DCT 269

Snow Plow Route Optimization in Delaware

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April, 2018

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for the

Delaware Department of Transportation

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16. Abstract

Winter road maintenance operations are of great importance for driver convenience, safety and mobility. For roadway that regularly encounters storms with snow and ice in an average year, removal of this snow and ice is essential for maintaining safe operations. This snow and ice removal must not only ensure safe operations but also must be efficient because efficient removal is crucial to reducing congestion and the resulting cost and impact that a snow storm has on a road. It is noteworthy to mention that snowplow operations involve more than simply sending out a fleet of snowplows when snow begins to accumulate at a depth of one inch or more on the street surface. Vehicle routing and scheduling problems require that a fleet of vehicles serves a number of requests in order to minimize operational costs. This research will conduct a critical examination of existing snow and ice control practices and procedures. The purpose of this study is to assist DelDOT in determining whether they are appropriately managing their snow and ice removal resources and applying engineering best practices. Specifically, the goal of this research is to develop a GIS-based approach for optimizing snow plow routing in order to minimize the total snow plow truck travel distance and travel times. GIS-based analyses were conducted to not only derive snowplow routing strategies using the proposed methodology, but also draw useful conclusions for winter road maintenance agencies. The research team summarized the results of tasks above, and incorporated the resultant insights and findings into a final report, which will describe how to apply various modeling tools for snow plow route optimization analysis.

17. Key Words		**18. Distribution Statement**	
Winter Road Maintenance, Snow Removal, Snow Plowing, Vehicle Routing, GIS, Network Analysis, Route Optimization		No restrictions.	
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Executive Summary

Winter road maintenance operations are of great importance for driver convenience, safety and mobility. For roadway that regularly encounters storms with snow and ice in an average year, removal of this snow and ice is essential for maintaining safe operations. This snow and ice removal must not only ensure safe operations but also must be efficient because efficient removal is crucial to reducing congestion and the resulting cost and impact that a snow storm has on a road. It is noteworthy to mention that snowplow operations involve more than simply sending out a fleet of snowplows when snow begins to accumulate at a depth of one inch or more on the street surface. Vehicle routing and scheduling problems require that a fleet of vehicles serves a number of requests in order to minimize operational costs.

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1. INTRODUCTION

1.1 Problem Statement

According to the Federal Highway Administration, more than 70% of the nation's roads are located in snowy regions[1]. Winter road maintenance operations are of great importance for driver convenience, safety and mobility. In the United States, road maintenance operations on snow and ice control operations consume over 2.3 billion dollars each year.

An important goal of winter maintenance is to keep roads for safe passage. It is noteworthy to mention that snowplow operations involve more than simply sending out a fleet of snowplows when snow begins to accumulate at a depth of one inch or more on the street surface. Vehicle routing and scheduling problems require that a fleet of vehicles serves a number of requests in order to minimize operational costs. Vehicle routing and scheduling problems play an important role in distribution management and have been investigated by several researchers.

The DelDOT snow plow fleet is fairly large, and the capabilities of the equipment have improved with time. Some advancement include: trucks with more plows on them, increased effectiveness of salt, and increased salt storage capacity. With these changes to DelDOT's equipment, the fleet can be looked at and a determination can be made as to what the correct composition is of the snow plow fleet and what numbers of each class of truck should be operational for a given desired level of service. DelDOT's performance standards for snow removal are: roadways clear and passable within 24 hours after the end of the snowfall when snowfall is less than 4 inches; between 4 and 8 inches, 48 hours; over 8 inches, 72 hours.

The problem, that this project investigates, is concerned with optimizing snow plow routing and the allocation and use of DelDOT resources with respect to the amount of equipment, supplies and personnel that are or should be available to address the impact snow and ice can have on transportation systems. Given their limited resources, it is essential that DelDOT appropriately manage these resources, ensure coordination of systems, apply appropriate engineering principles, and prevent congestion. The cost of being unprepared for a snow and ice storm can be quite high, but judgments must be made with regard to the amount of investment appropriate for DelDOT to be well equipped for an unusually large snow occurrence.

1.2 Motivation

The research presented here faces the following challenging questions:

[1] http://www.ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm

- What is the best allocation of snowplow trucks to sites and routes to snowplow trucks so as to minimize overall deadhead miles?
- Can the current routes for snow removal and brine application be improved?
- What is the optimized route for snow removal and brine application for each DelDOT area yard?
- What parameters of individual routes are most important in terms of overall safety and operation efficiency?

These questions and more should be considered in the design of an effective strategy for conducting winter road maintenance. The recommended schedule that answers these questions must have the minimum total cost among all possible schedules.

The goal of this research project is to develop a model for optimizing snow plow routing in order to be as effective as possible while meeting DelDOT's performance goals with the maximum efficiency: roadways clear and passable within 24 hours after the end of the snowfall when snowfall is less than 4 inches; between 4 and 8 inches, 48 hours; over 8 inches, 72 hours. The results will then be used by DelDOT to ensure that all primary road links are serviced and total operational costs are minimized.

This project will provide the following benefits:

- It will document the research current best practices with regard to snow plow route optimization.
- It will develop a model for optimizing snow plow routing in order to be as effective as possible.
- The method developed in this project is intended to be used for snow plow route management.

1.3 Report Outline

This report consists of four chapters, which are structured as follows: Chapter 1 gives a brief introduction to our research activities – the problem statement and motivation of our research, the research goal, and our approach.

Chapter 2 provides a comprehensive review of a large amount of previously published evidence about theoretical approaches conducted nationally and internationally as a basis of roadway snow and ice control for practitioners and researchers.

Chapter 3 describes describe the GIS-based snow plow route optimization approach.

Chapter 4 summarizes the findings. Concluding remarks, recommendations for implementation and future research extensions are given in this chapter.

2. LITERATURE REVIEW

2.1 Introduction

This task involves having a thorough understanding of current state of practice, and policies in winter highway maintenance, which is identified in a problem statement, conducting a critical examination of existing snow and ice control practices and procedures and to make recommendations to improve snow and ice control, and identifying the appropriate level of detail and tools. Evaluations of existing research conducted nationally and internationally will be synthesized for key lessons learned, and serve as a basis of roadway snow and ice control for practitioners and researchers.

Key National Snow Removal Analysis Resources

- Snow Removal/National Snow and Ice Data Center[2]
- TRB Surface Transportation Weather Task Force[3]
- TRB Surface Transportation Weather Program Subcommittee
- TRB Winter Maintenance Committee[4]
- TRB Snow Removal and Ice Control Technology Program Subcommittee
- National Weather Service[5]
- National Highway Traffic Safety Administration[6]
- FHWA Safety Program[7]
- AASHTO Highway Safety Manual
- AASHTO Snow and Ice Cooperative Program (SICOP)[8]
- NOAA Surface Weather Program[9]
- OFCM Weather Information for Surface Transportation (WIST)[10]
- Aurora Program[11]
- Clear Roads[12]
- Enterprise Program[13]

Key DelDOT Safety Analysis Resources

- Snow Information - Delaware Department of Transportation[14]
- Snow Facts - Delaware Department of Transportation
- **DEOS Snow Monitoring System**[15]
- Delaware Primary and Secondary Snow Routes[16]
- Delaware Office of Highway Safety

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[2] https://nsidc.org/cryosphere/snow/removal.html
[3] http://www.trb.org/AH010/AH010.aspx
[4] https://sites.google.com/site/trbcommitteeahd65/Home/subcommittees
[5] http://www.erh.noaa.gov/phi
[6] http://www.nhtsa.gov/
[7] http://safety.fhwa.dot.gov
[8] http://sicop.transportation.org/Pages/default.aspx
[9] http://surfaceweather.noaa.gov/
[10] http://www.ofcm.gov/wg-wist/wg-wist-index.htm
[11] http://www.aurora-program.org/
[12] http://clearroads.org/
[13] http://www.enterprise.prog.org/
[14] http://www.deldot.gov/information/community_programs_and_services/snow_prnews/index.shtml
[15] http://www.deos.udel.edu/odd-divas/snow_current.php
[16] http://www.deldot.gov/information/community_programs_and_services/snow

- DelDOT Road Design Manual
- Crash Analysis and Reporting

Academia

- Iowa State University, Center for Weather Impacts on Mobility and Safety[17]
- University Corporation for Atmospheric Research[18]
- University of North Dakota, Surface Transportation Weather Research Center[19]

2.2 Existing numerical and analytical approaches for winter road maintenance

To a significant extent, previous research studies have examined the methods for determining correct snow plow fleet sizing (***Table 1***).

Table 1: Description of the methods an and key findings

Study	Key findings
Abdel-Malek, et al. (2014)	This paper considers various costs caused by under estimating and over estimating the needed snow plow fleet sizing for a forthcoming snow season.
Bertsimas, et al. (1996)	This paper surveys new developments of vehicle routing problems with an emphasis on the insights gained on the algorithms proposed.
Boselly, et al. (2005)	This research used the level of service (LOS) goals from a maintenance management system (MMS) to make recommendations for improving procedures and acquiring resources in order to attain the LOS goals.
Campbell, et al. (2000)	This research highlights the difficulty of the problems and the weaknesses of theoretical arc routing models for snow and ice control.
Carvalho & Powell (2000)	They proposed a multiplier adjustment method for dynamic resource allocation problem.
Cheung & Powell (1996)	This research compares a successive convex approximation approach with two alternative methods on a set of dynamic fleet management problems.
Decker, et al. (2001)	Databases and resulting winter maintenance efficiency metrics were developed in this study.

[17] http://www.intrans.iastate.edu/cwims/
[18] http://www2.ucar.edu/
[19] http://www.atmos.und.edu/

Eiselt, et al. (1995)	This paper provided a two-part survey of the main known results on arc routing problems.
Fiedrich, et al. (2000)	A mathematical model allowing for calculation of an optimized resource schedule assigning resources in space and time to the affected areas is presented in this paper.
Funke, et al. (2005)	This paper proposes approach to find a local best neighbor and to reach a local optimum as quickly as possible.
Gendreau, et al. (1992)	This paper describes a new insertion procedure and a new post optimization routine for vehicle routing problem.
Gendreau, et al. (1996)	This paper provides a summary of the scientific literature on stochastic vehicle routing problems.
Glover (1992)	This paper introduces new ejection chain strategies designed to generate neighborhoods of compound moves with attractive properties for vehicle routing problems.
Godfrey & Powell (2002)	This research considers a stochastic version of dynamic resource allocation problem.
Haghani & Qiao (2001)	This research develops a decision support system for assisting the Maryland State Highway Administration Office of Maintenance staff in designing efficient routes for salting trucks in snow emergencies.
Hajibabai, et al. (2014)	A mixed integer linear program model is proposed to minimize the total operation time of all snowplow trucks.
Hanna (2009)	This digest summarizes the findings regarding performance measures of snow and ice control operations.
Jones & Zydiak (1993)	This research develops models for determining optimal steady-state fleet designs.
Kallehauge, et al. (2005)	This document reviews the algorithms proposed in the last three decades for the solution of the vehicle routing problem.
Kuemmel (1994)	This document presents information on the state of the practice in managing roadway snow and ice control occurred during the past 20 years to improve winter maintenance.
Laporte (1992)	This paper surveys some of the main known results relative to the Vehicle Routing Problem.
Liu, et al. (2014)	This research uses a mathematical optimization model based on the capacitated arc routing problem (CARP) to derive snowplow routing strategies.

Lotan, et al. (1996)	In this paper, a combined location and routing two-stage framework for salt spreading tours analysis is suggested.
Marks & Stricker (1971)	A literature review and description of available methods of routing for public service vehicles is presented.
Maze, et al. (2008)	This research surveys snow and ice control organizations in the United States, Canada, Europe, and Asia to determine the current trends in performance measurement.
Nixon & Foster (1996)	Two surveys were conducted in this report to review current strategies to improve winter maintenance practices.
Noble, et al. (2006)	This report presents a systematic, heuristic-based optimization approach to solve the primary problems involved in the winter road maintenance planning procedure.
Pallottino & Scutella (1998)	This paper presents in a framework for solving the shortest path problems in the transportation field.
Perrier, et al. (2006)	These papers review optimization models and solution algorithms for spreading and plowing operations.
Perrier, et al. (2007)	This paper reviews optimization models and solution algorithms for the design of winter road maintenance systems for spreading and plowing operations.
Perrier, et al. (2007a, 2007b)	These papers review optimization models and solution algorithms for the design of winter road maintenance systems for spreading and plowing operations.
Perrier, et al. (2008)	This paper presents a model and two heuristic solution approaches for the problem of partitioning a road network into sectors and allocating sectors to snow disposal sites for snow disposal operations.
Pillac, et al. (2013)	This paper presents a comprehensive review of applications and solution methods for dynamic vehicle routing problems.
Powell & Carvalho, (1998)	This paper presents new algorithms for updating the control variables in the dynamic fleet management problem.
Powell (1986)	This research presents an empty freight car distribution problem, where known supplies of cars must be allocated to different classification yards to meet uncertain demands.
Powell (1987)	This paper describes an alternative model which can be used in a real-time environment for determining how to manage a fleet of vehicles under uncertainty.

Regan, et al. (1996)	This paper evaluates the performance of assignment strategies for fleet management.
Salazar-Aguilar, et al. (2012)	This paper introduces an arc routing problem for snow plowing operation.
Salazar-Aguilar, et al. (2012)	This paper introduces an arc routing problem for snow plowing operation.
Scott & Rudd (2012)	This report provides "best practices" to Delaware local governments on tackling the issue of winter pedestrian-accessibility issues.
Sisiopiku (2011)	This paper reviews potential applications of ITS technologies and products for winter maintenance.
Sochor & Yu (2014)	This report focuses on route optimization for snowplows after snowfall.
Sugumaran, et al. (2005)	This research implements a web-based Winter Maintenance Decision Support System (WMDSS to evaluate different procedures for managing snow removal assets optimally.
Wang, et al. (1995)	This research introduces a route design decision support system for maintenance engineers of the Indiana Department of Transportation (INDOT) to use in designing snow and ice control service routes.
Wilson, et al. (2003)	This research develops a simulation model of snowplow operations a conceptual design for a predictive maintenance system.
Wright (1988)	This report presents analytical procedure for performing route design and analysis.

2.3 Scan of state programs for roadway snow and ice control

Roadway snow and ice control is one of the most complex and fascinating venues for routing applications (Campbell & Langevin, 2000). The primary problems involved in winter road maintenance planning and operation procedure include defining a service level policy, locating depots and assigning arcs to sectors, routing service vehicles, scheduling vehicles, and configuring the vehicle fleet (Noble, et al., 2006). Over the years, a substantial body of research on various aspects of snow and ice control has been created, the majority of it focuses mainly on managing snow and ice operations during the winter months. The New York State Department of Transportation (NYSDOT 2012) developed a highway maintenance guideline for winter road maintenance. The Ohio DOT (2011) developed a guideline and classified road sections into three levels with different priorities for snow removal and deicing operations. The Missouri DOT (2011) developed a systematic, heuristic-based optimization approach to integrate the winter road maintenance planning decisions and used the historical data to develop a statewide map of weather condition during winter season associated with winter maintenance operation parameters (i.e., winter severity index, winter stability index, and winter instability index. New Jersey Department of Transportation (NJDOT) utilizes contractors for plowing and spreading services in cold climates. Arizona DOT (ADOT) used the level of service (LOS) goals to make recommendations for improving procedures and acquiring resources in order to attain the LOS goals. For more information see ***Table 3***.

2.4 Overview of DelDOT policies and programs

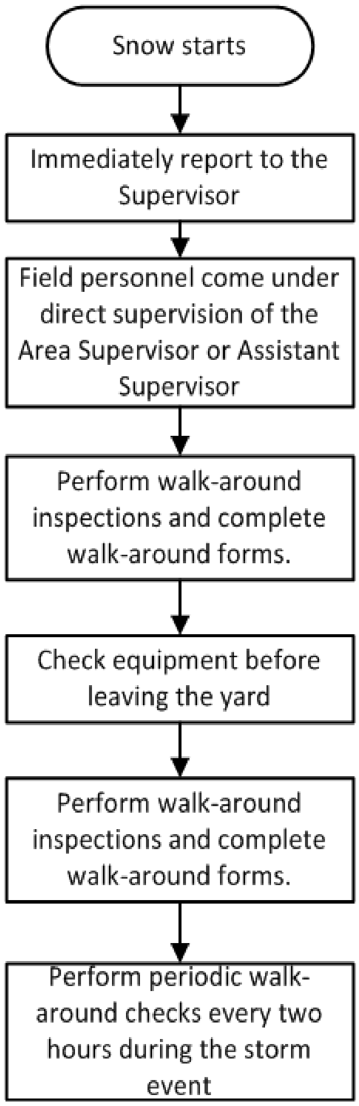


Figure 1: Standard Operating Procedure

2.5 A review of software developed for winter road maintenance

1. Service Autopilot[20]

This management software offers user-friendly interfaces designing to work on *mobile devices* for snowplow service companies. There are a lot of features in this software, which focus on how to provide convenience and improve profit for snowplow service companies. The inputs include service type, address, date, assigned crew, rate, and hours. The output is GPS tracking.

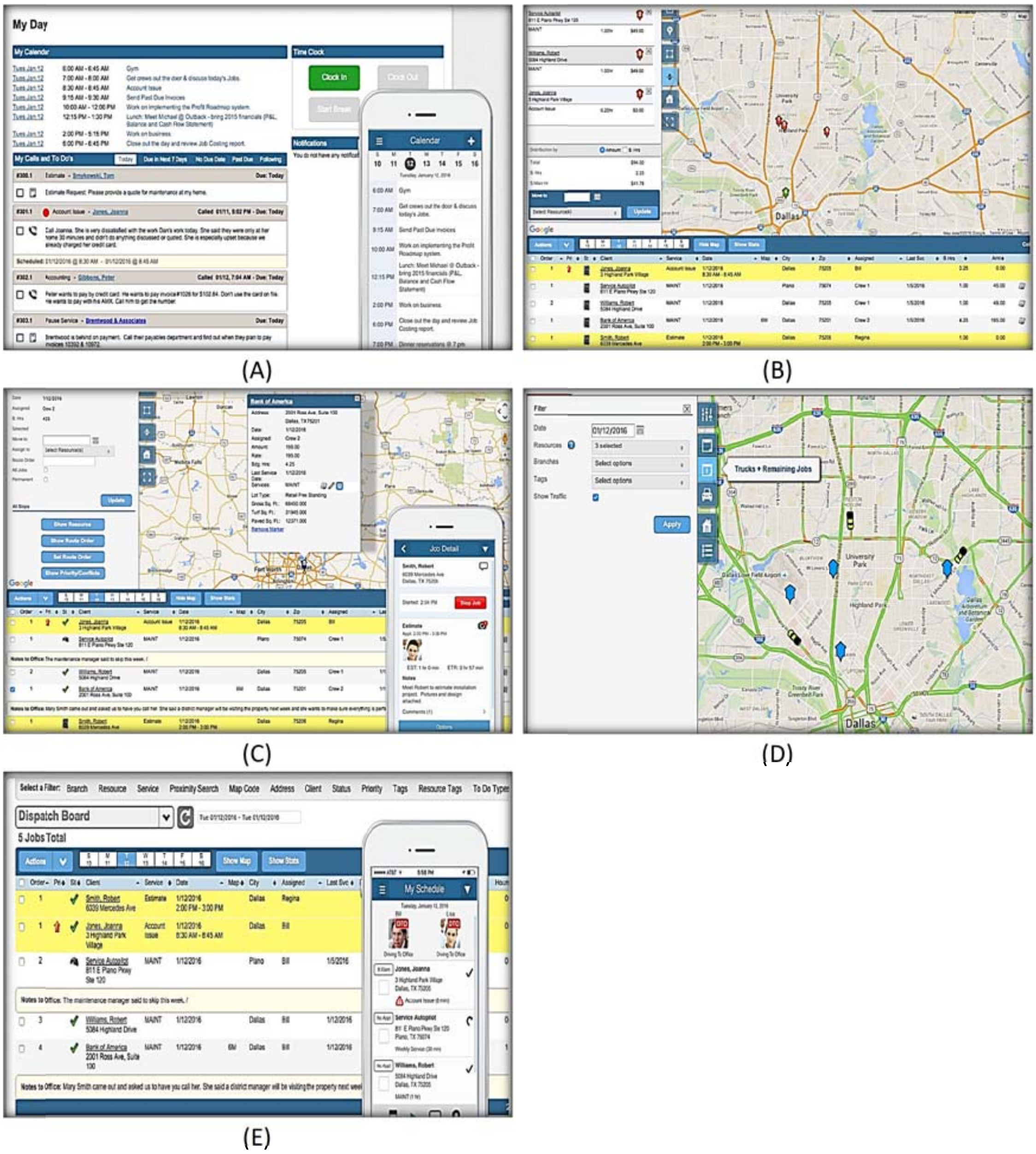


Figure 2: Screenshot illustration of Service Autopilot features

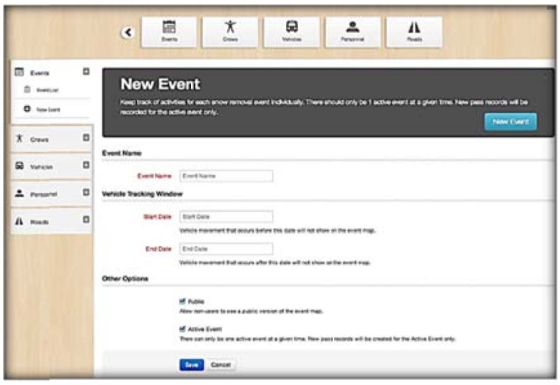
(A) Calendar, (B) Dispatch Crews, (C) Check the Process of Crews, (D) Move Job and (E) Verify Competed Jobs.

[20] https://www.serviceautopilot.com/snow-removal-software

There are a lot of features in this software, which focus on how to provide convenience and improve profit for snowplow service companies:

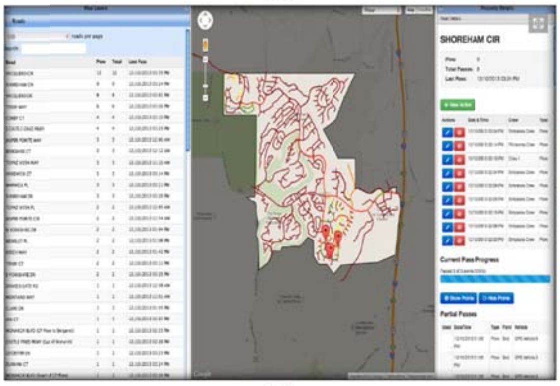
- Web-based
- Two Live 1-on-1 Custom Training Sessions
- Time Tracking & Time Cards
- Dashboards (graphs, charts, etc.)
- Task / To Do / Call Management
- Sales & Basic Marketing
- Email Tracking & Templates
- Advanced Estimating & Pricing System
- Job Costing & Analysis
- Asset Tracking (Installed Equipment)
- Knowledge Base (Wiki)
- Mobile GPS Tracking
- Automatic 2-Way QuickBooks Sync Option ($25/month)

2. Geo3o Snow Removal Tracking Software[21]



(A)

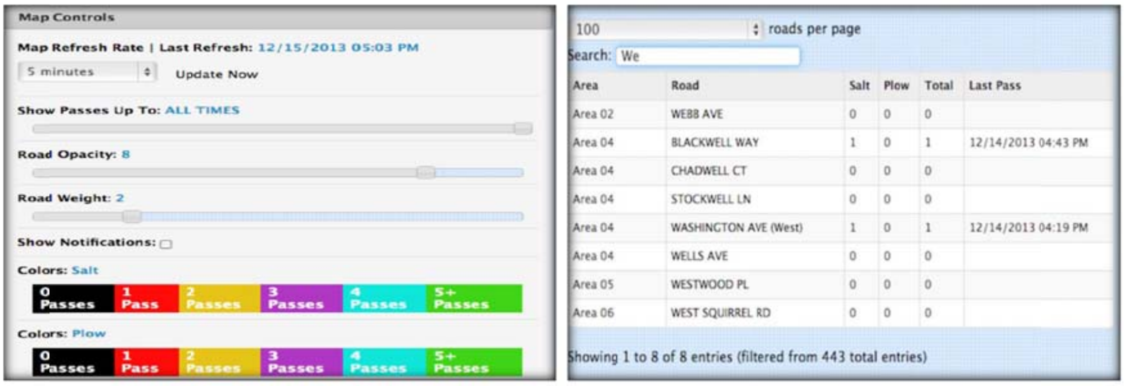
(B)



(C)

(D)

[21] http://geo3o.com/snow-removal/tracking-software/



(E) (F)

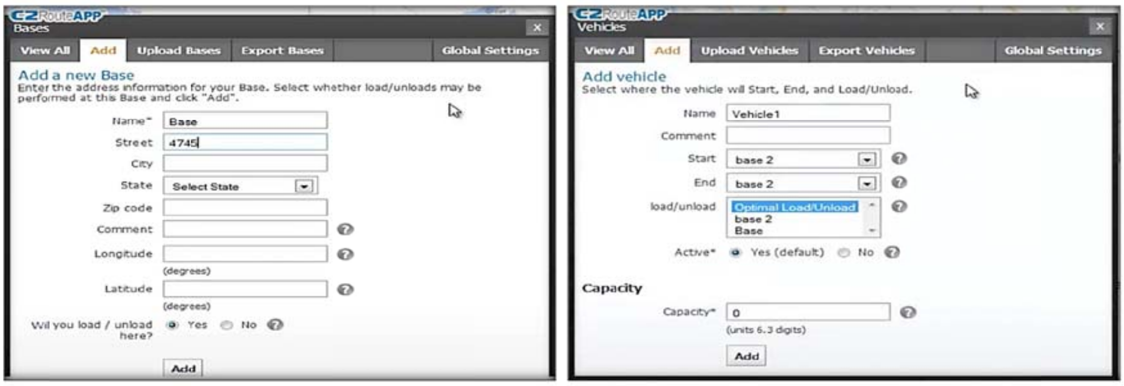
Figure 3: Screenshot illustration of Geo3o Snow Removal Tracking Software[22]

(A) Create Event, (B) Set Up Crews, (C) View an Event, (D) Satellite Map View of Tracking Activity (E) Map Setting and (F) Search.

The interface created in Geo3o provides a series of features to guide non-expert users in inputting the required information: Web-based

- Customize: "Many options are available to customize the application including road
- colors and action types (salt, plow, sand, etc)."
- GPS Enabled for Activity Tracking
- Alerts (road hazards, etc) can be created and displayed on map.
- Instant Search: "Search for roads instantly and see metrics like Last Pass Time, # of
- Plow Passes, Total Passes."

3. C2RouteApp[23]



(A) (B)

[22] http://geo3o.com/snow-removal/tracking-software
[23] http://www.c2logix.com
https://c2routeapp.com

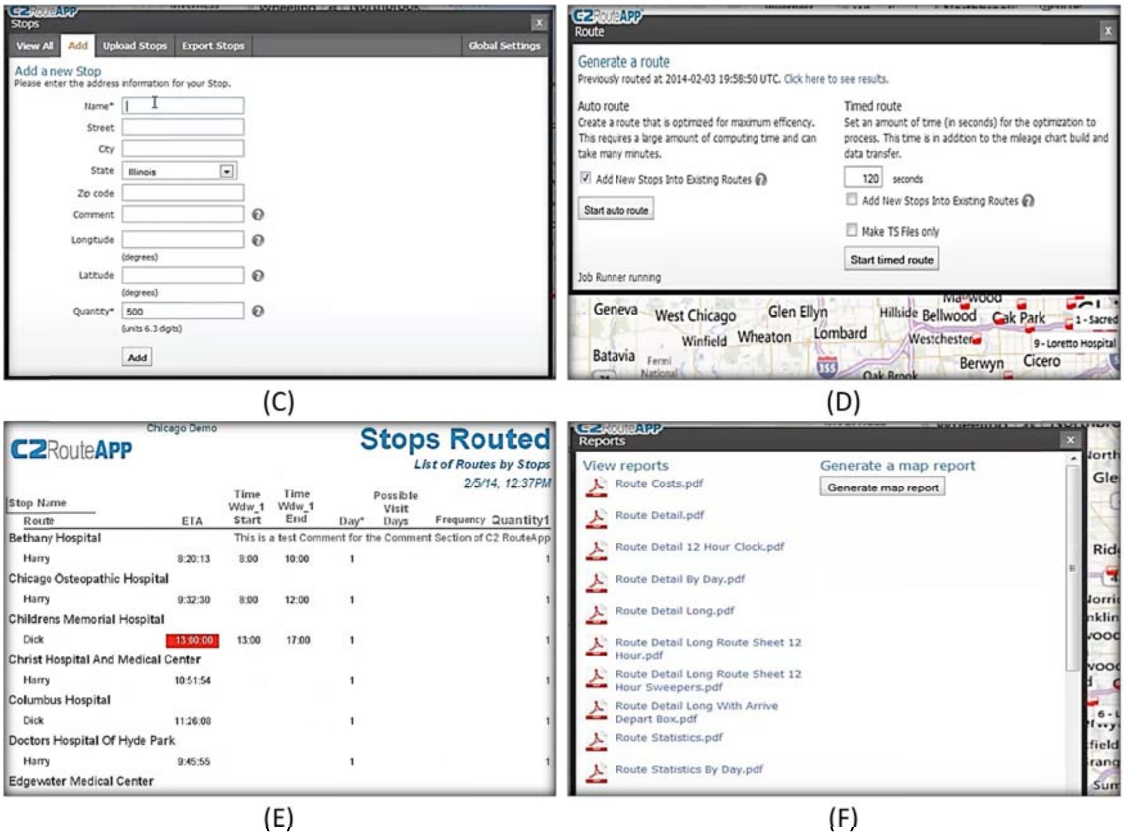


Figure 4: Screenshot illustration of C2RouteApp

(A) Add Bases, (B) Add Vehicles, (C) Add Stops, (D) Create Optimized Routes (E) Stops Routed Report and (F) View Reports.

C2RouteApp produces the following table and feature as output: turn-by-turn travel directions, export files to a gps device, route statistics reports, truck loading plans and detailed maps as described in ***Figure 4***.

4. Blizzard Buster

Blizzard Buster is desktop management software designed for snowplow service companies. It Include full features from managing customers to routing (***Figure 5***).

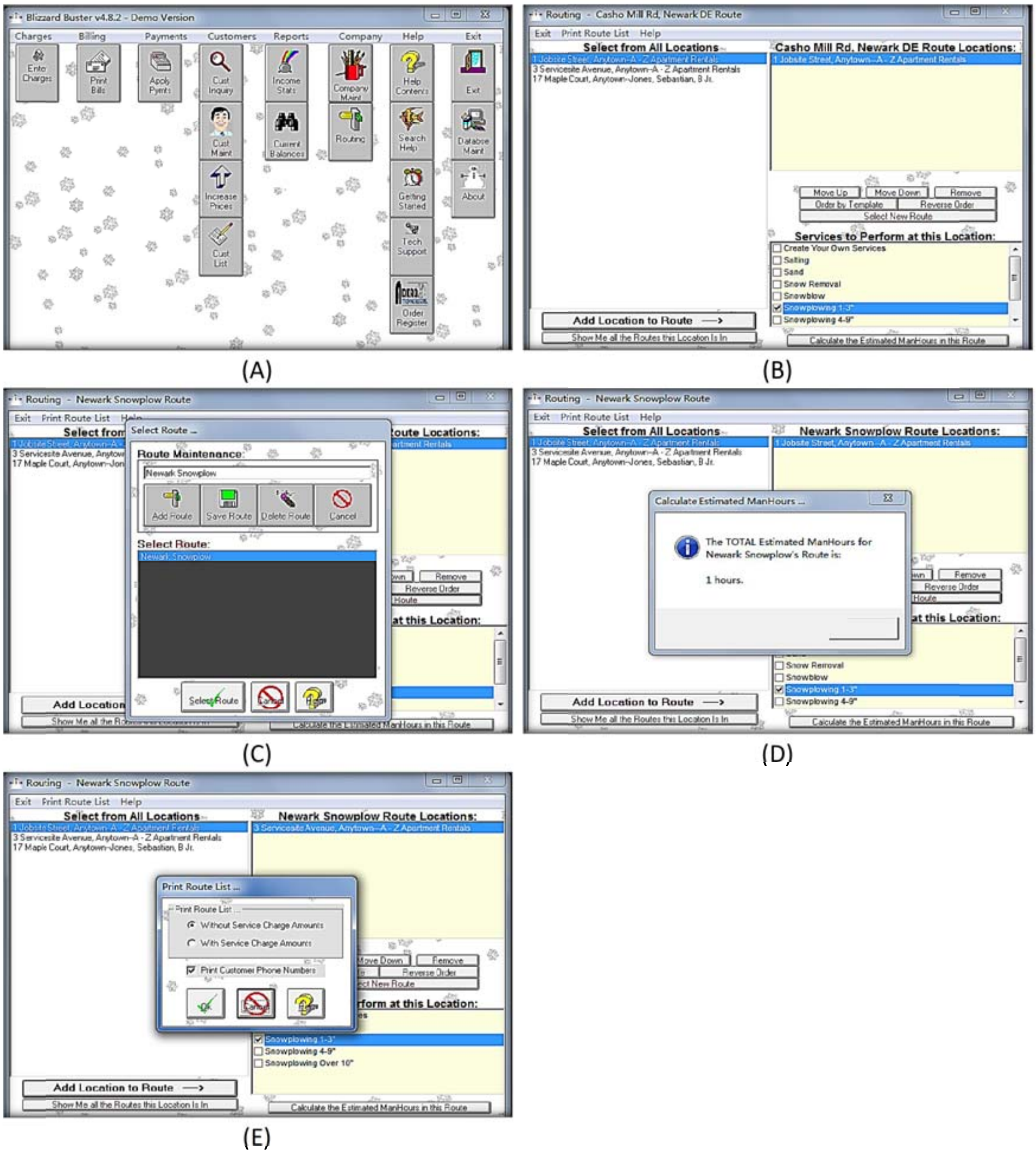


Figure 5.: Screenshot illustration of Blizzard Buster[24].

