An Integrated Systems Approach to the Development of Winter Maintenance/Management Systems

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Final Report
November 2006

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Technical Report Documentation Page

1. Report No. MTC Project 2005-03	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle An Integrated Systems Approach to the Development of Winter Maintenance/Management Systems		**5. Report Date** November 2006
		6. Performing Organization Code
7. Author(s) James S. Noble, Wooseung Jang, Cerry M. Klein, Charles J. Nemmers		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Midwest Transportation Consortium 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No.
12. Sponsoring Organization Name and Address U.S. Department of Transportation Research and Special Programs Administration 400 7th Street SW Washington DC 20590-0001		**13. Type of Report and Period Covered** Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

Winter road maintenance operations require many complex strategic and operational planning decisions. The five primary problems involved in this intricate planning procedure include locating depots, designing sectors, routing service vehicles, scheduling vehicles, and configuring the vehicle fleet. The complexity involved in each of these decisions has resulted mainly in research that approaches each of the problems separately and sequentially, which can lead to isolated and suboptimal solutions. After discussing the complexity of the relaxed subproblems that would need to be solved to optimize the intricate winter maintenance operations, the research turns to a heuristic approach to more feasibly address the interrelated problems.

This report subsequently presents a systematic, heuristic-based optimization approach to integrate the winter road maintenance planning decisions for depot location, sector design, vehicle route design, vehicle scheduling, and fleet configuration. The approach presented is illustrated through an example of public sector winter road maintenance planning for a rural transportation network in Boone County, Missouri.

When applied to the real-world winter road maintenance planning problems for Boone County, the methodology delivered very promising results. The solution methodology successfully achieves the objective of a more integrated and less sequential approach to the problems considered. The integrated solution would allow the Missouri Department of Transportation (MoDOT) to maintain the same high level of service with significantly fewer resources. The results indicate that this methodology is a successful step towards solving realistic multiple-depot problems involving heterogeneous winter maintenance fleets.

17. Key Words asset management—depot location—fleet management—operations management—snow removal—system optimization—vehicle routing—winter maintenance		**18. Distribution Statement** No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 88 pages	**22. Price** NA

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

AN INTEGRATED SYSTEMS APPROACH TO THE DEVELOPMENT OF WINTER MAINTENANCE/ MANAGEMENT SYSTEMS

Final Report
November 2006

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Preparation of this report was financed in part
through funds provided by the U.S. Department of Transportation
through the Midwest Transportation Consortium, Project 2005-03.

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ACKNOWLEDGEMENTS

The research team would like to thank the Missouri Department of Transportation (MoDOT) for their assistance in data collection and for providing feedback throughout the project. We would especially like to recognize Bob Lannert and Eric Schroeter’s contributions to this project in their roles as technical advisors.

EXECUTIVE SUMMARY

Winter road maintenance operations require many complex strategic and operational planning decisions; the five primary problems include locating depots, designing sectors, routing service vehicles, scheduling vehicles, and configuring the vehicle fleet. The complexity involved in each of these decisions has resulted mainly in research that approaches each of the problems separately and sequentially, which can lead to isolated and suboptimal solutions. In addition to being integrated, a successful approach to these problems must consider the necessary practical aspects of each problem and include an explicable and easily executable solution methodology; otherwise it is unlikely to be implemented.

This research proposes a systematic, heuristic-based optimization approach which uses a route first methodology to integrate the winter road maintenance planning decisions for the five interrelated planning decisions. The planning decisions include determination of the following: 1) locations of a predetermined number of depots, 2) the corresponding sectors for each depot, 3) the routes needed to service each sector, 4) a vehicle schedule dictating the route(s) assigned to each vehicle and the order of service, and 5) the number of each type of vehicle needed at each depot. The approach presented in this work is illustrated through an example of public sector winter road maintenance planning for a rural transportation network.

The decision objective is to meet predefined guidelines for a high level of service while minimizing the required number of vehicles. The quality of the service is defined using performance measures for the frequency of service for each road segment within the network (maximum route duration constraints) and the efficiency with which the entire network receives service (total weighted deadhead travel time).

The application of the integrated solution methodology developed in this research to the winter maintenance planning problems of Boone County, Missouri, resulted in a very promising solution. The initial routing approach applied in this research reduced the number of vehicles required from 23 to 18, a fleet reduction of 20%. A subsequent unconstrained approach yielded a solution which provides for the same level of service with an additional 10% reduction in resources (one fewer depot and two fewer vehicles) and a slight reduction of weighted deadhead travel time.

The results from this real-world test problem support the relevance of a more integrated approach to winter road maintenance problems. The integrated approach allowed the initial decision on the number of depots to open to be based on insight gained from the interrelated problems of route design and sector design. The solution methodology is designed to aid winter road maintenance planners in making decisions regarding the interrelated problems studied in this research, based on the effect that these decisions have on the agency’s ability to achieve a desired level of service. The ability to solve the winter road maintenance planning problems in a more integrated manner should provide planners with the ability to make more informed, successful decisions.

While this research addresses the problems of winter maintenance, there is potential to use an integrated systems design/operation approach such as this to address other department of transportation (DOT) maintenance activities such as pavement striping, mowing, and herbicide application. The potential cost savings to the DOTs would accrue in many areas.

CHAPTER 1: INTRODUCTION

1.1 Overview of Winter Road Maintenance Operations

Winter road maintenance operations require many complex planning decisions; the main strategic and operational problems include defining a service-level policy, locating depots, designing sectors, routing service vehicles, configuring the vehicle fleet, and scheduling the vehicles. Since the definition of a service-level policy is a prerequisite for the rest of these planning decisions, it can be handled separately. However, the remaining activities are all interrelated, in that the effect each decision has on some or all of the other decisions impacts the agency's ability to provide the desired level of service. Figure 1 presents an influence diagram for the complex interactions between the different winter road maintenance planning decisions.

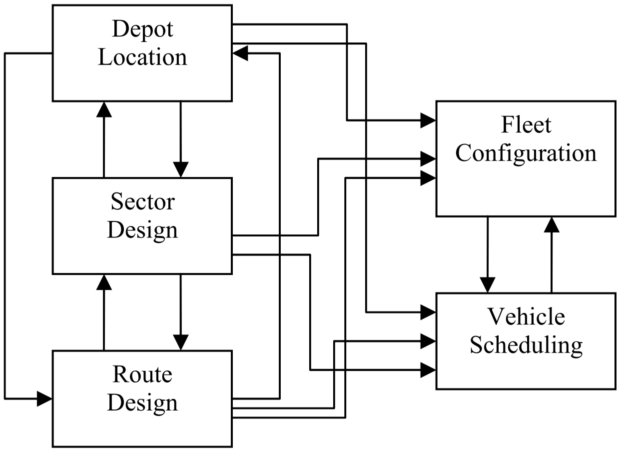


Figure 1. Influence diagram for winter road maintenance planning decisions

The problem of locating depots entails determining the number of depots to open and where to open them. The depot location problem is often solved by choosing to open a preset number of depots from a set of candidate sites based on predefined strategic and operational objective(s). Since designing sectors involves the assignment of arcs requiring service to the depots responsible for servicing them, the sector design problem is often solved in conjunction with the depot location problem, both in practice and in existing research methods.

Winter road maintenance routing problems usually require that a set of routes is determined to optimize some performance criteria. These routes are serviced by vehicles starting and ending at their respective depots, such that all required road segments are serviced and all the operational constraints are satisfied. Routes are typically restricted either by duration or distance limitations. If a maximum duration—the time by which a route must receive further service—constrains the route length, then the number of routes and vehicles required are equivalent; this is often the case in existing research. If the maximum distance constraint dominates the duration constraint, then it may be possible for a vehicle to service multiple routes prior to reservicing any of them. If this is the case, then the vehicle scheduling problem must be solved as well.

The process of determining fleet configuration depends on whether or not the fleet is homogeneous. Many research studies assume the fleet to be homogenous, although heterogeneous fleets are often the norm in practice. If the fleet is assumed to be homogeneous, the problem is reduced to a fleet sizing problem with the objective of determining the number of vehicles required at each depot. Otherwise, the problem is more complex and consists of determining the number of each type of vehicle that should be based at each depot. The solution to the fleet configuration problem is dictated by the vehicle routes and schedule.

In the context of public-sector winter road maintenance, the problems of locating depots, designing sectors, routing service vehicles, and configuring the vehicle fleet are especially complex. The inherent complexity of these winter road maintenance planning problems stems from 1) the difficult-to-quantify objective of maximizing the public's perceptions of service, 2) the urgent nature of the service requirements, 3) the varying operating conditions and constraints, and 4) the budgetary limitations on resources.

1.2 Optimization-Based Approach to Aid Decision Making

Public agencies have been performing winter road maintenance planning and operational activities since as early as 1881 (Campbell and Langevin 2000). However, surveys by Gupta (1998) and Campbell and Langevin (2000) found that most agencies do not utilize any formal methods for locating depots or designing routes, respectively. Both works suggest that most agencies still rely in large part on assessments dictated by field experiences when making depot location and vehicle routing decisions. There is considerable research which highlights the benefits of an optimization-based approach and proposes such methods designed to aid planners in making winter road maintenance decisions.

One of the most compelling reasons for the use of a formal optimization-based methodology is that changes in personnel often result in insufficient experience to make effective decisions. Additionally, changes in service-level requirements, the road network, traffic levels, budgetary constraints, or other operational constraints may increase the complexity of planning decisions and cause discontinuities between past and present operational requirements. As a result, past experience would become less relevant in the decision-making process.

Another motivation for implementing an optimization-based approach is that current winter road maintenance planning decisions would not be not restricted by previous ones. Often, public service agencies make minor annual adjustments in an attempt to improve operations, but these adjustments cause new decisions to be restricted by the efficacy of those made previously. In contrast, an optimization-based approach attempts to make decisions based on strategic objectives, operational constraints, and the topology of the road network. Therefore, new solutions are not restricted by previous practices or existing operational beliefs. This is not to say that experience is not a significant aspect of winter road maintenance planning; it is crucial that any optimization-based approach utilizes the knowledge of experienced planners to determine the objectives, constraints, and other factors. This will increase the chances of a solution being both accepted and implemented. A successful optimization-based approach to winter road maintenance will most likely be one that aims to aid planners in the decision-making process rather than dictate final solutions.

