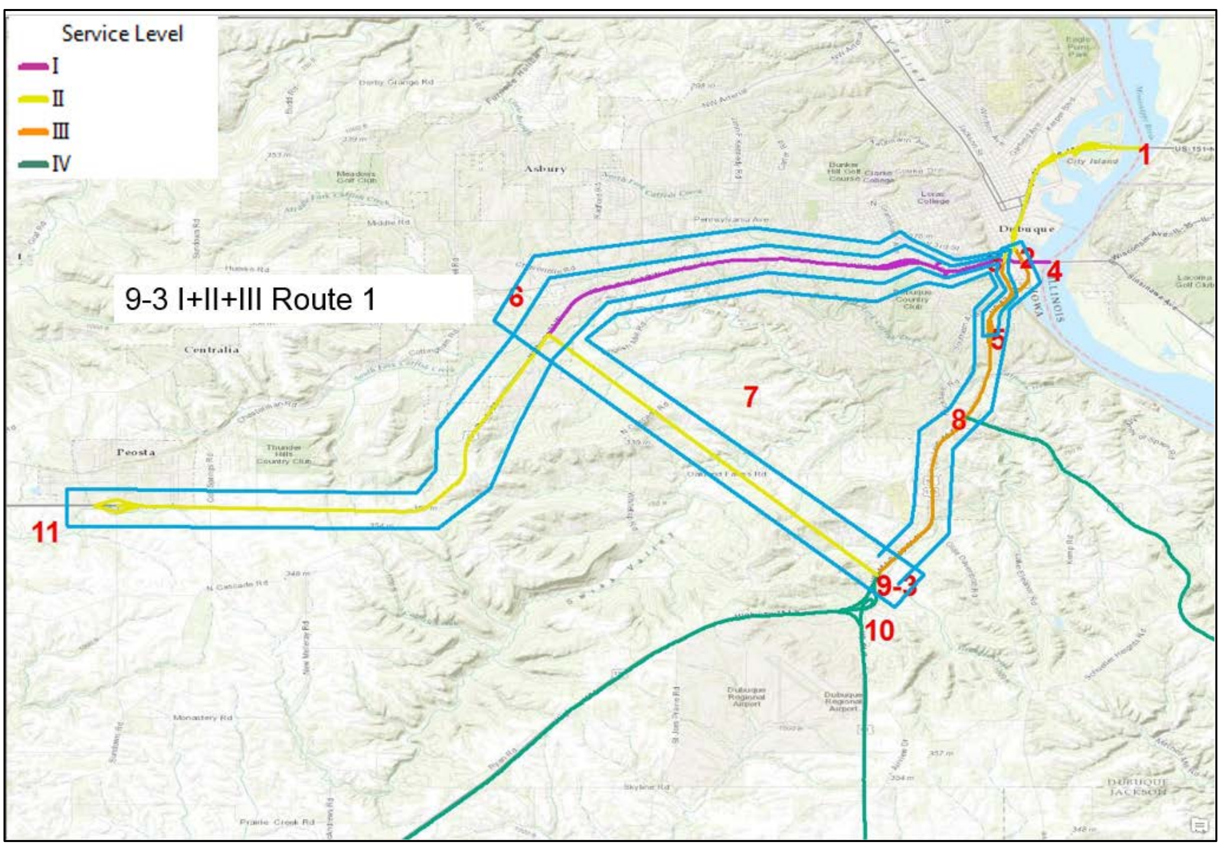
APPENDIX D. OPTIMAL SNOW ROUTES FOR DUBUQUE GARAGE

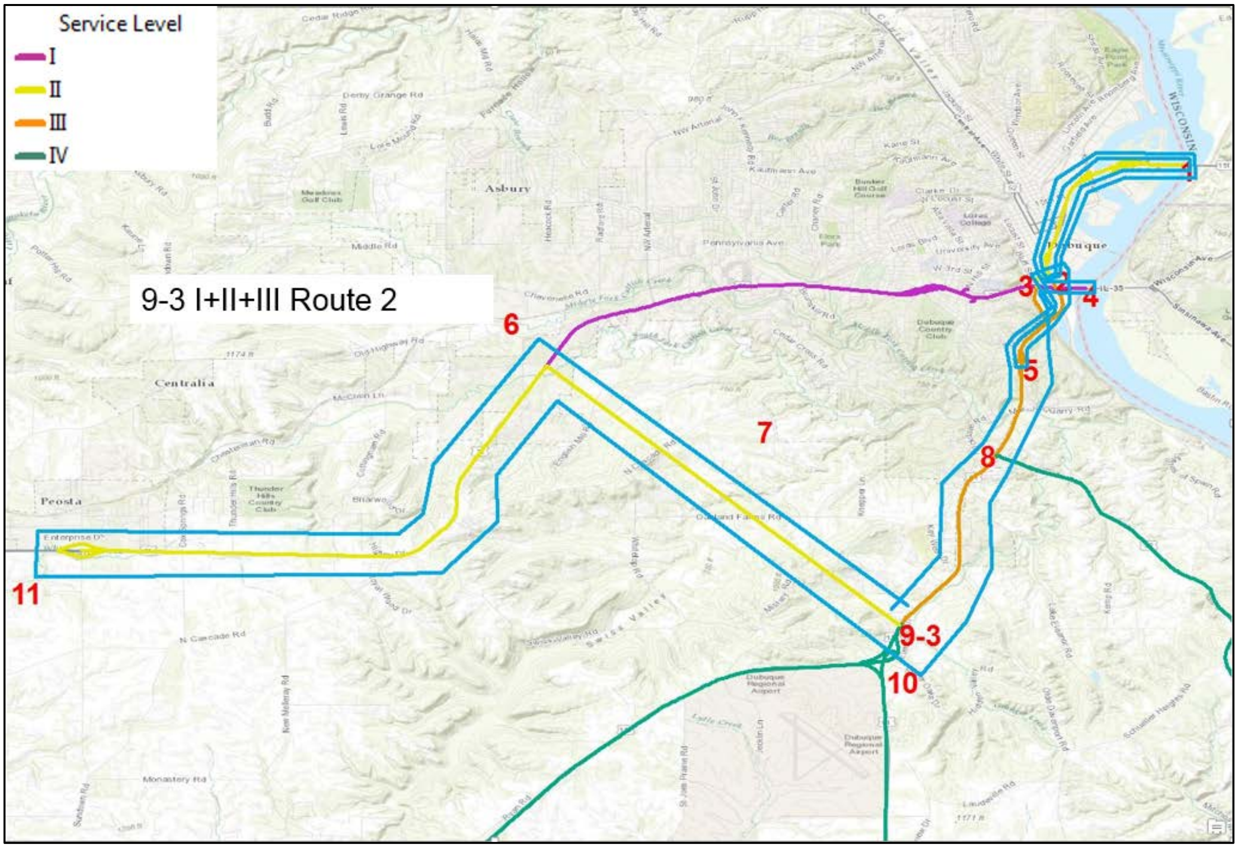
The maps in this appendix show the optimal routes, color-coded by service level, for site 9-3. Blue lines outline servicing segments, while black lines indicate deadhead segments.