(A) Main Page, (B) Routing, (C) Add Route, (D) Calculate Estimated Hours and (E) Print Route List.

5. Jobber

Jobber Software offers the *following features*:

- GPS Tracking

[24] https://www.adkad.com/learn-more/learn-more-blizzard-buster.cfm

- Web-based
- Customer relationship management.
- Invocing
- Scheduling
- Team Management

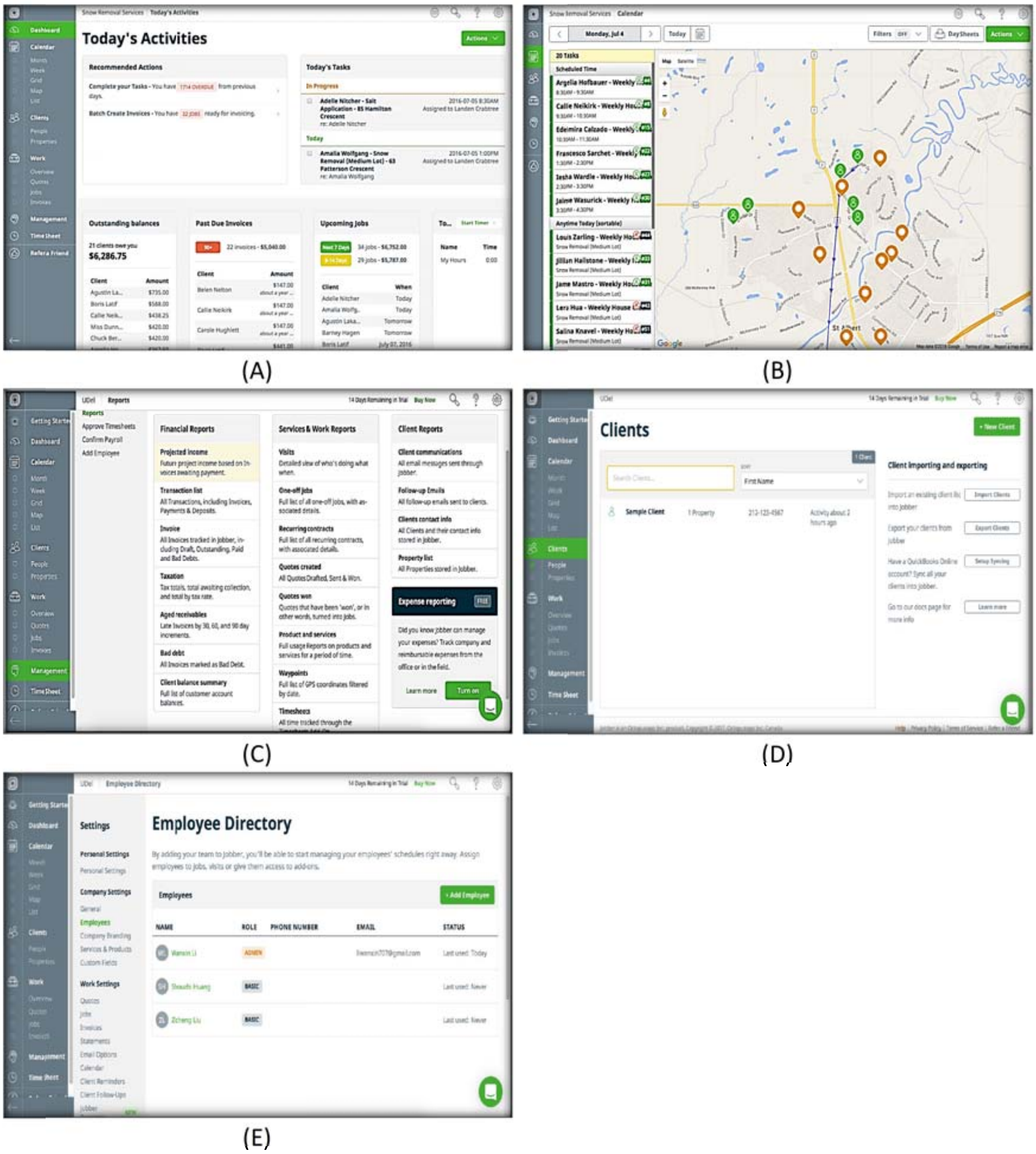


Figure 6: Screenshot illustration of Jobber[25]

(A) Dashboard, (B) Routing, (C) Management, (D) Clients and (E) Add employee.

[25] https://getjobber.com

3 METHODOLOGY

The goal of this research project is to develop a model for optimizing snow plow routing in order to be as effective as possible while meeting DelDOT's performance goals with the maximum efficiency: roadways clear and passable within 24 hours after the end of the snowfall when snowfall is less than 4 inches; between 4 and 8 inches, 48 hours; over 8 inches, 72 hours. The results will then be used by DelDOT to ensure that all primary road links are serviced and total operational costs are minimized.

3.1 Snow fact in Delaware

Snow Fact

- Approx. 45,000 Tons of Stored Salt in 20 stockpiles around the state
- On an average storm, 12,000 tons of salt used statewide
- 450 pieces of equipment
- 575 snow-fighting personnel (inc. volunteers)
- Over 13,450 lane miles maintained (not including subdivisions), 87%+ roads within the state.

(A) (B)

Figure 7: Salt stockpiles and equipment

(Photo taken on January 4, 2018 Smyrna, DE)

The DelDOT is able to track its plows on the interactive map on the agency's website or on its app available for Android devices and the iPhone during snow storms (***Figure 8*** **,** ***Figure 9***).

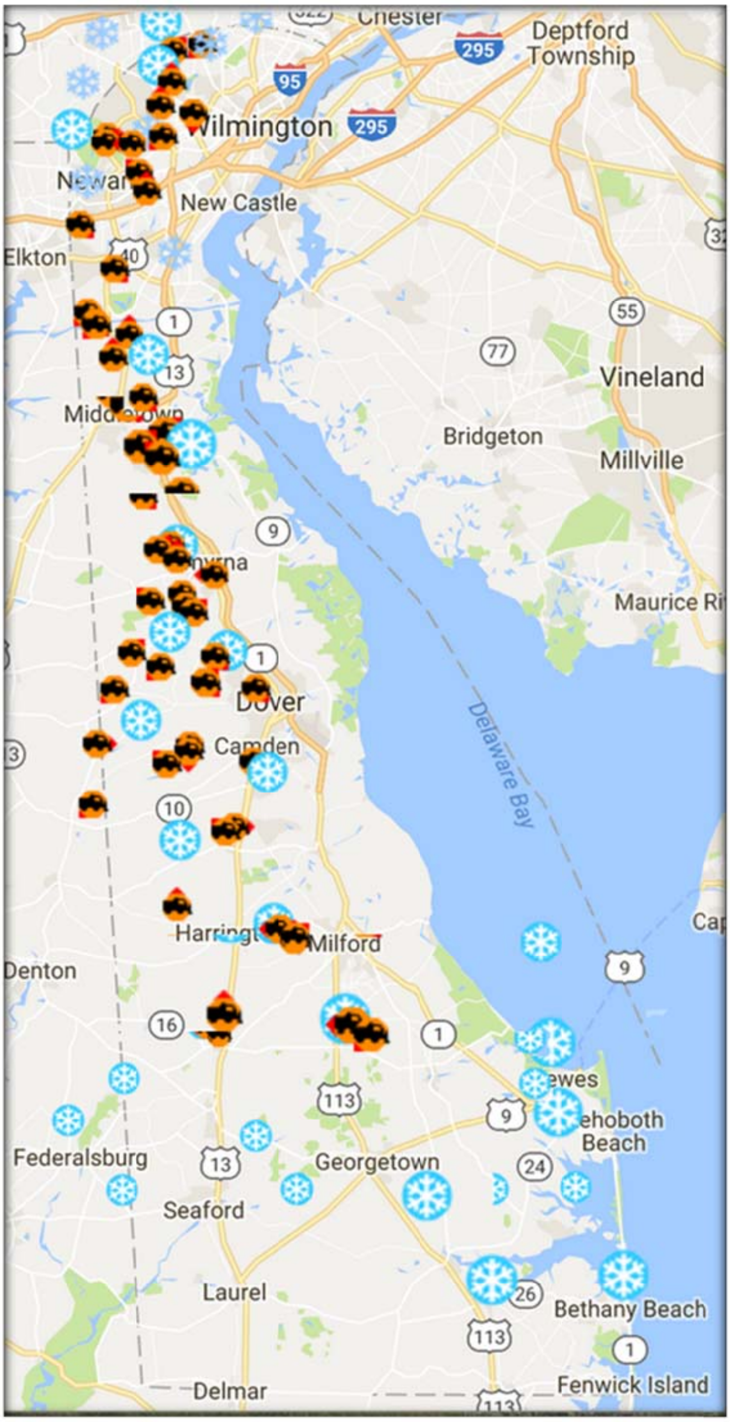


Figure 8: Screenshot illustration of snowplow tracking map
(03/21/2018 10:04 AM)

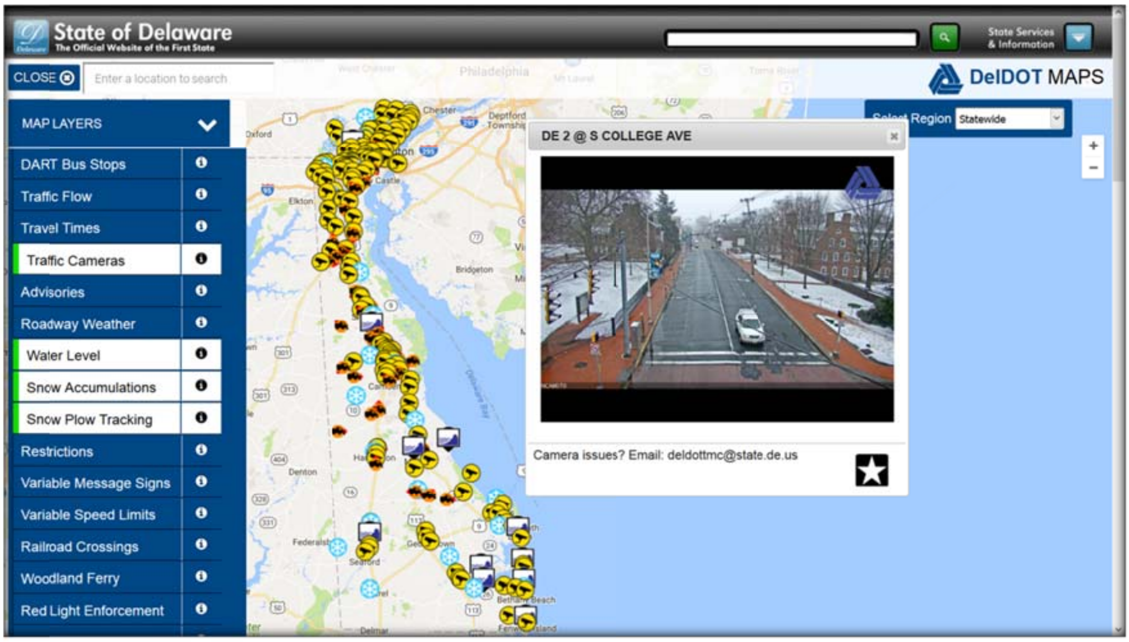


Figure 9: Screenshot illustration of snowplow tracking App interface
(03/21/2018 10.10 AM)

3.2 GIS-based snow plow route optimization

ArcGIS is one of the most widely used platforms with integrated collection of GIS software products. ArcMap, the main component of ArcGIS, has abundant sophisticated tools for spatial analysis, geographic data management and building maps. In addition, ArcGIS platform has a good scripting and model builder.

ArcMap Network Analyst provides network-based spatial analysis tools for solving complex routing problems. One of the essential functions of Network Analyst toolset is the Vehicle Routing Problem solver. The VRP solver's goal is to develop optimized routing solution by minimizing the overall operation cost for the fleets. The VRP solver is developed based on Tabu search metaheuristic. It's a method for mathematic optimization. The structure of the GIS-based snow plow route optimization method is described as a flowchart in ***Figure 10***. For more information, see ***Appendix D***: GIS-based network analyst and snow plowing route optimization tutorial.

A basic vehicle routing problem (VRP) usually presents a node-to-node routing problem, but our snow plow routing problem is a network covering problem. To convert snow plow routing problem to a basic VRP, some elements are added to the network.

Before solving snow plow routing problem with VRP solver, some preprocessing are needed for establishing a proper GIS map, such as road classification, number of lanes, alignment correcting intersection modification, etc.

Based on the DelDOT Snow Book, the snow plow classification information has been added to GIS map's attribute table as a new field.

- Interstates – I-95, I-295, I-495
- Primaries (or Arterials) – SR 1, 7, 13, 40, etc.
- Secondaries – Harvey Rd, Pine Tree Rd, Hazelville Rd, Roxana Rd (SR 17), etc.

- Locals – Snuff Mill Road, Blue Jay Ln, Salt Barn Rd, etc.
- Subdivisions – Not in reimbursement program

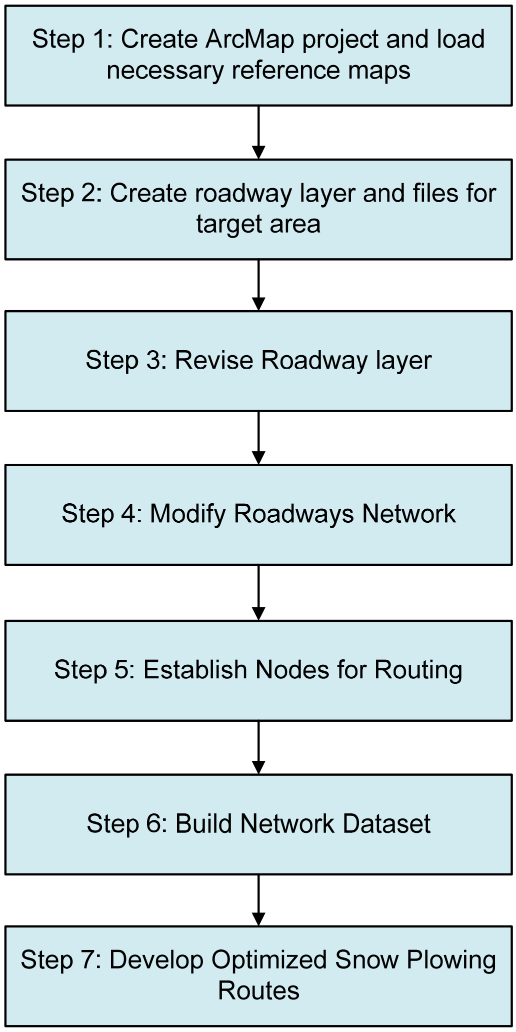


Figure 10: Flow chart for GIS-based snow plow route optimization

After network modification, the next critical step is inserting and processing necessary data and information.

- Length Measurement (Using build-in tools to measure the length of each segment; Equidistance coordinate system);
- Travel Time Calculation (Travel Time = Length / Speed Limit);
- Direction information (One-way or Two-way; “FT”, Blank).

After new point layers are created, the nodes were added for every segment (a lane that linking two intersections is one segment). Each segment has at least one node. Since the vehicles are only allowed to make turns at intersections and dead-ends, if the node(s) along a segment is (are) visited, the segment is at least covered by one snow plowing route (***Figure 11***).

Figure 11: Modified segments with nodes added

According to the Snow Book, there are two major models of snow removal trucks – 6-wheelers and 10-wheelers.To solve the routing problem, for several sectors, tests were taken within two scenarios. Results are recorded in the final report. For the first scenario, the size of truck was ignored; there was no limitation for 10-wheelers to access lower-class roadways. In the second scenario, the size of truck mattered. 10-wheelers only served primary and secondary roadways.

For example, according to Snow Book, there are three 6-wheelers and two 10-wheelers serving Area 5, Sector D. As mentioned, in the first scenario, both 6-wheelers and 10-wheelers could be assigned to serve low-class roadways; in the second scenario, only 6 wheelers can serve low-class roadways (***Figure 12***).

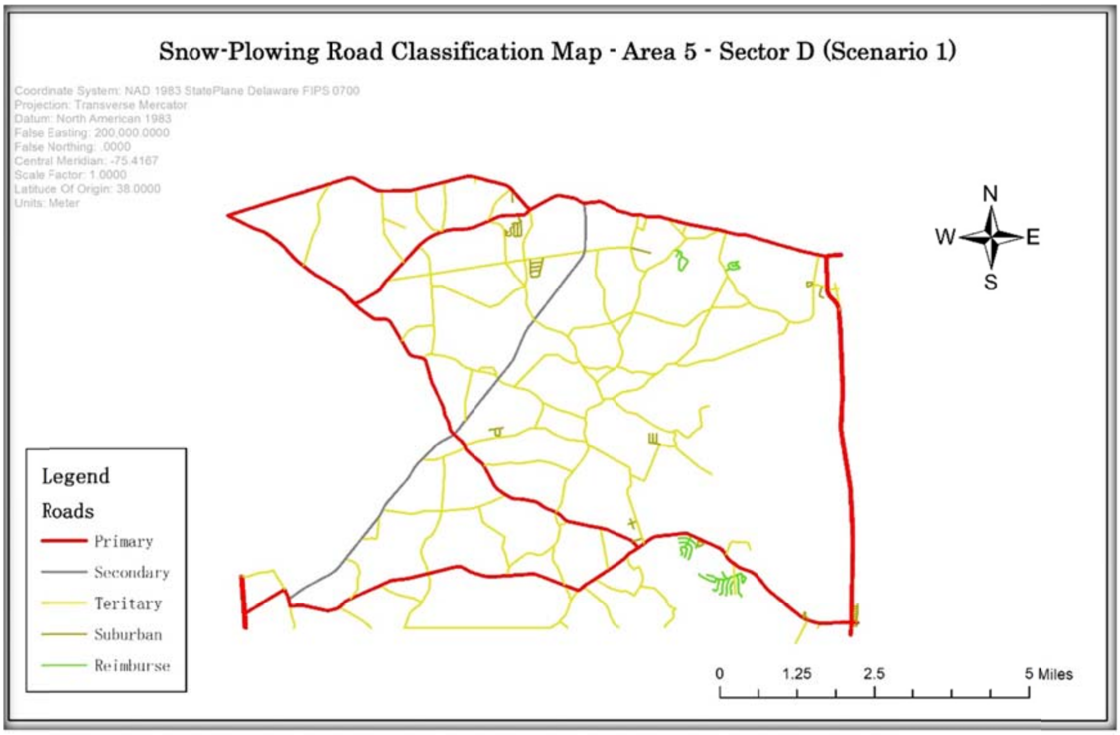


Figure 12: Example for scenario 1

The following table shows the comparison of the test results for two scenarios. As shown, the access limitation under scenario 2 causes increasing on all statistics. But the total travel time increase is less than 10%; Because of the access limitation, the location of the depots and the proportion of lower-class roadways in network, the trucks might spend more time on necessary trips.

Table 2: Example for scenario 2

Travel Time (Minutes)		
Vehicle	Scenario	
	1	2
1	124.90	100.61
2	95.94	101.31
3	125.88	123.49
4	103.08	152.61
5	128.16	140.30
Sum	577.96	618.32
Min	95.94	100.61
Max	128.16	152.61
Standard Deviation	13.3655	20.7163

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The purpose of this study is to assist DelDOT in determining whether they are appropriately managing their snow and ice removal resources and applying engineering best practices. Specifically, the goal of this research is to develop a GIS-based approach for optimizing snow plow routing in order to minimize the total snow plow truck travel distance and travel times.

GIS-based analyses were conducted to not only derive snowplow routing strategies using the proposed methodology, but also draw useful conclusions for winter road maintenance agencies. The research team summarized the results of tasks above, and incorporated the resultant insights and findings into a final report, which will describe how to apply various modeling tools for snow plow route optimization analysis.

The GIS-based method provides a visually based route optimization tool that may be utilized by DelDOT highway maintenance personnel who perform snow and ice control activities. The GIS data and maps are processed for running routing solution. The model is able to create optimized snow plow routes for three counties in Delaware, as well as provide the total cycle times for completing each route. The method is examined repeatedly for different areas under different scenarios. A tutorial is accomplished for instruction.

4.2 Directions for Future Work

In this research, we have presents a route optimization model created for the snow plow routes maintained by the DelDOT. The future recommendation for Roadway snow and ice control operation may include how to assist DelDOT in determining whether they are appropriately managing their snow and ice removal resources and applying engineering best practices. Specifically, what is the correct size and composition of the DelDOT snow plow fleet for snow removal operations? Data collection and categorization will be conducted by means of an Excel spreadsheet to model the weather forecast data and information, pre-assigned vehicles, fleet size, service level and service routes. The input information, in turn, generates the output consisting of delays and costs associated with a given scenario. The analysis will evaluate DelDOT's snow plow fleet size to determine an optimal size while still being able to effectively meet performance goals. Additionally, a sensitivity analysis will be performed to evaluate the impact of model parameters on the optimum solution.

It is noteworthy to mention that snowplow operations involve more than simply sending out a fleet of snowplows when snow begins to accumulate at a depth of one inch or more on the street surface. Vehicle routing and scheduling problems require that a fleet of vehicles serves a number of requests in order to minimize operational costs. A recent literature review was performed. The research presented here faces the following challenging questions:

- What is the correct size of the DelDOT snow plow fleet for snow removal operations?

- What the correct composition is of the snow plow fleet?
- What numbers of each class of truck should be operational for a given desired level of service?

These questions and more should be considered in the future design of an effective strategy for conducting winter road maintenance. The goal of this research project is to evaluate DelDOT's snow plow fleet size to determine an optimal size while still being able to effectively meet performance goals. This project will developed a methodology for efficient deployment of available crew, estimation of workforce requirements, and economic evaluation of the impact of using contract employees and split shifts.

In order to achieve these goals, a fundamental question that needed to be addressed first was the determination of the amount of work induced by different types of storms that occur in Delaware. The purpose of this study is to assist DelDOT in determining whether they are appropriately managing their snow and ice removal resources and applying engineering best practices. To achieve this objective, this project will:

- Analyze relevant snow storm data from a variety of weather reporting sources.
- Tabulate average snowfall for the DelDOT with an inventory of equipment and man power available to address the problems generated by the average snowstorm.
- Consider what can or should be done to prepare for exceptional circumstances and analyze whether or not the DelDOT are appropriately, under-, or over-prepared in being able to manage crisis level snow removal.
- Provide a basis that can potentially assist DelDOT and other agencies in determining whether they are correctly or under managing their winter resources.

The structure of the proposed framework and algorithms solved using a branch-and-bound method is described as a flowchart in ***Figure 13*****.**

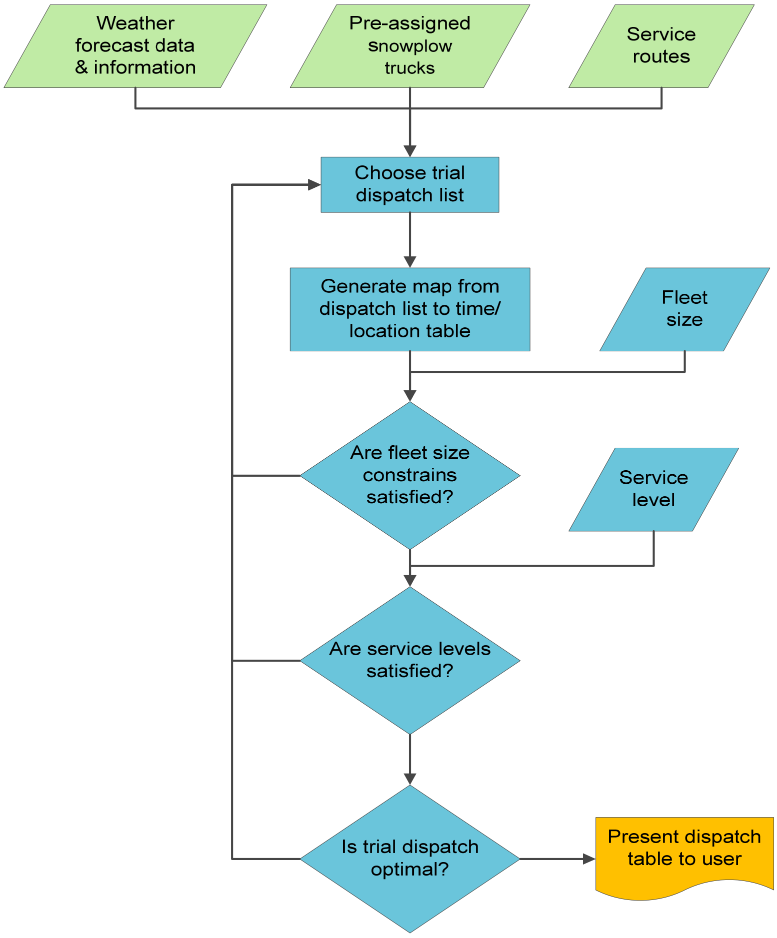


Figure 13: Proposed framework for determining the optimal size of the DelDOT snow plow fleet

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APPENDICES

Appendix A: Snow and ice removal studies by the state DOTs

Table 3: Snow and ice removal by various states

State DOTs	Title of Documents	Year	Link
ADOT&PF	▪ Winter Road Maintenance Priority Map ▪ Winter Road Maintenance Priority Map ▪ Highway Winter Maintenance Schedule ▪ Emerging Practices in Winter Highway Maintenance	2018	http://dot.alaska.gov/stwdmno/wintermap/
ADOT	▪ Procedures for Winter Storm Maintenance Operations ▪ Winter Storm Management Operations Manual	2005/ 2014	https://apps.azdot.gov/ADOTLibrary/publications/project_reports/PDF/AZ461.pdf https://www.azdot.gov/docs/default-source/environmental-planning-library/wsm-of-az-state-highways-september-2014.pdf?sfvrsn=2
AHTD	Maintenance Supervisor's Manual	2015	https://www.arkansashighways.com/maintenance_division/Maintenance_Supervisors_Manual.pdf
Caltrans	Snow Removal Operations And General Information	2009	http://www.dot.ca.gov/dist3/departments/mtce/documents/SnowRemovalOps.pdf
CDOT	Snow Route Optimization	2016	https://www.codot.gov/programs/research/pdfs/2016-research-reports/snow-route-optimization
CONNDOT	Connecticut's Winter Operations Winter Highway Maintenance Operations: Connecticut	2005 2015	https://www.t2center.uconn.edu/pdfs/Winter%20RoundtableCompleteReport.pdf https://www.ctcase.org/reports/WinterHighway2015/winter-highway-2015.pdf
DELDOT	South District Emergency Operations Manual	2017	N/A
GDOT	Georgia DOT Winter Weather Preparedness	2013	http://www.dot.ga.gov/PartnerSmart/Public/PressReleases/Georgia%20DOT%20Winter%20Weather%20Preparedness%2012-16-2013.pdf#search=snowplow%2A

State DOTs	Title of Documents	Year	Link
ITD	Idaho DOT Anti-Icing/Deicing Operations		https://ops.fhwa.dot.gov/weather/Publications/Case%20Studies/07.pdf
IDOT	Snowfighter's Handbook	2007	https://www.google.com/url?q=https://idot.illinois.gov/Assets/uploads/files/Transportation-System/Manuals-Guides-%26-Handbooks/T2/L026%2520The%2520Snowfighters%2520Handbook.pdf&sa=U&ved=0ahUKEwjHuqGevtPaAhWqUt8KHSo3B-gQFggGMAE&client=internal-uds-cse&cx=001777681116861149309:quxgcrlpktu&usg=AOvVaw3Qyfp-0WKqIDCCSfAGyga9
INDOT	Annual Winter Maintenance Report INDOT Plowing Procedures	2013	**https://in.gov/indot/files/FY13WinterMaintenanceReport.pdf** **https://www.in.gov/indot/3222.htm**
Iowa DOT	Snow removal operations	N/A	https://iowadot.gov/maintenance/winter-operations/snow-removal-operations
KDOT	Managing Snow and Ice - KDOT	2007	https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjI8sfswNPaAhUP02MKHcTPDMYQFggpMAA&url=https%3A%2F%2Fwww.ksdot.org%2FPDF_Files%2FSnowandIceEfforts.pdf&usg=AOvVaw3GZue2KYRmr5KPqQdHXPEe
KYTC	Snow and Ice - Knowing your salts	N/A	https://transportation.ky.gov/DistrictEleven/Pages/Snow-and-Ice---Knowing-your-salts.aspx
MaineDOT	Maine Environmental Best Management Practices (BMP) Manual for Snow and Ice Control	2015	http://maine.gov/mdot/csdold/mlrc/documents/2015-08-17-June2015FINALversion.pdf
MassDOT	Snow And Ice Control Policy	2015	https://www.townofmilton.org/department-public-works/files/snow-and-ice-control-policy
MDOT	Michigan Winter Maintenance Manual Promoting Safe Roads and Clean Water	2012	http://miwintermaintenance.weebly.com/uploads/1/7/1/6/17161926/mi_winter_maintenance_manual_2

State DOTs	Title of Documents	Year	Link
			013.pdf
Mn/DOT	Mn/DOT Anti-Icing Guide	2010	**https://www.dot.state.mn.us/maintenance/pdf/research/AntiIcingGuide8Full.pdf**
MoDOT	Snow and Ice Control Operations	2015	**http://epg.modot.mo.gov/index.php?title=133.4_Snow_and_Ice_Control_Operations**
MDT	Maintenance Manual, Chapter 9 - Winter Maintenance	2009	http://www.mdt.mt.gov/publications/manuals/maint_manual.shtml
NDOT	Winter Maintenance Improvements	2008	https://www.nevadadot.com/doing-business/about-ndot/ndot-divisions/planning/research/research-reports
NHDOT	Highway Maintenance	2015	https://www.nh.gov/dot/org/operations/highwaymaintenance/index.htm
NJDOT	NJDOT WINTER OPERATIONS	2015	http://www.state.nj.us/transportation/about/winter/pdf/snowremovalcontractproposal2015.pdf
NMDOT	Winter Maintenance Guide	2014	http://dot.state.nm.us/content/dam/intrans/hwyops/go/2014_2015WinterMaintGuide.pdf
NYSDOT	Control of Blowing Snow using SnowMan (Snow Management)	2008	https://www.dot.ny.gov/divisions/engineering/technical-services/trans-r-and-d-repository/C-01-67_user%20manual.pdf
NCDOT	Severe Weather - Winter Storms	N/A	https://www.ncdot.gov/travel/severeweather/winter.html
NDDOT	Snow and Ice Control	N/A	http://www.dot.nd.gov/divisions/maintenance/snow-ice-control.htm
ODOT	Snow & Ice Practices - Ohio Department of Transportation	2011	https://www.dot.state.oh.us/Divisions/Operations/Maintenance/SnowandIce/Snow%20and%20Ice%20Best%20Practices/ODOT%20Snow%20and%20Ice%20Practices%20March%202011.pdf
ODOT	ODOT Winter Salt Pilot Project	2017	http://www.oregon.gov/ODOT/Maintenance/Documents/2017%20annual%20salt%20report.pdf

State DOTs	Title of Documents	Year	Link
PennDOT	Winter Operations & Safety - PennDOT	2016	http://www.penndot.gov/Documents/DOTcom/DOTcomNov16.pdf
SDDOT	South Dakota Winter Highway Maintenance Plan	2017	http://www.sddot.com/resources/manuals/WinterMaintPlan20172018.pdf
TxDOT	Snow and Ice Control Operations Manual (SIC)	2017	http://onlinemanuals.txdot.gov/txdotmanuals/sic/sic.pdf
UDOT	Snowplow Operator Driving Time	2016	https://www.udot.utah.gov/main/uconowner.gf?n=30088028310434736
VTrans	Snow and Ice Control Plan Winter Service Guide Tow Plow Training Manual	2013 2013 2012	http://vtrans.vermont.gov/sites/aot/files/operations/documents/AOT-OPS_SnowAndIceControlPlan.pdf http://vtrans.vermont.gov/sites/aot/files/operations/documents/AOT-OPS_Winter_Services_Guide.pdf http://vtrans.vermont.gov/sites/aot/files/vttc/documents/Tow_Plow_Manual.pdf
VDOT	VDOT and Emergency Response	2017	http://www.virginiadot.org/about/emer_response.asp
WSDOT	Snow and Ice Control	2017	http://www.wsdot.wa.gov/publications/manuals/fulltext/M51-01/Chapter7.pdf
WVDOT	Statewide Snow Removal & Ice Control	2018	https://transportation.wv.gov/winterdriving/Pages/Downloads.aspx
WisDOT	2016-2017 Annual Winter Maintenance Report	2017	http://wisconsindot.gov/Documents/doing-bus/local-gov/hwy-mnt/winter-maintenance/workers/2016-2017annualreport.pdf
WYDOT	Winter Wheelin	2011	http://www.dot.state.wy.us/files/live/sites/wydot/files/shared/Public%20Affairs/Winter%20Wheelin'.pdf

Appendix B: Optimized routes

Sector Maps

Following maps present the snow-plowing classification maps for all sectors within Delaware's South District of snow-plowing program. There are 5 snow-plowing roads classifications. They are "Primary", "Secondary", "Tertiary", "Suburban" and "Reimburse".