Although the benefits of an optimization-based approach to winter road maintenance planning are undeniable, this formal approach is seldom implemented because the methods are unappealing to public service agencies or seem too difficult to implement. Campbell and Langevin (2000) cited the distrust of computer-based “black box” approaches and an inability to capture the necessary operational complexities as primary reasons that neither optimization approaches nor software have been utilized in practice. To increase the chance of acceptance and implementation, a solution methodology should be explainable to planning personnel, at least to the level that the objectives and operational constraints included are clear and the desired solution can easily be achieved.

1.3 Opportunity for an Integrated Solution Methodology

The multifaceted complexity of winter road maintenance planning indicates how difficult it is to make planning decisions based solely on experience. These complexities create an opportunity for improving the planning process through the implementation of a formal optimization-based methodology. Ironically, it is the same complexities which have hindered progress in developing successful optimization-based approaches to these problems. The lack of research which attempts to integrate the chief winter road maintenance planning decisions can not be attributed to a lack of recognition of the importance of doing so; rather, it is a result of the complexity of each of the problems involved. Reinert, Miller, and Dickerson (1985) pointed out that the four problems of depot location, sector design, vehicle routing, and vehicle scheduling would “ideally be solved simultaneously” but dismissed the idea saying that it is “not practically accomplished.” Traditionally, research approaches have followed this same belief, addressing the main winter road maintenance problems separately or, in a few cases, sequentially.

The problem of sector design is usually solved in conjunction with depot location. Vehicle routing problems usually assume a predetermined depot location and corresponding sector. As a result, there are few research works that solve the combined problems of sector design, depot location, and vehicle routing, and those that do combine them invariably approach the problems sequentially.

Most of the existing research on winter road maintenance vehicle routing and combined location routing problems assumes that the number of routes is equivalent to the number of vehicles. In practice, however, the capacity constraint may dominate the time duration constraint, making it possible for a vehicle to service multiple routes prior to reservicing any of them. If this is the case, then the vehicle scheduling problem must be solved as well.

Additionally, most winter road maintenance vehicle routing problems and combined location routing problems assume a homogeneous fleet. To make the problems more realistic, a heterogeneous fleet should be assumed, and the fleet configuration and vehicle scheduling problems should be addressed in addition to the sector assignment, depot location, and vehicle route design problems.

In addition to the compelling aforementioned reasons for a systematic optimization-based approach to winter road maintenance planning, an integrated approach provides further benefits. The primary argument for an integrated approach is to provide higher-quality solutions by avoiding the suboptimization or local optimization that may occur in approaches which treat each problem individually. Suboptimization can result from treating each problem individually in succession, since the solution to each problem is restricted by the solutions to any preceding problems.

Perhaps the reason most appealing to winter road maintenance planners is the ability to assess the impact that depot location decisions have on the agency's ability to provide a high level of service. Currently, there is little research which allows planners to assess the impact of changes in the number and locations of depots on an agency's ability to provide a high level of service.

1.4 Framework for Integrating Winter Road Maintenance Problems

The complexities involved in each of the individual problems of depot location, sector design, vehicle routing, vehicle scheduling, and fleet configuration necessitate careful analysis to determine the significant aspects of each problem in order to unify them in an integrated approach. Recognition of a common objective or objectives is the first step in integrating these winter road maintenance planning decisions. Stricker (1970) discussed differences in the objectives of private-sector and public-sector routing operations. The author concluded that, while the former is driven by economic objectives—usually costs—the latter is motivated by a desire to improve service and instead treats cost as a budgetary constraint. The desire to provide an acceptable level of service in order to increase public safety and welfare is also the objective of the winter road maintenance operations in Boone County, Missouri, and it is the primary objective of the integrated solution methodology presented in this research.

In addition to identifying a common objective, it is necessary to determine the scope of each problem involved. The determination of an acceptable scope for the integration of the winter road maintenance planning problems ensures the inclusion of a pragmatic level of complexity for each of the included problems. It could be argued that the location of a depot should be based on the annual road maintenance performed by the facility. However, considering additional year-round operations increases the complexity of the decision-making process considerably and may not improve the desired result, because winter road maintenance operations are the most significant. Gupta (1998) found that, although other activities are important, they will "not have an impact on the location of garage or outpost, because a single activity such as snow and ice control dominates the budget." In states where snow and ice control does not significantly dominate the budget, it can still be argued that this operation is the most important. Gupta (1998) stated that "snow removal and ice control, if not executed properly, can be the single most deterrent [factor] to the quality of service of highways, thus creating the most hazard and loss to the economy." For this reason, winter road maintenance operations require more urgent service than any other planned maintenance activities. Therefore, depots should be in a position to increase the speed of the winter road maintenance service response. While maintenance activities such as road resurfacing and pothole filling may be required often, the locations are unpredictable. In contrast, winter road maintenance occurs on the same defined road network every year. Therefore, the consistency of the operations is another reason that it dominates the location of the depots. Finally, the objective of winter road maintenance results in depot locations which provide better service to higher priority roads than lower priority roads, which lends itself well to other operations which also aim to focus service on the roads which provide the greatest benefit to the public. Therefore, the scope of the depot location problem for this research is limited to winter road maintenance activities—a scope which does not detract from the quality of the solution and makes a feasible solution more easily attainable.

Winter road maintenance operations by themselves still present a great level of complexity. The main operations involved in winter road maintenance include pre-treating or spreading, combined spreading and plowing operations, and pure plowing. Pre-treatment usually occurs prior to a storm event, and pure plowing—often called cleanup—occurs once a storm has subsided. Though all of the operations are important, the most significant to the depot location is the plowing-and-spreading operation that occurs during a winter storm event. The combined plowing and spreading operation is the bottleneck winter road maintenance activity because it has the most urgent demand, requires the greatest service effort in terms of total time spent, and has the strictest capacity constraints. As a result, all other winter road maintenance operations can be performed more quickly and require fewer resources in terms of operators, vehicles, and material. For this reason, the scope of the winter road maintenance operations included in the integrated planning approach is limited to the combined spreading and plowing operation.

A careful analysis of the winter road maintenance operations and planning decisions has led to a logical and reasonable problem scope, which should allow for the included decisions to be handled in an integrated manner. However, the complexity of the integrated winter road maintenance planning decisions, within the defined problem scope, still prevents the realization of an optimal solution. Ideally, a fully integrated integer or mixed-integer program would be developed to include all of the individual characteristics of each of the five major problems—depot location, sector design, route design, vehicle scheduling, and fleet configuration—and the complex interactions between them. This type of solution approach would allow for the problems to be simultaneously and optimally solved. However, the complexity of the individual winter road maintenance planning decisions considered in this research and the limitations on computer processing speed make the realization of an optimal solution currently infeasible.

As a result, this research takes a heuristic-based approach to the five integrated winter road maintenance problems. The solution approach solves the integrated problem in phases, integrating some—but not all—of the individual problems in each phase. The initial solution phase solves the integrated problems of depot location, sector design, and route design. Then the solution improvement phase attempts to improve the solution to the route design and sector design problem (based on the already-determined depot locations), and determine the solutions to the vehicle scheduling and fleet configuration problems. Figure 2 shows the problems and the interactions that are considered in the two solution phases.

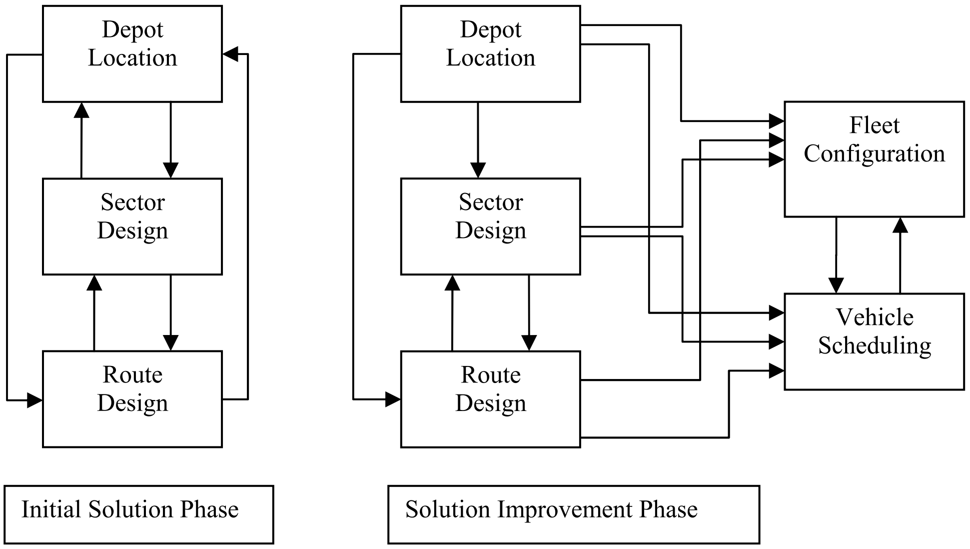


Figure 2. Problems and interactions by solution phase

A successful solution methodology should be explainable to winter road maintenance planners and easily solvable by them; otherwise, it is unlikely to be accepted, much less implemented. A heuristic-based approach lends itself to the goal of an explicable and easily solvable solution methodology. A formal optimization solution methodology that can not be logically explicated is likely to be dismissed by planners, because they may not understand the motivation and methodology and therefore perceive it as a "black box" solution. Also, a formal optimization-based method is likely to be much more complex and it is most likely not able to solve problems of realistic size in a reasonable amount of computing time; on the other hand, a heuristic-based optimization approach lends itself to the goals of an explicable and easily solvable solution methodology and is capable of solving an integrated winter road maintenance problem of realistic size and scope.

The vehicle routing problem is the most complex of the winter road maintenance problems included in this research. Therefore, the solution approach for the routing problem forms the basis of the integrated solution methodology. There are two common heuristic approaches to arc routing problems: 1) a cluster first–route second approach and 2) a route first–cluster second approach. The cluster first–route second approach divides the transportation network into mutually exclusive subsets and then constructs a route for each subset. In contrast, the route first approach creates one giant route throughout the entire transportation network, and then partitions the route into smaller feasible routes. There is little research that approaches winter road maintenance problems using a route first–cluster second approach; much research in this area instead utilizes a cluster first–route second approach. Figures 3 and 4 show each of these two methods as applied to a small network.