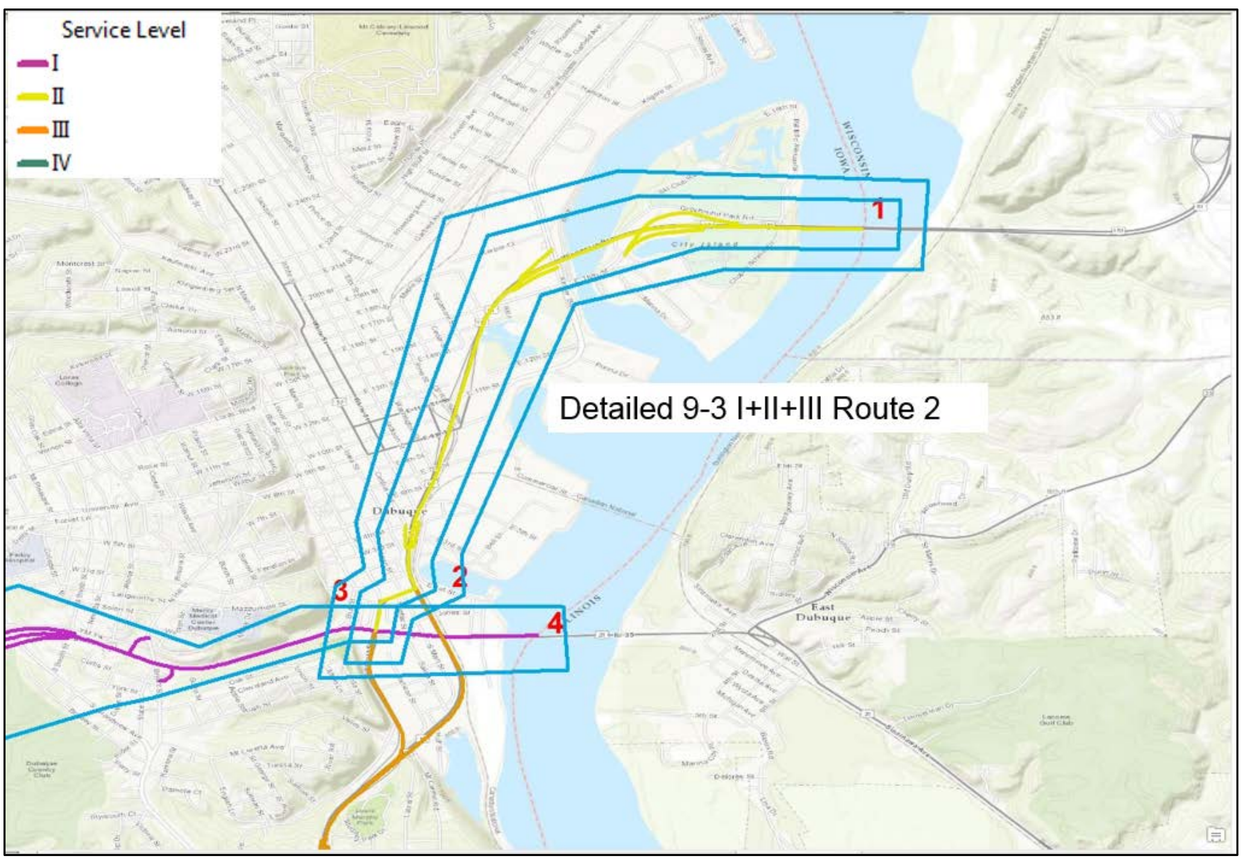


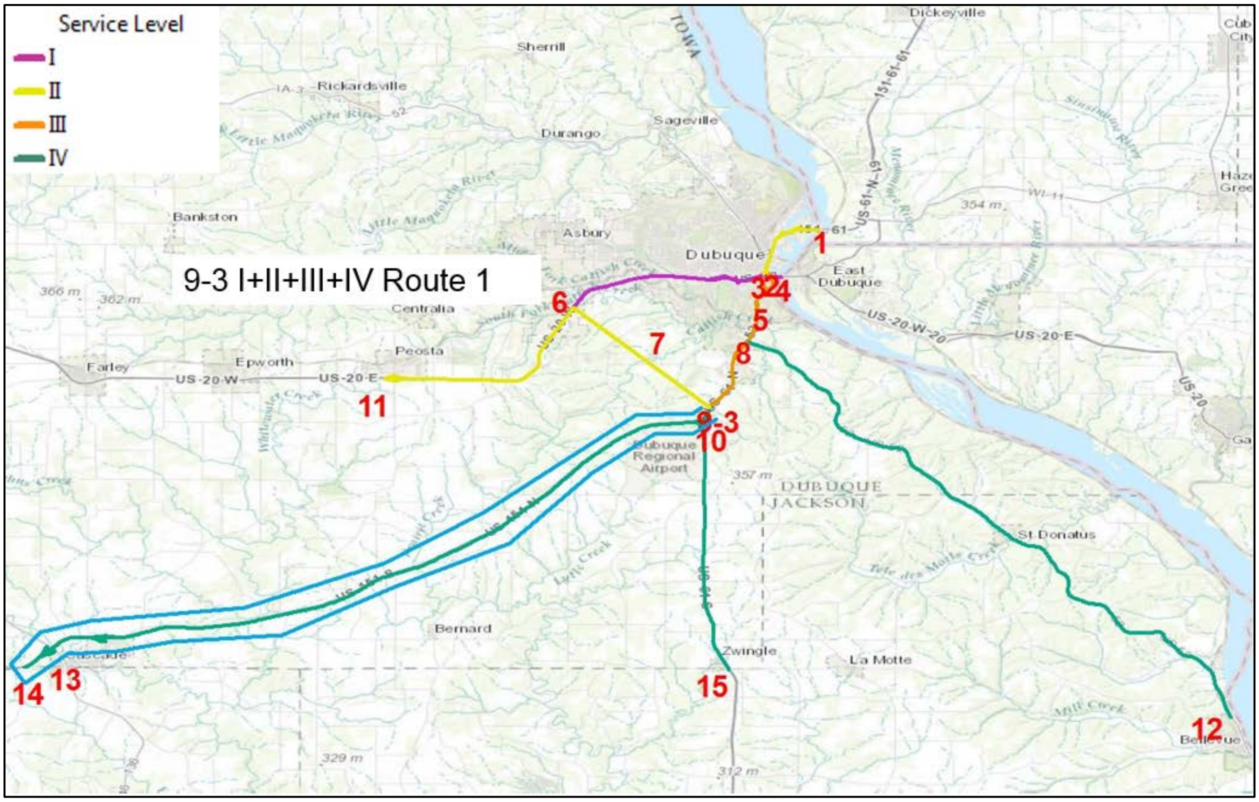


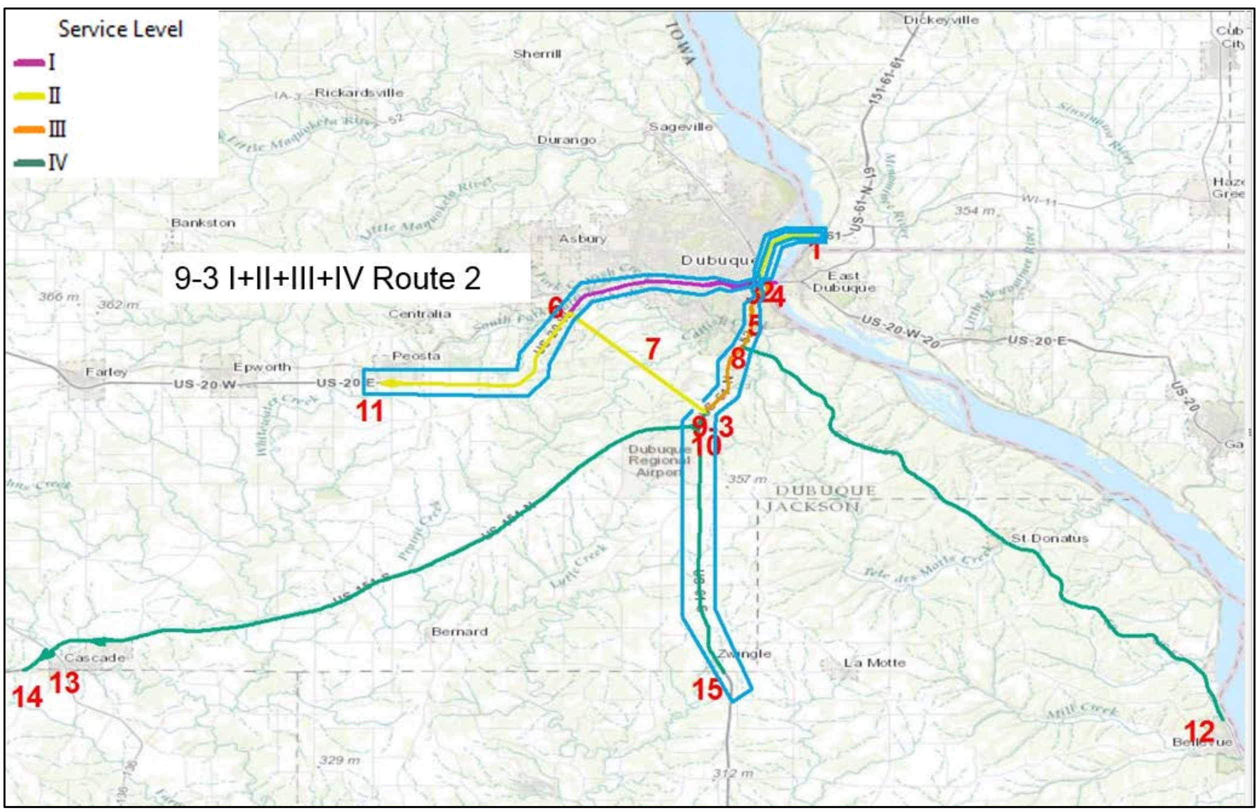

Service Level
I
II
III
IV
9-3 I+II Route 2
1
2
3
4
5
6
7
8
9-3
10
Dubuque
Dubuque Country Club
Dubuque Regional Airport
Pennsylvania Ave
Loras Blvd
University Ave
Chavenelle Rd
Cedar Cross Rd
N Cascade Rd
English Mill Rd
Oakland Farms Rd