Table 4: List of the snow-plowing classification maps

Area 1	Sector A
	Sector B
	Sector C
	Sector D
Area 2	Sector A
	Sector B
	Sector C
	Sector D
Area 3	Sector A
	Sector B
	Sector C
	Sector D
	Sector E
Area 4	Sector A
	Sector B
	Sector C
	Sector D
Area 5	Sector A
	Sector B
	Sector C
	Sector D

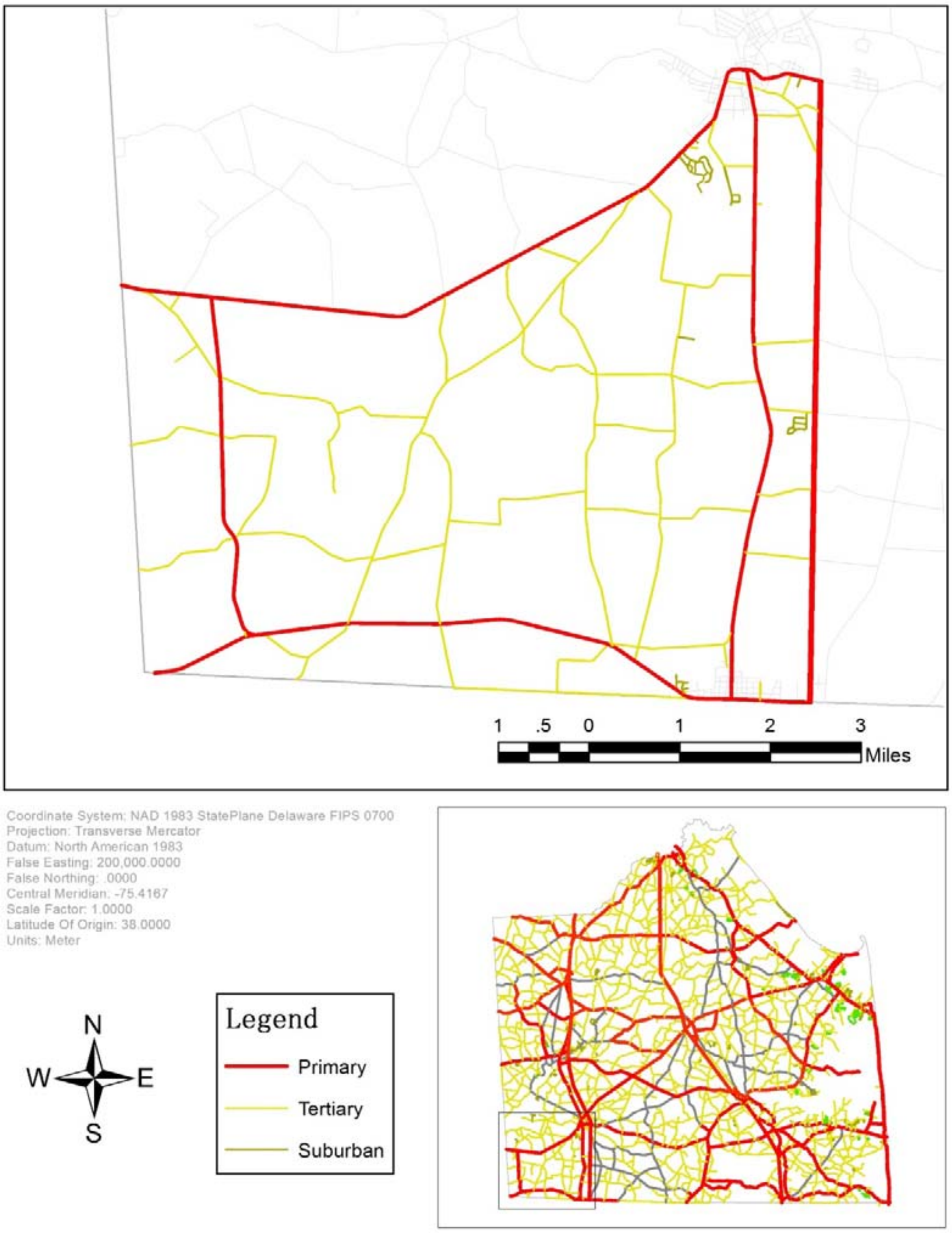

Figure 14: Snow Plow Roads Classification Map – Area 1, Sector A

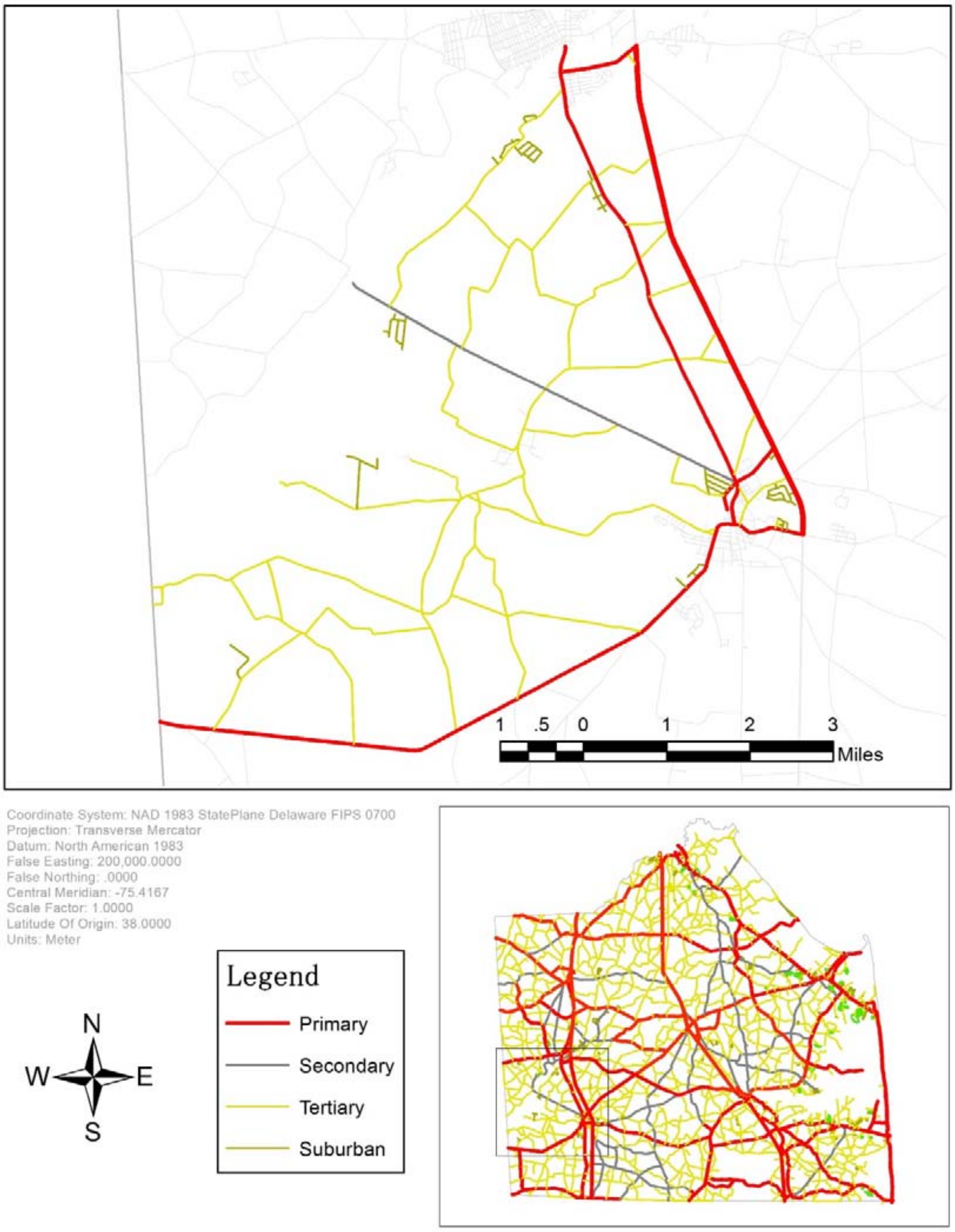

Figure 15: Snow Plow Roads Classification Map – Area 1, Sector B

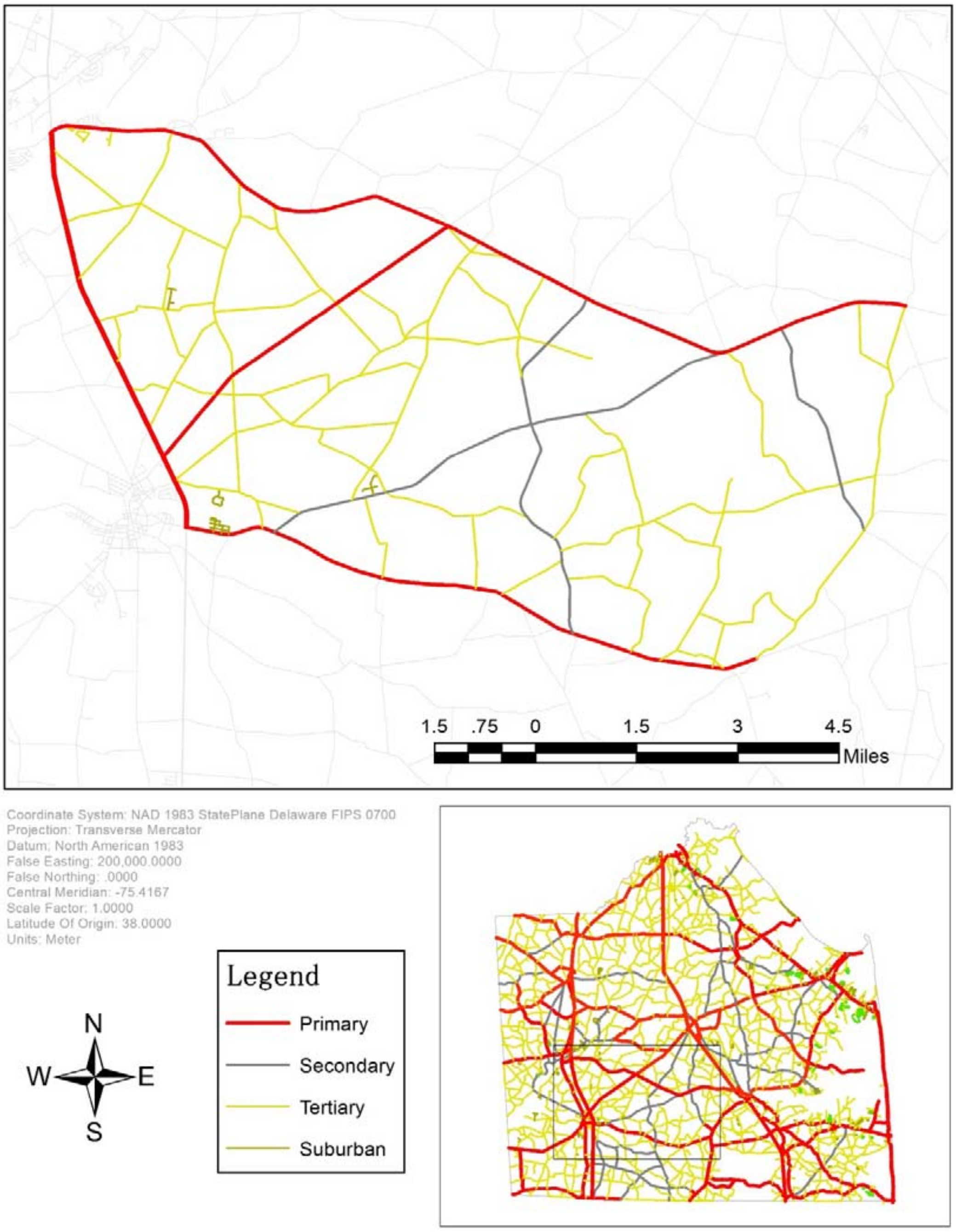

Figure 16: Snow Plow Roads Classification Map – Area 1, Sector C

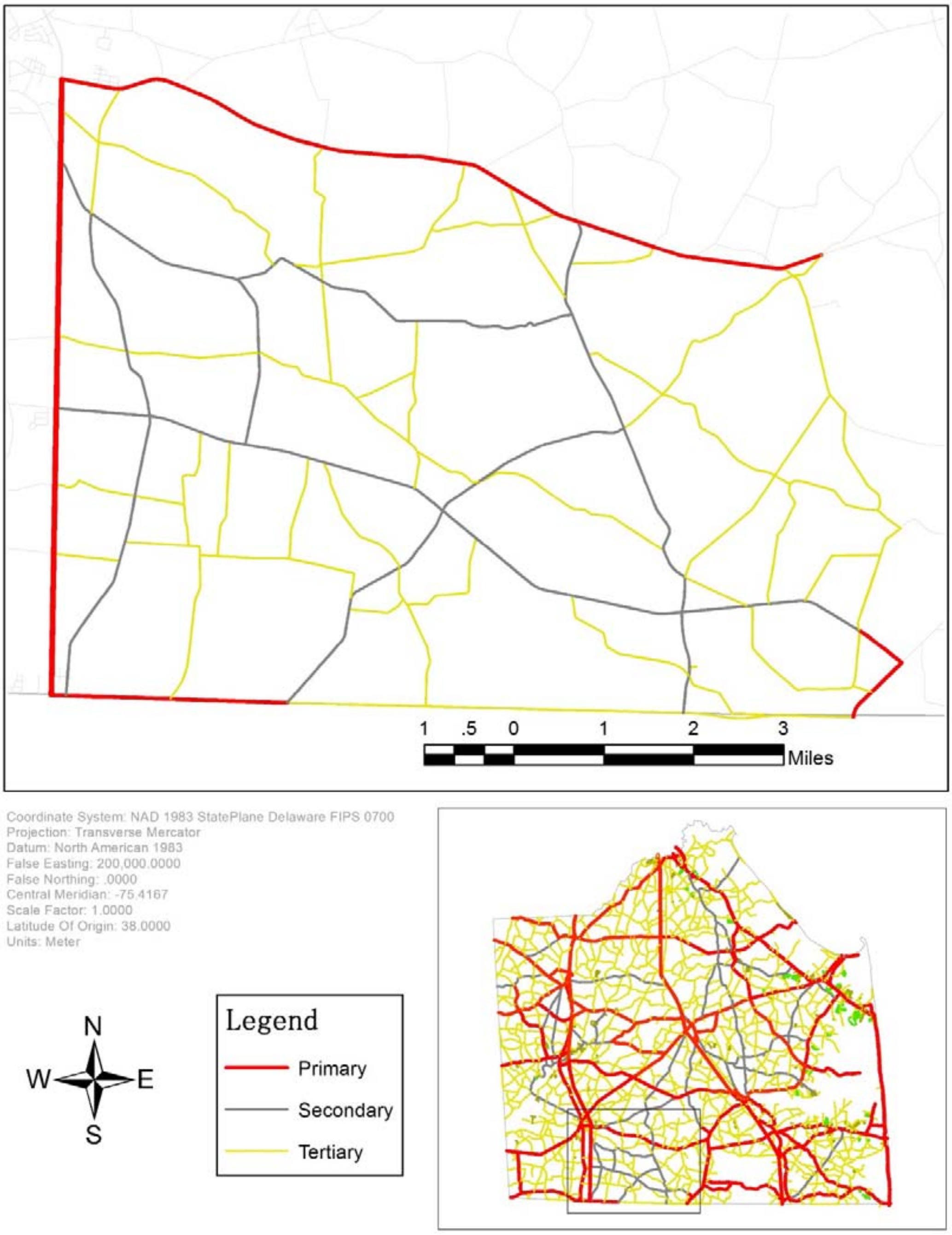

Figure 17: Snow Plow Roads Classification Map – Area 1, Sector D

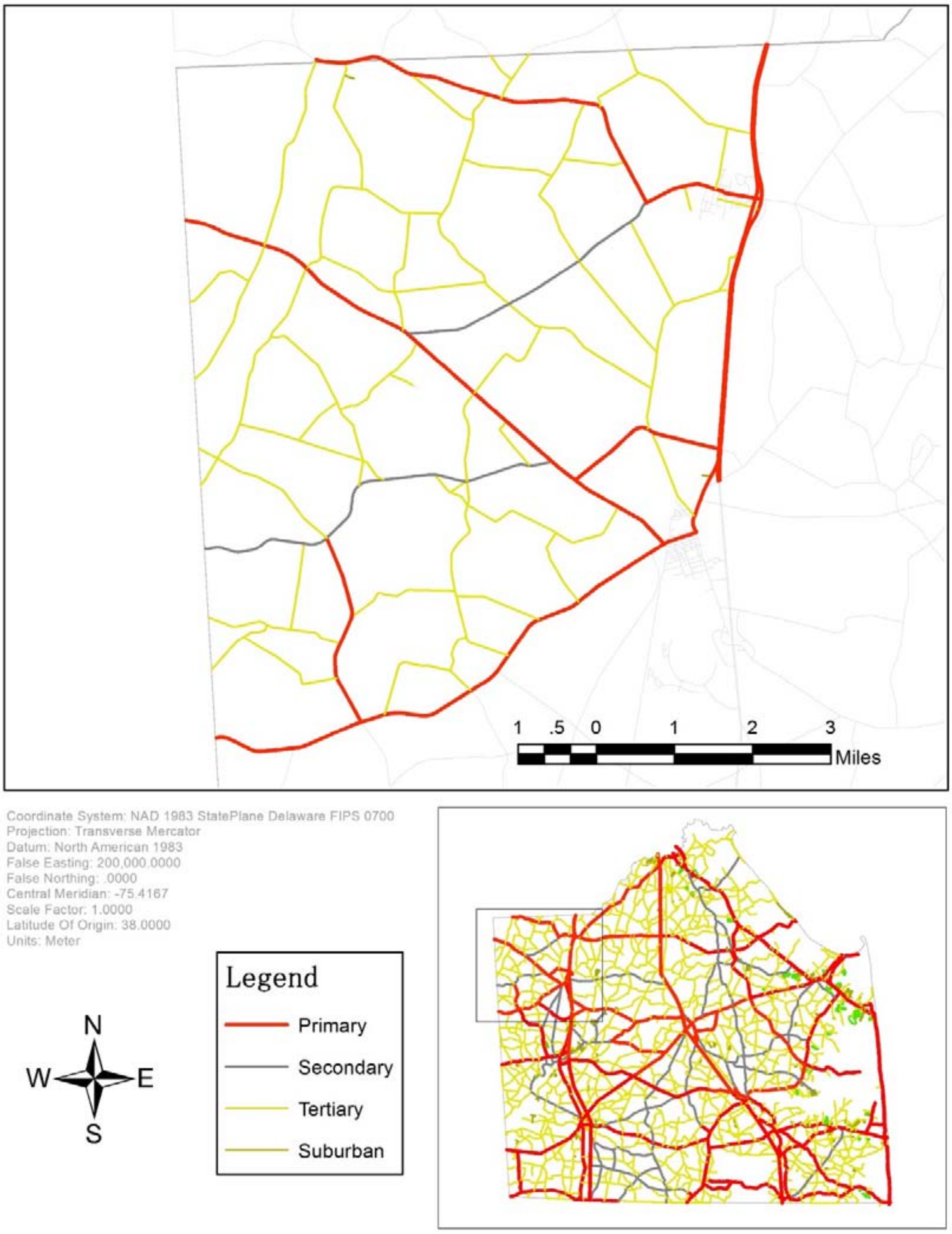

Figure 18: Snow Plow Roads Classification Map – Area 2, Sector A

Figure 19: Snow Plow Roads Classification Map – Area 2, Sector B

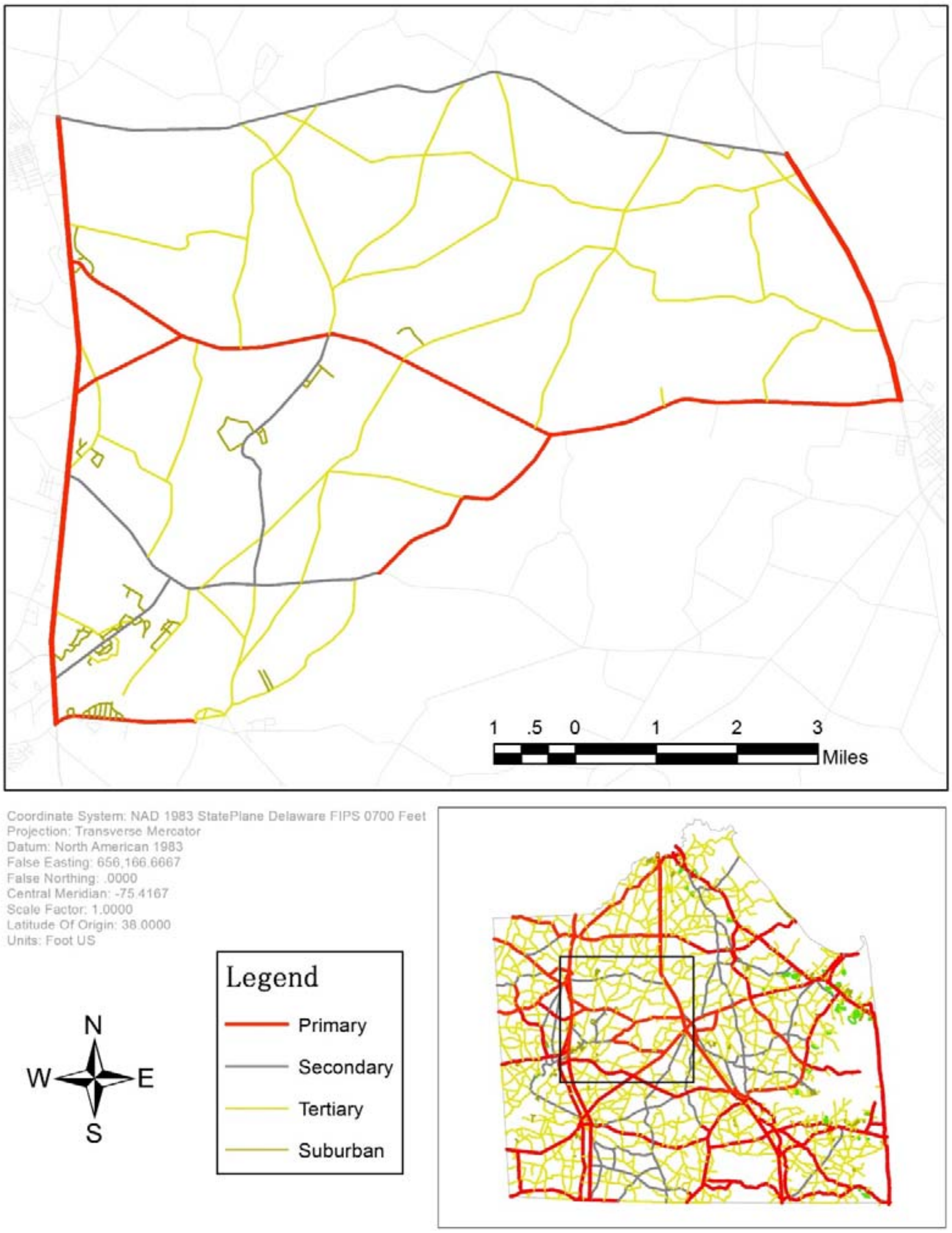

Figure 20: Snow Plow Roads Classification Map – Area 2, Sector C

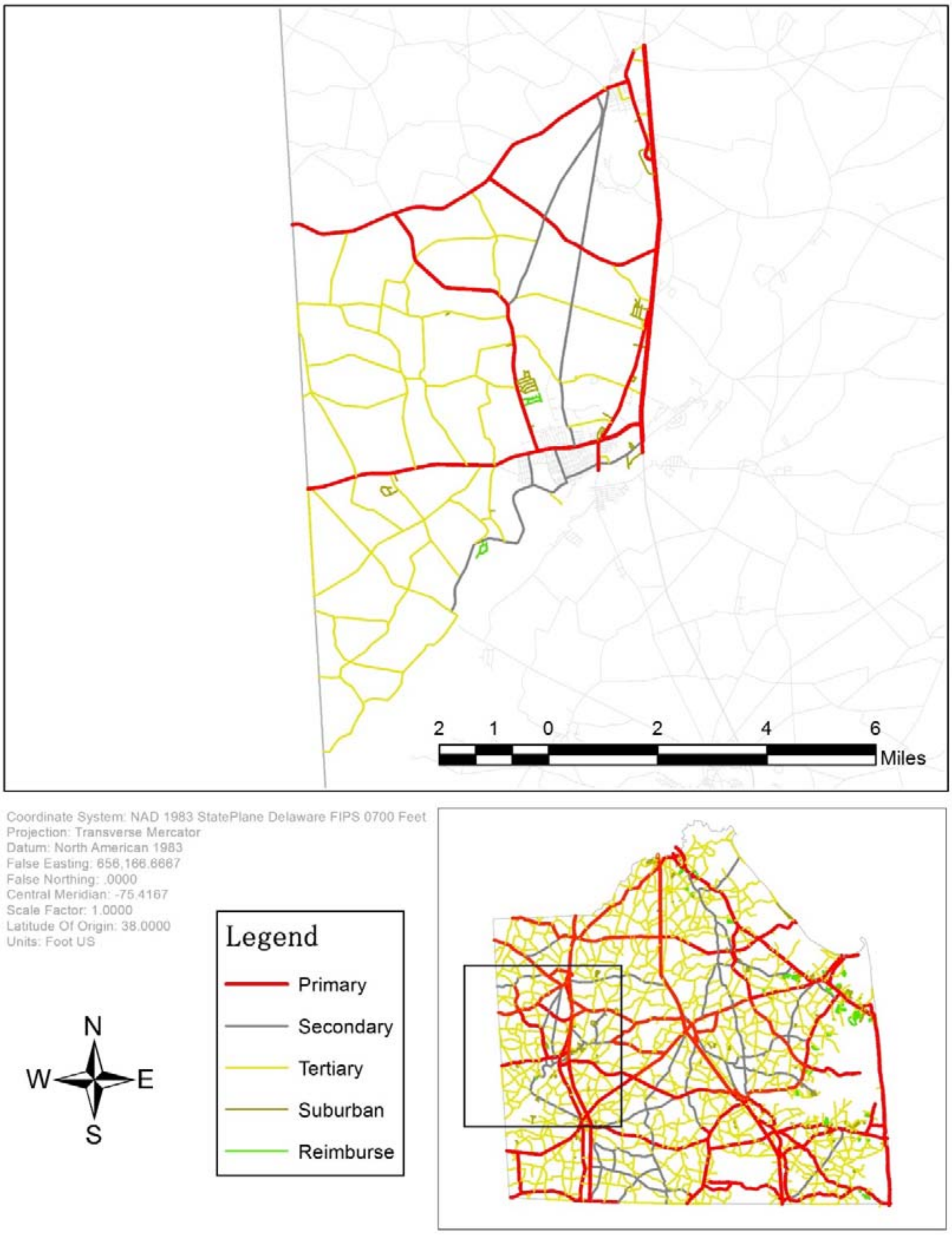

Figure 21: Snow Plow Roads Classification Map – Area 2, Sector D

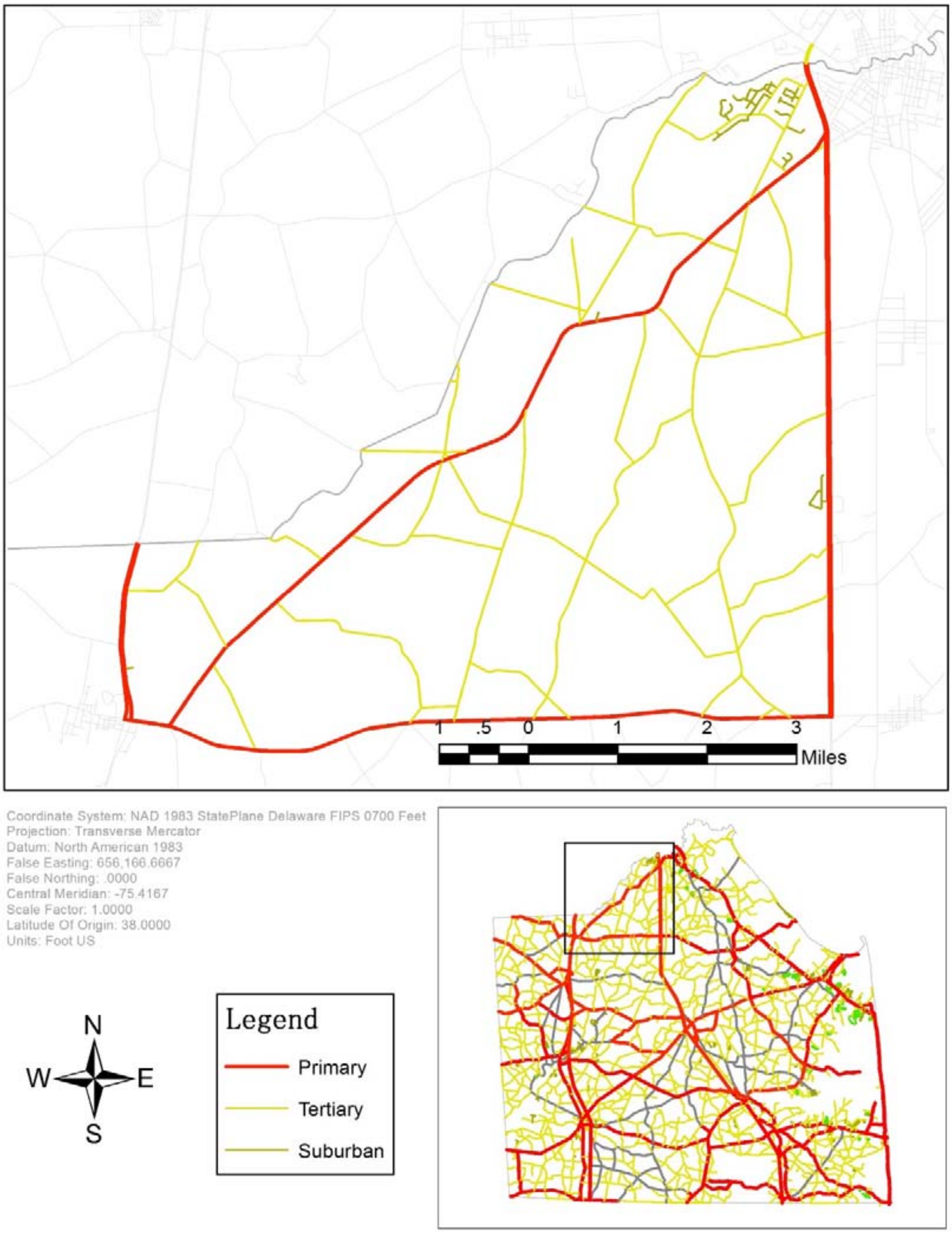

Figure 22: Snow Plow Roads Classification Map – Area 3, Sector A

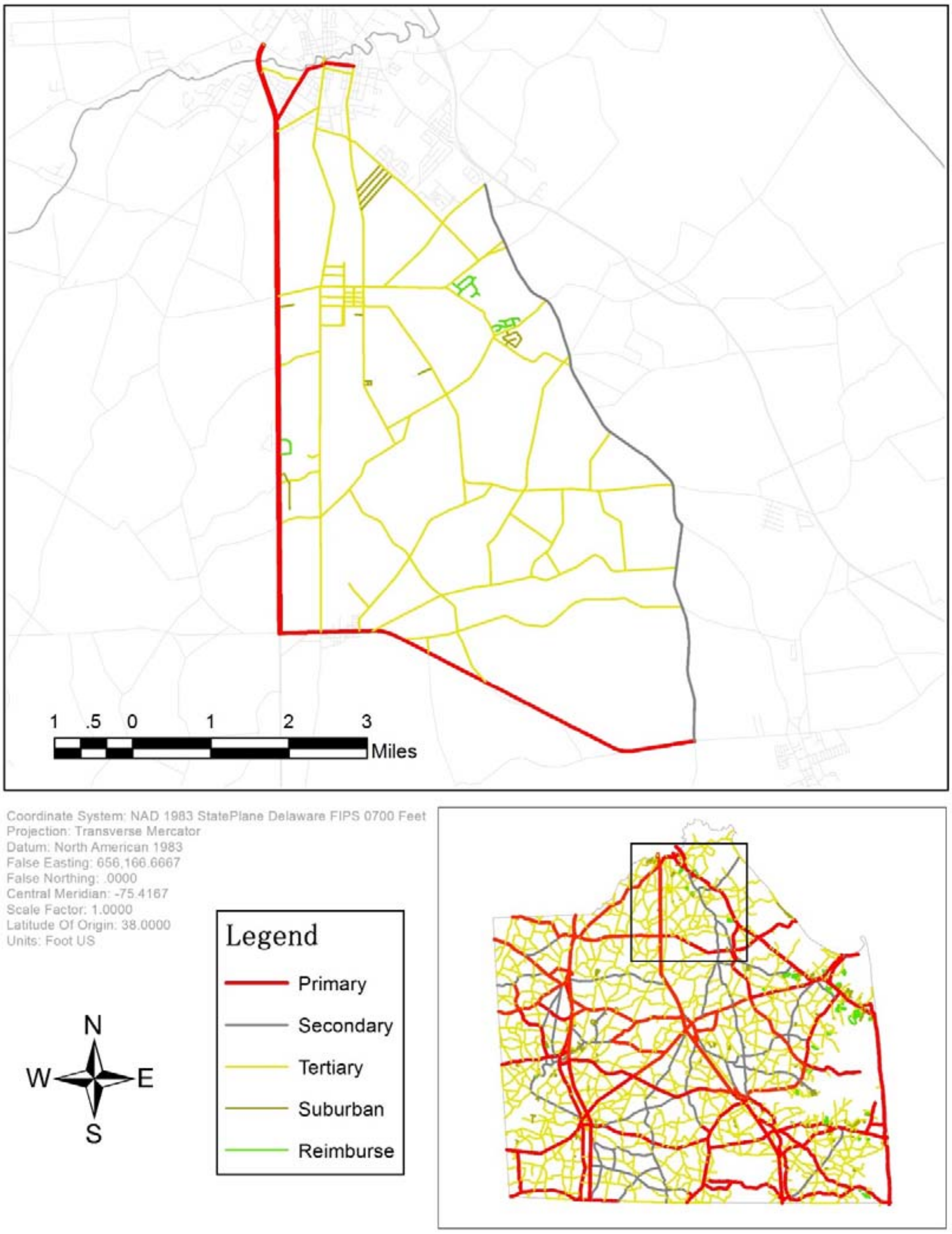

Figure 23: Snow Plow Roads Classification Map – Area 3, Sector B

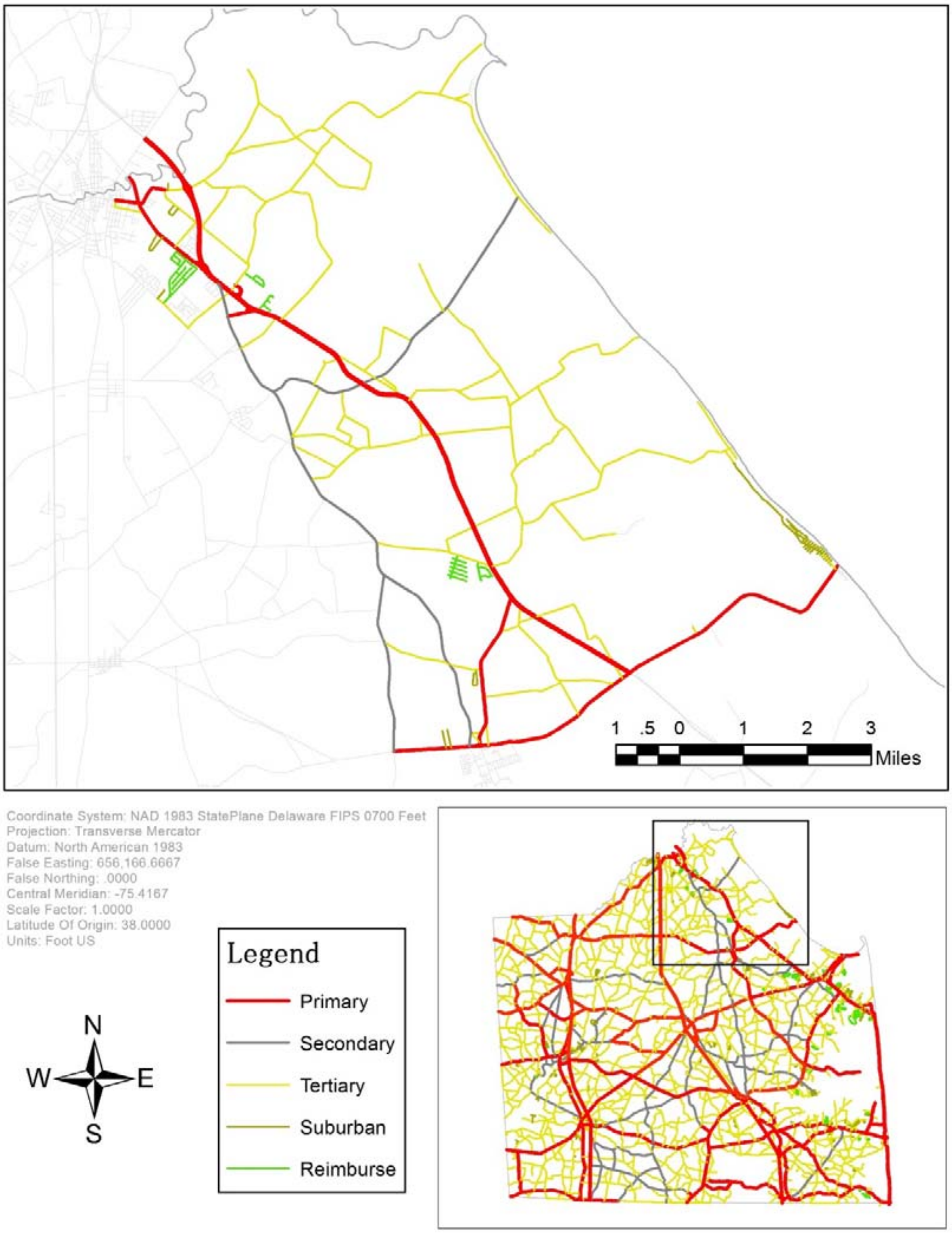

Figure 24: Snow Plow Roads Classification Map – Area 3, Sector C

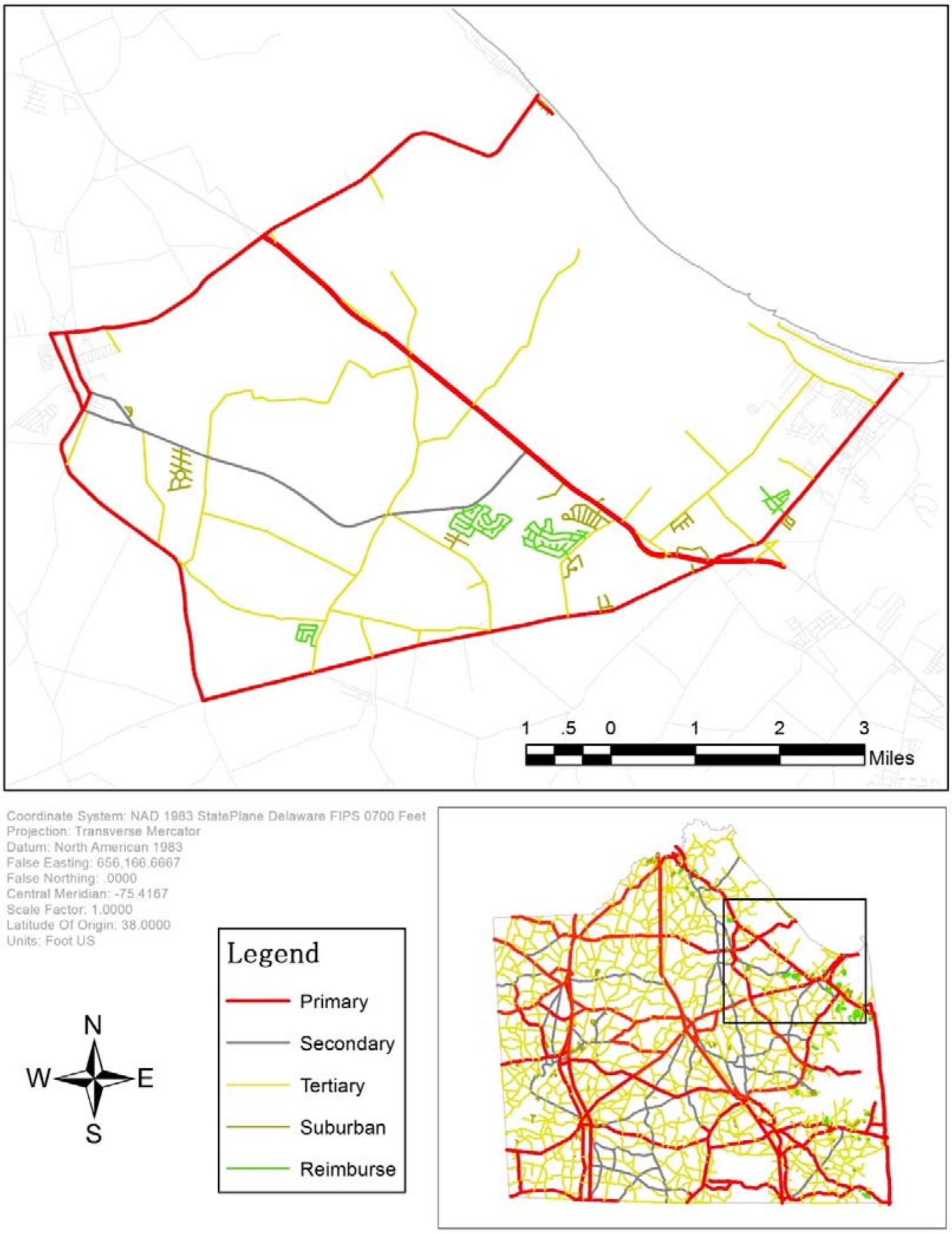

Figure 25: Snow Plow Roads Classification Map – Area 3, Sector D

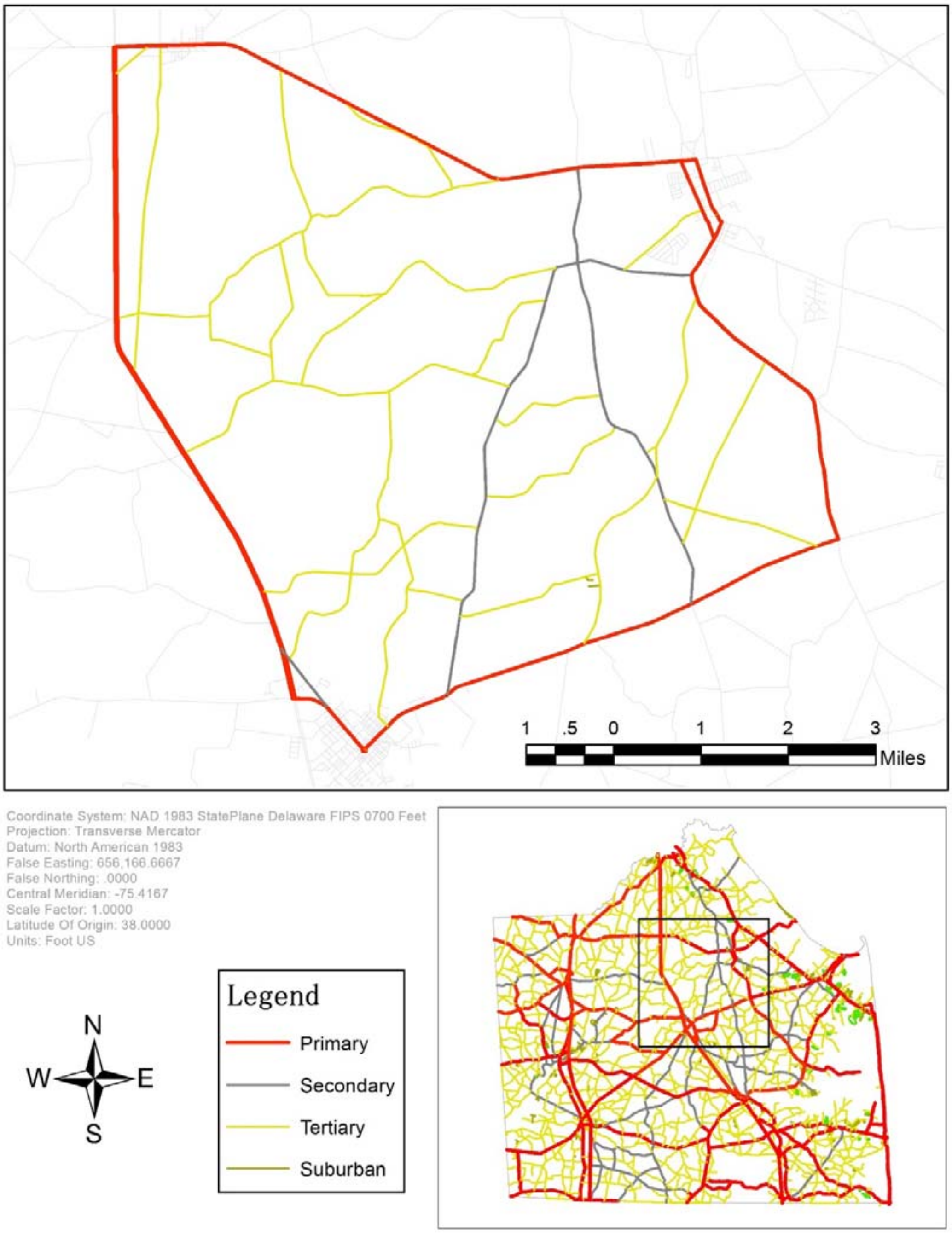

Figure 26: Snow Plow Roads Classification Map – Area 3, Sector E

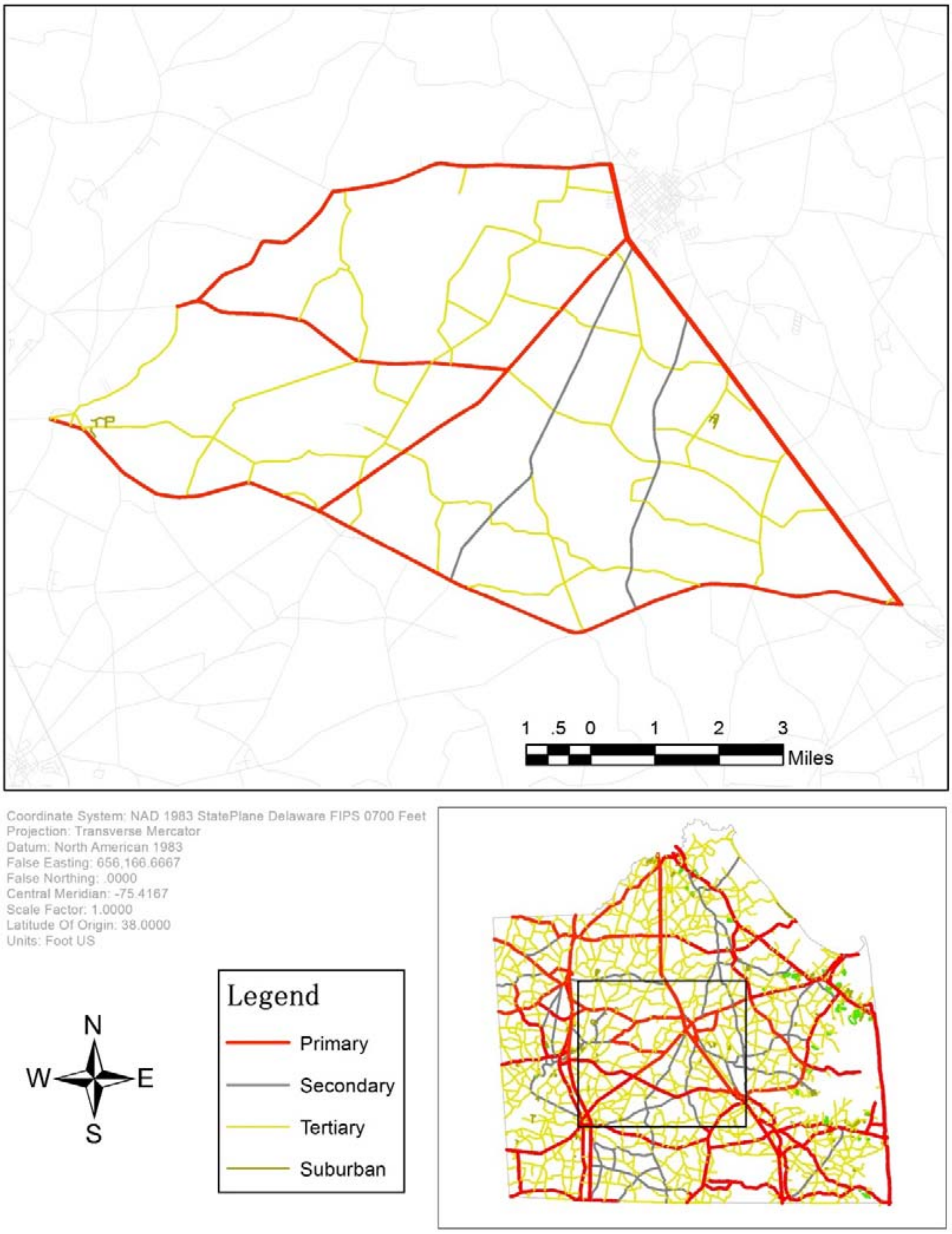

Figure 27: Snow Plow Roads Classification Map – Area 4, Sector A