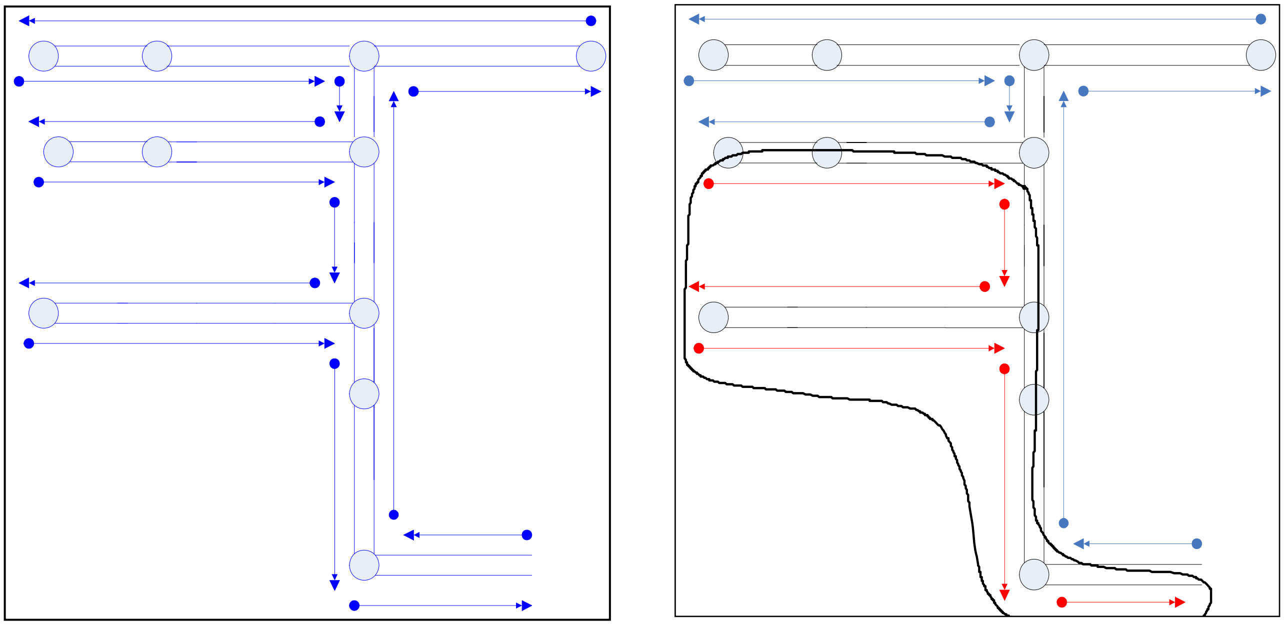


Figure 3. Route first–cluster second method

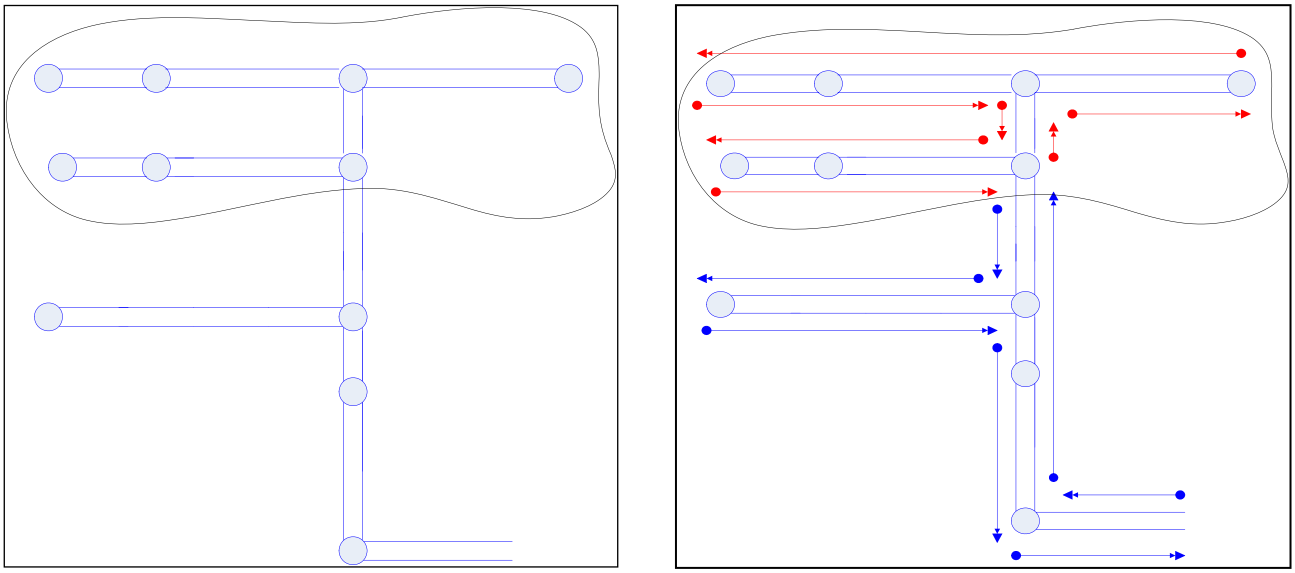


Figure 4. Cluster first–route second method

Robinson, Ogawa, and Frickenstein (1990) compared the two approaches on a two-snowplow routing problem on a test network in Wicomico County, Maryland. The results showed that both methods resulted in the same total mileage, but the cluster first–route second method produced fewer u-turns and more balanced routes. However, the authors mentioned that the cluster first–route second approach attempted to balance the routes and reduce u-turns, while the route first–cluster second method included no mention of attempting to reduce u-turns or balance the routes.

In addition, Bodin and Berman (1979) compared the two methods for a school bus routing problem and reported that the route first–cluster second approach provided better solutions than the other approach. It is difficult to determine which approach is better suited to winter road maintenance routing problems, because there is insufficient research that utilizes a route first–cluster second approach to winter maintenance or that compares the two methods.

For the winter road maintenance routing problem on a directed transportation network, the route first–cluster second approach seems the more logical approach because it factors in the direction of traffic flow, the accessibility of an arc from each of the other arcs, and the total travel time throughout the network. The contrasting cluster first–route second approach attempts to create compact clusters by dividing the network based on the distances between each of the arcs. Also, many cluster first–route second approaches to routing define clusters based on the location of the depots; that strategy is not an option for this research, since the depot locations are determined in conjunction with the routes. Therefore, a route first–cluster second routing approach is the basis for the integrated approach to the winter road maintenance problems that is proposed in this research.

1.5 Summary of the Research Objective

A systematic, heuristic-based optimization approach allows planners to deal with discontinuities between past and current operational requirements, which may result in new decision-making challenges. The utilization of a formal method prevents new winter road maintenance planning decisions from being restricted by previous decisions and traditional operational beliefs; instead it promotes decisions based on strategic objectives, operational constraints, and the topology of the road network.

This research develops a more integrated and less sequential approach to the main winter road maintenance planning decisions in an attempt to provide higher quality solutions, avoiding the suboptimization that may occur in treating each problem individually. Additionally, an integrated approach provides planners with a means for assessing the impact of depot location decisions on the agency's ability to provide a high level of service.

The approach discussed in this research is developed with respect to Missouri Department of Transportation's (MoDOT) winter road maintenance operations and planning for Boone County, Missouri; therefore, this study focuses on public sector winter road maintenance planning for a rural transportation network. It should be stressed that the integrated approach developed in this research is targeted towards aiding winter road maintenance planners rather than dictating a final solution to them. This research proposes a systematic, heuristic-based optimization approach to integrate the winter road maintenance planning decisions for depot location, sector design, vehicle route design, vehicle scheduling, and fleet configuration.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview of Relevant Literature

This chapter discusses previous research that is relevant to the development of a systematic, heuristic-based optimization approach that integrates the winter road maintenance planning components defined within the scope of this research. Relevant literature includes research addressing the problems of depot location, sector design, arc routing on a directed network, fleet sizing, vehicle scheduling, and fleet configuration within the context of winter road maintenance, either as individual factors or in combination.

The following sections cover research combining the factors of 1) depot location and sector design, 2) depot location, sector design, and fleet sizing, 3) winter maintenance-related arc routing problems on directed networks, and 4) depot location and routing problems. For further discussion on models and solution methods which address winter road maintenance planning decisions with an analytical and optimization-based approach, see Assad and Golden (1995), Campbell and Langevin (2000), and a very thorough four-part survey by Perrier, Langevin, and Campbell (2006a, 2006b, 2007a, 2007b).

2.2 Depot Location and Sector Design

Korhonen et al. (1992) developed a decision support system for locating vehicle depots and designing sectors for winter road maintenance operations in Finland (Perrier, Langevin, and Campbell 2007a). The system allows planners to select vehicle depots and their corresponding sectors such that variable transport costs and fixed vehicle depot costs are minimized over a ten-year planning horizon. The model only considers transport costs for high-class roadways. They solved the depot location problem using a construction heuristic that opens depots sequentially until no further savings are realized. Their solution method does not include a rule for determining the order in which the depots should be opened.

Rahja and Korhonen (1994) discussed a decision support tool that assists planners in 1) locating storage facilities for abrasives used in spreading operations and 2) designating the sectors or demand zones assigned to each depot. The system was tested on the Finnish national road network, which was divided into very small, balanced geographic zones; each zone had a demand for both salt and sand. The objective of the system is to open depots and design sectors around them which minimize the demand-weighted distance between each demand zone and its assigned storage facility.

2.3 Depot Location, Sector Design, and Fleet Sizing

Hayman and Howard (1972) introduced a model that combined the vehicle depot location, material depot location, vehicle fleet sizing, and sector design decisions for the spreading operations in Wyoming. Material storage depots could be located within vehicle depots or on separate sites. The objective was to minimize the sum of the operational costs and depreciation costs. The operational costs included the cost of traveling from the vehicle depots to the material depots, the cost of delivering the material to the roadways, the cost of acquiring the material, and the depot depreciation cost. Constraints ensure that each class of roadway could be serviced prior to its deadline and that each storage depot contained the necessary amount of material to service each of its assigned roadways. The model is formulated as a mixed-integer program (MIP). The authors achieved a substantial reduction in the size of the model by eliminating any combinations of vehicle depots assigned to storage depots and storage depots assigned to roadways which required "too much" deadhead distance. The linear program (LP) relaxation of the model was solved using the simplex algorithm; the total number of vehicles required at each vehicle and material depot was rounded up to the nearest integer value. In the optimal solution, if no vehicle is assigned to a vehicle depot or a material storage depot, then that site is not opened.