Whitetop Rd
Military Rd
Swiss Valley Rd
Knepper Ln
Key West Dr
Lake Eleanor Rd
Kemp Rd
Rockdale Rd
Mt Jo Quarry Rd
Southern Ave
Loras College
Bunker Hill Golf Course
Flora Park

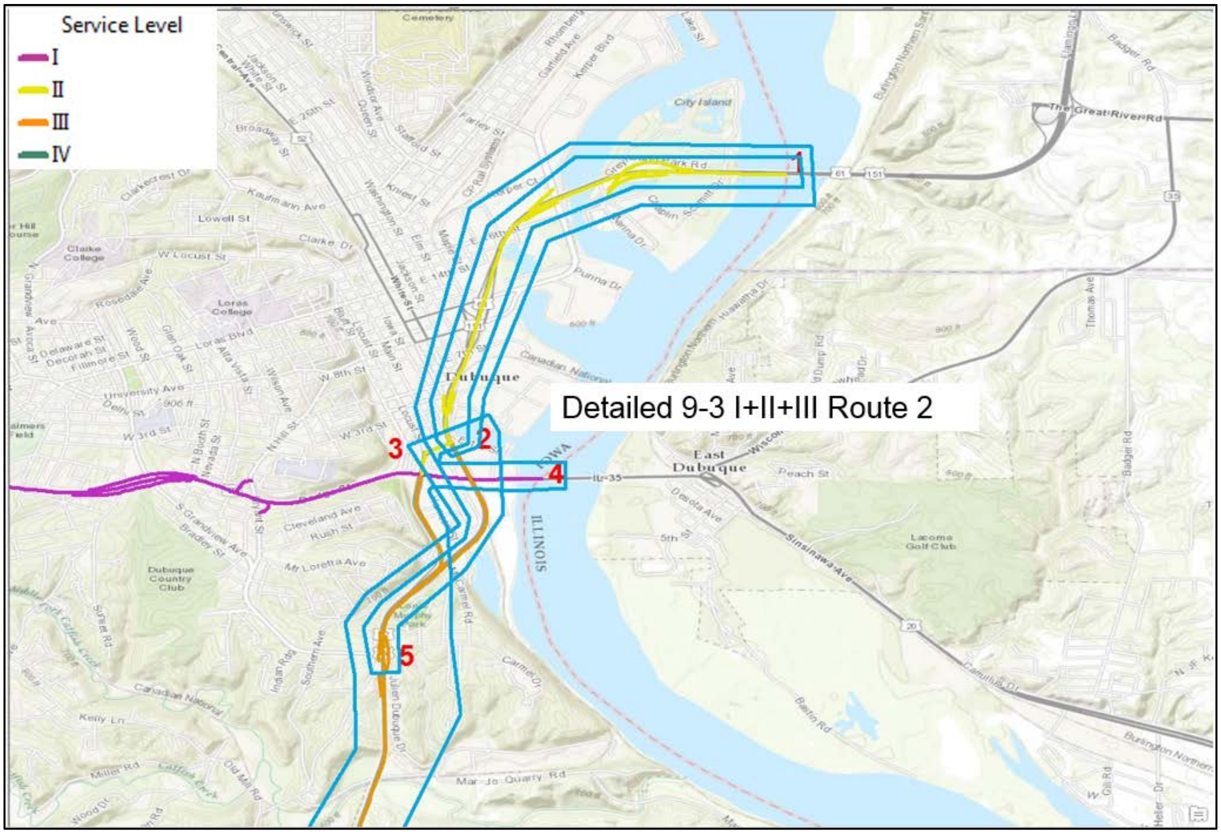

Service Level
I
II
III
IV
9-3 I+II+III Route 1
1
2
4
5
6
7
8
9-3
10
11
Asbury
Centralia
Peosta
Dubuque
Dubuque Regional Airport