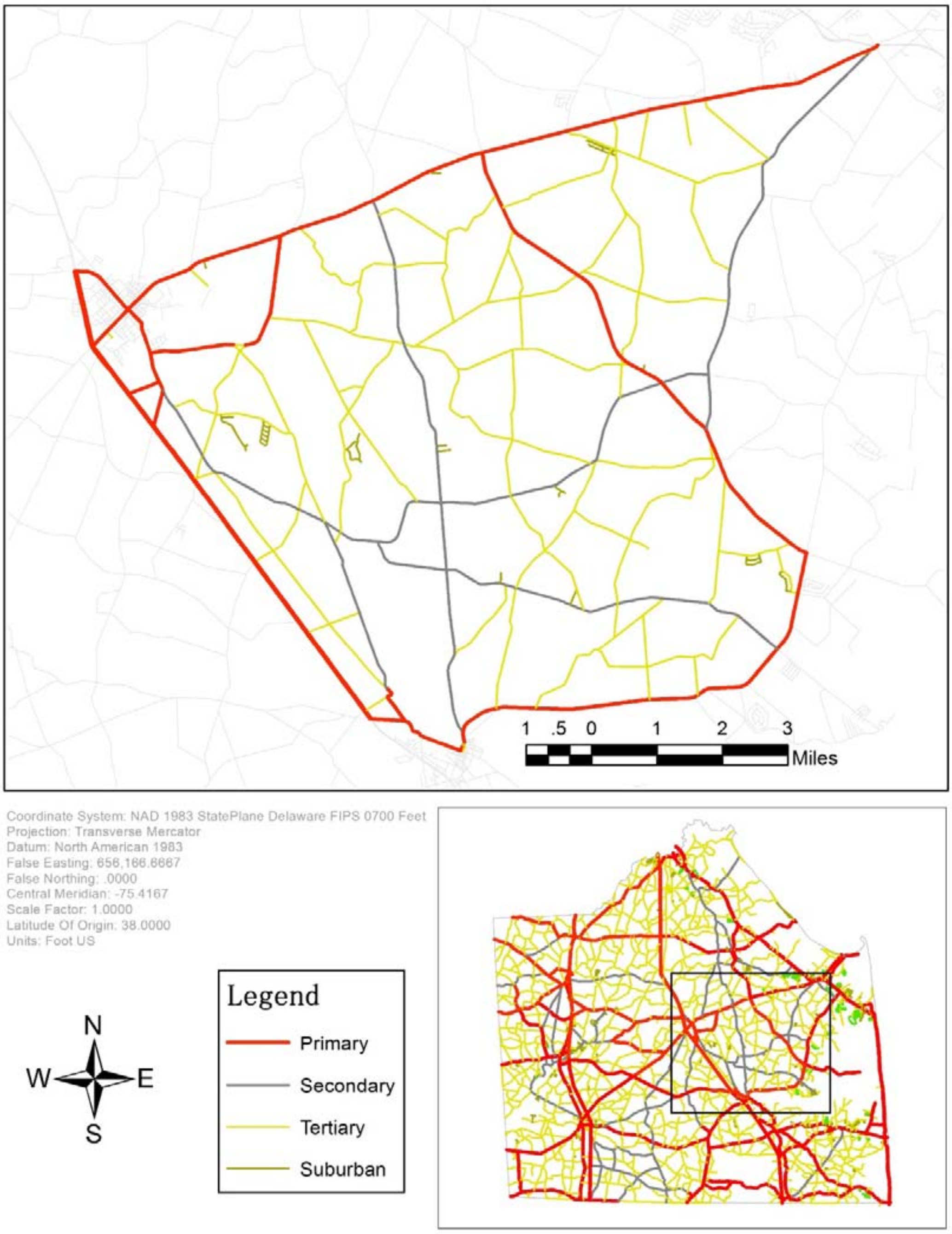

Figure 28: Snow Plow Roads Classification Map – Area 4, Sector B

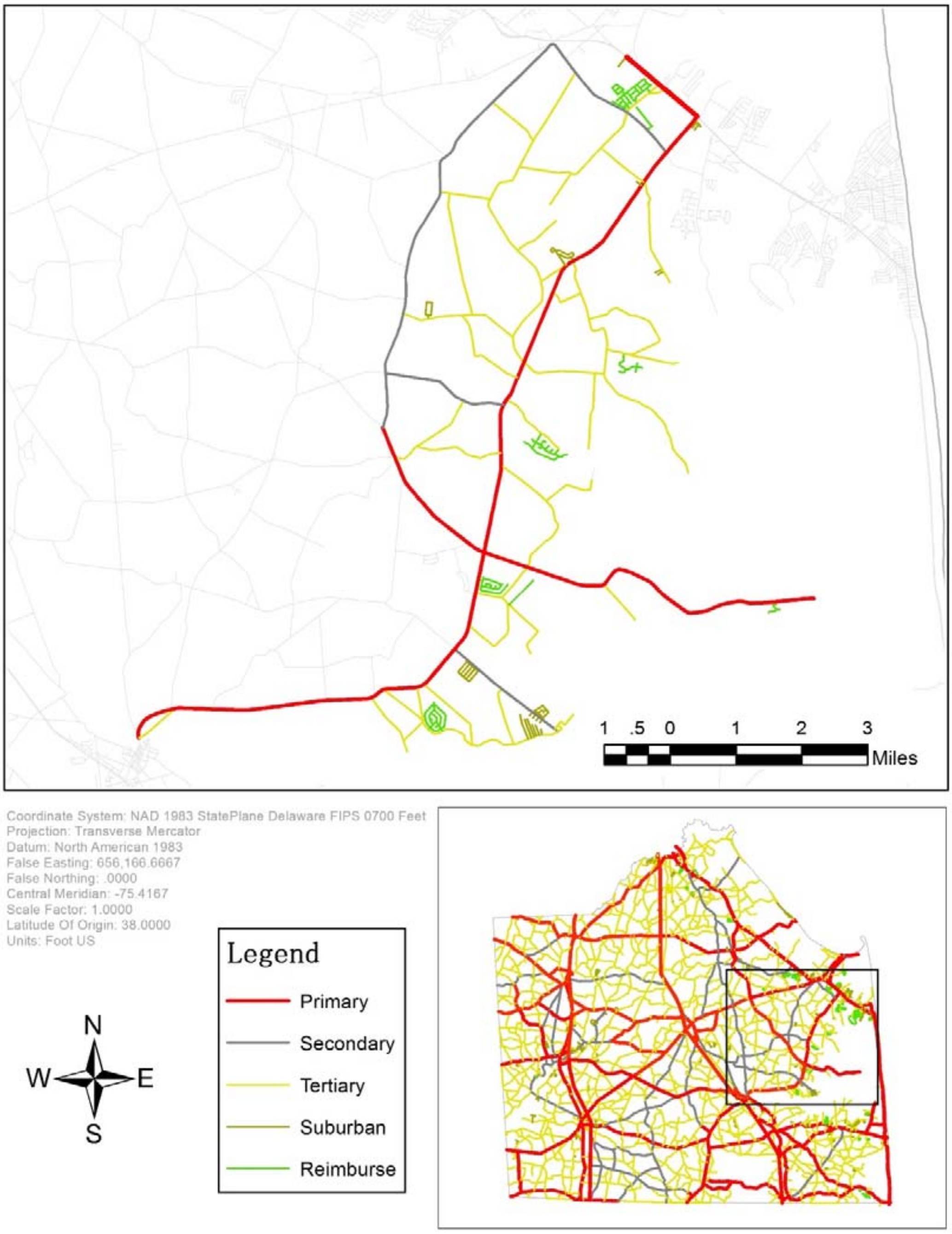

Figure 29: Snow Plow Roads Classification Map – Area 4, Sector C

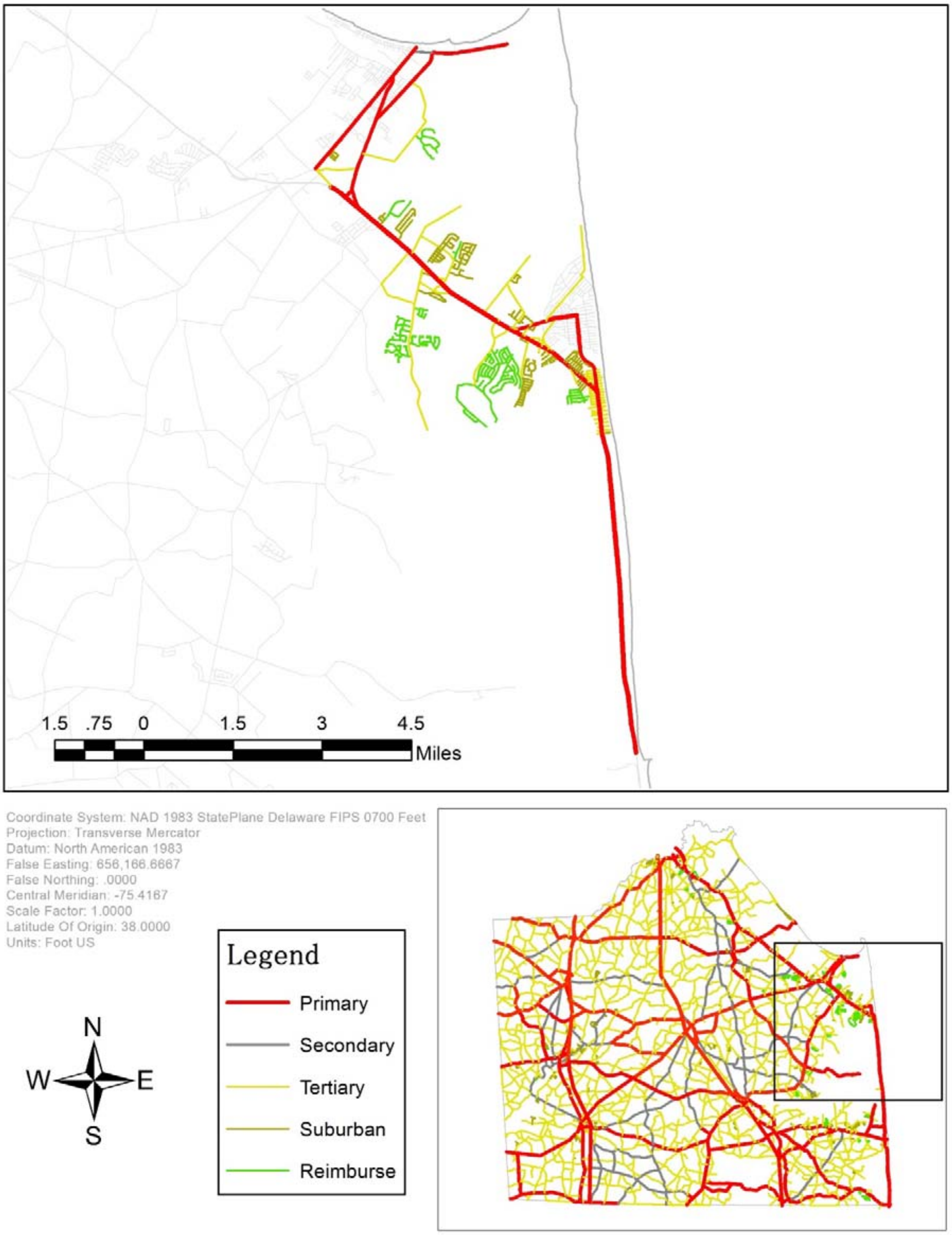

Figure 30: Snow Plow Roads Classification Map – Area 4, Sector D

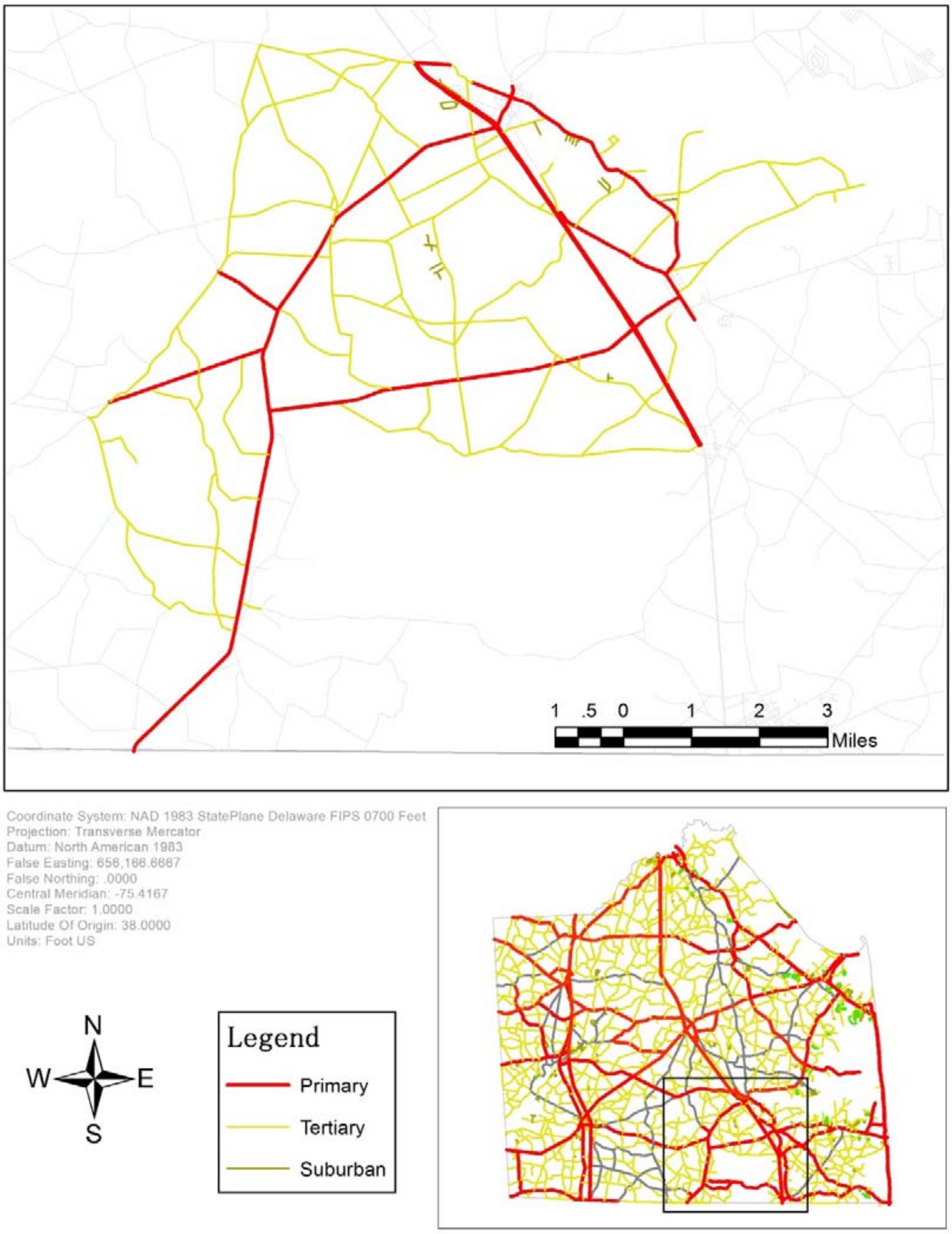

Figure 31: Snow Plow Roads Classification Map – Area 5, Sector A

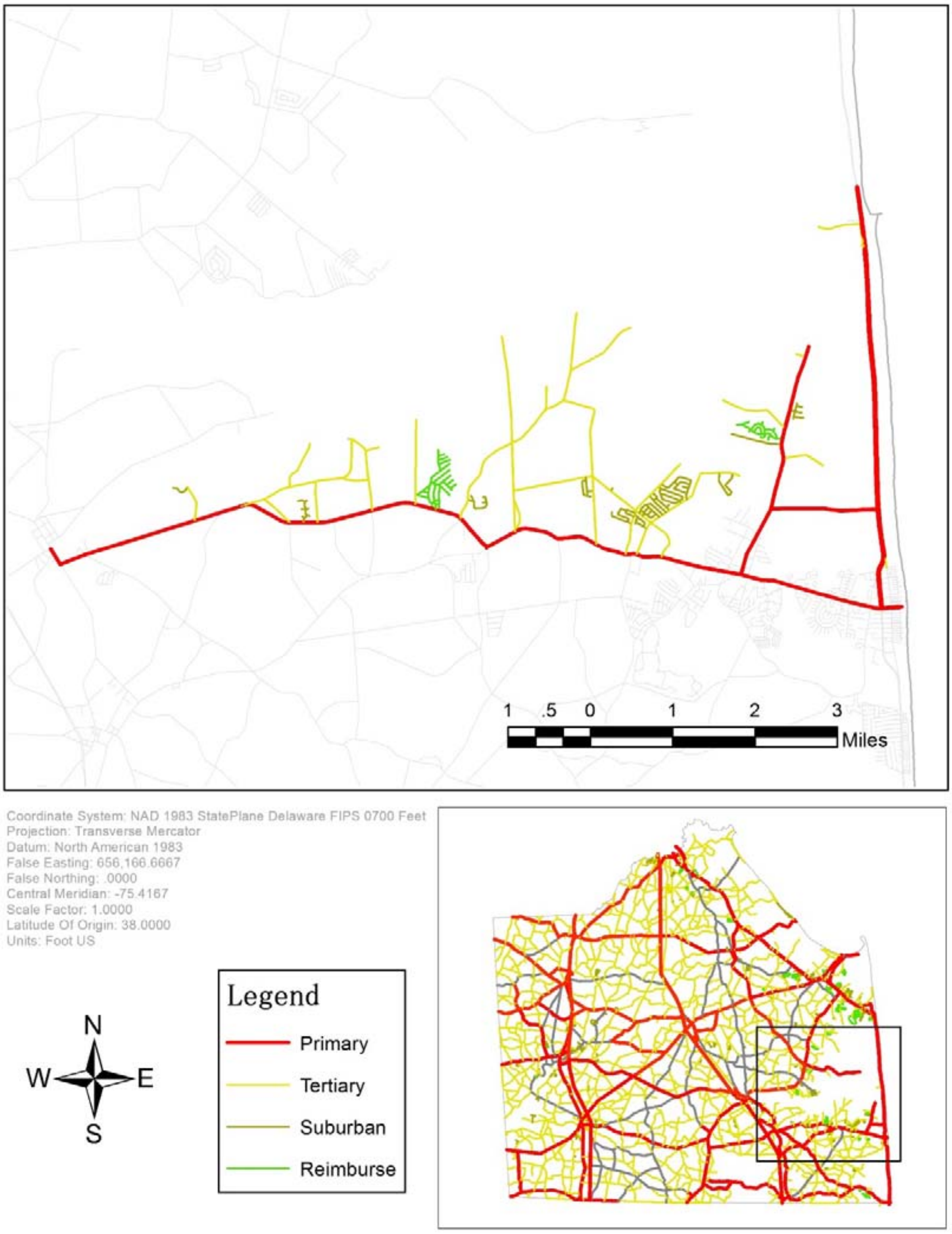

Figure 32: Snow Plow Roads Classification Map – Area 5, Sector B

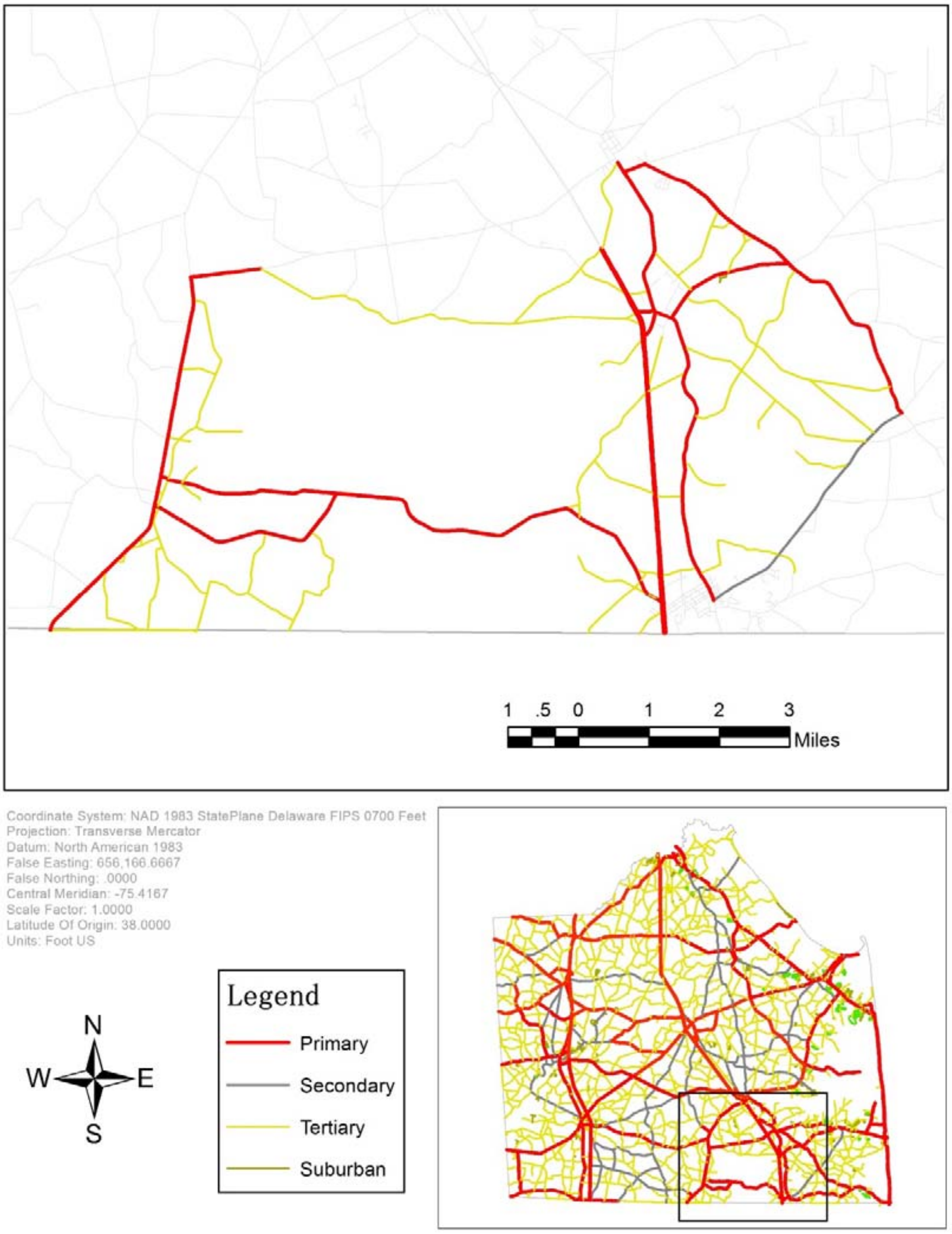

Figure 33: Snow Plow Roads Classification Map – Area 5, Sector C

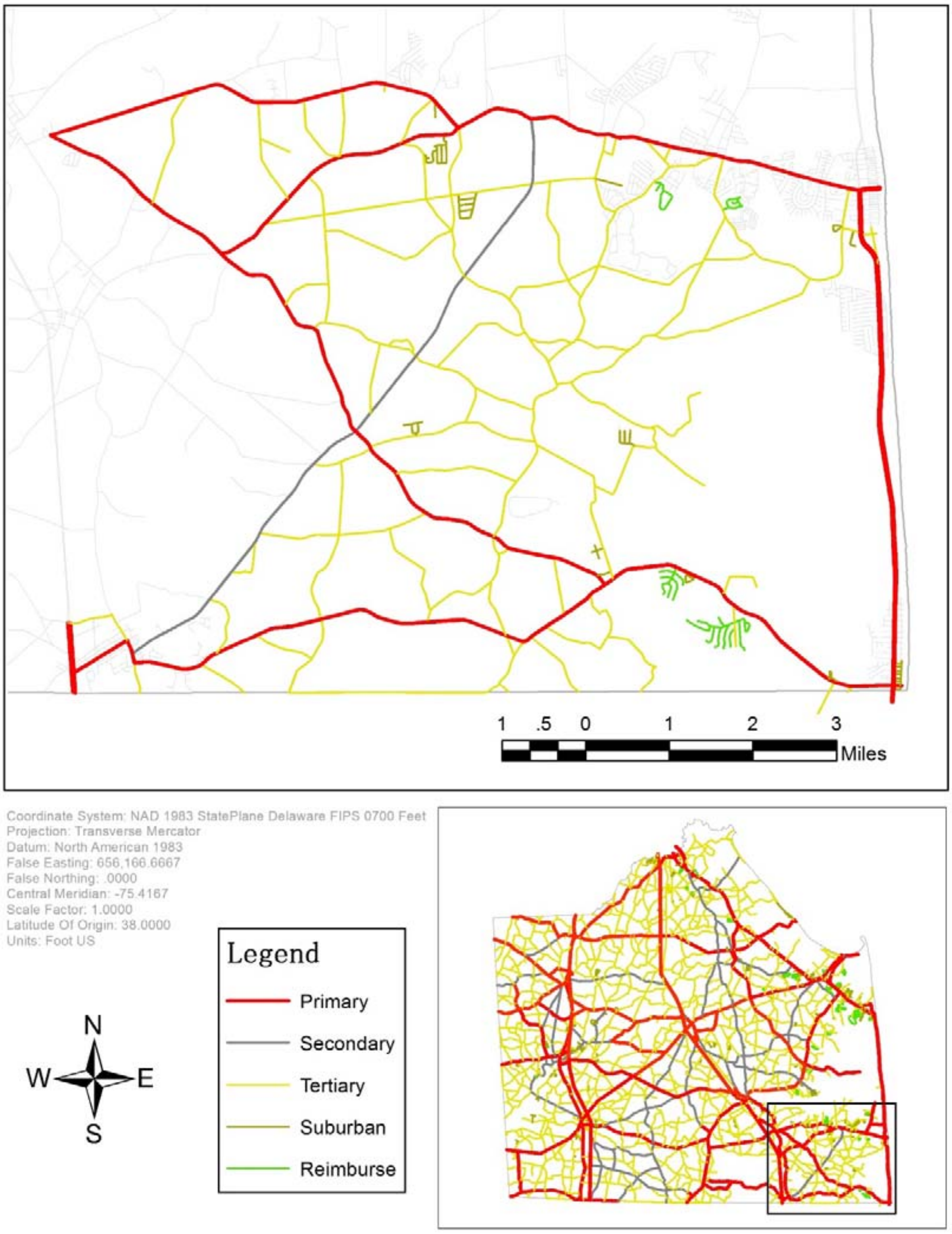

Figure 34: Snow Plow Roads Classification Map – Area 5, Sector D

Area 3 – Sector A

To test the ArcGIS based method to solve routing problem, three routing solution has been developed according to two different scenarios. For all scenarios, four vehicles are assumed to complete the snow plowing task for this area. The solution of the routing problem is time-based. The solution will develop the overall least-time-consuming route for each vehicle.

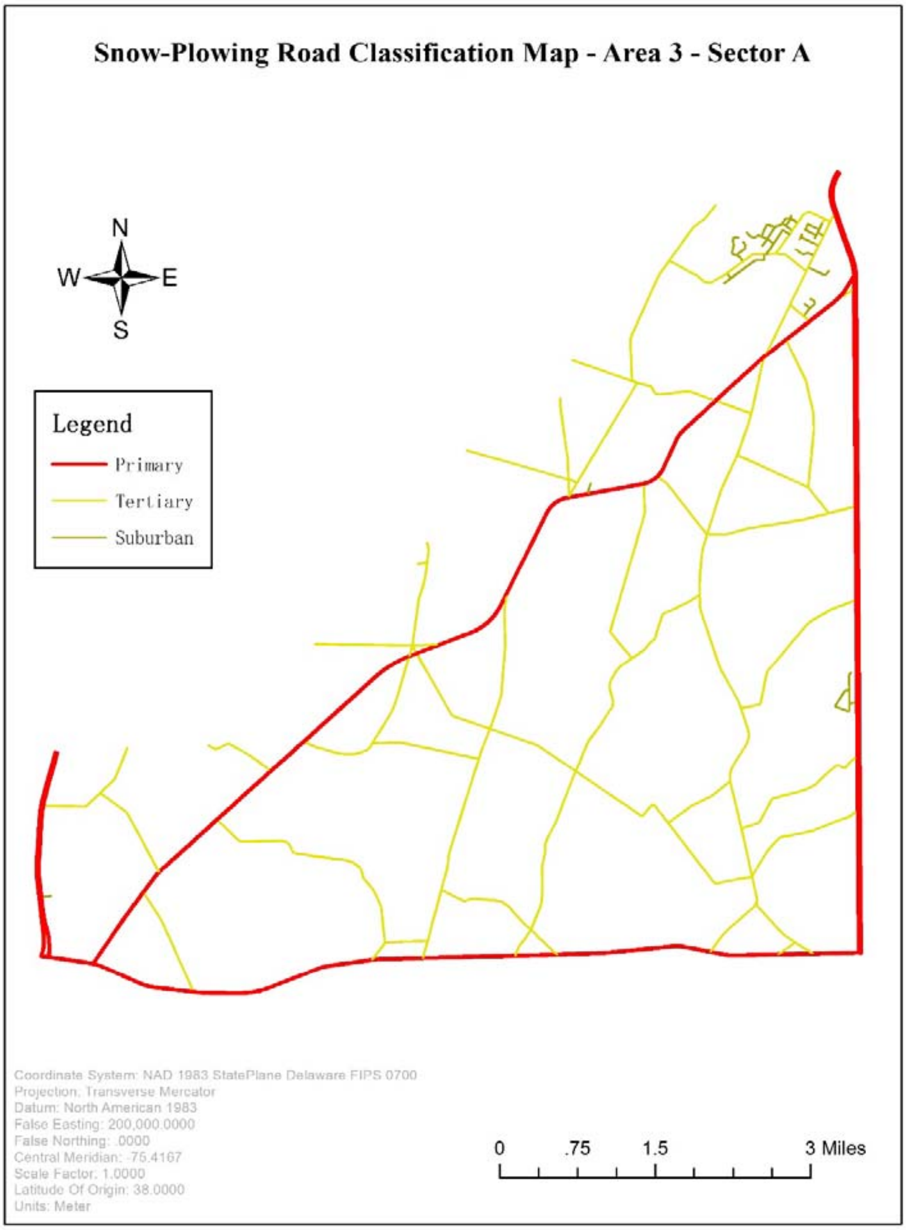

Figure 35: Snow Plow Roads and Classification Map – Area 3, Sector A

The Solution of Routing Problem - Scenario 1:

For this scenario, all specifications of snow-plow vehicles are ignored. Drivers are assumed to be able to operate all types of vehicles without difficulties on all level roadways.

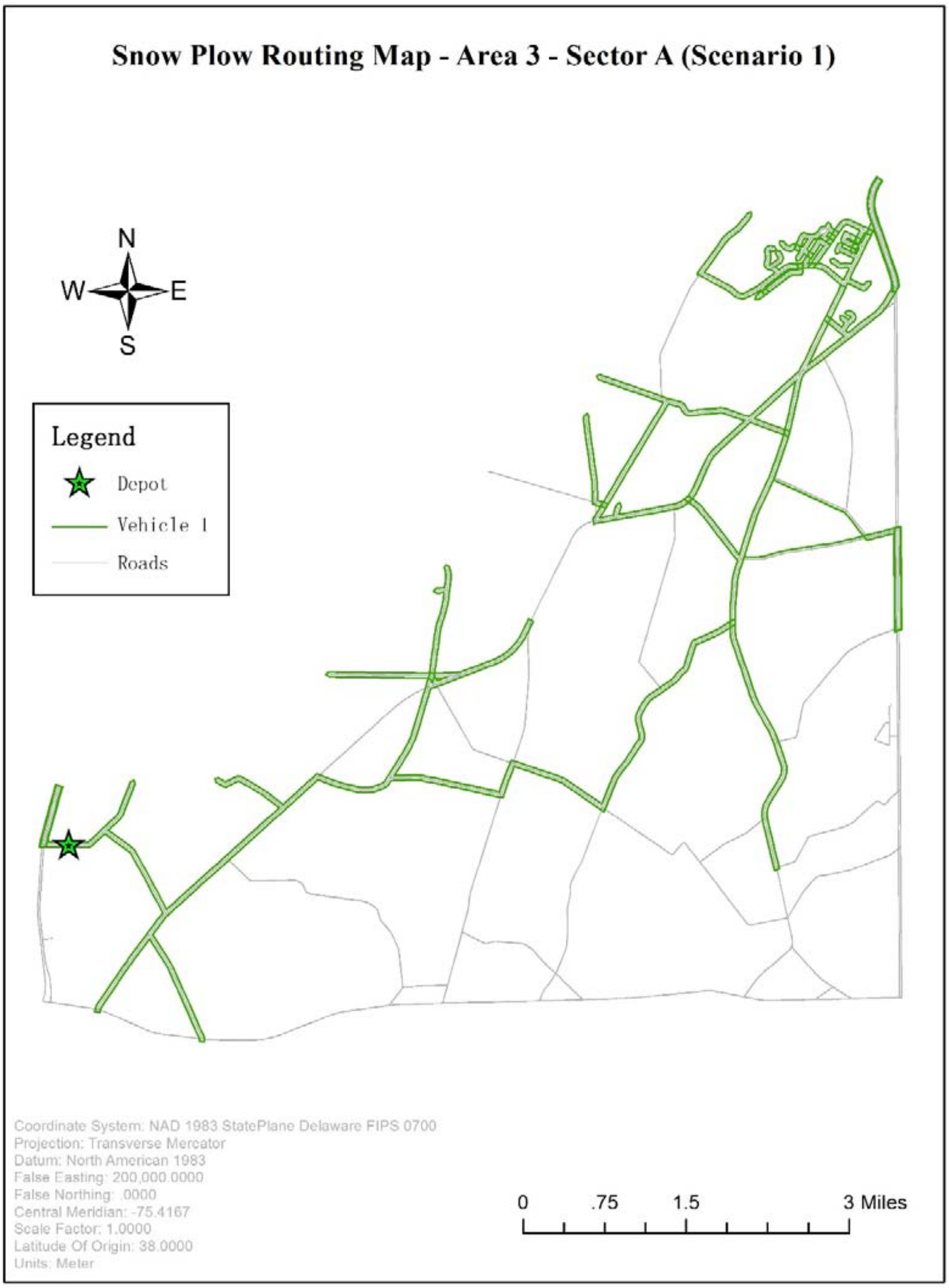

Figure 36: Snow Plow Route Map – Area 3, Sector A. Scenario 1, Vehicle 1

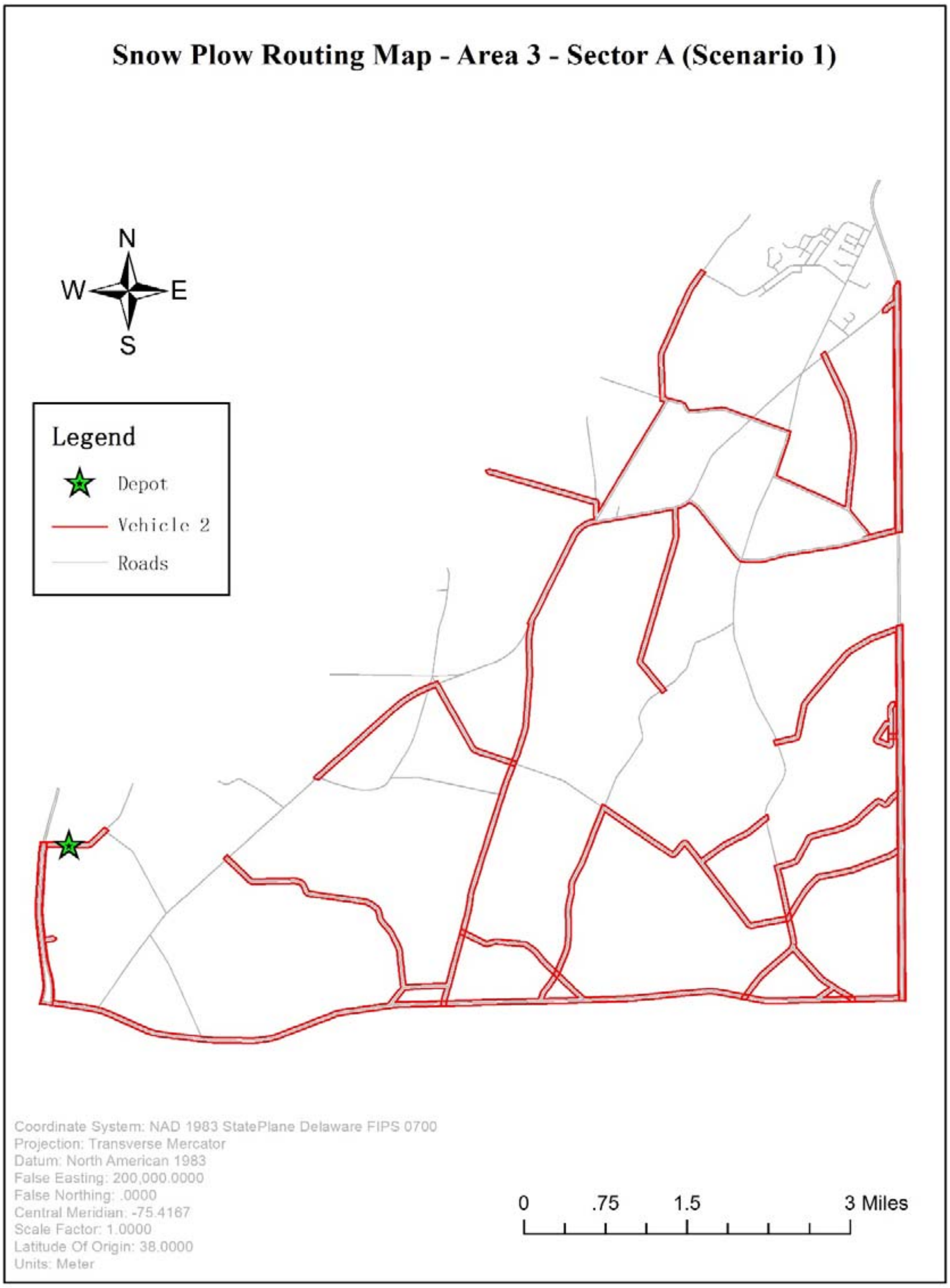

Figure 37: Snow Plow Route Map – Area 3, Sector A. Scenario 1, Vehicle 2