The model was tested on a road network in Wyoming consisting of 15 potential vehicle depot sites, each containing a material storage depot, 6 additional storage depots, and 41 roadway segments. The solution required opening 14 of the 15 vehicle depot sites and 20 of the 21 material depot sites. The authors also developed a very similar model to represent the plowing operations on the same road network—the differences being that plowing operations had different service deadlines, required a different number of passes for each roadway, and did not require material spreading or material depots. The spreading and plowing models resulted in slightly altered vehicle depot and fleet size requirements. Several variations of the models were run to examine the effect of the costs included, and it was found that the depreciation cost had a significant impact on the solution.

Reinert, Miller, and Dickerson (1985) developed a model that combines the decisions for the location and capacity of storage depots with the assignment of pre-defined winter road maintenance routes to each depot. The model is formulated as a (MIP), with the objective of minimizing the total weighted travel distance between the median points of each route and its assigned storage depot. Constraints ensure that each route is assigned to exactly one material depot and that the maximum number of depots opened is not violated. The model allows the user to predefine some or all of the depot sites, pre-assign certain routes to depots, and to limit the capacity of some or all of the depots. The LP relaxation to the MIP was solved using IBM's MPSX mathematical programming package; the authors noted that the program always produces integer solutions. The model was tested on the District of Columbia's abrasive spreading operations, using the current routes and 14 potential depot sites, each with an unlimited capacity. First, the model was run using the current depot configuration. Then the model was run four additional times, and the maximum number of depots allowed was increased with each subsequent trial. Since the solution generated by this model always results in the maximum number of depots, the results show the tradeoff between the number of depots, the deadheading distance between the routes, and the assigned storage depots.

Kandula and Wright (1995) described a model combining sector design, depot location, and fleet sizing for plowing and spreading operations in the La Porte district of Indiana. The model was formulated as a MIP with the objective of minimizing the sum of the distances of the shortest paths between each depot and the endpoints of the road segments assigned to that depot. The author describes the objective function as a surrogate measure for maximizing the compactness of each sector. To improve compactness, constraints are included for service hierarchy, class continuity for each vehicle with possible upgrading, contiguity of road segments in each sector, and the number of trucks (or routes) in each sector. A solution to this model designates which depot sites to open, assigns of each road segment to exactly one depot, and provides the number of trucks (or routes) assigned to each depot. The model calculates the number of trucks necessary to simultaneously service all road segments while respecting the previously mentioned constraints. Calculating the number of routes based on the kilometers of each class of roadway per depot—while accounting for a deadheading factor—provides the solution for the number of trucks required at each depot.

Since the model does not provide actual routes, it can not calculate the deadheading required. Therefore, a factor is included in the model to approximate deadheading; the quality of the solution is significantly affected by the choice of this deadheading factor. The authors tested the model using data from the La Porte, Indiana district, which included three priority classes of roadways, four depots, and a network of 63 vertices and 79 edges. The model was solved using the CPLEX Mixed Integer Optimizer. The authors also solved the LP relaxation of the model and found that the relaxation provided similar depot and roadway assignment results with fewer required vehicles. The difference in the relaxation model was that partial road segments were assigned to depots rather than being assigned in their entirety. The authors concluded from the LP relaxation that better results to the MIP may have been achieved if the road segments were further split into smaller road segments.

2.4 Arc Routing Models for Directed Transportation Networks

Marks and Stricker (1971) modeled the plow routing problem as a multiple vehicle Chinese postman problem (CPP). The problem attempts to minimize deadhead distance while respecting the multiple pass service requirements and vehicle capacity constraints. Multiple passes are handled by adding one edge for each required pass over the street it represents. Marks and Stricker state that the model is sufficient for both directed and undirected networks. For streets requiring service in both directions, the authors suggest inserting additional arcs, although no method for handling direction was included. Additionally, the authors also propose some ideas for handling service hierarchy; they suggest either weighting roads in a manner which makes the higher priority roads more attractive or partitioning the network into mutually exclusive subnetworks, with one for each class. However, service hierarchy was not included in the problem studied by the authors. Two approaches are given for solving the problem: a cluster first–route second approach and a route first–cluster second approach. The cluster first–route second approach involves partitioning the transportation network into a predetermined number of sectors and solving a separate CPP for each sector. The number of sectors is chosen based on the number of available vehicles. The route first–cluster second approach requires that first a CPP is solved for the entire network; then, the resulting tour must be partitioned such that an Eulerian tour can be found for each one without duplication of any edges. The cluster first–route second heuristic was tested on a sample network representing Cambridge, Massachusetts, with approximately 250 edges and 144 nodes. The problem was solved by hand in less than three hours. The city did not maintain any existing routes for comparison with the newly generated routes.

Liebling (1973) developed a cluster first–route second heuristic for the salt spreading operations in the city of Zurich. The first phase divides the directed transportation network into the minimum number of disjointed sectors that can be serviced while meeting capacity, time duration, and service frequency constraints. The second phase determines spreader routes for each sector by solving a directed CPP. The heuristic can be applied to snowplowing by adjusting the previously mentioned constraints. The city of Zurich successfully implemented the procedure and found that it resulted in routes more streamlined than the existing ones.

Cook and Alprin (1976) proposed a simple construction algorithm to create vehicle routes for spreading operations in Tulsa, Oklahoma. The routes are assigned dynamically using a greedy heuristic that assigns the closest unassigned street segment to each truck as it leaves the depot. Each route includes the distance of the required street segment and the deadhead distance to and from the depot. The authors define a street segment as the distance along which a street can be salted on both sides with one truckload of salt applied at the desired rate. The method for dividing the directed transportation network into street segments is not explained; it appears to be performed arbitrarily. The closest street heuristic attempts to balance the total workload while meeting the vehicle capacity and both-sides service constraints. Additionally, the procedure provides contiguous routes, a reduction in total time required to service the network, and safer deadhead travel between routes and depots over previously serviced segments. The heuristic makes no attempt to minimize deadheading. The procedure was embedded into a discrete event simulation model and used to evaluate the benefits of increasing the number of materials depots, the fleet size, and the vehicle capacity.

Lemieux and Campagna (1984) modeled a single-plow routing problem with hierarchical service constraints and u-turn restrictions. Since both sides of each street require service, the transportation network is directed. The algorithm creates a closed tour throughout the transportation network such that each arc is covered exactly once—hence no deadheading—while respecting the service hierarchy constraints and u-turn restrictions. To ensure that an Eulerian tour is feasible, the constraints are treated as soft constraints (i.e., constraints that can be relaxed to achieve feasibility). The authors propose two different rules for satisfying the service hierarchy and u-turn constraints; one rule favors the selection of higher priority streets at the expense of u-turns, while the other rule allows class upgrading to prevent u-turns when possible. The authors tested the algorithm on a sample network with 2 classes of roadways, 9 nodes, and 24 arcs. The algorithm was run one time for each of the two selection rules discussed above, and the results were compared. Both rules resulted in some Class 2 roads being serviced prior to some Class 1 roads.

In 1990, students from universities across the U.S. participated in a competition to design service routes for two snowplows in Wicomico County, Maryland. The transportation network is a strongly connected directed graph with 139 vertices and 374 arcs. The objective was to minimize the service completion time—or, equivalently, the total mileage—with a homogeneous two-plow fleet. Each team could include additional assumptions as to make the problem more realistic. The four papers described below (Atkins, Dierckman, and O'Bryant 1990; Chernak, Kustiner, and Phillips 1990; Robinson, Ogawa, and Frickenstein 1990; and Hartman, Hogenson, and Miller 1990) were chosen as the best submissions.

Atkins, Dierckman, and O'Bryant (1990) proposed a traditional cluster first–route second heuristic. First, the transportation network was divided manually into two subdistricts with approximately the same total mileage. Then an optimal Eulerian tour was manually found for each subdistrict by constructing a spanning tree for the undirected equivalent subgraph, adding the additional required edges to create a directed tree, and finally tracing a closed tour on the directed spanning tree.

Chernak, Kustiner, and Phillips (1990) added service hierarchy constraints and multiple pass requirements to the problem being studied. The proposed heuristic constructs two routes for each snowplow. An initial route, with no deadheading, services high priority roads, and a secondary route services the remaining roads. The problem was solved manually using a construction heuristic, although details for the heuristic were omitted from the paper.

Robinson, Ogawa, and Frickenstein (1990) suggested a cluster first–route second method and a route first–cluster second method for routing the two snowplows. In addition to the primary objective of minimizing total mileage, the authors included the secondary objectives of minimizing u-turns and balancing the workload. In the cluster first–route second method, roads were first manually organized into two balanced subdistricts using an “eyeball method.” The authors attempted to create subdistricts which would result in fewer u-turns and balanced workloads. However, no methods for decreasing u-turns or balancing workloads were mentioned for the route first–cluster second method. An Euler tour was manually created for each subdistrict using Trémeaux’s depth-first search algorithm. The authors also found a lower bound on the number of possible Euler tours for the network. In the route first–cluster second method, an Eulerian tour was first manually constructed using the depth-first search algorithm and then divided into two feasible subtours. The authors did not describe the method for dividing the tour, although they do mention that the solutions are very sensitive to the procedures used for bisecting the network and the tour for the cluster first and route first methods, respectively. Comparisons showed that the cluster first–route second method produced fewer u-turns and more balanced routes than the route first–cluster second method; both methods resulted in the same total mileage.

Finally, Hartman, Hogenson, and Miller (1990) developed a heuristic which simultaneously constructs two Eulerian circuits of approximately equal length. Unlike the other works entered in the contest, the authors created a computerized solution method. The solution procedure, based on Hierholzer’s algorithm, iteratively built two routes—one from each seed point—by adding one un-serviced road segment to the shorter of the two routes until all roads are serviced. This method allows for several rules to be embedded into the heuristic for adding each new segment. Once each route is finished, the heuristic checks to see if the routes are unbalanced (route lengths differed by more than five miles). If the routes are unbalanced, the program finds circuits which can be deleted from the longer route and added to the shorter route. This process was repeated until the routes were balanced or no possible exchanges existed for the Wicomico County transportation network.