Service Level
I
II
III
IV
9-3 I+II+III Route 2
1
3
4
5
6
7
8
9-3
10
11

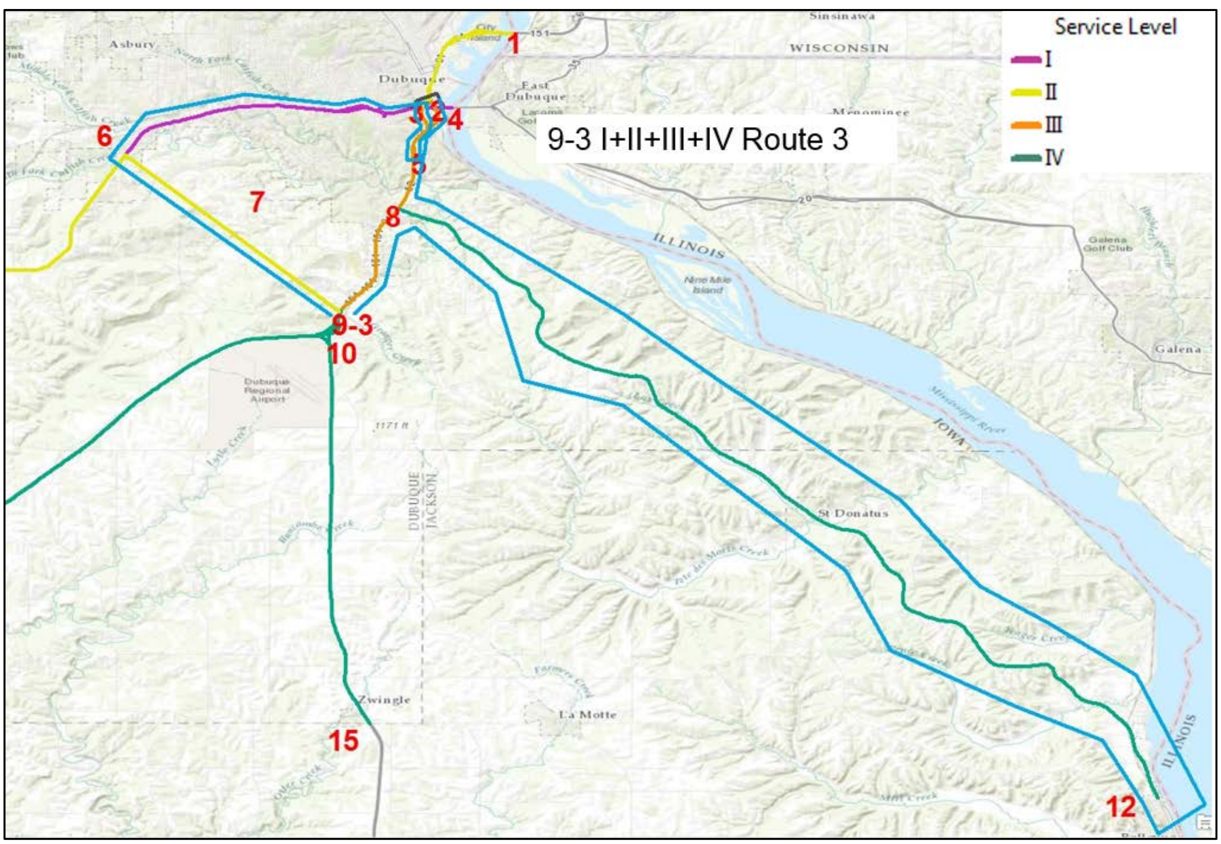

Service Level
I
II
III
IV
Detailed 9-3 I+II+III Route 2
1
2
3
4


Service Level
I
II
III
IV
9-3 I+II+III+IV Route 1
1
324
5
6
7
8
9-3
10
11
12
13
14
15

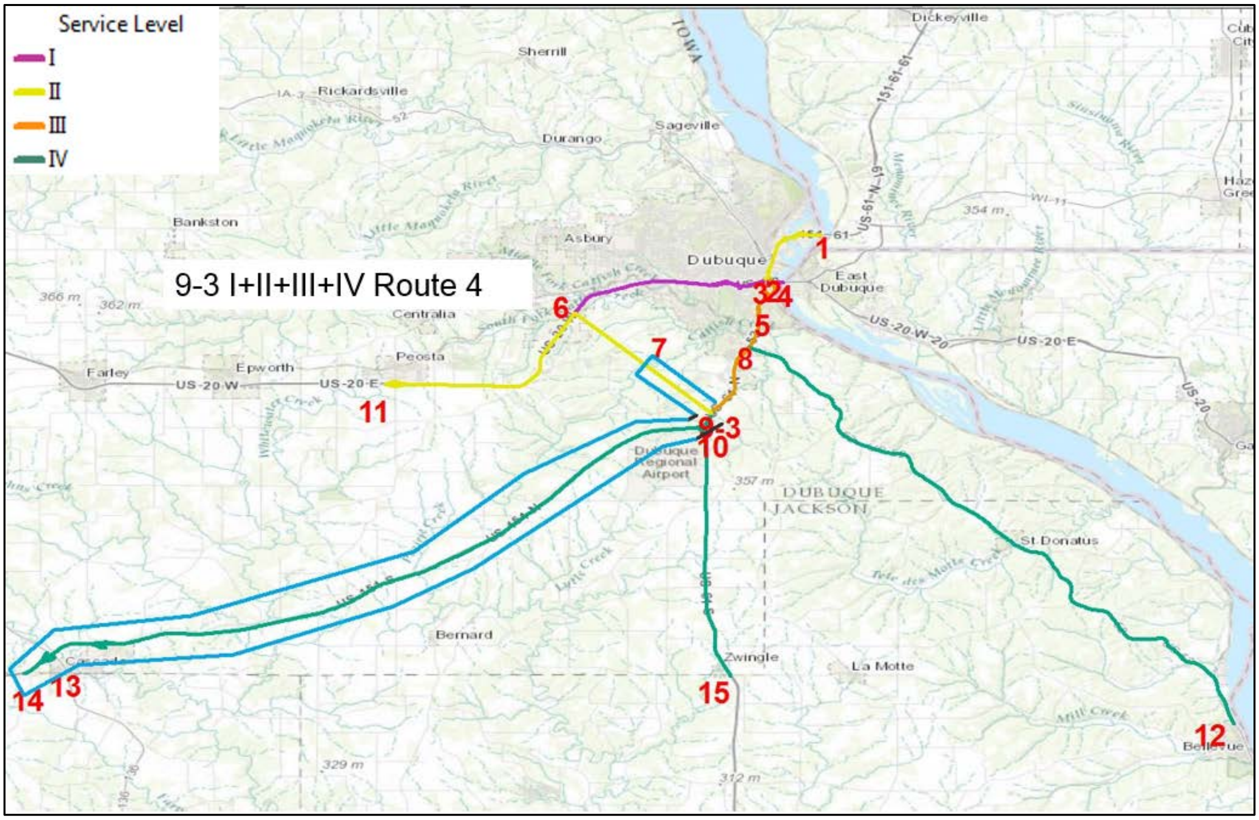

Service Level
I
II
III
IV
9-3 I+II+III+IV Route 2
1
324
5
6
7
8
9-3
10
11
12
13
14
15