The Solution of Routing Problem - Scenario 2:

For this scenario, the model of snow-plow vehicles was added into consideration. 10-Wheel snow-plowing trucks are only assigned to serve the primary and secondary roads. The 6-Wheel snow-plowing truck is assigned to serve other classes of roads – tertiary, suburban and reimburse. ***Figure 38*** and ***Figure 39*** present the routing problem solution for the 10-Wheels truck.

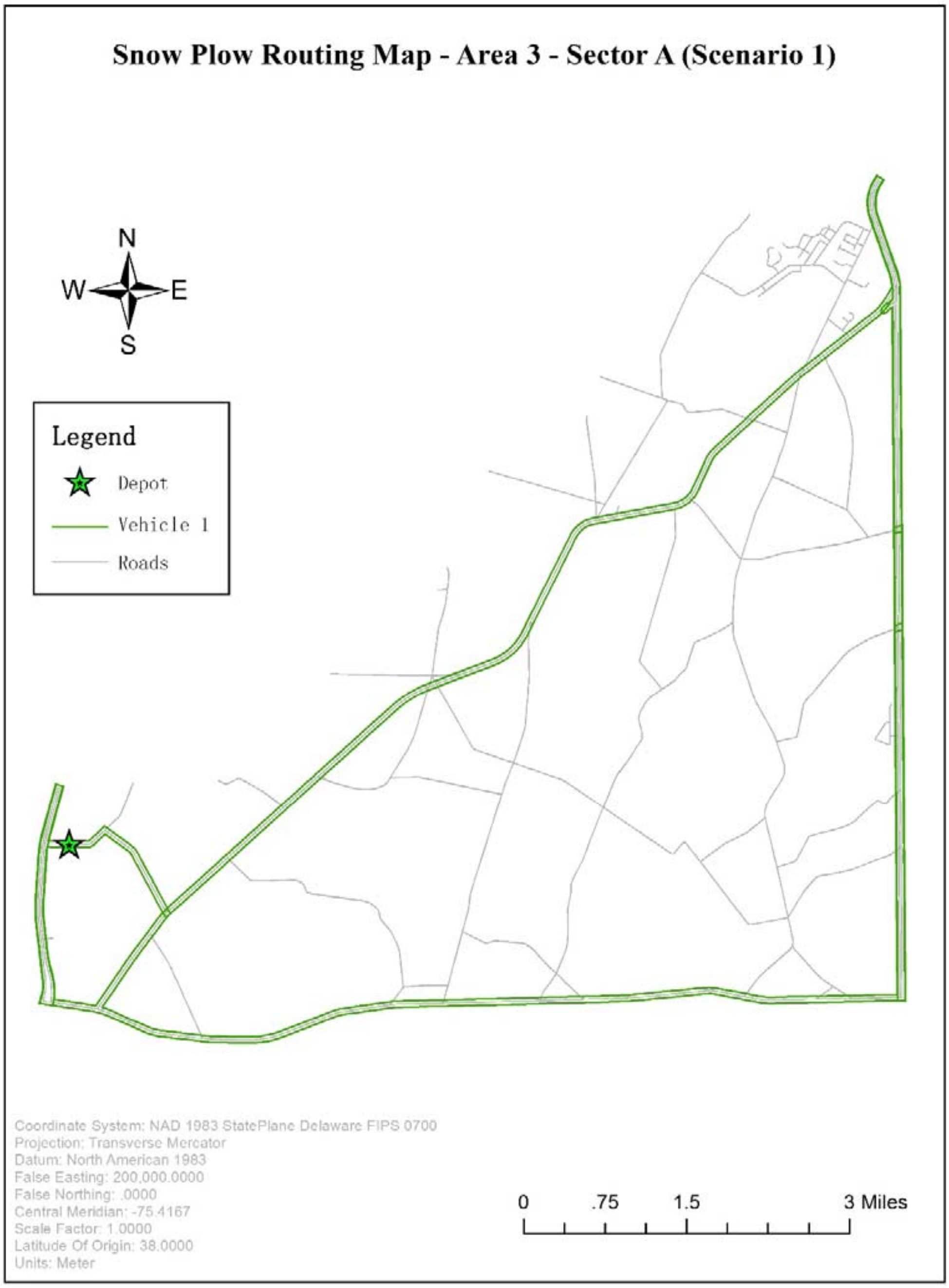

Figure 38: Snow Plow Route Map – Area 3, Sector A. Scenario 2, Vehicle 1

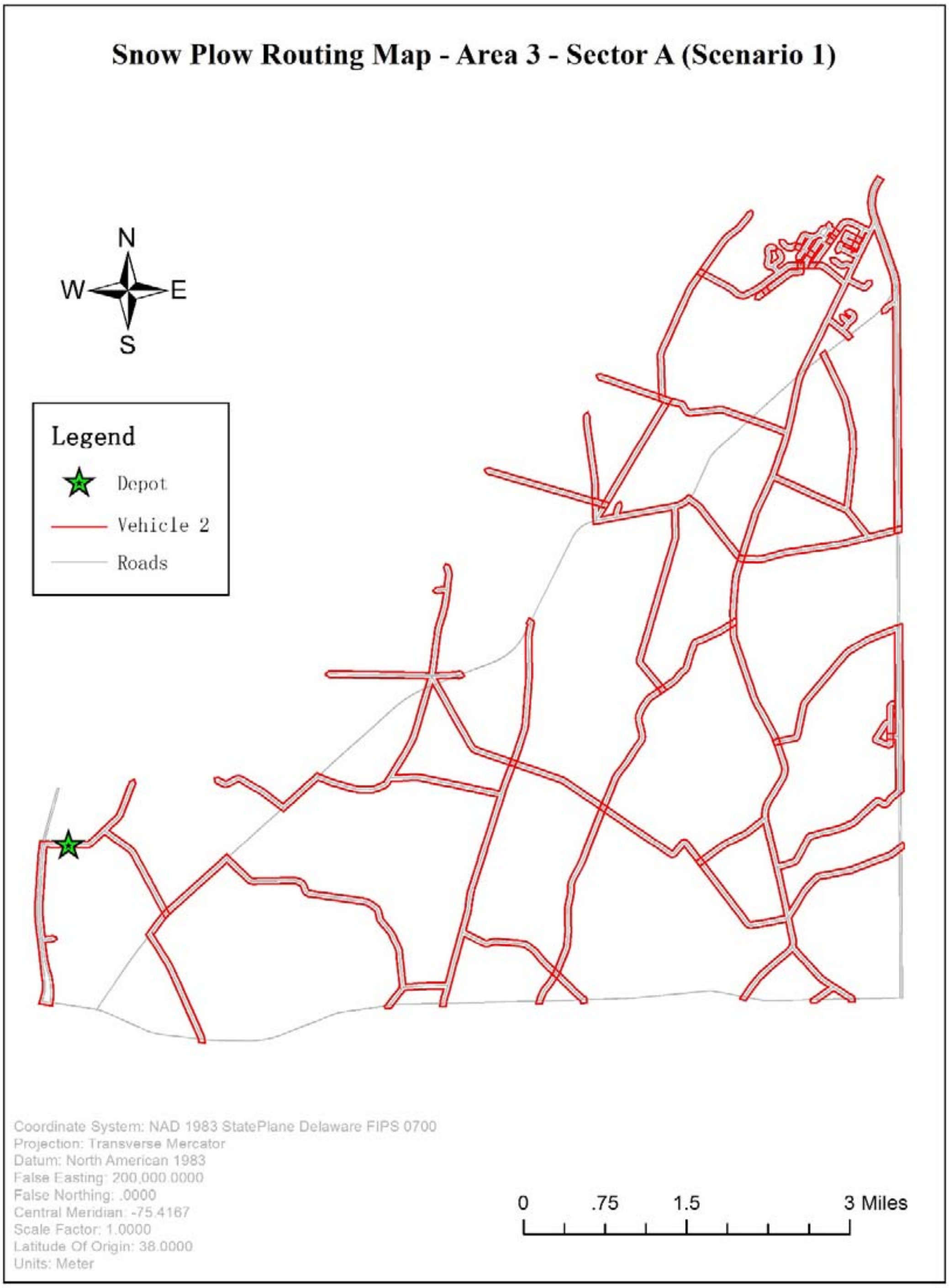

Figure 39: Snow Plow Route Map – Area 3, Sector A. Scenario 2, Vehicle 2

Result Comparison:

The snow plow routing results of two scenarios are shown below.

Table 5: Snow Plow Routing Results – Area 4, Sector B

Travel Time (Minutes)		
Vehicle	**Scenario**	
	1	**2**
1	129.73	97.77
2	140.89	188.01
Sum	270.62	285.78
Min	129.73	97.77
Max	140.89	188.01
STD	5.5800	45.1200

As shown by this table, the total travel times for the two scenarios are similar. Three scenarios have similar total travel time. The maximum of travel time under Scenario 1 are lower. But, the minimum travel time for Scenario 2 are lower. The standard deviation of travel time for Scenario 1 is smaller. However, by comparing the total travel time for all vehicles, it seems the results according to two scenarios are similar.

Area 4 – Sector B

To test the ArcGIS based method to solve routing problem, three routing solution has been developed according to two different scenarios. For all scenarios, four vehicles are assumed to complete the snow plowing task for this area. The solution of the routing problem is time-based. The solution will develop the overall least-time-consuming route for each vehicle.