Haslam and Wright (1991) developed a decision support system for planners to develop snowplow routes for the Indiana Department of Transportation (INDOT). The interactive procedure aids in the creation of routes with the primary objective of minimize deadheading miles and the secondary objective of minimizing the number of required vehicles. The authors discussed many of the practical considerations of snowplowing operations and included many of them in the problem studied. These constraints included service hierarchy, class continuity with possible upgrading, and maximum route length. INDOT is responsible for servicing interstates, highways, and state roads, but some county roads could be traversed in the process. The transportation network is represented as a directed graph in which not all of the roads required service. The procedure includes a method for calculating a lower bound on the number of required routes (equivalently, the number of vehicles), a route generation heuristic, and two improvement heuristics. First, the lower bound for the number of routes needed to service each class is calculated by dividing the total number of lane miles in the class by the maximum distance a plow may travel when servicing that class. The route generation method requires the user to input seed nodes such that the number of nodes is greater than or equal to the lower bound for the number of routes. The procedure generates the routes from the depot to the seed node and back such that each route only services one class and does not exceed the maximum route length. Remaining unassigned roads of the same class are then added to each route, and finally, roads of different classes can be added such that classes are upgraded; both modifications must respect the maximum route length constraint. A drawback to this heuristic is that not all roads requiring service were assigned to routes.

The authors also suggested using the current routes as the initial route solution. Once routes are established, they are improved using elimination and swap heuristics. The elimination heuristic attempts to reduce the number of routes by breaking up some of the routes and distributing their arcs to other existing routes. This procedure must be performed by a knowledgeable decision maker. The swap heuristic attempts to reduce deadheading by swapping arcs between existing routes. The entire procedure was tested on a subnetwork of the Fowler subdistrict with 21 nodes, 54 arcs, and 3 classes of roads. Unfortunately, the solution did not include all of the arcs requiring service. The interactive improvement procedures were also tested on the entire district of Fowler, which contained 99 nodes, 362 arcs, and 3 classes of roads. The swap and elimination heuristics successfully aided in the creation of routes which required fewer vehicles and less deadheading mileage than the existing routes.

Wang and Wright (1994) developed an interactive decision support system, called CASPER (Computer Aided System for Planning Efficient Routes), to assist planners from INDOT in the design of winter road maintenance routes. The system can handle spreader and plow routing problems with service time windows, class continuity, and class upgrading; these constraints are included in a weighted multiple objective penalty function, which minimizes deadhead distance, service time window violations, and total distance of class upgraded road segments. CASPER includes a route generation heuristic and an interactive tabu search-based improvement heuristic. If desired, the user can specify the initial routes to be improved. The route generation procedure starts by estimating the number of routes required to service each class of roadway in the given sector. The number of routes for each class is calculated by dividing the total workload (in kilometers) by the total kilometers which can be serviced within the time constraint, then adding in a deadheading factor that estimates the impact of deadheading on the required number of routes. Routes are constructed one at a time, for each class, by adding segments which are adjacent to the maximum number of nonserviced segments within the same class, such that the route does not exceed the maximum allowable duration. The remaining required arcs are then sequentially inserted into established routes using four insertion rules, which attempt to minimize the penalty function while relaxing either one or both of the class continuity and route duration constraints. Since the routes are generated using a penalty function, the initial solution may be infeasible. Once the initial routes are established, they are input into the tabu-based interactive improvement heuristic. The improvement algorithm uses the previously described penalty function. The weights for the penalty function, the number of iterations, class upgrading allowances, and the routes available for improvement are input by the user. The improvement solution defines a neighborhood and attempts to reduce the objective function by removing an arc or pair of arcs from a route and adding them to another route. Once the possible moves within the neighborhood are exhausted, a new neighborhood is selected. The heuristic continues until the maximum number of iterations is reached. The heuristic successfully reduced deadhead distance, the number of routes, and violations of the service time windows in several test districts in Indiana.

Kandula and Wright (1997) developed an interactive bounds-based heuristic for winter road maintenance routing in the state of Indiana. The heuristic attempts to minimize deadhead distance while taking into account class continuity, maximum route duration for each class, and both-sides service. The authors noted that the heuristic does not penalize short routes. The procedure identifies a set of seed nodes which correspond to the number of routes required to service the network within the time limit. Next, the maximum number of routes that can be constructed from each seed node is calculated, and a lower bound on the amount of required deadheading is found using a modified version of a procedure developed by Assad, Pearn, and Golden (1987) for the capacitated Chinese postman problem (CPP). Routes are constructed one at a time from each seed node, based on a greedy method which chooses the nearest nonserviced edge that is farthest away from the depot and will not violate the previously mentioned constraints. If no such edge can be found, then the partially constructed route is extended to the depot using the shortest path of deadhead edges. Once an initial solution is found, an interactive improvement procedure is applied which attempts to improve the feasibility and quality of that solution. The improvement procedure involves manually swapping edges among the routes or deleting an edge from one route and adding it to another. The heuristic was compared with the previously discussed tabu search algorithm developed by Wang and Wright (1994). Both methods were tested on five networks from Indiana, and the results showed that the interactive bounds-based procedure performed better than the tabu search-based method for a predefined number of iterations.

Campbell and Langevin (2000) discussed the commercially available interactive decision support system GeoRoute for designing vehicle routes for postal delivery, winter maintenance, meter reading, street cleaning, and waste collection problems. GeoRoute can develop routes for plowing, spreading, and snow blowing operations. The objective function is a weighted additive multi-criteria function defined by the user which includes optional constraints for service time windows, service frequency, vehicle capacities, spreading rates, turn restrictions, street segment dependencies, and both-sides service. Since GeoRoute is a proprietary software package, the algorithms used to develop vehicle routes are not publicly available. The authors describe the method as a two-phase cluster first–route second method, which constructs one route at a time. Clusters are determined by allocating segments to predetermined seed nodes. Then routes within each cluster are developed using a composite routing procedure. Campbell and Langevin (2000) report that the software has been implemented in several cities and counties in Canada and England for winter road maintenance operations.

Haghani and Qiao (2001) proposed a heuristic for routing spreader trucks in Calvert County, Maryland. The problem considers a single-depot, homogeneous-fleet, capacitated arc routing problem on a directed transportation network. Although both sides of each two-lane highway can be serviced once from either direction, the direction is arbitrarily fixed prior to the application of the solution method. Therefore, the problem is a directed capacitated arc routing problem. The authors suggest that the solution method could be modified for plow routing. (The transportation network and the capacity constraints would be different for a snowplow routing problem.)

The authors proposed a four-stage solution procedure. An initial solution is found in the first stage, and then the heuristic attempts to minimize the total deadhead distance by means of three successive improvement stages. Two methods for determining an initial routing solution are proposed in the paper. The first and simpler procedure creates one route for every road segment that requires service. Each route consists of 1) the shortest path from the depot to the beginning of the road segment, 2) the road segment, and 3) the shortest path from the end of the road segment to the depot. The second method begins with the furthest road segment from the depot and sequentially adds the nearest required segments to the route as long as the vehicle capacity constraint permits; finally, the shortest paths from the depot to the route and from the route to the depot are included. This procedure is continued until all required road segments are included for service in exactly one route.

The augment algorithm determines whether a larger route can service another smaller route. If so, the smaller route is discarded and its required road segments are included in the larger route. The merge procedure also attempts to join two routes by combining them at the common node, which results in the best improvement and meets the required constraints. Both the augment and merge algorithms are modifications of algorithms developed by Golden and Wong (1981) for the undirected case. The delete-and-insert algorithm deletes a required arc from a route, redefines that route such that all of the remaining arcs are serviced in the best order, and inserts previously deleted arc into another route at the point which provides the greatest improvement. The link exchange algorithm is similar to the delete-and-insert algorithm, except that two required arcs are exchanged between the two routes, such that the greatest improvement is achieved.

The second stage—the first improvement stage—applies the augment, merge, and delete-and-insert algorithms in succession. The third stage improves upon the output from the second stage by applying augment, merge, delete-and-insert, and link exchange algorithms in that order. Finally, the fourth stage takes the output from the third stage and iteratively applies the delete-and-insert, and link exchange algorithms until no further improvements can be made. The authors tested the four-stage heuristic on three subdistricts in Calvert County, Maryland, with up to 42 nodes and 104 edges. The solution was obtained very quickly—in less than two minutes—and resulted in a reduction in both deadhead distance and the number of vehicles required, when compared to the existing route and fleet configuration.

Salim et al. (2002) developed an artificial intelligence-based decision support system called SRAM (Snow Removal Asset Management) for making asset management and routing decisions related to winter road maintenance operations. (Sugumaran et al. 2005 embedded this approach in a Web-based GIS environment.) The system develops routes for plowing and spreading operations and assigns those routes to the vehicles available in Black Hawk County, Iowa. The routing procedure aims to minimize total service time while ensuring that strict service hierarchy constraints and maximum route time constraints are not violated. First, the procedure estimates the number of vehicles assigned to service each priority level by dividing the total estimated plowing time by the maximum allowable plowing time for one vehicle. Then, routes are constructed one at a time for each vehicle using a simple greedy heuristic which starts with a seed node and continues to add the nearest segment to the route until the maximum allowable plowing time is reached. The system continues until all required segments are assigned to exactly one route. Routes are created separately for each class of roads, ensuring class continuity. The system includes detailed operational information gained from interviews with winter maintenance planners and embedded into the GIS system, which allows for accurate estimates of required service times. In addition, the routes vary depending on the forecasted intensity of the storm. Once routes are established, the available vehicles are assigned to those routes—for each class of roads—using one of two methods, depending on the user's preference. If the user specifies that a vehicle can be assigned to exactly one route and that each route can be assigned exactly one vehicle, then an assignment problem is solved using the Hungarian algorithm. Otherwise, if a vehicle can be assigned to more than one route and a route can be assigned to more than one vehicle, then the vehicle scheduling problem is solved as a transportation problem using the stepping stone solution technique.

Both the assignment problem and the transportation problem have the objective of minimizing the total cost of operations, which consists of an operating cost per unit of time for each vehicle and the operating time required by each route. Since the cost for each vehicle is independent of the route it services, it appears that all vehicles are located at the same depot, but require different operating costs. The procedure also determines the required quantities of material required by each route for spreading operations. The system was found to be very user friendly and successful in generating routes which required less total service time than those previously in use. In addition, the system proved useful in analyzing the impact of changes in the available number of vehicles, the storm intensity, the road segments requiring service, and other parameters on the total service time and total operating costs.