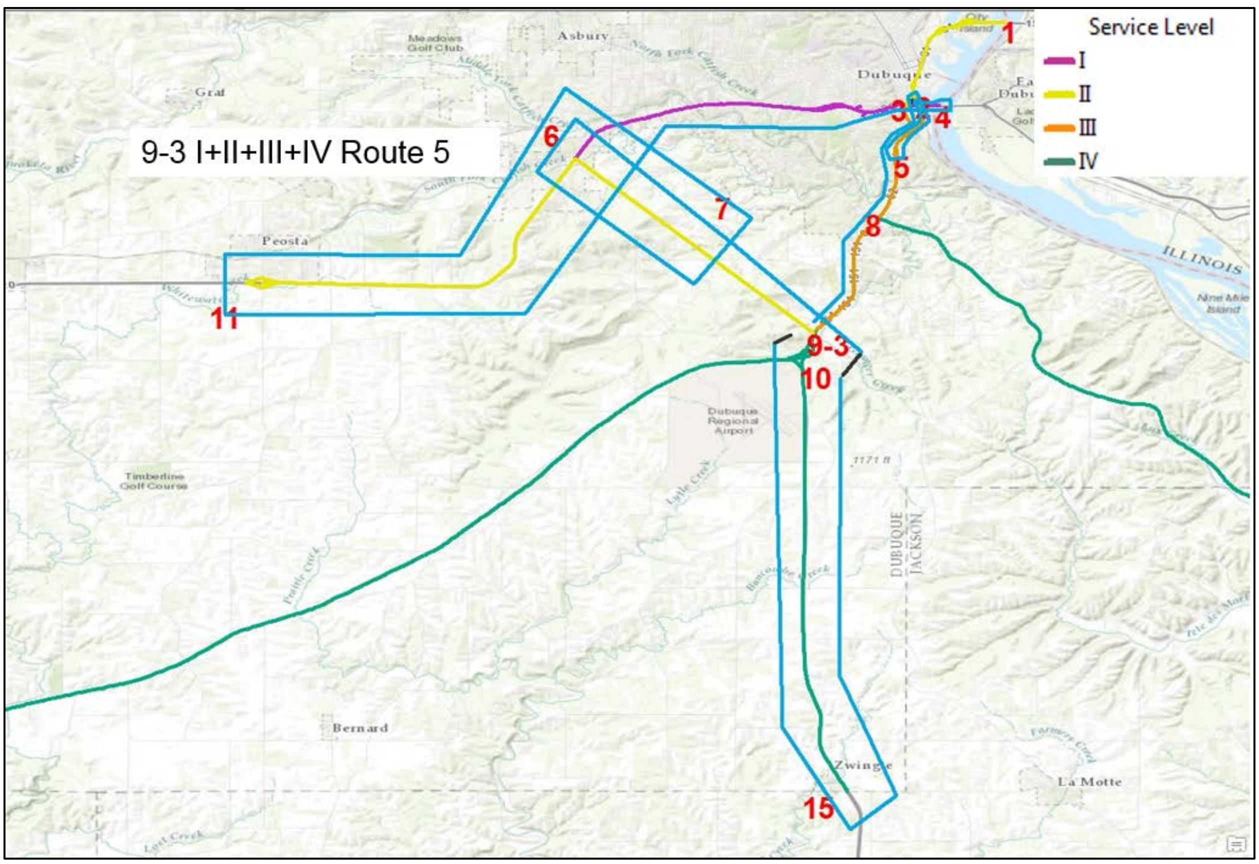


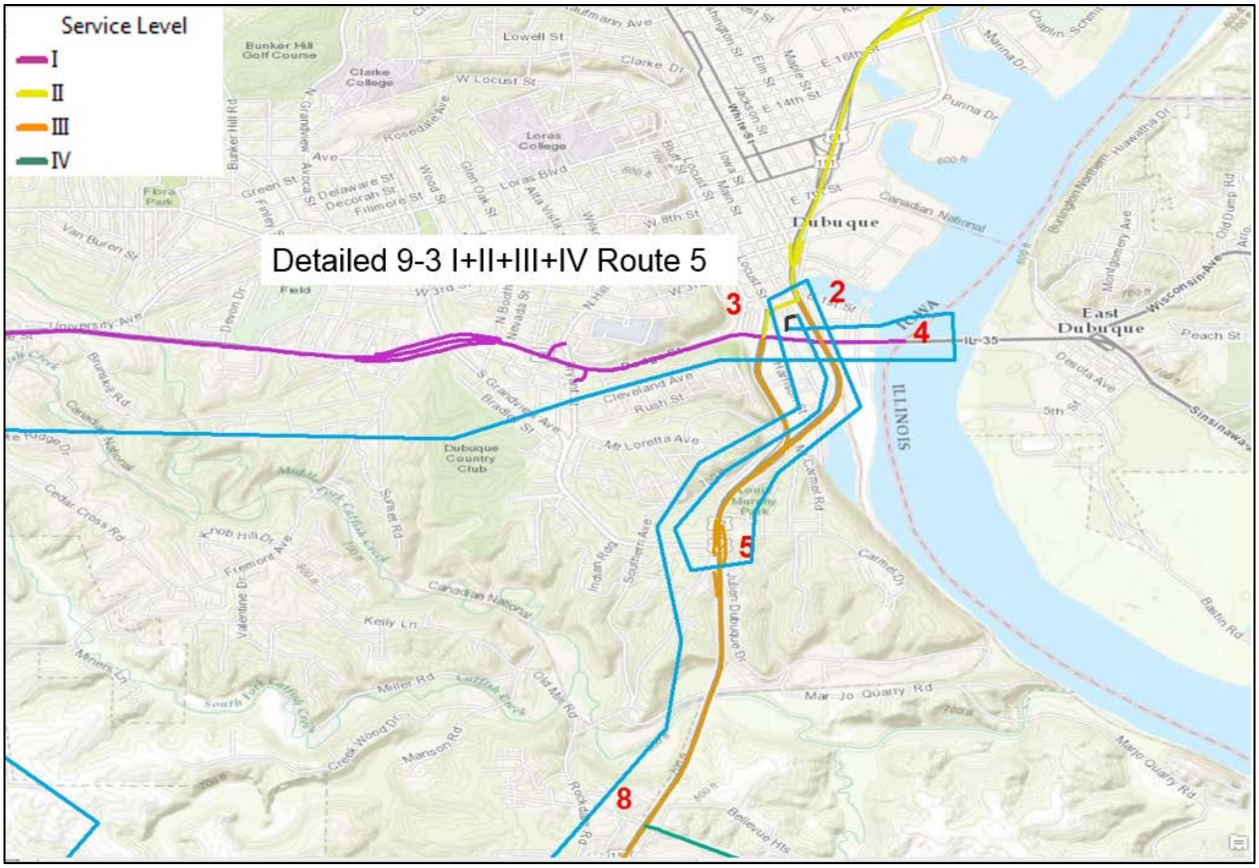
Service Level
I
II
III
IV
Detailed 9-3 I+II+III Route 2
1
2
3
4
5
Dubuque
East Dubuque
IOWA
ILLINOIS