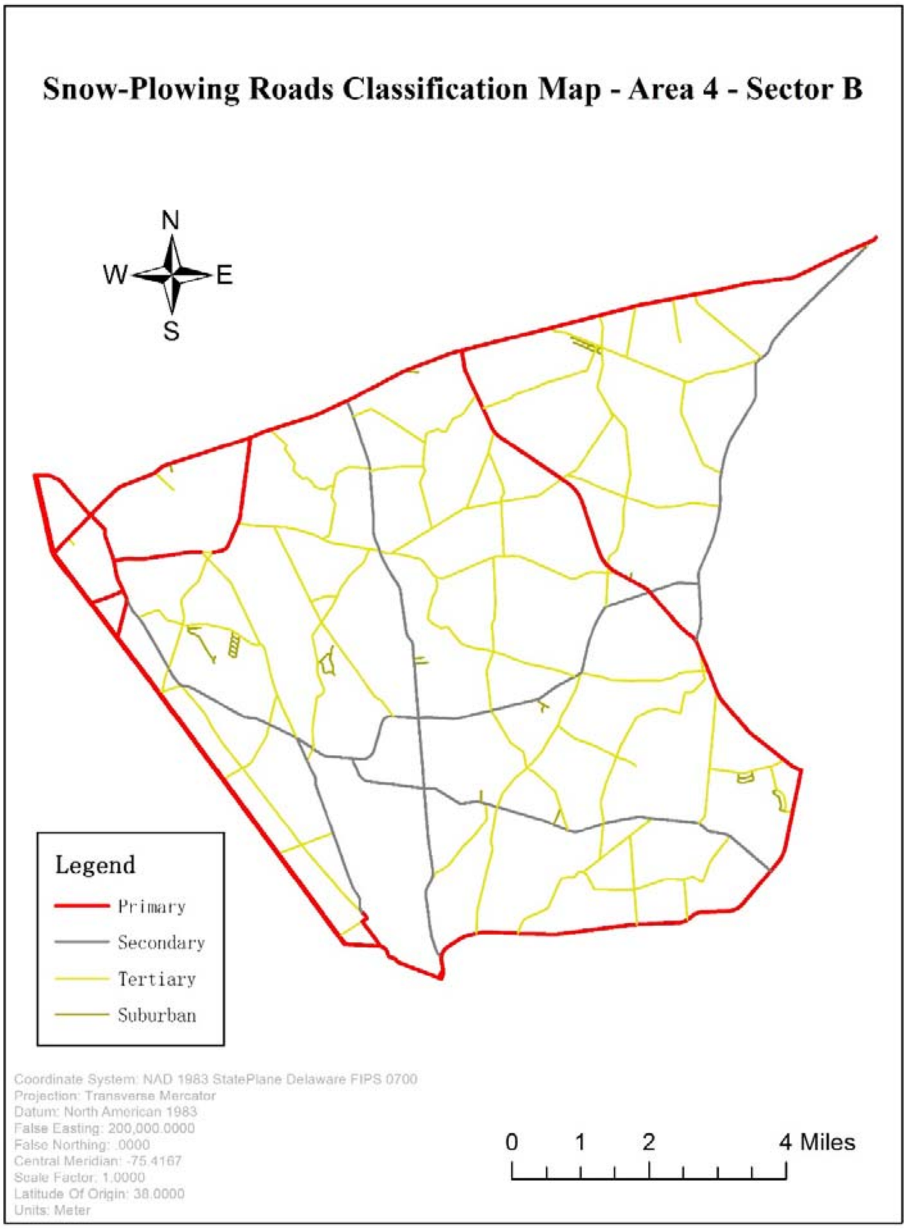

Figure 40: Snow Plow Roads and Classification Map – Area 4, Sector B

The Solution of Routing Problem - Scenario 1:

For this scenario, all specifications of snow-plow vehicles are ignored. Drivers are assumed to be able to operate all types of vehicles without difficulties on all level roadways.

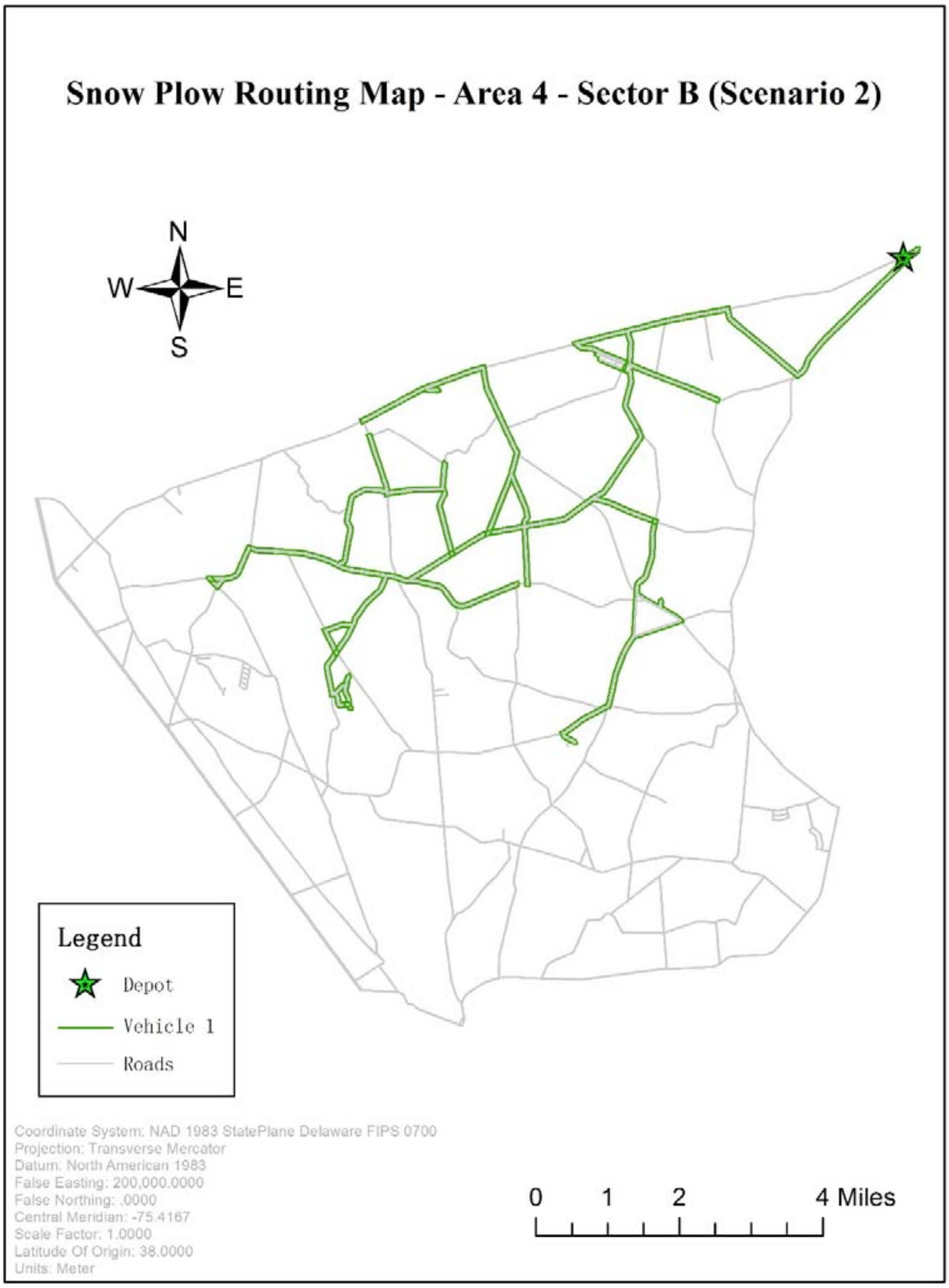

Figure 41: Snow Plow Route Map – Area 4, Sector B. Scenario 1, Vehicle 1.

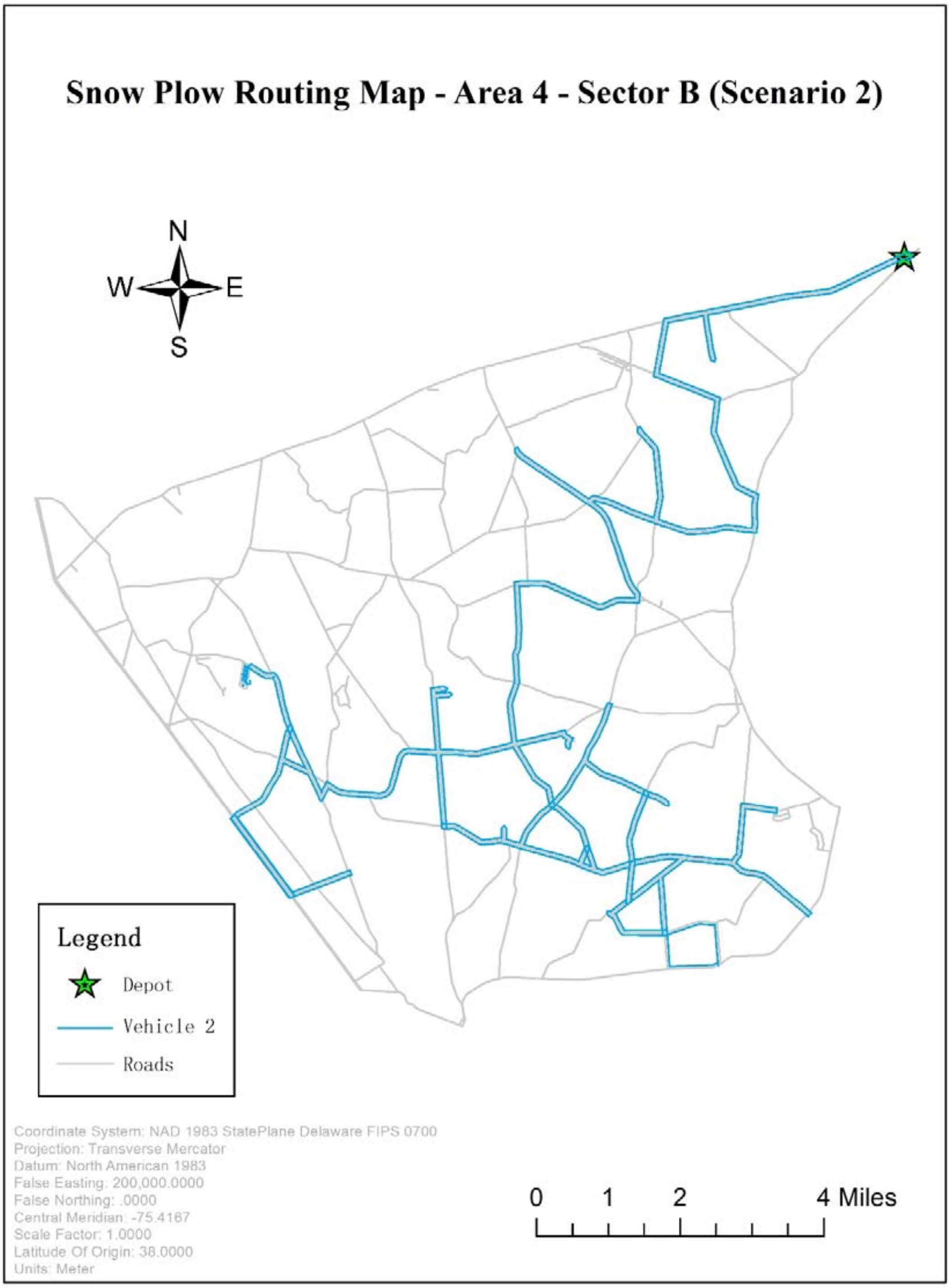

Figure 42: Snow Plow Route Map – Area 4, Sector B. Scenario 1, Vehicle 2.

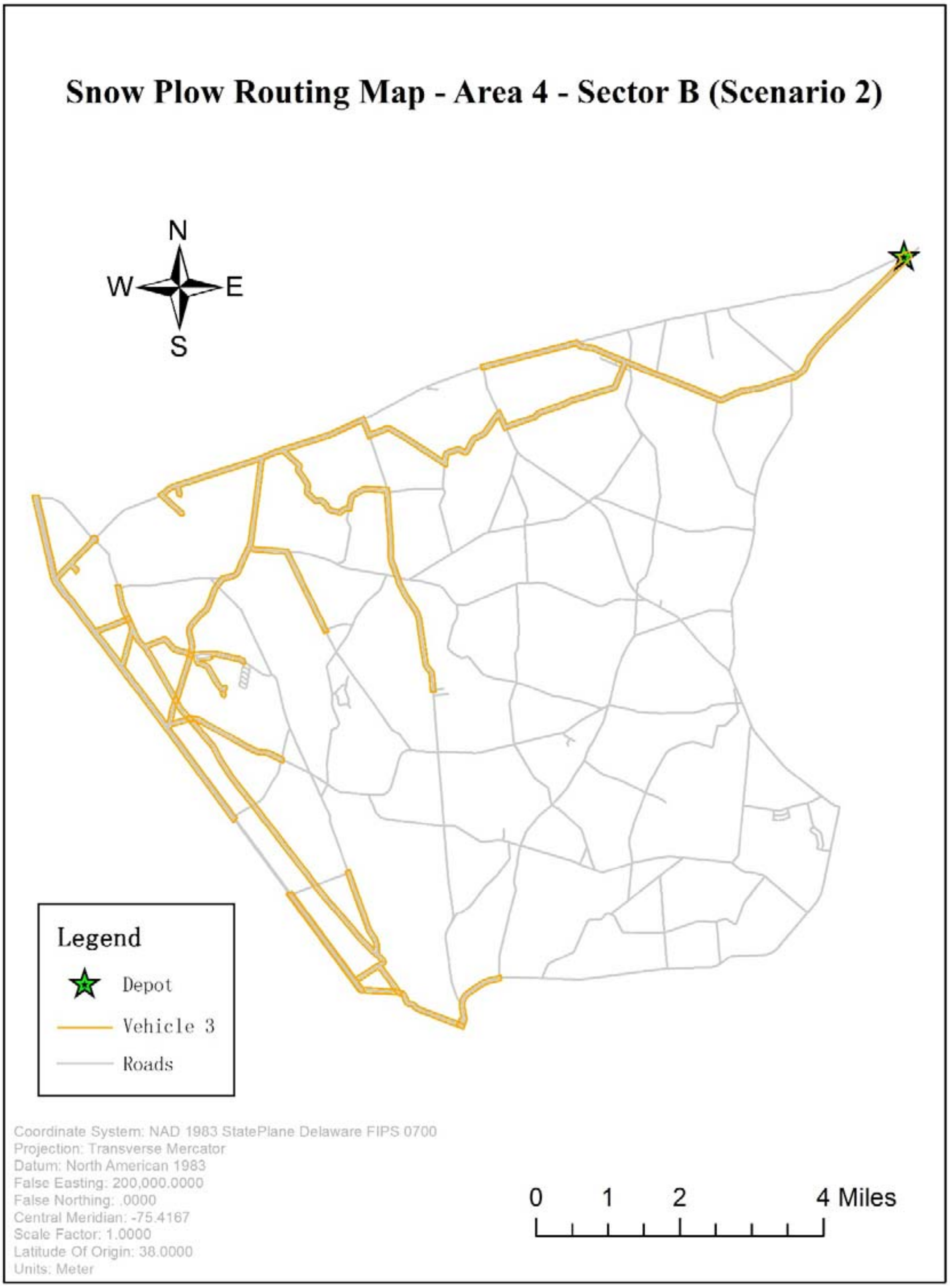

Figure 43: Snow Plow Route Map – Area 4, Sector B. Scenario 1, Vehicle 3.

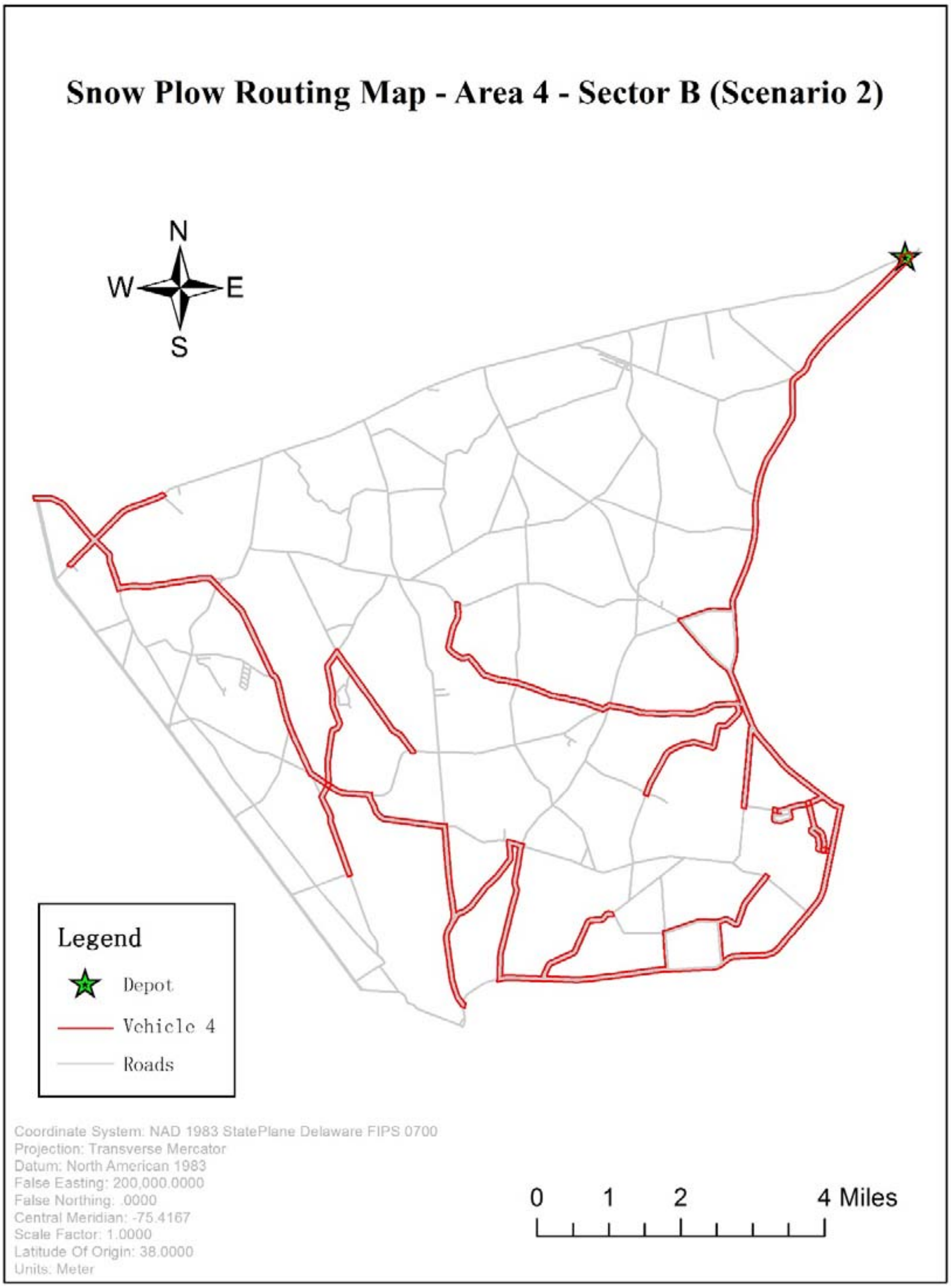

Figure 44: Snow Plow Route Map – Area 4, Sector B. Scenario 1, Vehicle 4.

The Solution of Routing Problem - Scenario 2:

For this scenario, the model of snow-plow vehicles was added into consideration. 10-Wheels snow-plowing trucks are only assigned to serve the primary and secondary roads; 6-Wheels snow-plowing trucks are assigned to serve other classes of roads – tertiary, suburban and reimburse. ***Figure 45*** and ***Figure 46*** present the routing problem solution for two 10-Wheels trucks.

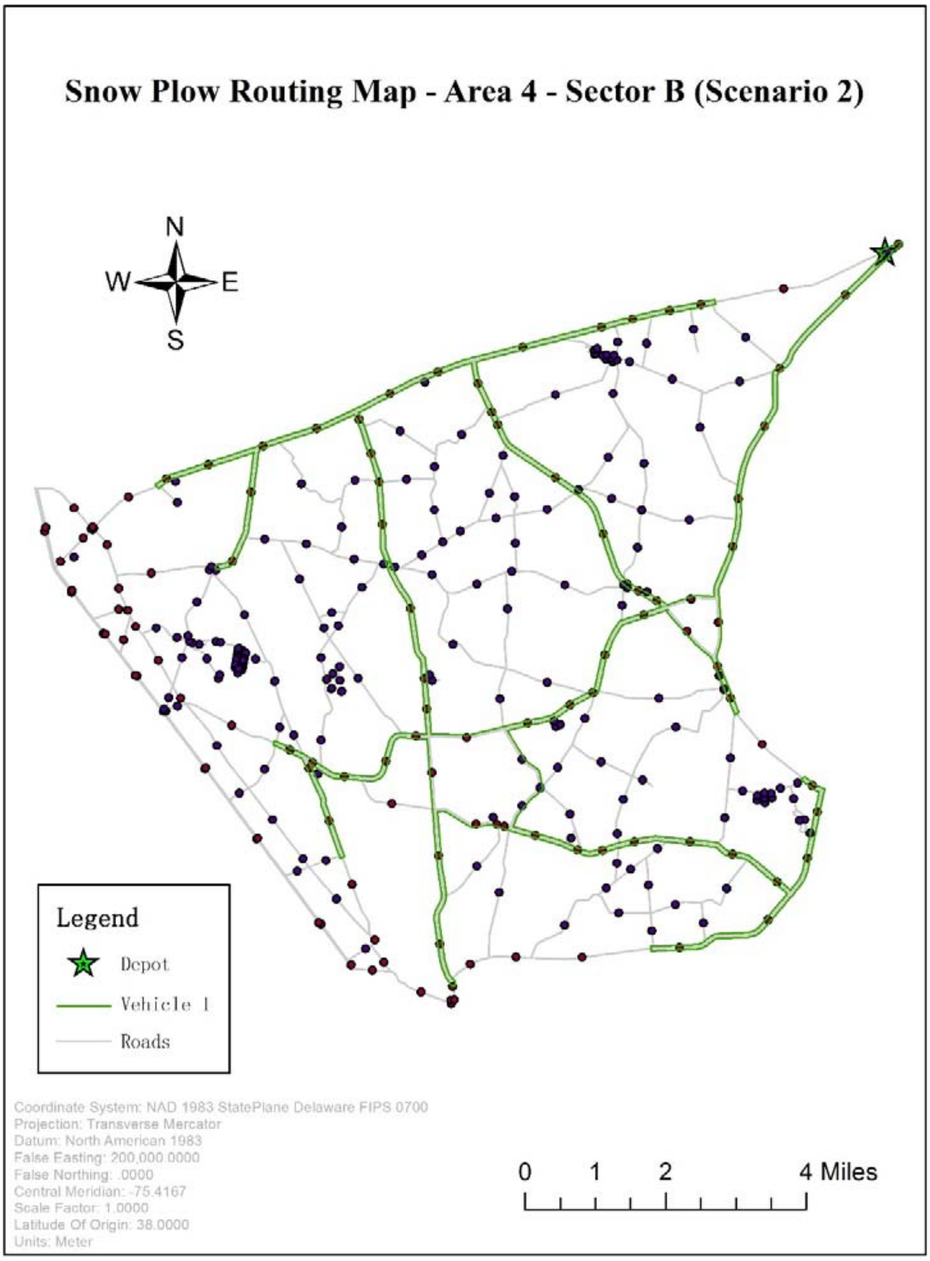

Figure 45: Snow Plow Route Map – Area 4, Sector B. Scenario 2, Vehicle 1.

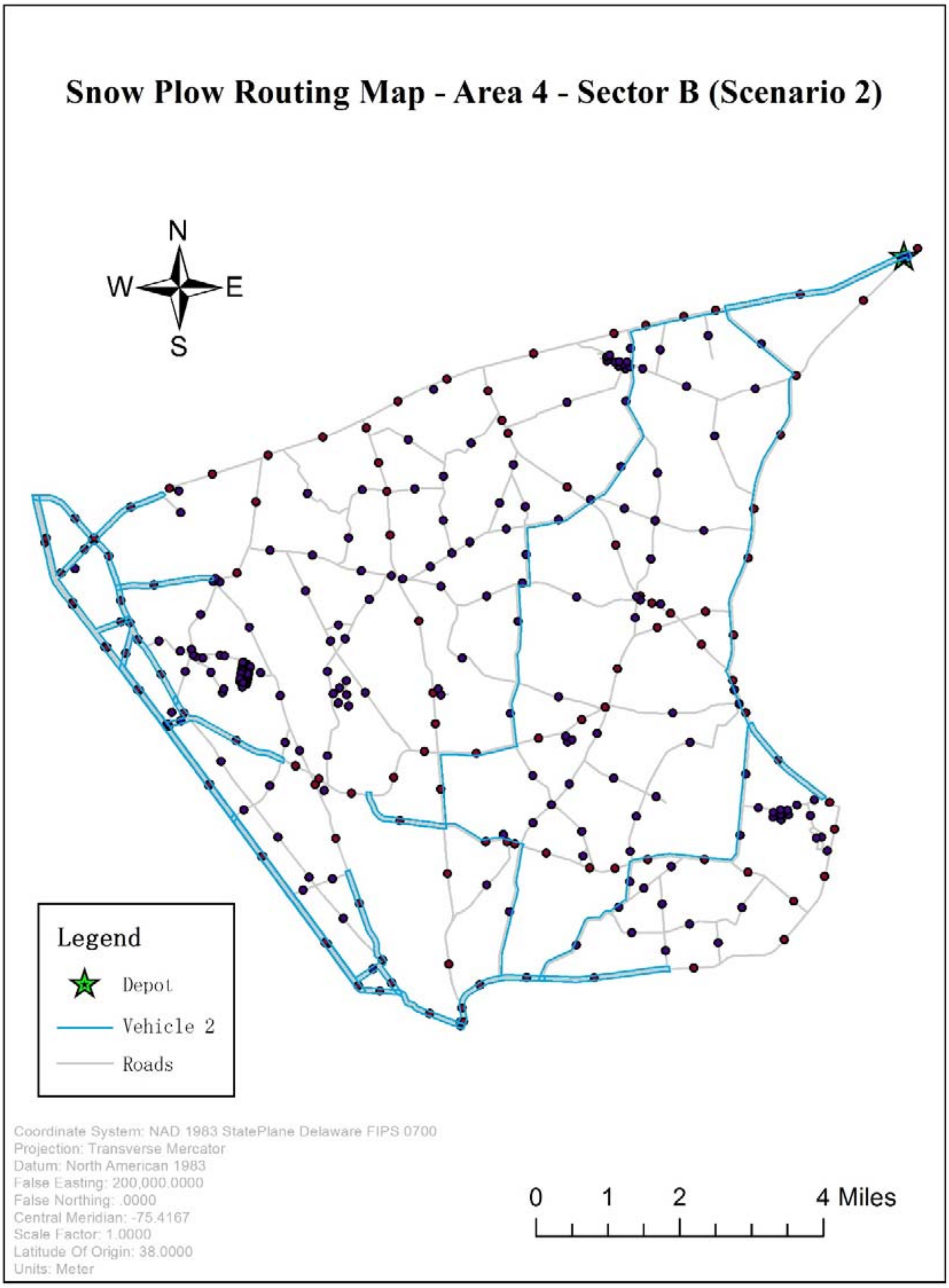

Figure 46: Snow Plow Route Map – Area 4, Sector B. Scenario 2, Vehicle 2.

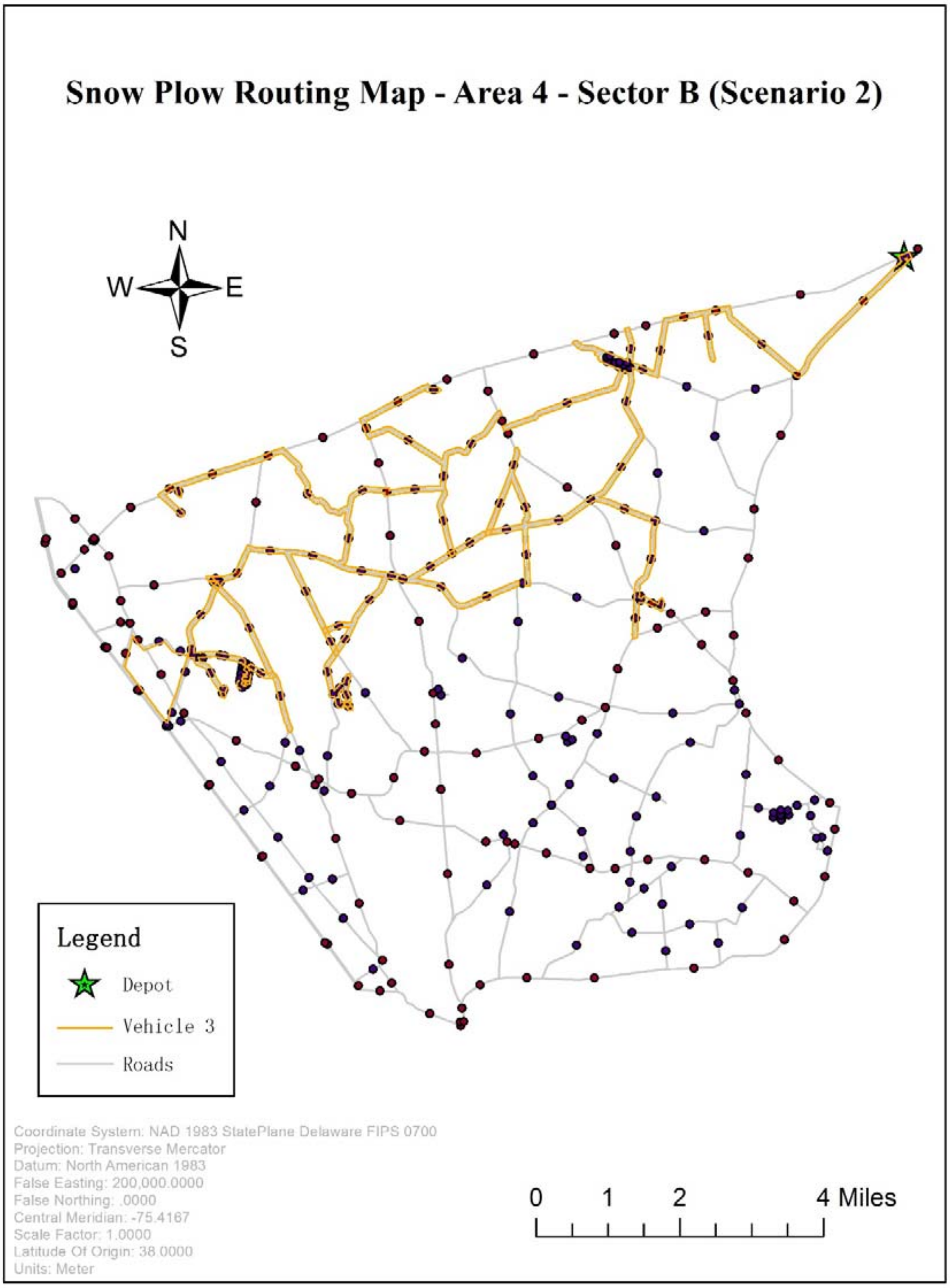

Figure 47: Snow Plow Route Map – Area 4, Sector B. Scenario 2, Vehicle 3.

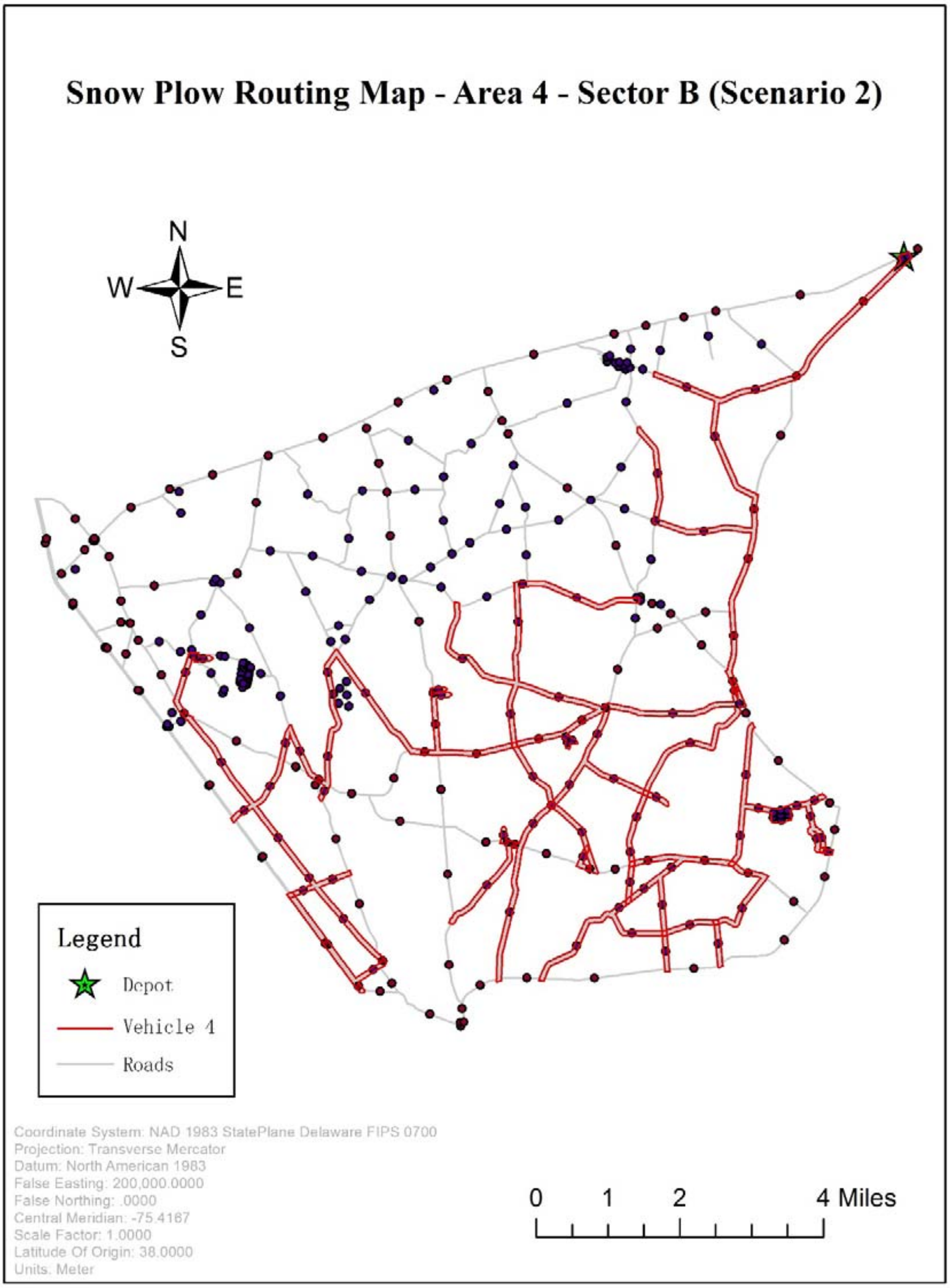

Figure 48: Snow Plow Route Map – Area 4, Sector B. Scenario 2, Vehicle 4.