2.5 Depot Location and Routing

Lotan et al. (1996) discussed a systematic location and routing problem for spreading operations in Antwerp, Belgium. The methodology aims to locate both vehicle and storage depots and create vehicle routes, while achieving the multiple and conflicting objectives of minimizing total mileage, minimizing the number of depots, and minimizing the number of routes (or, equivalently, the number of vehicles required). The problem includes capacity constraints for a homogeneous vehicle fleet and two levels of service hierarchy, with a service completion deadline for each class. Additionally, high priority roads require one pass in each direction, while low priority roads can be serviced with one pass in either direction.

The authors solve the combined location and routing problem in two stages. The first stage integrates the vehicle depot locations and the construction of feasible routes for the high-priority network. Initially, an upper bound is determined on the number of depots required to service the high-priority roads with no deadhead mileage. Then, the methodology iteratively solves the location routing problem for the high-priority network, each time with a decreasing number of depots below the upper bound. The results show the tradeoff between the number of depots and deadhead mileage; an acceptable solution to the number and location of vehicle depots and the corresponding vehicle routes is then decided by a qualified decision maker based on this tradeoff. The first stage was tested on the province of Antwerp, Belgium. The number of nodes and road segments in the high-priority network were not specified.

The second stage allocates the low-priority roads to the previously established depots, establishes feasible routes for each depot, and locates secondary storage depots, with the objective of minimizing total distance. The methodology includes a districting procedure which allocates the roads to the nearest depot, with the secondary objective of creating Eulerian subgraphs for each district. Once districts are established, the routing problem is modeled as a single-depot capacitated arc routing problem (CARP), with one subproblem for each depot. The objective of the CARP is to minimize total travel distance, while minimizing the number of vehicle routes by increasing the capacity of some tours through the introduction of storage depots. The problem is formulated with the following features: routes must begin and end in the depot from which they originate; routes can only service their assigned district; routes may include refill at a secondary storage facility, which doubles the route's capacity; and roads can be serviced once in either direction, resulting in a mixed network. The CARP is then solved for each depot using the augment-insert construction algorithm for the CARP on sparse networks with large arc demands, described in Pearn (1991). Finally, a secondary storage depot is added to improve the previously constructed routes. The author did not include any rules for determining the location of the silo. The second stage was tested on the network of Brecht, Belgium that includes 33 nodes and 43 road segments.

In 1997, Kandula and Wright described a modified version of the combined sector design, depot location, and fleet sizing model previously described (Kandula and Wright 1995). The new model was formulated as a mixed-integer programming (MIP) model with the multiple objectives of minimizing 1) the sum of the distances of the shortest paths between each depot and the endpoints of the road segments assigned to it, 2) the total deadheading time, 3) the total number of time units of all the commodities on each arc, and 4) the total number of vehicles used. The model includes additional flow constraints designed to provide a better estimate of the amount of deadheading by improving the estimate of the number of routes required. For a predefined number of depots to open, the model determines which depot sites to open, the assignment of each road segment to exactly one depot, and the number of trucks (or routes) assigned to each depot. To improve compactness, the model still includes constraints for contiguity of road segments in each sector and for the sector size. However, the model no longer considers service hierarchy. The model was solved using the CPLEX Mixed Integer Optimizer for five different districts in Indiana, each with up to 3 depots, 62 nodes, and 73 edges. The newly designed sector, depot, and fleet configurations were tested using two routing procedures: CASPER and a lower bound-based procedure (Wang and Wright 1994). The results showed more compact sectors in all cases, but only reduced deadheading and the required number of vehicles about half of the time when compared with the earlier model described by Kandula and Wright (1995). Since the new model had different constraints and the results were similar to the previous model, the authors concluded that it is a good alternative to the existing model, but not necessarily an improvement.

Gupta (1998) developed a decision support system which aids planners in estimating the economical impacts of the following four scenarios: closing an existing facility, opening a new facility, simultaneously closing an existing facility and opening a new facility, or maintaining the current facility configuration. The model allows planners to compare any two of the four scenarios. Gupta's model included estimates for the annualized cost of winter road maintenance activities, capital costs of vehicles, annualized cost of facility infrastructure associated with the opening of a new facility, and a one-time cost of environmental treatment required to close an existing facility. Since the annualized cost of winter road maintenance depends on the total distance of the vehicle routes, a solution to the snowplow routing problem must be established first. The snowplow routing problem is solved using the Snowmaster software (Evans and Weant 1990). Snowmaster models the routing problem as a multiple-depot, multiple-vehicle Chinese postman problem (CPP) with vehicle capacities and route duration constraints. The software offers the user a choice of the five route generation rules which attempt to minimize total distance. The rules are as follows: shortest available road segment first, longest available road segment first, node closest to the depot first, node farthest from depot first, and node farthest when going out and closest when returning. Once all of the costs described above are estimated, the model can be solved for any of the two scenarios in question to determine the better scenario. The model was tested using data from Hamilton County, Ohio, with a transportation network that included 360 nodes and 855 arcs.

2.6 Summary of Relevant Literature

The review of existing research shows an opportunity for improving winter road maintenance planning by approaching the problems of depot location, sector design, route design, and fleet configuration in a systematic, integrated manner. There is little research that addresses the problems in combination, and a review of those that have reveals an opportunity for a method which approaches them in a more integrated and less sequential manner. Research which has addressed the main winter road maintenance problems of depot location, sector design, route design, and fleet sizing in combination includes solution methods that are very computationally demanding; this prevents the determination of multiple depot locations or only allows unrealistically small problems to be considered.

Additionally, the existing research has assumed homogeneous fleets—an assumption which results in the number of routes being equivalent to the number of required vehicles. In practice, however, service agencies often utilize heterogeneous fleets. The introduction of a more realistic, heterogeneous fleet presents the additional challenge of determining the fleet configuration.

Vehicle scheduling is required when a vehicle can service additional routes prior to providing further service to any of the routes it has previously serviced; this occurs when a vehicle's routes are constrained by capacity rather than time limits. The only research effort described in this chapter which included the vehicle scheduling problem is the research performed by Salim et al. (2002); in this case, the authors solved the problem as a transportation problem where the routes represent the demand and the vehicles represent the supply.

The existing research on winter road maintenance routing described in this chapter assumes that one predefined depot location and sector exists, around which routes are designed. To integrate the decisions for vehicle route design, depot location, and sector design, it is necessary to include a routing solution method that can handle multiple depots and consider adjustments to the sector design to possibly improve the overall solution.

An integrated approach to winter road maintenance planning can be built upon many of the existing research methods and concepts discussed in this chapter. However, modifications of previous methods and new ideas are also required. The integrated solution approach developed in this research builds upon the route first–cluster second approach suggested by Marks and Stricker (1971), the depot location solution method proposed by Reinert, Miller, and Dickerson (1985), and the vehicle routing methodology proposed in Haghani and Qiao (2001). The methods are adapted to integrate the decisions involved and to handle the problem characteristics defined within the scope of this research effort. In addition to integrating the decisions, the method also incorporates the aspects of multiple-depot vehicle routing, fleet configuration, and vehicle scheduling.

CHAPTER 3: PROBLEM FORMULATION AND SOLUTION METHODOLOGY

3.1 Problem Formulation

When dealing with such complex problems as winter road maintenance, it is often advantageous to formulate the problem or a relaxed version of the problem to help in the development of solution methodologies. The basic underlying problems, which are discussed in the previous section, can be formulated mathematically. However, each of these basic problems are nonpolynomial (NP)-complete or NP-hard problems. This means they are not computationally tractable, and either very sophisticated techniques must be used—which require a great deal of solution time—or heuristic approaches must be employed.

Due to the difficulty in formulating and solving the integrated model, it was decided to formulate aspects of the overall problem that could be used in possible solution methodologies. These smaller, relaxed integrated problems can then be used to generate initial solutions and to form a basis from which it would be possible to add constraints—through column generation—to approach the solution to the integrated problem. Through this brief discussion of the formulation of smaller problems, an appreciation of the task of formulating and solving the overall integrated problem can be had.

The most basic underlying problem is that of arc routing, meaning that it is necessary to ensure that every road segment to be maintained is visited by a vehicle. This classic problem goes by several names, but is generally called the Chinese postman problem (CPP). A variant of that problem related to snow removal can be formulated as follows based on the work presented in Perrier, Langevin, and Campbell (2006a).

Let $G = (V, E)$ be an undirected graph where V is the vertex set and E is the edge set, and let K be the set of vehicles. For each node $v_i \in V$, let $E(v_i) = \{v_j \in V: (v_i, v_j) \in E\}$ be the set of nodes adjacent to node v_i , which can be reached directly by traversing one arc. Let every edge $(v_i, v_j) \in E$ have a nonnegative length c_{ij}. For each vehicle $k \in K$, define b_k as the maximum distance vehicle k can service, based on its capacity. For each edge $(v_i, v_j) \in E$ and for each vehicle $k \in K$, let x_{ijk} be a binary variable equal to 1 if and only if edge (v_i, v_j) is serviced from v_i to v_j by truck k. The problem is then formulated as a linear 0-1 integer program as follows:

Minimize $$\sum_{k \in K} \sum_{(v_i, v_j) \in E} c_{ij} (x_{ijk} + x_{jik})$$

Subject to

$$\sum_{k \in K} (x_{ijk} + x_{jik}) \geq 1 \qquad ((v_i, v_j) \in E)$$

$$\sum_{(v_i,v_j)\in E} c_{ij}(x_{ijk} + x_{jik}) \le b_k \qquad (k \in K)$$

$$\sum_{\{v_j:(v_j,v_i)\in E\}} x_{jik} - \sum_{\{v_j:(v_i,v_j)\in E\}} x_{ijk} = 0 \qquad (v_i \in V, k \in K)$$

$$\sum_{\{v_j:(v_0,v_j)\in E\}} x_{0jk} \ge 1 \qquad (k \in K)$$

$$\sum_{\{v_j:(v_j,v_0)\in E\}} x_{j0k} \ge 1 \qquad (k \in K)$$

$$x_{ijk} \in \{0,1\} \qquad ((v_i, v_j) \in E, k \in K)$$

The objective in this formulation is to minimize the total distance traveled. The constraints guarantee that 1) each road segment is serviced at least once, 2) there is a limit on the distance each vehicle can travel, 3) there is flow conservation at every node, 4) each vehicle starts and ends its route at a depot, and 5) all x_{ijk} variables are binary. Note that this model can be solved by commercial software, even though it may be time consuming.

This formulation is only concerned with the routing of vehicles. If both the routing of the vehicles and the location of the depots is considered, the problem becomes more difficult. The following formulation models this integration of concepts. This formulation is based on the work presented by Daskin (1995).