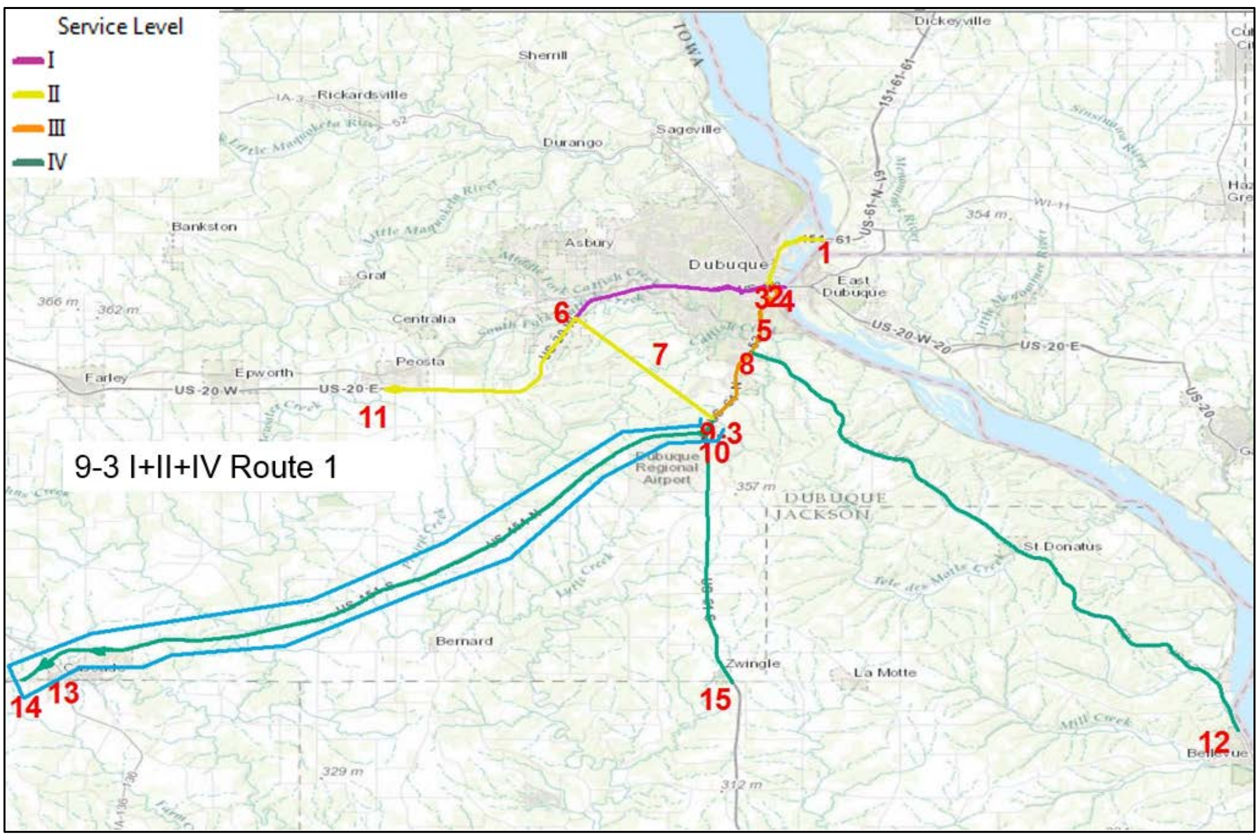


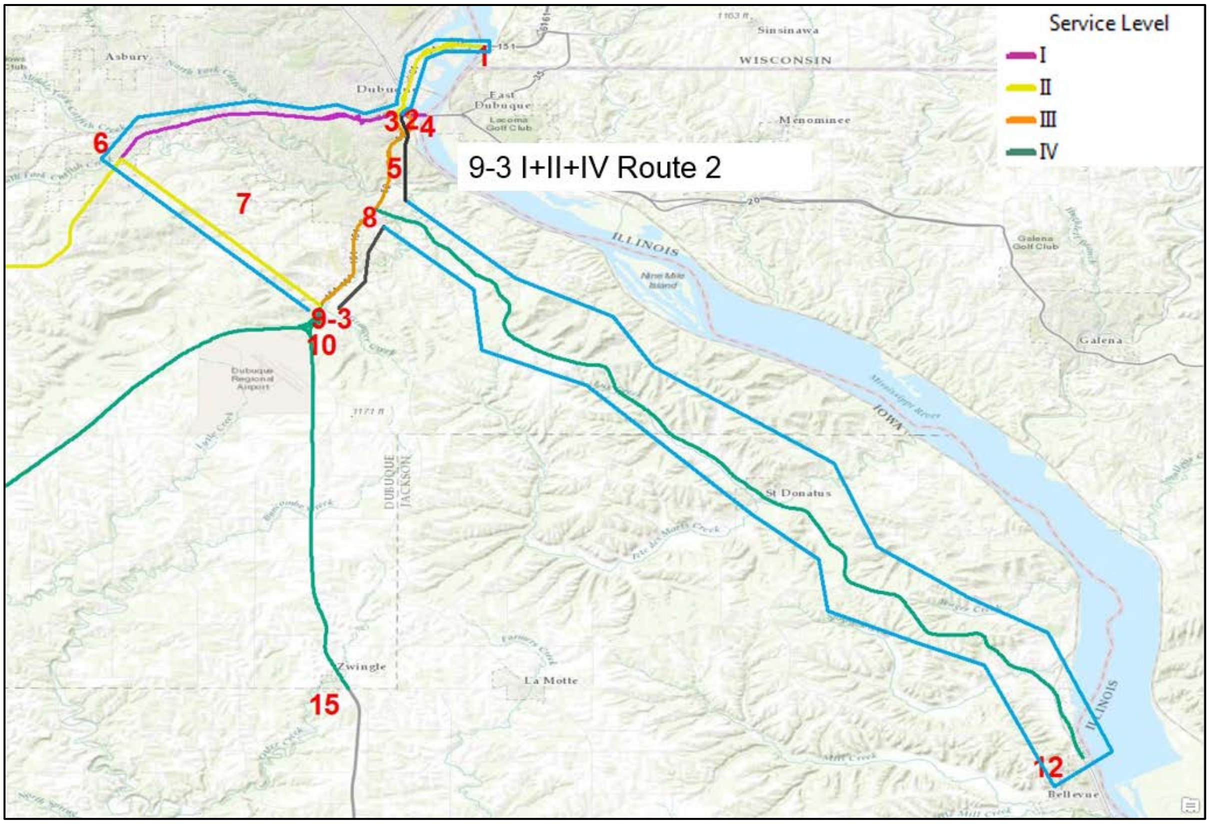
Service Level
I
II
III
IV
9-3 I+II+III+IV Route 3
1
3
2
4
5
6
7
8
9-3
10
12
15
Dubuque
East Dubuque
WISCONSIN
ILLINOIS
IOWA
Asbury
St Donatus
Zwingle
La Motte
Galena

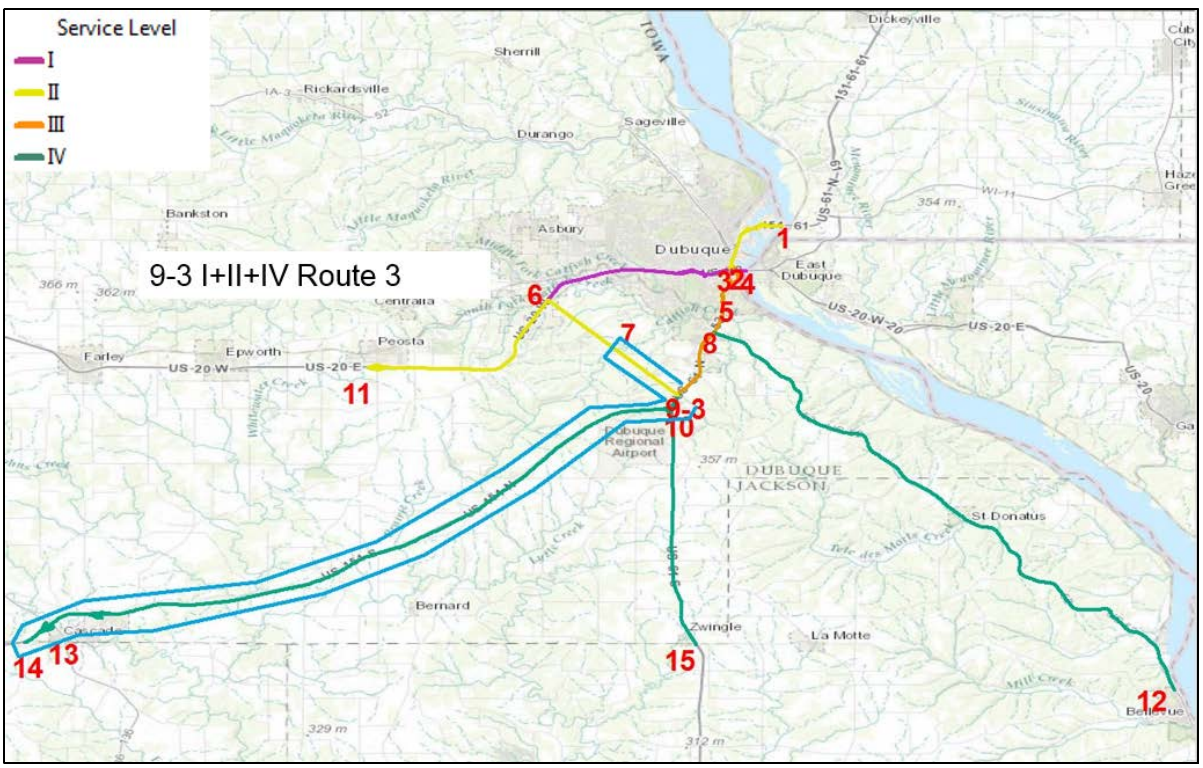

Service Level
I
II
III
IV
9-3 I+II+III+IV Route 4
Sherrill
Rickardsville
Durango
Sageville
Dickeyville
Bankston
Asbury
Dubuque
East Dubuque
Centralia
Peosta
Farley
Epworth
US-20-W
US-20-E
Dubuque Regional Airport
DUBUQUE
JACKSON
St Donatus
Bernard
Zwingle
La Motte
Bellevue
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