Result Comparison:

The snow plow routing results of two scenarios are shown below.

Table 6: Snow Plow Routing Results – Area 4, Sector B

Travel Time (Minutes)		
Vehicle	**Scenario**	
	1.00	**2.00**
1	112.91	125.80
2	140.45	139.48
3	155.38	158.67
4	141.05	179.63
Sum	549.79	603.58
Min	112.91	125.80
Max	155.38	179.63
STD	15.3758	20.2868

As shown by this table, the total travel times for the two scenarios are similar. Three scenarios have similar total travel time. The maximum of travel time under Scenario 1 are lower. Additionally, the standard deviation of travel time for Scenario 1 is smaller. However, by comparing the total travel time for all vehicles, it seems the results according to two scenarios are similar.

Area 4 – Sector D

To test the ArcGIS based method to solve routing problem, three routing solution has been developed according to two different scenarios. For all scenarios, four vehicles are assumed to complete the snow plowing task for this area. The solution of the routing problem is time-based. The solution will develop the overall least-time-consuming route for each vehicle.

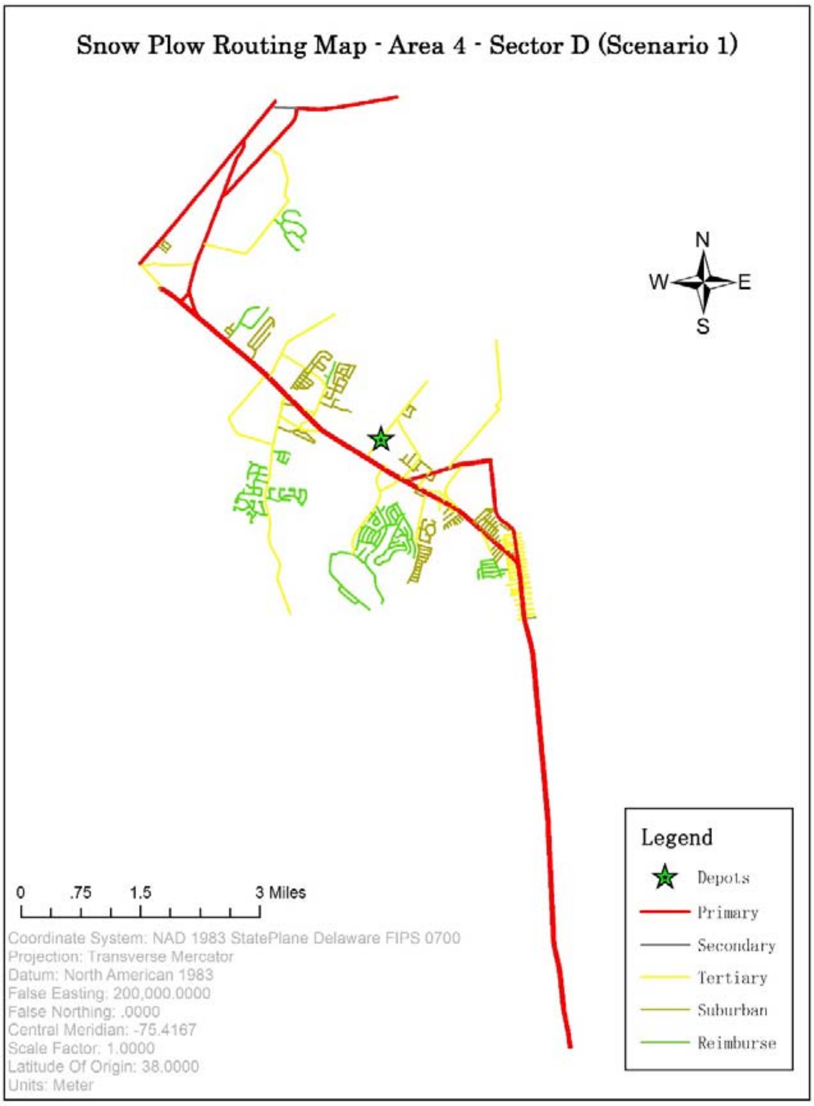

Figure 49: Snow Plow Roads and Classification Map – Area 4, Sector D

The Solution of Routing Problem - Scenario 1:

For this scenario, all specifications of snow-plow vehicles are ignored. Drivers are assumed to be able to operate all types of vehicles without difficulties on all level roadways.

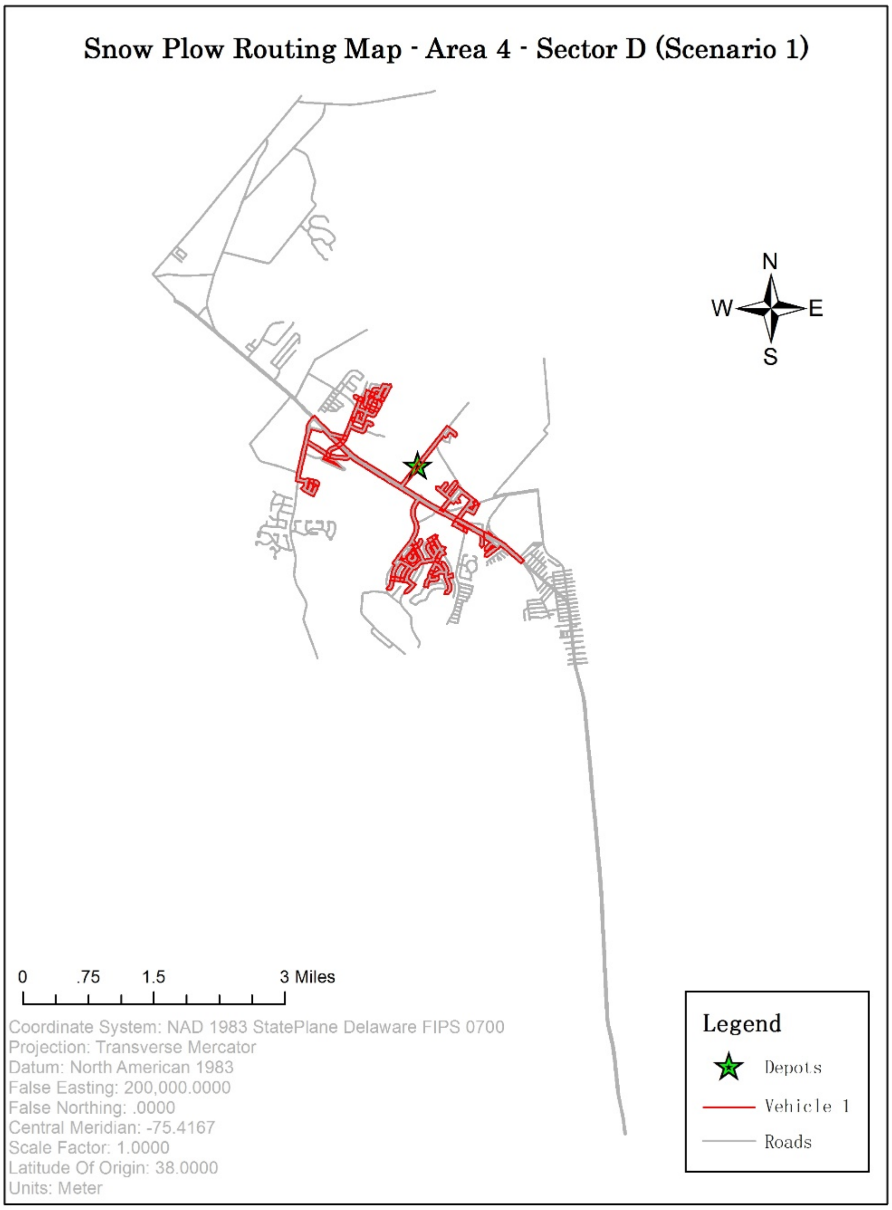

Figure 50: Snow Plow Route Map – Area 4, Sector D. Scenario 1, Vehicle 1

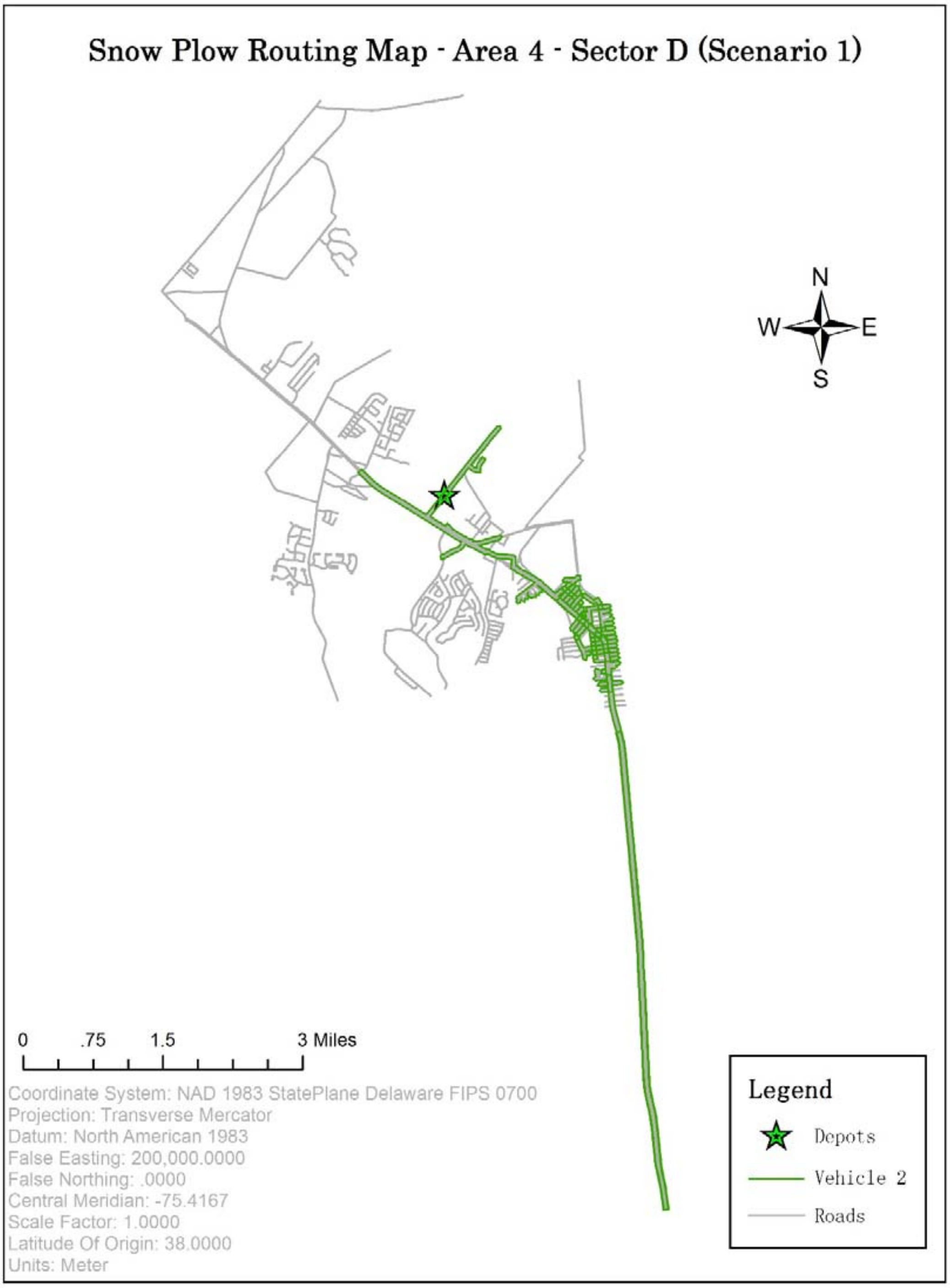

Figure 51: Snow Plow Route Map – Area 4, Sector D. Scenario 1, Vehicle 2

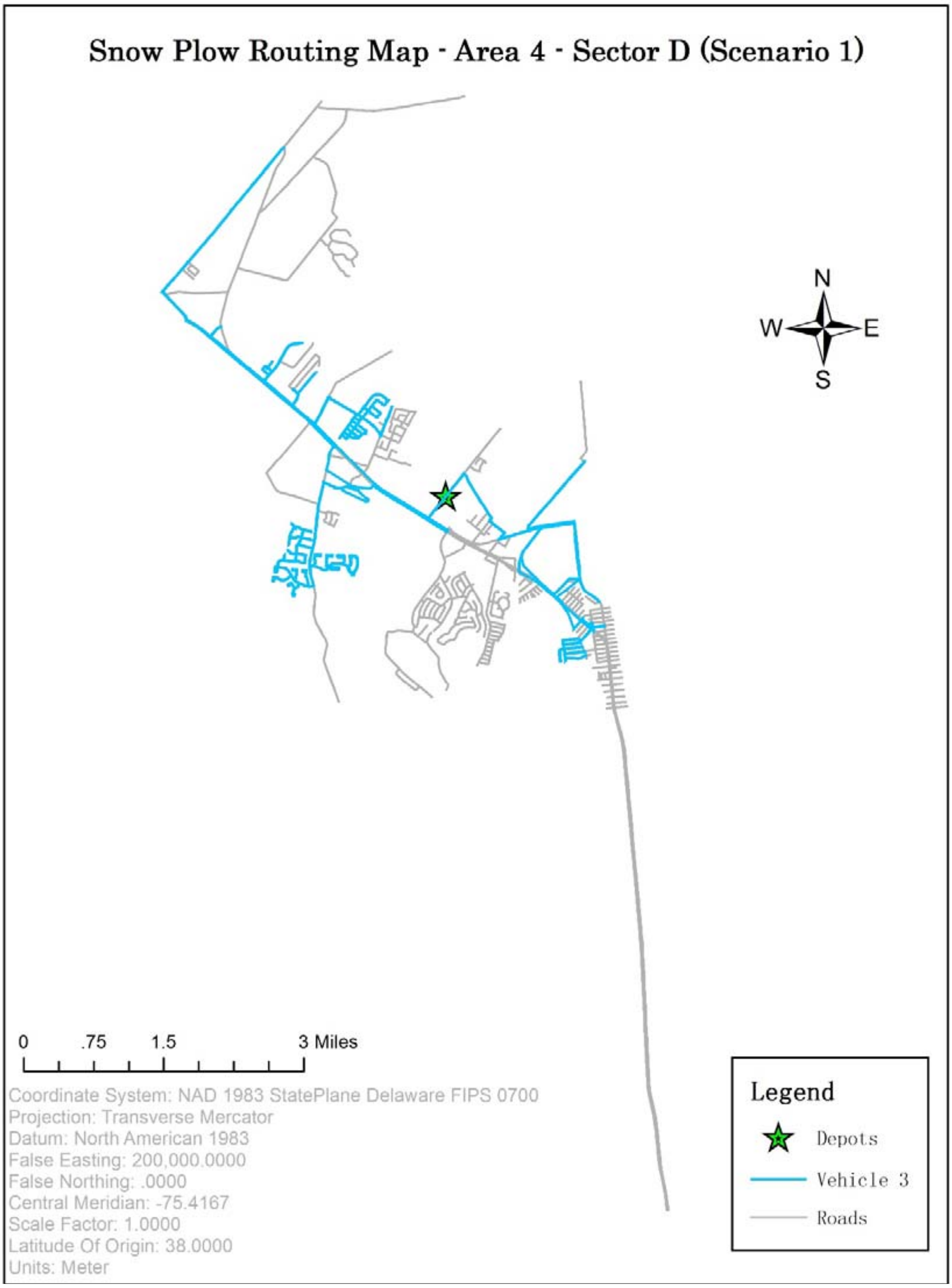

Figure 52: Snow Plow Route Map – Area 4, Sector D. Scenario 1, Vehicle 3

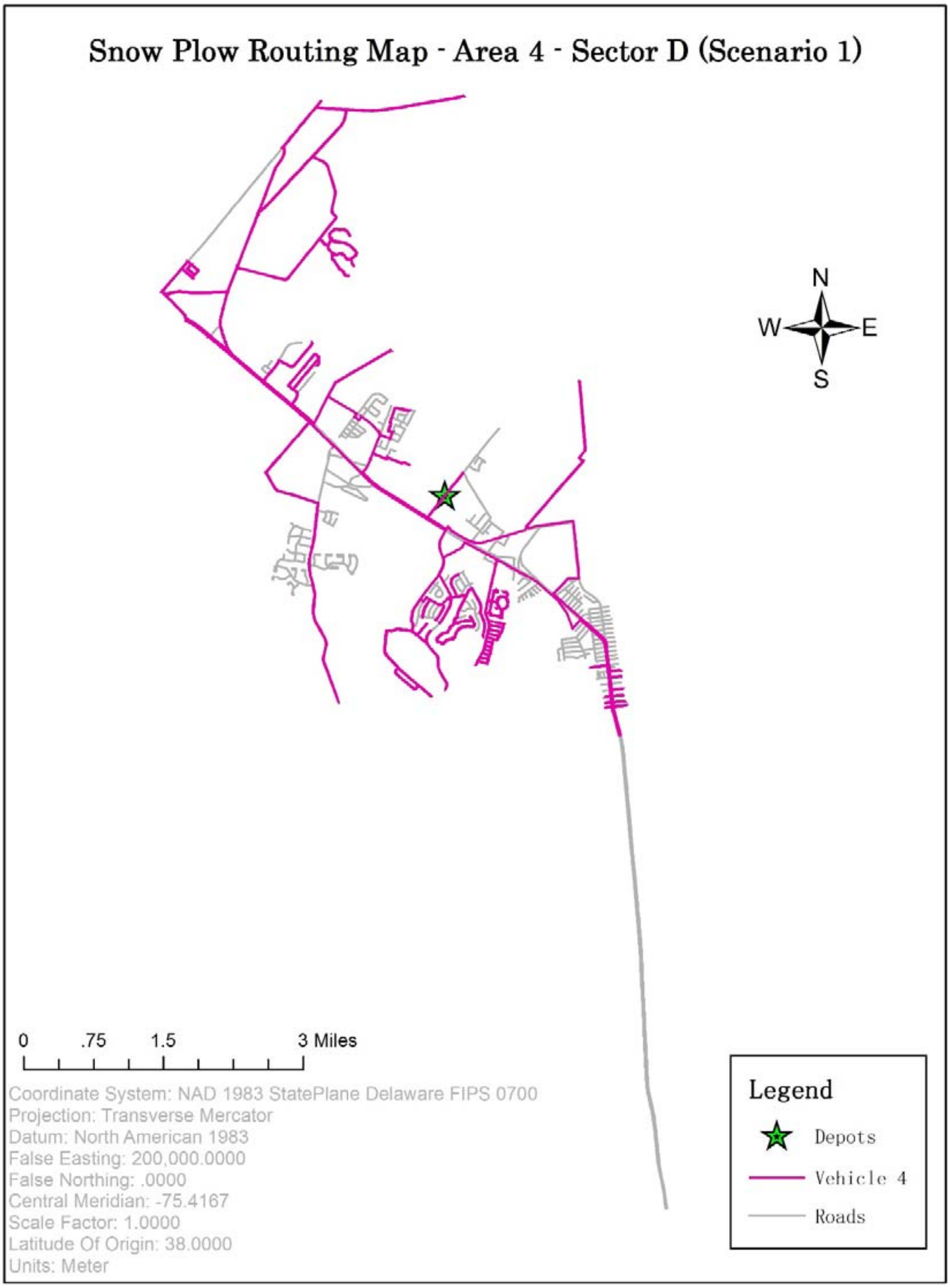

Figure 53: Snow Plow Route Map – Area 4, Sector D. Scenario 1, Vehicle 4

The Solution of Routing Problem - Scenario 2-1:

For this scenario, the model of snow-plow vehicles was added into consideration. 10-Wheels snow-plowing trucks are only assigned to serve the primary and secondary roads; 6-Wheels snow-plowing trucks are assigned to serve other classes of roads – tertiary, suburban and reimburse. ***Figure 54*** and ***Figure 55*** present the routing problem solution for two 10-Wheels trucks.

Figure 54: Snow Plow Route Map – Area 4, Sector D. Scenario 2-1, Vehicle 1

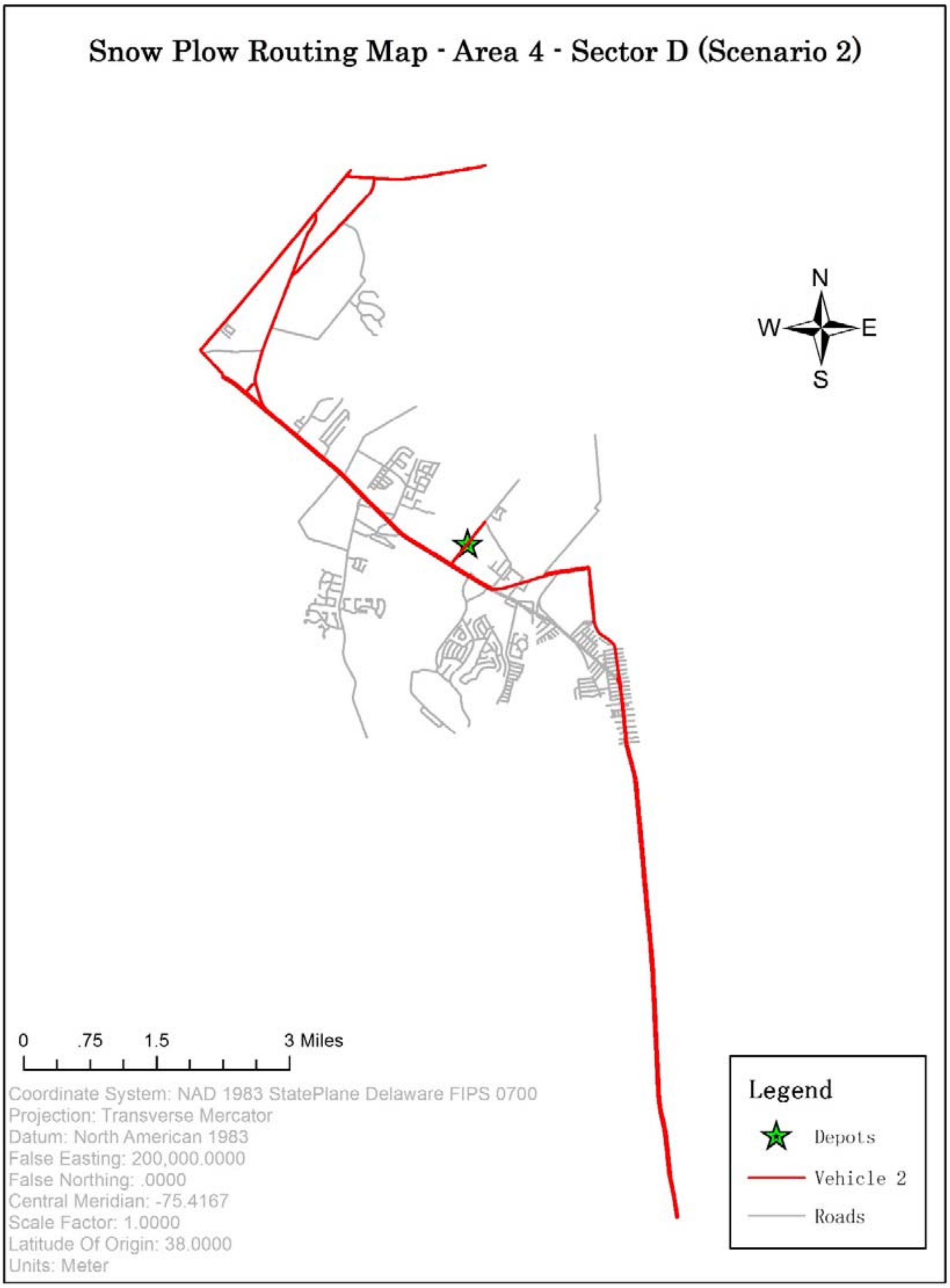

Figure 55: Snow Plow Route Map – Area 4, Sector D. Scenario 2-1, Vehicle 2

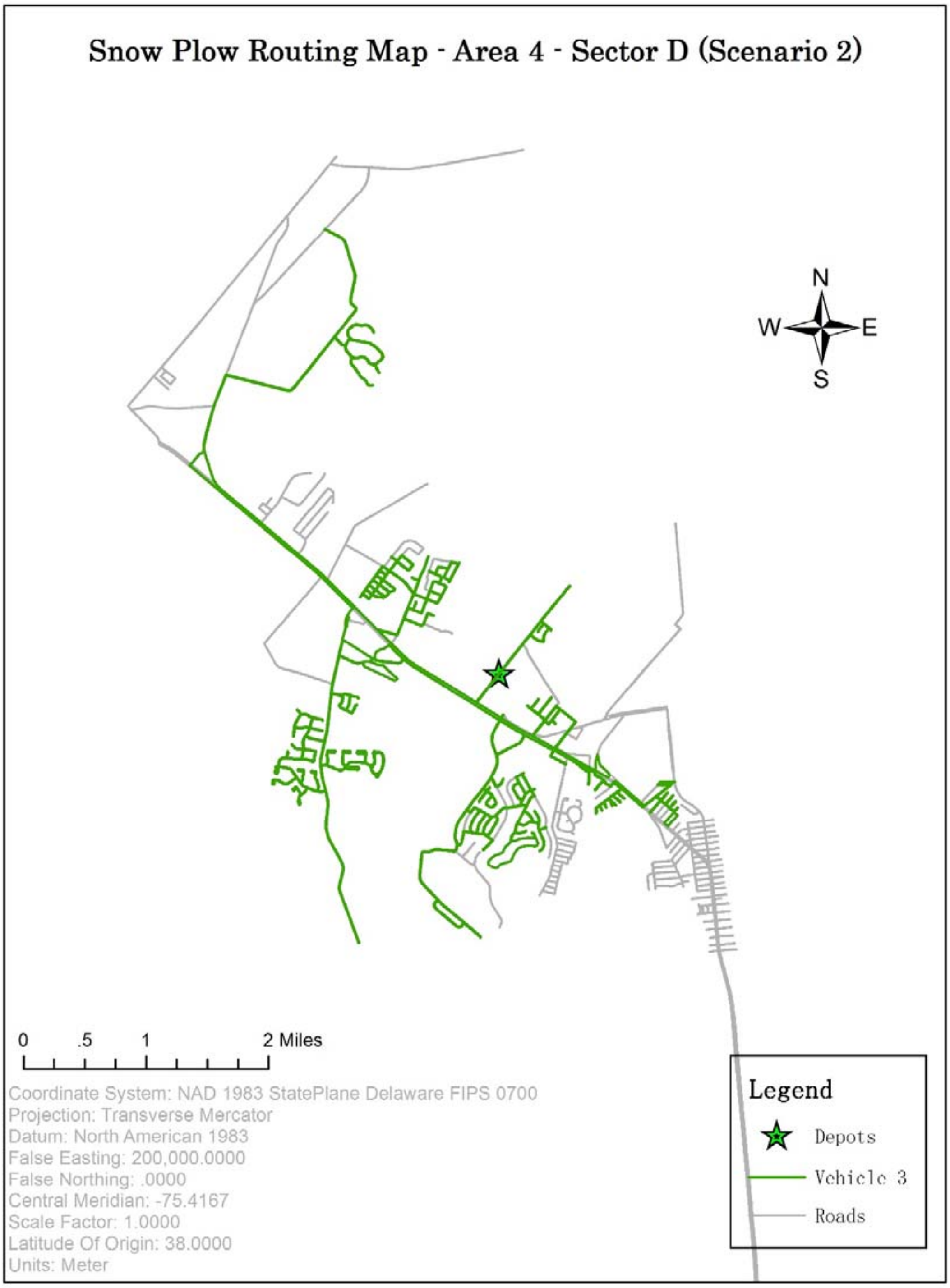

Figure 56: Snow Plow Route Map – Area 4, Sector D. Scenario 2-1, Vehicle 3

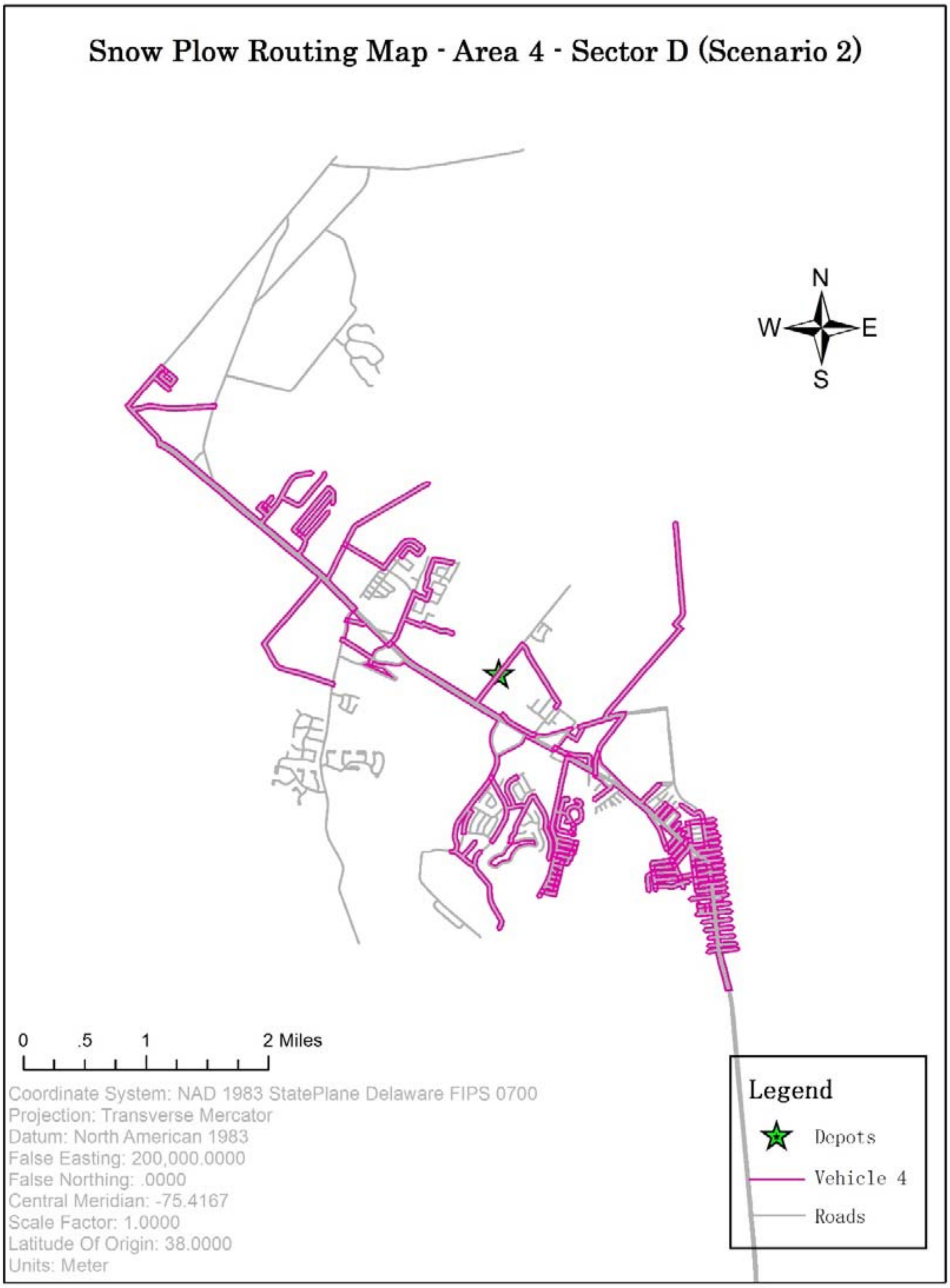

Figure 57: Snow Plow Route Map – Area 4, Sector D. Scenario 2-1, Vehicle 4

The Solution of Routing Problem - Scenario 2-2:

Under Scenario 2-1, as show in ***Figure 58*****,** the serving route of the vehicle 1 was too short. To improve the effectiveness of the routing result, the task to plow all primary roads are assigned to one vehicle instead of two. The vehicle 2 has been removed from the routing. The routing result was the same as the previous scenario for the vehicle 3 and 4.