Let I = the set of nodes (where each node represents a road segment needing service), let J = the set of candidate depot locations, let $N = I \cup J$ = the set of all nodes, and let K = set vehicles. Additionally, let h_i = service time required by the road segment represented by node i, let f_j = fixed cost of locating a facility at candidate site j, let c_{ijk} = the cost of servicing node i from location j using vehicle k, let g_k = fixed cost of using vehicle k, and let u_k = capacity of vehicle k. The decision variables for the problem are as follows:

$$x_j = \begin{pmatrix} 1 & \text{if we locate at candidate site } j \\ 0 & \text{if not} \end{pmatrix}$$

$$y_{jk} = \begin{pmatrix} 1 & \text{if vehicle } k \text{ operates out of a depot at candidate site } j \\ 0 & \text{if not} \end{pmatrix}$$

$$z_{ijk} = \begin{pmatrix} 1 & \text{if node } i \text{ immediately precedes node } j \\ 0 & \text{if not} \end{pmatrix}$$

The problem is then formulated as

Minimize $$\sum_{j\in J} f_j x_j + \sum_{i\in N}\sum_{j\in N}\sum_{k\in K} c_{ijk} z_{ijk} + \sum_{j\in J}\sum_{k\in K} g_k y_{jk}$$

Subject to

$$\sum_{k\in K}\sum_{i\in N} z_{ijk} = 1 \qquad \forall j \in \mathrm{I}$$

$$\sum_{i\in N} z_{ijk} - \sum_{i\in N} z_{jik} = 0 \qquad \forall j \in N; \forall k \in K$$

$$\sum_{i=\Omega}\sum_{j\in\Omega}\sum_{k\in\Omega} z_{ijk} \le |\Omega| - 1 \qquad 2 \le |\Omega| \le |I| \quad \forall \Omega \subseteq I$$

$$\sum_{i\in I} z_{ijk} = y_{jk} \qquad \forall j \in J; \forall k \in K$$

$$\sum_{i\in I} z_{jik} = y_{jk} \qquad \forall j \in J; \forall k \in K$$

$$y_{jk} \le x_j \qquad \forall j \in J; \forall k \in K$$

$$\sum_{j\in J} y_{jk} \le 1 \qquad \forall k \in K$$

$$\sum_{i\in I} h_i \left\{ \sum_{j\in J} z_{ijk} \right\} \le u_k \left\{ \sum_{j\in J} y_{jk} \right\} \qquad \forall k \in K$$

$$x_j = 0,1 \qquad \forall j \in J$$

$$y_{jk} = 0,1 \qquad \forall j \in J; \forall k \in K$$

$$z_{ijk} = 0,1 \qquad \forall i, j \in N; \forall k \in K$$

The objective function minimizes the sum of the fixed facility location costs, the distance-related routing costs, and the fixed costs associated with using the vehicles. The constraints restrict each road segment to one route so that each segment is serviced by one vehicle and flow conservation is maintained. Additionally, the constraints involving Ω are subtour elimination constraints. This is done by requiring that for any subset (Ω) of segments, the total number of connections between pairs of nodes in the subset must be less than or equal to the cardinality of the subset minus 1.

Lastly, it is possible to formulate one more integrated subproblem of the overall problem. The formulation presented below is for the sector design, depot location, and fleet sizing problem as presented in Kandula and Wright (1995) and Perrier, Langevin, and Campbell (2007a).

Let $g = (V,E)$ be a connected undirected graph where $V = \{v_1, v_2, \ldots, v_n\}$ is the vertex set and $E = \{(v_i, v_j) : v_i, v_j \in V \text{ and } i \neq j\}$ is the edge set. A nonnegative length c_{ij} and a positive number of circulation lanes l_{ij} are associated with every edge (v_i, v_j). Let sc_{ij} be the length of the shortest chain linking vertex v_i to vertex v_j in G. Let $D \subset V$ be a set of potential depot sites. For every depot $v_d \in D$, define dhf_d as the deadhead factor used for road segments associated with depot v_d ($dhf_d \geq 1$ for all $v_d \in D$), define cap_d as the maximum number of kilometers assigned to depot v_d, and define $sumsc_d$ as the limit on the sum of the lengths of the shortest chains from depot v_d. For every edge $(v_i, v_j) \in E$, and for every potential depot site $v_d \in D$, let x_{ijd} be a binary variable equal to 1, if and only if edge $(v_i. v_j)$ is assigned to depot v_d, if it is opened.

Let $P_K = \{E_1, E_2, \ldots, E_K\}$ be a partition of E, with $E_1 \cup E_2 \cup ... \cup E_K = E_K = E$ and $E_i \cap E_j = \varnothing$ for all $i, j \in \{1,2,\ldots,K\}$, $i \neq j$. For every depot $v_d \in D$ and every class $E_k \subseteq P_K$, let n_{kd} be a nonnegative integer variable representing the number of vehicles based at depot v_d to service edges of class E_k assigned to depot v_d. For every depot $v_d \in D$ and every class $E_k \subseteq P_K$, define cl_{kd} as the maximum number of class k kilometers assigned to depot v_d. For every class $E_k \subseteq P_K$, define f_k as the frequency of service in hours that must be provided to road segments of class k. The vehicle speed, expressed as kilometers per hour, is denoted by s.

Finally, define $numv$ as the maximum number of vehicles to be used, $numd$ as the maximum number of depots to be operative, and $sumsc$ as the limit on the sum of the lengths of the shortest chains from operative depots to both ends of road segments that are assigned to these depots. The modified version of the Kandula and Wright (1995) formulation given by Perrier, Langevin, and Campbell (2007a) is

Minimize $$\sum_{v_d \in d} \sum_{(v_i, v_j) \in E} (sc_{id} + sc_{jd}) x_{ijd}$$

Subject to

$$\sum_{(v_i, v_j) \in E_k} l_{ij} c_{ij} x_{ijd} \leq cl_{kd} \quad (v_d \in D, E_k \subseteq P_K)$$

$$n_{kd} \geq \frac{dhf_d cl_{kd}}{f_k s} \quad (v_d \in D, E_k \subseteq P_K \quad)$$

$$\sum_{v_d \in D} \sum_{E_k \in P_K} n_{kd} \leq numv$$

$$\sum_{v_d \in D} y_d = numd$$

$$\sum_{v_i, v_j) \in E} l_{ij} c_{ij} x_{ijd} \le cap_d y_d \quad (v_d \in D)$$

$$\sum_{v_d \in D} x_{ijd} = 1 \quad ((v_i, v_j) \in E)$$

$$w_{ijd} \le M x_{ijd} \quad ((v_i, v_j) \in E, v_d \in D)$$

$$w_{jid} \le M x_{ijd} \quad ((v_i, v_j) \in E, v_d \in D)$$

$$\sum_{\{v_j : (v_i, v_j) \in A_1 \cup A_3\}} w_{ijd} - \sum_{\{v_j : (v_j, v_i) \in A_1\}} w_{jid} = 0 \quad (v_i \in V \setminus D, v_d \in D)$$

$$\sum_{\{v_j : (v_i, v_j) \in A_1\}} w_{ijd} - \sum_{\{v_j : (v_j, v_i) \in A_1 \cup A_2\}} w_{jid} = 0 \quad (v_i \in V \setminus D, v_d \in D)$$

$$\sum_{v_d \in D} w_{ijd} \ge 1 \quad ((v_i, v_j) \in A_3)$$

$$\sum_{v_d \in D} \sum_{(v_i v_j) \in A_2} w_{ijd} \ge |V \setminus D|$$

$$w_{ijd} = 0 \quad ((v_i, v_j) \in A_2, v_d \in D, v_j \ne v_d)$$

$$x_{ijd} \le w_{i0d} \quad ((v_i, v_j) \in E, v_d \in D)$$

$$x_{ijd} \le w_{j0d} \quad ((v_i, v_j) \in E, v_d \in D)$$

$$Sc_{id} + sc_{jd}) x_{ijd} \le sumsc \quad ((v_i, v_j) \in E, v_d \in D)$$

$$\sum_{(v_i, v_j) \in E} (sc_{id} + sc_{jd}) x_{ijd} \le sumsc_d \quad (v_d \in D)$$

$$w_{ijd} \ge 0 \quad ((v_i, v_j) \in A_1 \cup A_2 \cup A_3, v_d \in D)$$

$$n_{kd} \ge 0 \text{ and integer} \quad (v_d \in D, E_k \in P_K)$$

$$x_{ijd} \text{ and } y_d \in \{0,1\} \quad ((v_i, v_j) \in E, v_d \in D)$$

A formulation of the integrated model presented in this work would require the combination of the above models with additional factors and coupling variables and constraints. The resulting model would be intractable, and any solution methodology would be dependent on the appropriate solution of these relaxed subproblems. Therefore, an overall integrated model was not developed.

Likewise, the complexity of the problems and their formulations require heuristic approaches to be employed in the solution of the problem. The presented formulations, though, help in the development of the heuristics and bring to light the tradeoffs between the heuristic approach and exact methods. The formulations also give a framework for building an integrated solution and for possibly determining bounds on the solution. The heuristic procedure is presented in the next section.

3.2 Overview of the Methodology

The solution methodology consists of three phases: a network initialization phase, an initial solution phase, and finally, a solution improvement phase. The network initialization phase prepares the network for input into the initial solution phase. The first step is to check whether the transportation network is set up correctly by verifying that the network is strongly connected. Then the shortest paths from each node to every other node in the network are determined. The first two steps are achieved simultaneously using an algorithm for the directed Chinese postman problem (CPP). Finally, four strongly connected subnetworks—one for each hierarchical class of roadway—are created from the original transportation subnetwork.

The initial solution phase simultaneously determines the location of the depots as well as the initial solutions for the sector design, vehicle routes. (It should be noted that the solutions to the fleet configuration and vehicle scheduling problems could be solved in this phase as well; however, they would need to be solved again in the solution improvement phase, if the routes and sectors are improved in that phase.) First, a Chinese postman tour (CPT) is found for each of the four subnetworks created in the network initialization phase. The CPT serves as the basis for the initial routes, which are created in this phase.