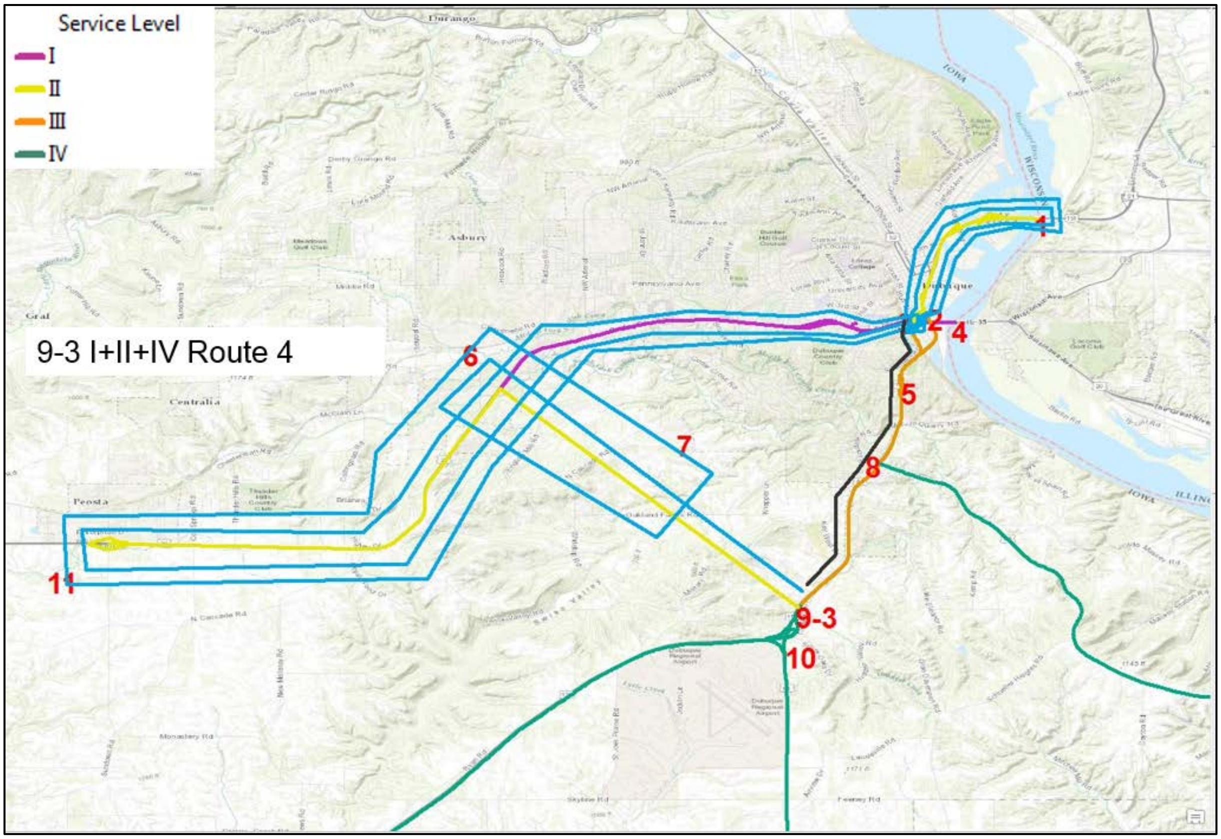

Service Level
I
II
III
IV
9-3 I+II+III+IV Route 5
Meadows Golf Club
Asbury
Graf
Dubuque
Peosta
Dubuque Regional Airport
Timberline Golf Course
DUBUQUE
JACKSON
ILLINOIS
Bernard
Zwingle
La Motte
1
3
4
5
6
7
8
9-3
10
11
15

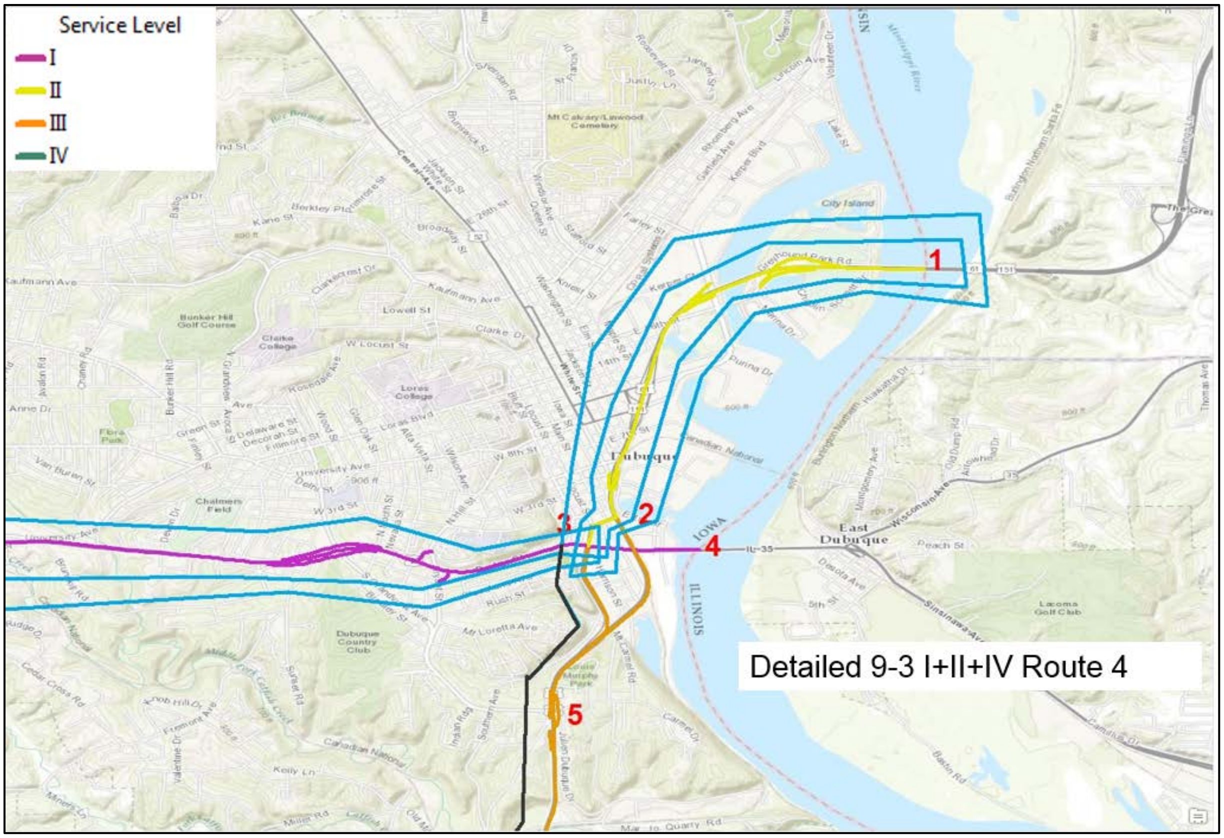

Service Level
I
II
III
IV
Detailed 9-3 I+II+III+IV Route 5
Dubuque
East Dubuque
IOWA
ILLINOIS
1
2
3
4
5
8