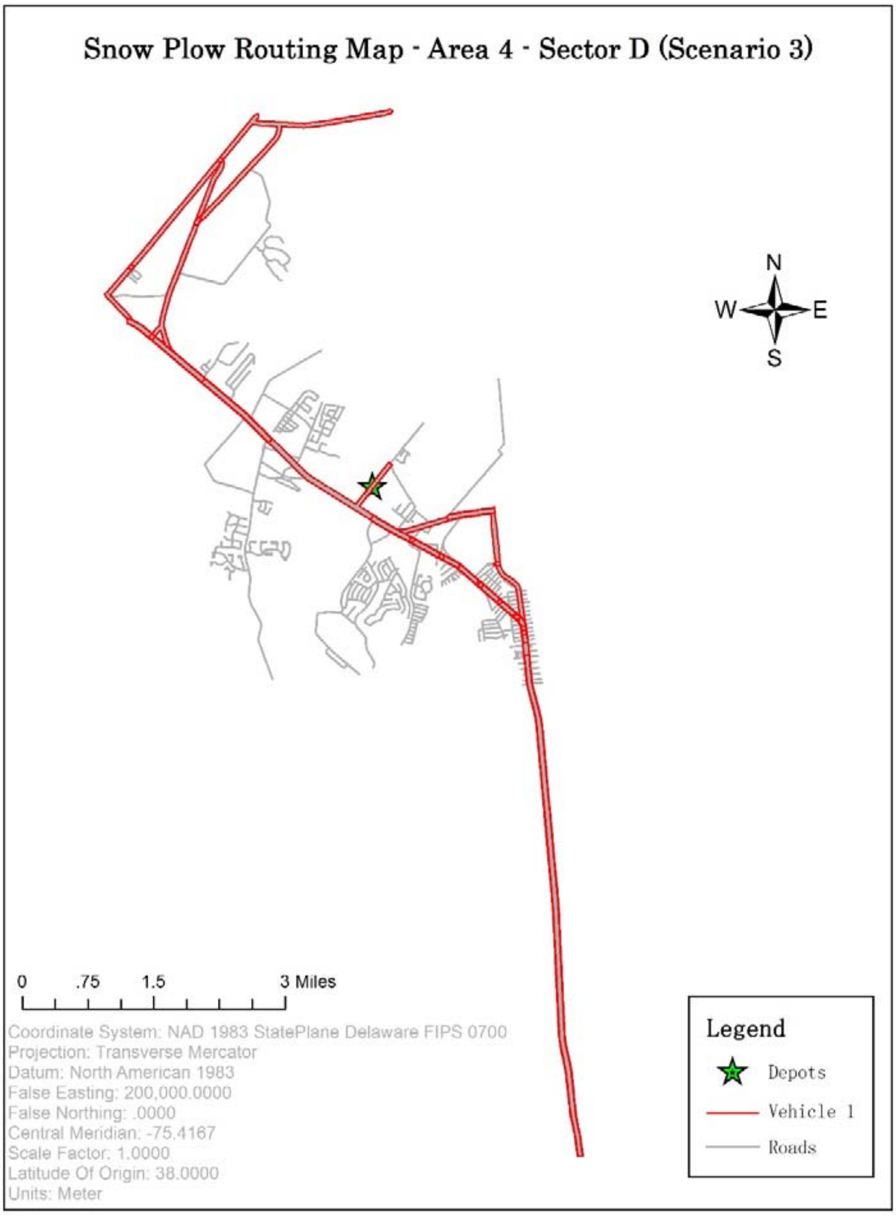

Figure 58: Snow Plow Route Map – Area 4, Sector D. Scenario 2-2, Vehicle 1

Result Comparison:

The snow plow routing results of two scenarios are shown below.

Table 7: Snow Plow Routing Results – Area 4. Sector D

Travel Time (Minutes)			
Vehicle	**Scenario**		
	1	**2-1**	**2-2**
1	74.05	22.12	114.08
2	88.97	94.21	-
3	116.56	158.67	158.67
4	169.07	180.00	180.00
Sum	448.65	455.00	452.75
Min	74.05	22.12	114.08
Max	169.07	180.00	180.00
STD	36.22242494	61.61318325	27.46448899

As shown by this table, the total travel times for the two scenarios are similar. Three scenarios have similar total travel time. The maximum of travel time under Scenario 1 are lower. Additionally, the standard deviation of travel time for Scenario 1 is small.

Area 5 – Sector D

To test the ArcGIS based method to solve routing problem, two routing solution has been developed according to two different scenarios. For both scenarios, five vehicles are assumed to complete the snow plowing task for this area. The solution of the routing problem is time-based. The solution will develop the overall least-time-consuming route for each vehicle.

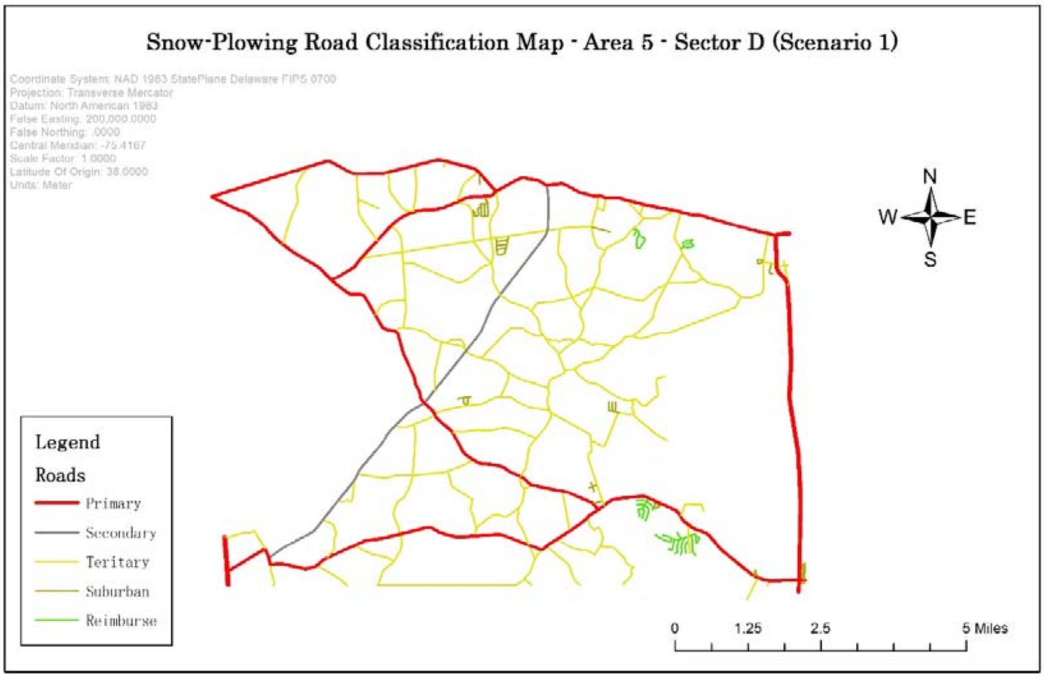

Figure 59: Snow Plow Roads and Classification Map – Area 5. Sector D

The Solution of Routing Problem - Scenario 1:

For this scenario, all specifications of snow-plow vehicles are ignored. Drivers are assumed to be able to operate all types of vehicles without difficulties on all level roadways.

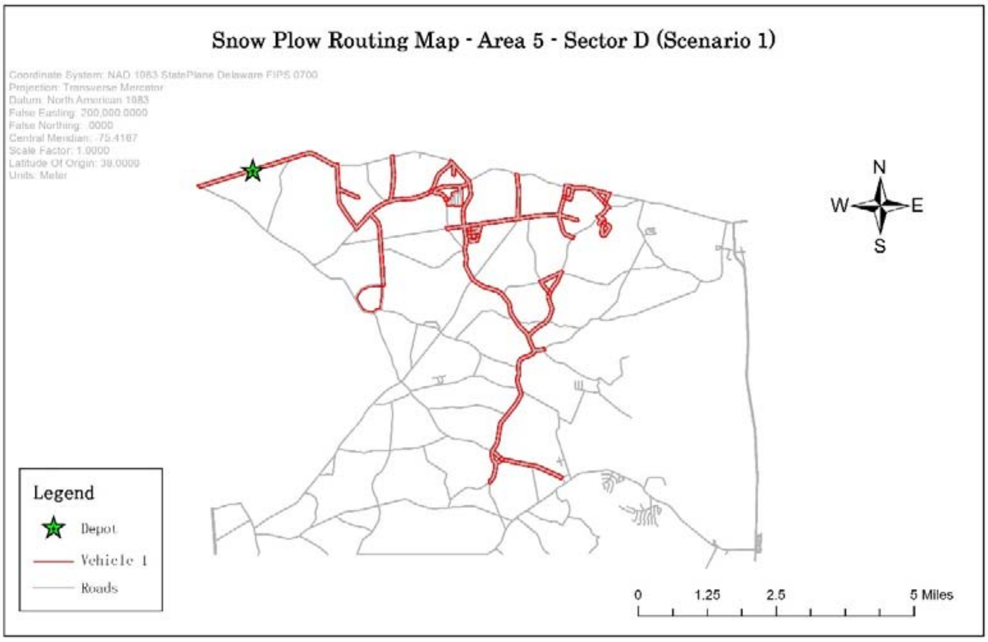

Figure 60: Snow Plow Route Map – Area 5. Sector D. Scenario 1, Vehicle 3

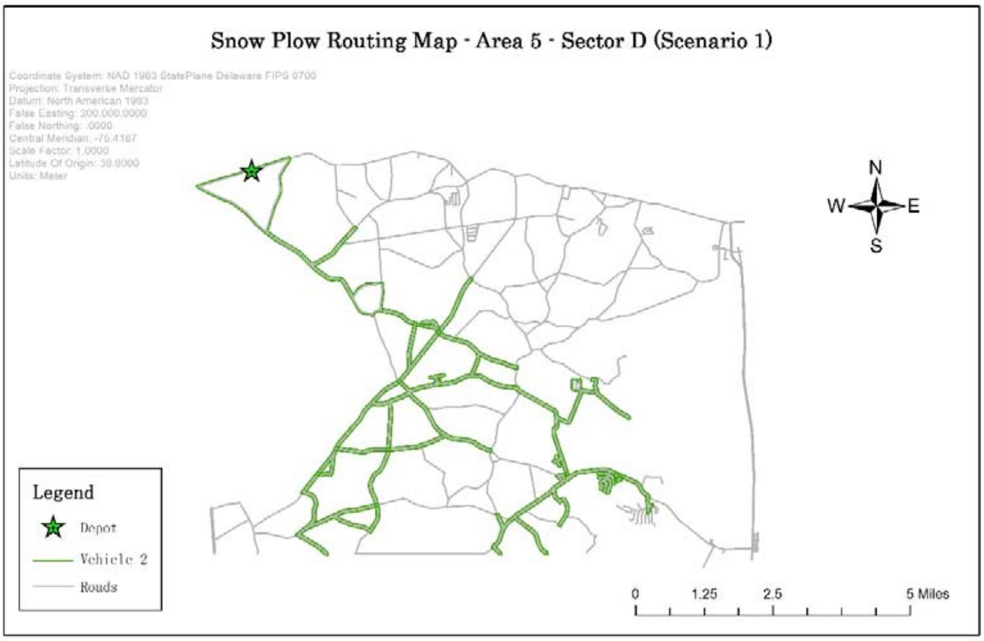

Figure 61: Snow Plow Route Map – Area 5. Sector D. Scenario 1, Vehicle 2

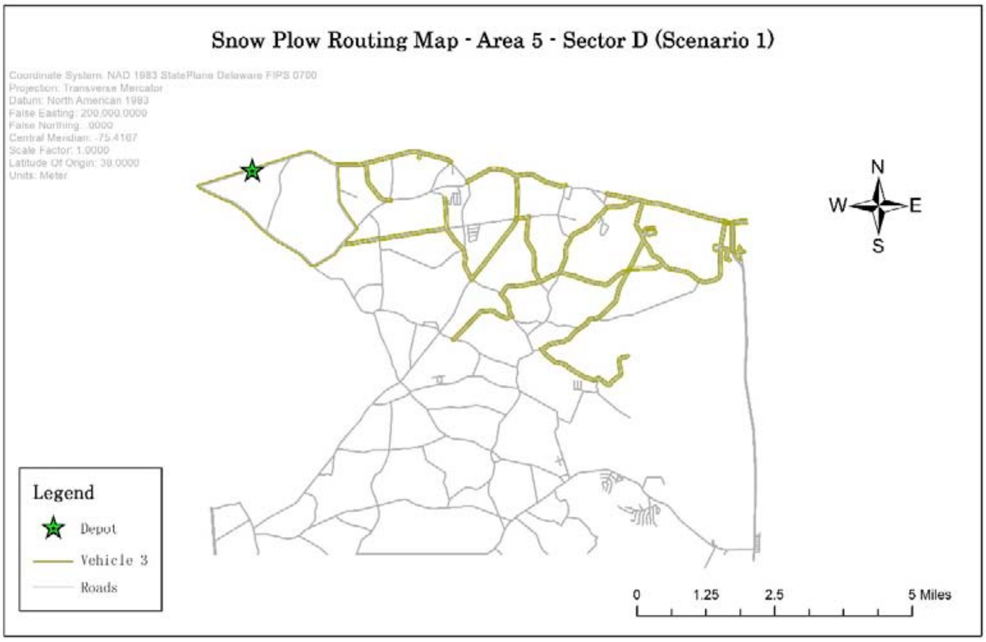

Figure 62: Snow Plow Route Map – Area 5. Sector D. Scenario 1, Vehicle 3

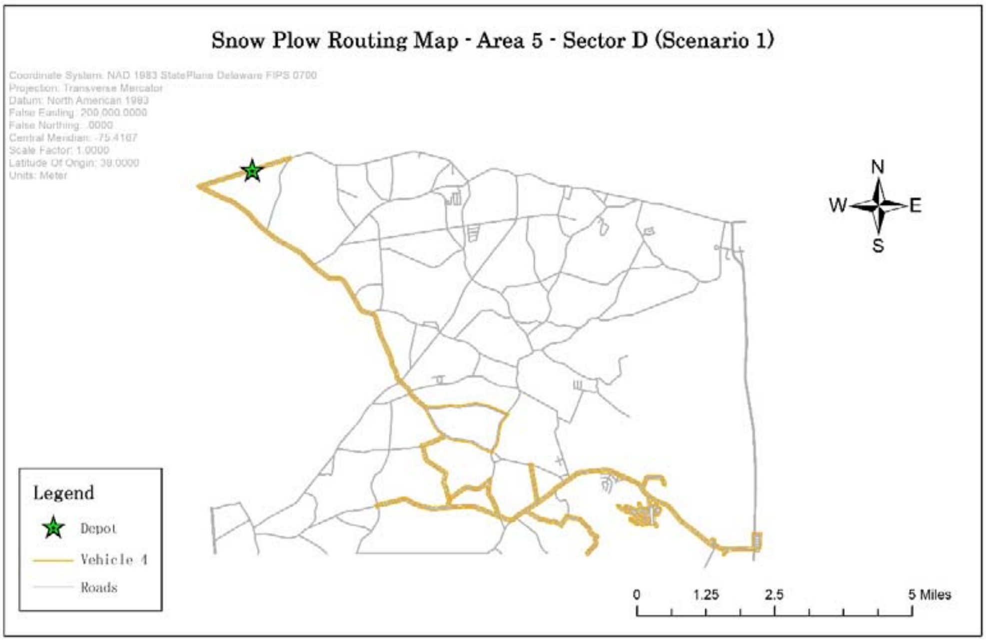

Figure 63: Snow Plow Route Map – Area 5. Sector D. Scenario 1, Vehicle 4

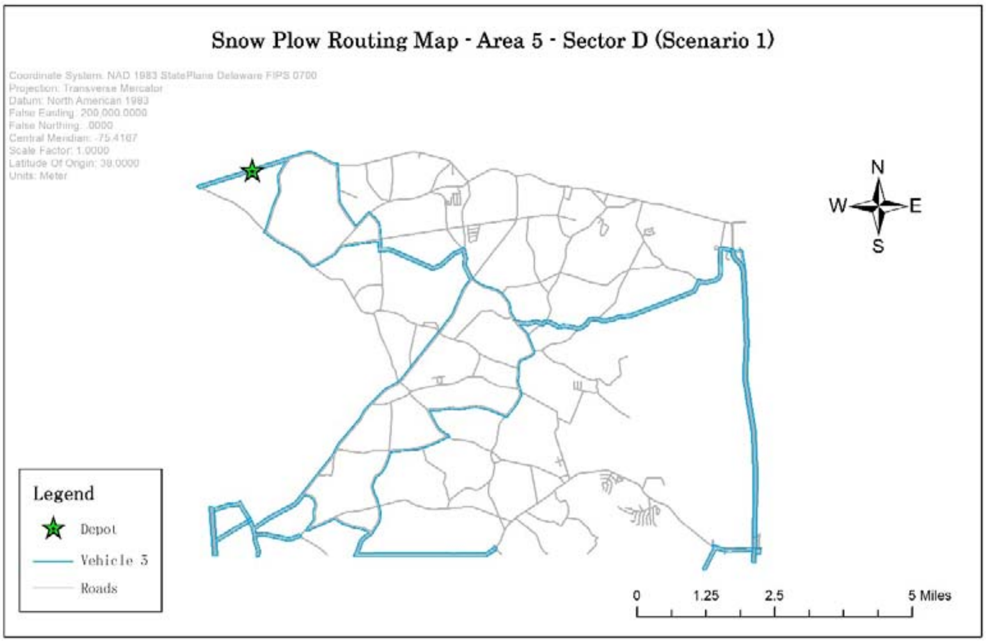

Figure 64: Snow Plow Route Map – Area 5. Sector D. Scenario 1, Vehicle 5

The Solution of Routing Problem - Scenario 2:

For this scenario, the model of snow-plow vehicles was added into consideration. 10-Wheels snow-plowing trucks are only assigned to serve the primary and secondary roads; 6-Wheels snow-plowing trucks are assigned to serve other classes of roads – tertiary, suburban and reimburse. ***Figure 65*** and ***Figure 66*** present the routing problem solution for two 10-Wheels trucks.

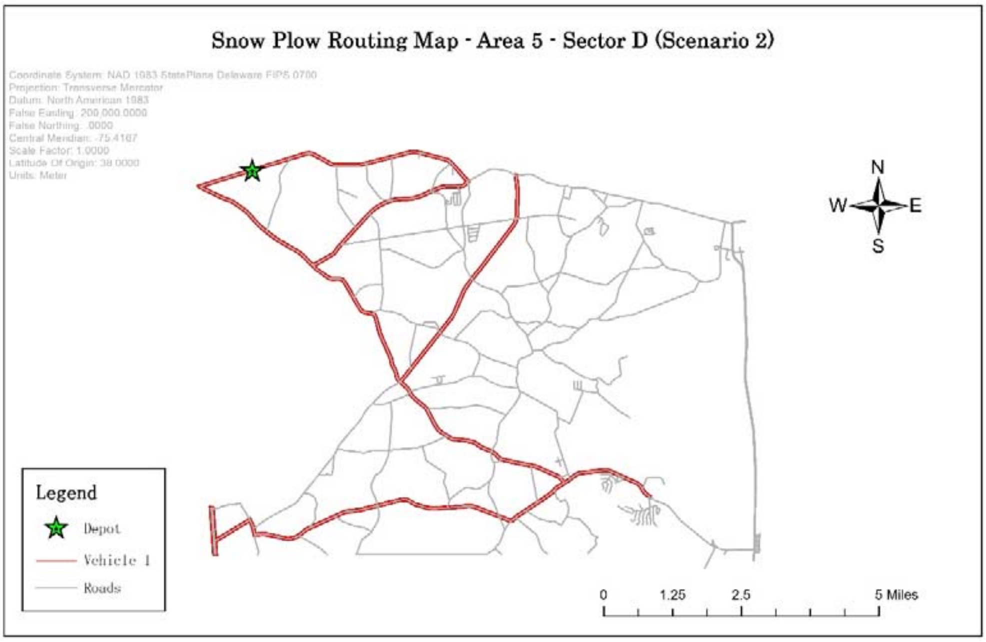

Figure 65: Snow Plow Route Map – Area 5. Sector D. Scenario 2, Vehicle 1

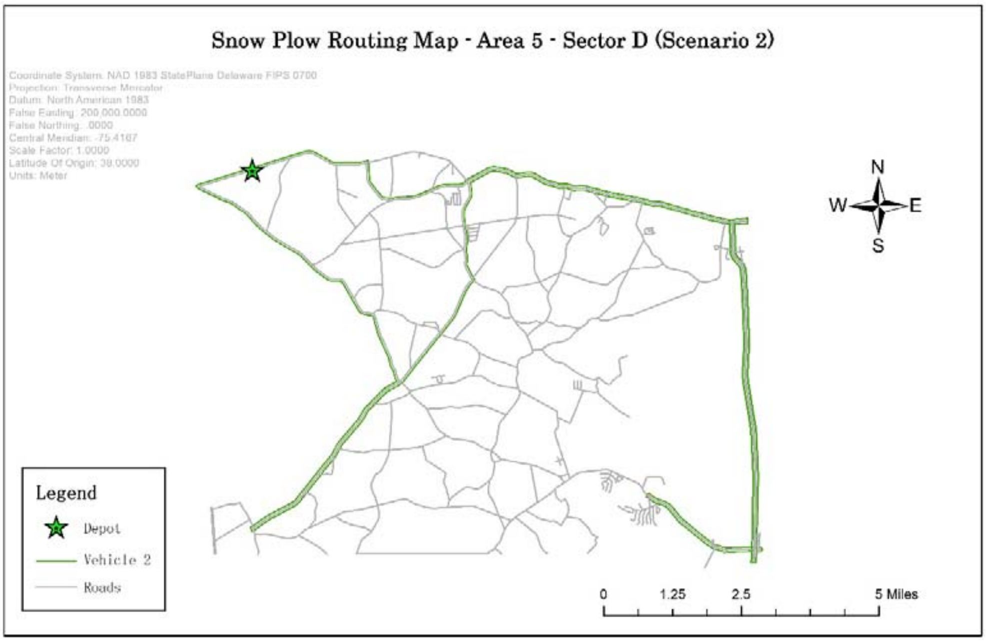

Figure 66: Snow Plow Route Map – Area 5. Sector D. Scenario 2, Vehicle 2

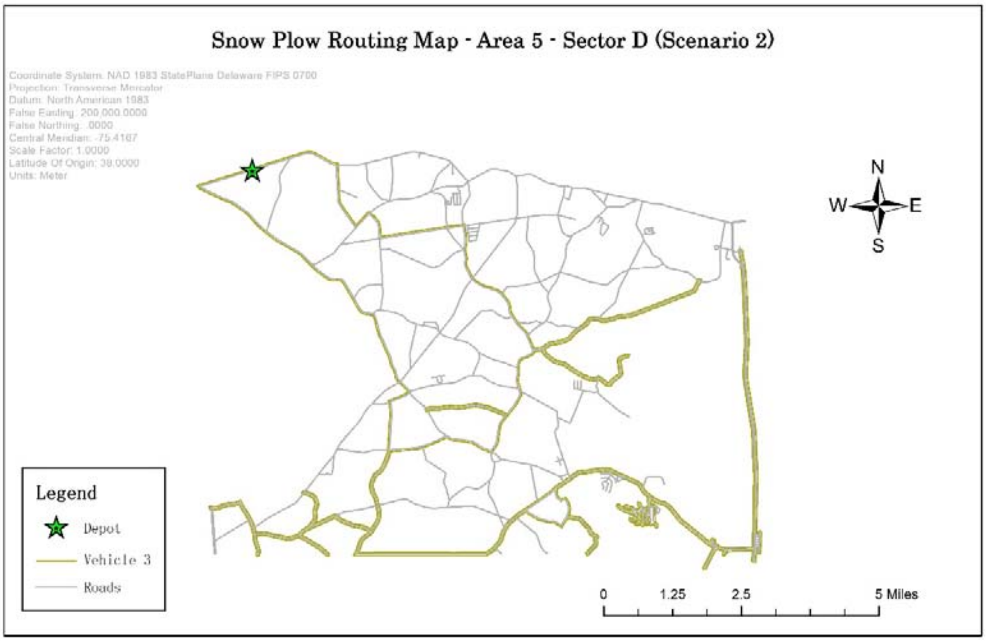

Figure 67: Snow Plow Route Map – Area 5. Sector D. Scenario 2, Vehicle 3

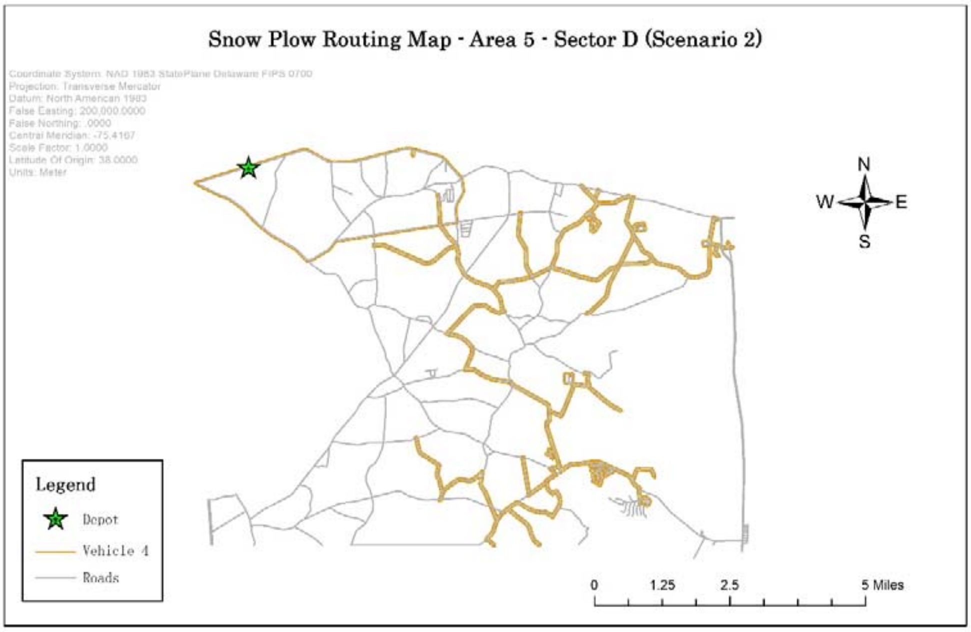

Figure 68: Snow Plow Route Map – Area 5. Sector D. Scenario 2, Vehicle 4

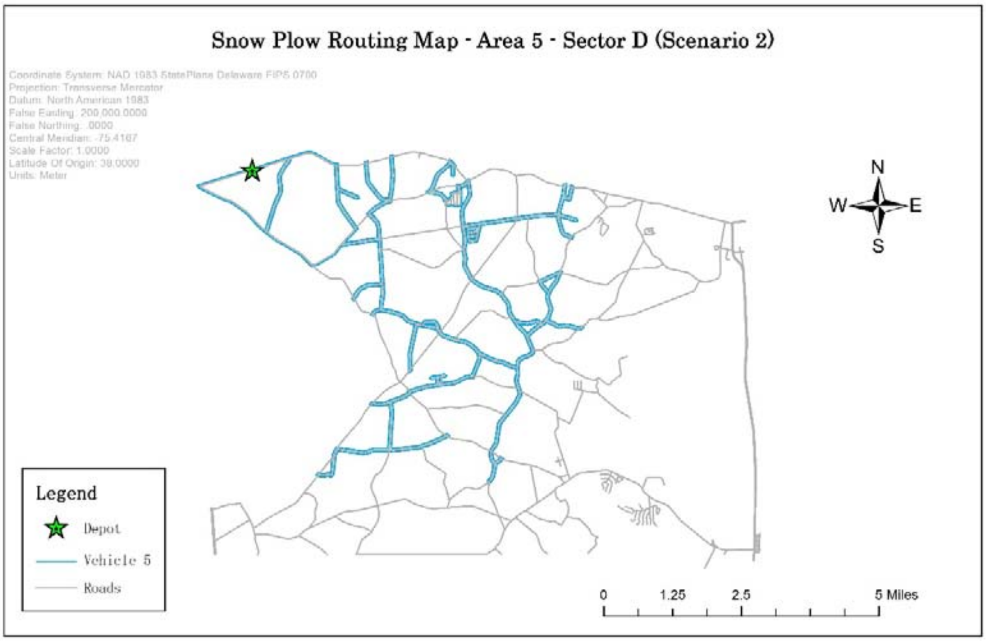

Figure 69: Snow Plow Route Map – Area 5. Sector D. Scenario 2, Vehicle 5

Result Comparison:

The snow plow routing results of two scenarios are shown below.

Table 8: Snow Plow Routing Results – Area 5. Sector D

Travel Time (Minutes)		
Vehicle	**Scenario**	
	1	**2**
1	124.90	100.61
2	95.94	101.31
3	125.88	123.49
4	103.08	152.61
5	128.16	140.30
Sum	577.96	618.32
Min	95.94	100.61
Max	128.16	152.61
STD	13.36553538	20.71639891

As shown by this table, the total travel times for the two scenarios are similar. The Scenario 1 has a lower total travel time than the other. The maximum and minimum and the standard deviation of travel time under Scenario 1 are lower.

Appendix C: List of Acronyms

ADOT	**Arizona Department of Transportation**
AHTD	**Arkansas State Highway and Transportation Department**
ALDOT	**Alabama State Department of Transportation**
Caltrans	**California Department of Transportation**
CDOT	**Colorado Department of Transportation**
CONNDOT	**Connecticut Department of Transportation**
DE	**Delaware**
DELDOT	**Delaware Department of Transportation**
ADOT&PF	**Alaska Department of Transportation and Public Facilities**
DOTD	**Louisiana Department of Transportation and Development**
FDOT	**Florida Department of Transportation**
FHWA	**Federal Highway Administration**
GDOT	**Georgia Department of Transportation**
GIS	**Geographic Information System**
HDOT	**Hawaii Department of Transportation**
I	**Interstate (route)**
IDOT	**Illinois Department of Transportation**
INDOT	**Indiana Department of Transportation**
Iowa DOT	**Iowa Department of Transportation**
ITD	**Idaho Transportation Department**
KDOT	**Kansas Department of Transportation**
KYTC	**Kentucky Transportation Cabinet**
MaineDOT	**Maine Department of Transportation**
MassDOT	**Massachusetts Department of Transportation**
Max	**Maximum**
MDOT	**Maryland Department of Transportation**
MDOT	**Michigan Department of Transportation**
MDOT	**Mississippi Department of Transportation**
MDT	**Montana Department of Transportation**
Min	**Minimum**
MnDOT	**Minnesota Department of Transportation**
MoDOT	**Missouri Department of Transportation**
NCDOT	**North Carolina Department of Transportation**
NCHRP	**National Cooperative Highway Research Program**
NDDOT	**North Dakota Department of Transportation**
NDOR	**Nebraska Department of Roads**
NDOT	**Nevada Department of Transportation**

NHDOT	**New Hampshire Department of Transportation**
NJDOT	**New Jersey Department of Transportation**
NMDOT	**New Mexico Department of Transportation**
NYSDOT	**New York State Department of Transportation**
ODOT	**Ohio Department of Transportation**
ODOT	**Oklahoma Department of Transportation**
ODOT	**Oregon Department of Transportation**
PennDOT	**Pennsylvania Department of Transportation**
RIDOT	**Rhode Island Department of Transportation**
SCDOT	**South Carolina Department of Transportation**
SDDOT	**South Dakota Department of Transportation**
SR	**State Route**
STD	**Standard Deviation**
TDOT	**Tennessee Department of Transportation**
TxDOT	**Texas Department of Transportation**
UDOT	**Utah Department of Transportation**
US	**United States (route)**
USDOT	**United States Department of Transportation**
VDOT	**Virginia Department of Transportation**
VPH	**Vehicles Per Hour**
VTrans	**Vermont Agency of Transportation**
WisDOT	**Wisconsin Department of Transportation**
WSDOT	**Washington State Department of Transportation**
WVDOT	**West Virginia Department of Transportation**
WYDOT	**Wyoming Department of Transportation**

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AN EQUAL OPPORTUNITY/AFFIRMATIVE ACTION EMPLOYER