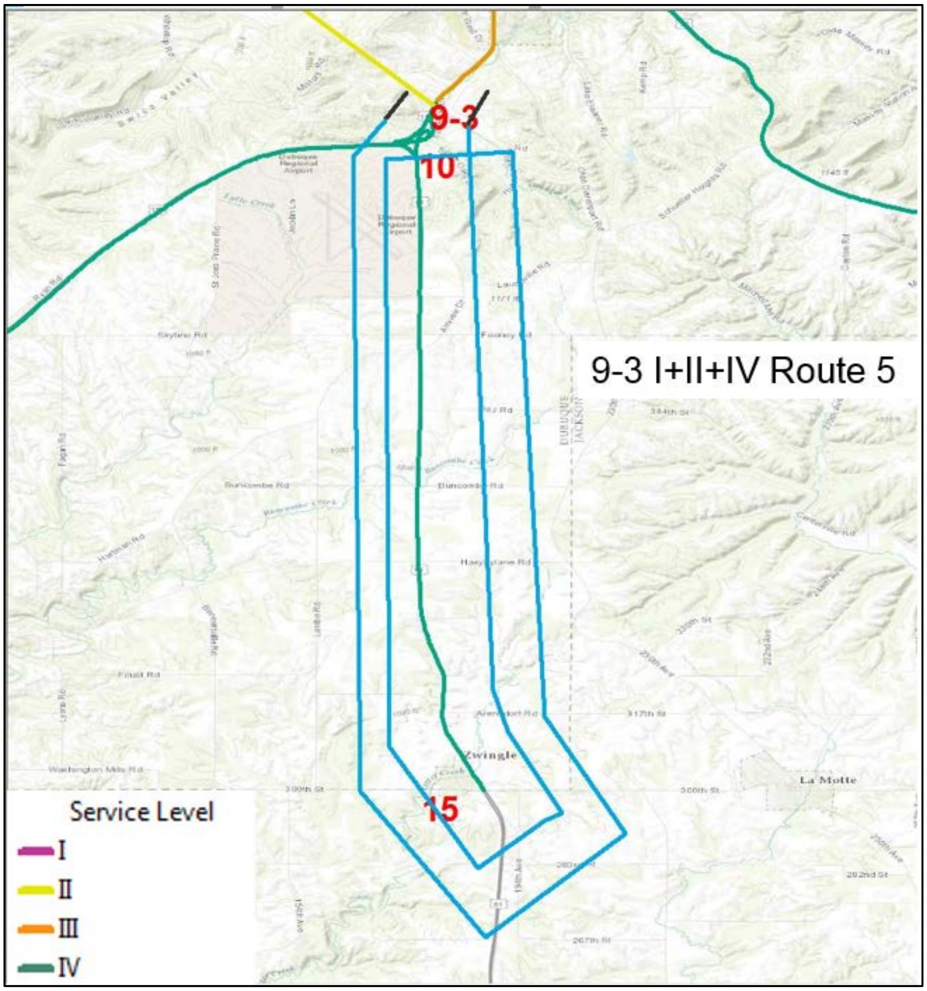

Service Level
I
II
III
IV
9-3 I+II+IV Route 1
Dubuque
East Dubuque
Sherrill
Rickardsville
Durango
Sageville
Dickeyville
Bankston
Asbury
Graf
Centralia
Peosta
Farley
Epworth
Dubuque Regional Airport
Bernard
Zwingle
La Motte
St Donatus
Bellevue
DUBUQUE
JACKSON
1
3
2
4
5
6
7
8
9
3
10
11
12
13
14
15

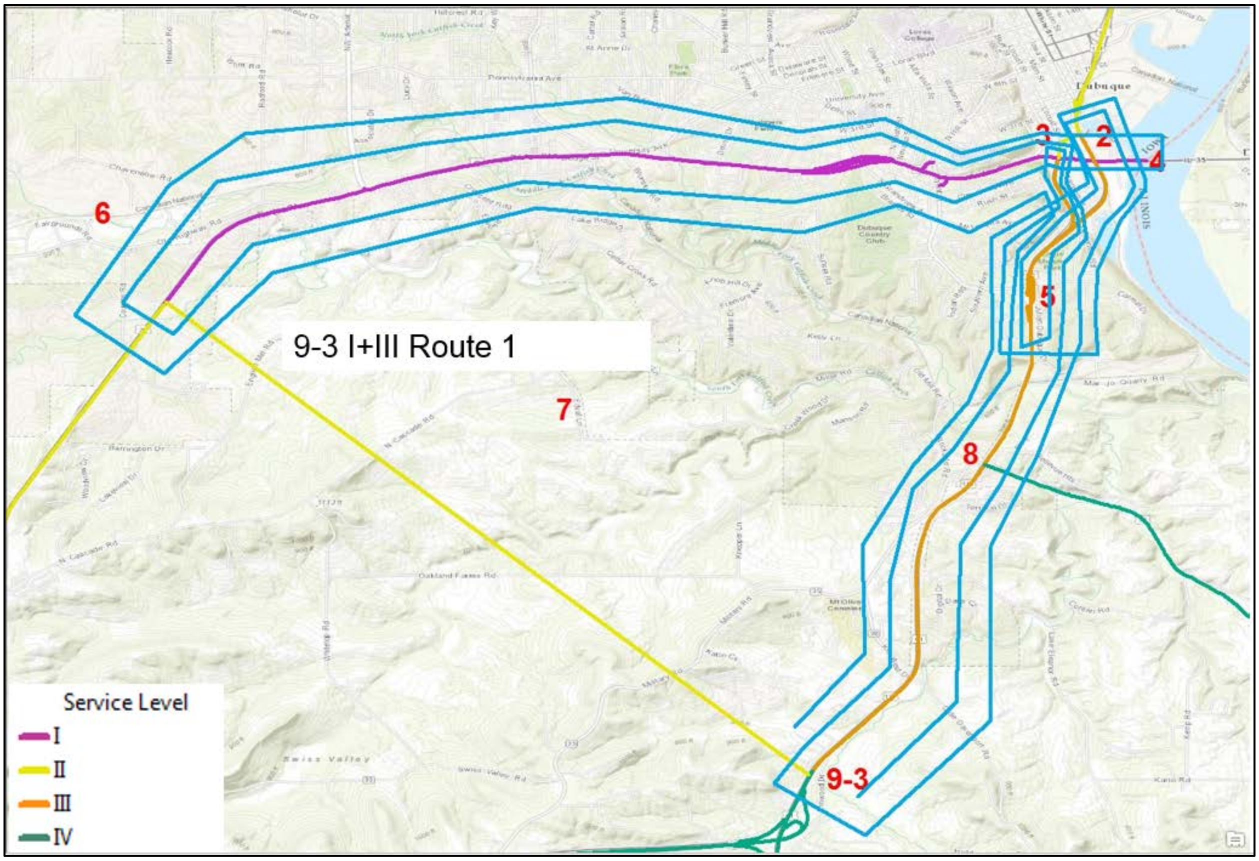

Service Level
I
II
III
IV
9-3 I+II+IV Route 2
1
2
3
4
5
6
7
8
9-3
10
12
15
WISCONSIN
ILLINOIS
IOWA
Asbury
Dubuque
East Dubuque
Menominee
Sinsinawa
Galena
St Donatus
Zwingle
La Motte
Bellevue


Service Level
I
II
III
IV
9-3 I+II+IV Route 3
1
3
2
4
5
6
7
8
9-3
10
11
12
13
14
15
IOWA
Dickeyville
Sherrill
Rickardsville
Durango
Sageville
Bankston
Asbury
Dubuque
East Dubuque
Centralia
Peosta
Farley
Epworth
US-20-W
US-20-E
Dubuque Regional Airport
DUBUQUE
JACKSON
St Donatus
Bernard
Cascade
Zwingle
La Motte
Bellevue


Service Level
I
II
III
IV
9-3 I+II+IV Route 4
1
2
4
5
6
7
8
9-3
10
11


Service Level
I
II
III
IV
Detailed 9-3 I+II+IV Route 4
1
2
3
4
5


9-3
10
15
9-3 I+II+IV Route 5
Zwingle
La Motte
Service Level
I
II
III
IV


9-3 I+III Route 1
6
7
8
5
3
2
4
9-3
Service Level
I
II
III
IV