Once the CPT is determined for a subnetwork, it is then partitioned into routes according to the maximum route duration and service distance constraints; at this point the initial routes are incomplete, because they do not begin and end at a depot. The algorithm for dividing the CPT into feasible routes attempts to meet but not exceed the maximum service distance and duration constraints which, consequently, minimizes the number of routes created. Minimizing the number of routes attempts to satisfy the objective of providing the desired service level with a minimum number of required vehicles. There are many possible outcomes for partitioning the CPT into feasible tours; therefore, the objective of minimizing the deadhead travel between the routes and their assigned depots is considered in this step. The algorithm determines each of the possible outcomes for dividing the CPT into routes. Then it chooses the one that results in the least total deadheading between all routes and all depots.

Next, the completed initial routes, sectors, and depot location are simultaneously determined. The depot location problem involves the selection of a predetermined number of depot sites to be opened out of a larger set of candidate depot sites, based on the objective of minimizing the weighted deadhead travel time between each route and its assigned depot. The sector design is achieved through the assignment of the required routes to opened depots, with the same objective of minimizing deadhead travel time. The initial routes are completed by extending each of the previously determined routes to and from the depot to which it is assigned. The initial solutions developed in this stage are also analyzed to determine the number of depots to open.

The third phase, the solution improvement phase, attempts to improve the quality of the initial solutions to the sector design and plow and spreader route design problems, based on the determined depot locations. The improvement heuristic attempts to enhance the quality of the sector and route designs by making two different types of moves: 1) removing an arc from one route, then inserting it into another route and 2) exchanging arcs between two routes. The heuristic only allows moves which satisfy the operational constraints and improve the objective of minimizing total deadhead travel time. Moves between two routes in the same sector improve the route design, while moves between two routes in different sectors improve both the route design and the sector design. The improvement heuristic is applied separately to all four subnetworks. Then, once the routes are designed, the third phase concludes by determining the fleet configuration and vehicle schedules necessary to service the routes. The following diagram outlines the three-phase solution methodology.

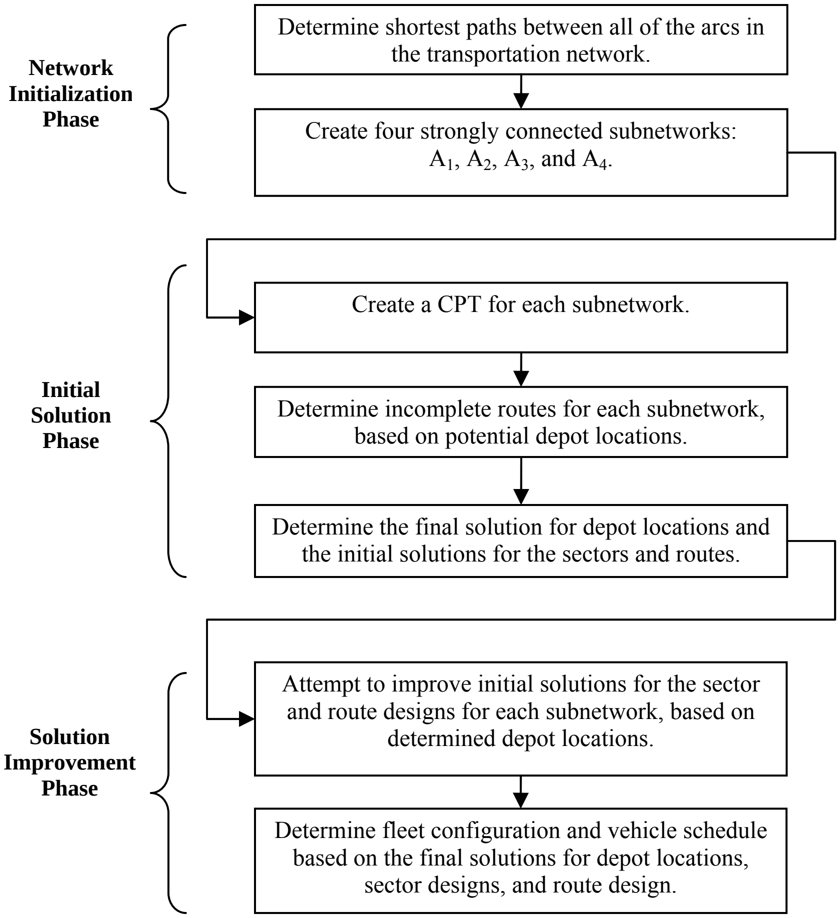


Figure 5. Three-phase solution methodology

3.3 Network Initialization Phase

The network initialization phase determines the inputs necessary for the initial solution phase. The first step in the phase is to create one tour throughout the entire transportation network; this step achieves two purposes: 1) verification that the network is strongly connected and 2) calculation of the shortest paths between every node and their corresponding costs. While there are many algorithms for solving the CPP, this research uses the algorithm for the closed CPP presented in Thimblebly (2003). Thimblebly's algorithm was chosen for several reasons: the readily available Java code provides an executable solution method rather than just a description of the algorithm; the program is very user friendly; and finally, the program is quick and efficient. The author states that the solution to the CPP requires the solution to an integer linear program, and until a quicker method for solving an integer program becomes available, no significantly faster algorithm for solving the CPP is attainable (Thimblebly 2003). The program is very user friendly, requiring the transportation network (a directed multi-graph) to be represented as a collection of arcs, where each arc from vertex *i* to vertex *j* is labeled and assigned a cost.

The algorithm determines an optimal CPT and the associated cost of the tour. If possible, the algorithm determines an Eulerian tour; otherwise an optimal tour with some required deadheading is determined. The algorithm creates an initial solution using a greedy heuristic and then iteratively improves the solution using a cycle canceling algorithm, until no further improvement is possible. Additionally, the algorithm verifies that the network is strongly connected and provides both the shortest paths between every node and corresponding costs. Checking to see that the network is strongly connected—that every node can be reached from every other node—is necessary to verify that the transportation network was input correctly. The algorithm determines the shortest path from each node to every other node in the transportation network using the Floyd-Warshall algorithm and stores the corresponding costs in a matrix where they can be easily called upon for use in the algorithm (Skiena 1998). The shortest paths are an integral part of the solution methodology presented in this paper and will be used frequently.

Since the service for the roadways must be provided according to priority rather than geography, the initial routing is performed separately for each class of roadway. The second step makes this possible by creating four subnetworks, one for each class, from the existing transportation network. The four subnetworks included in this research—A_1, A_2, A_3, and A_4—are comprised of Class 1 highways, Class 1 non-highway roadways, Class 2 roadways, and Class 3 roadways, respectively. In order to determine a CPT throughout each of the subnetworks, they must all be strongly connected. Since it may be necessary to travel on a Class 1 highway in the subnetwork A_1 in order to reach a Class 2 roadway that requires service in subnetwork A_2, it may be necessary to add additional arcs from the other classes to each subnetwork for connectivity purposes. The original arcs in any subnetwork are treated as service arcs for the purpose of routing, while any arcs added for connectivity are considered deadhead arcs in the routing stage for that subnetwork. To connect the remaining subnetworks, the following greedy procedure is applied for each subnetwork:

1) Randomly choose an isolated arc that is part of the disconnected subnetwork.
2) Using the shortest paths, determine the nearest node of the same class.
3) Add all of the arcs that make up the shortest path between the two nodes in the subnetwork.
4) Repeat this procedure until the entire subnetwork is strongly connected.

3.4 Initial Solution Phase

3.4.1 Overview of Initial Solution Phase

The initial solution phase determines the location of the depots as well as the initial solutions for the sector design and vehicle routes. The first stage of the initial solution phase creates the initial routes for the combined spreading and plowing operations; the routes determined in this step are still incomplete because they do not begin and end at a depot. In the second stage, the initial solutions for the sector designs, depot locations, and completed initial routes are derived simultaneously.

3.4.2 Stage 1: Initial Incomplete Route Development

The initial incomplete routes for each class of roadway are determined using a method based on the route first–cluster second method suggested by Marks and Stricker (1971) that includes additional constraints. The route design problem includes vehicle capacity and service frequency constraints. The vehicle capacity constraints are expressed as a maximum distance which can be serviced by one route, which depends on the type of vehicle. Subnetwork A_1 is serviced using vehicles which can service 100 lane miles. Subnetworks A_2, A_3, and A_4 are serviced by vehicles with a maximum service distance of 75 lane miles. As previously discussed, any higher class roadways added to a subnetwork for connectivity are considered deadhead arcs and therefore are not included the total service distance. The service frequency constraints are expressed as maximum time duration constraints, which depend on the class of roadway being serviced. The maximum route durations for A_1, A_2, A_3, and A_4 are 2, 2, 6, and 12 hours, respectively.

The route first–cluster second approach involves first solving a CPP for the transportation network, then partitioning the resulting tour into routes based on the defined objective(s) and operational constraint(s). For each transportation subnetwork A_1, A_2, A_3, and A_4, a CPT is found using Thimblebly's (2003) algorithm for the closed CPP. If the CPT includes more than one pass over a service arc, the additional passes are considered deadheading. The CPT creates the foundation for the initial routes, based on the objective of minimizing the deadhead travel needed to service all of the required arcs within the subnetwork.

The CPT must then be divided into feasible routes, based on the operational constraints for maximum service distance and maximum duration. The algorithm for dividing the CPT into feasible routes attempts to meet but not exceed the maximum service distance and duration constraints and, consequently, minimizes the number of routes created. Minimizing the number of routes attempts to satisfy the objective of providing the desired level of service with a minimum number of required vehicles. Since the depot locations are still undetermined, the duration of a route is calculated using the service time and an approximation of deadhead travel time between each route and its assigned depot. The heuristic approximates deadhead travel time between the depots and routes by calculating average deadhead travel times on the shortest paths between the endpoints of each route and the ten nearest depot candidate sites.

There are many possible outcomes for partitioning the CPT into feasible tours. Since the CPT begins and ends at the same point, a tour containing *n* arcs can be divided into *n* possible combinations of routes with one route starting at each arc. It is possible that a better partitioning of the CPT into feasible routes will lead to a solution requiring less deadheading between the routes and depots as well as a fewer number of required routes. Therefore, the objective of minimizing the deadhead travel between the routes and their assigned depots is considered in this step. The algorithm determines each of the possible outcomes for dividing the CPT into routes, then chooses the one that results in the least total deadheading between all routes and all depots. Since the depot locations have yet to be determined, the algorithm uses the total deadheading between depots and all routes to evaluate the quality of the solution to the problem of partitioning the CPT into the initial incomplete routes. The following diagram shows the relationship between the depot location problem and the route design problem established in this stage.

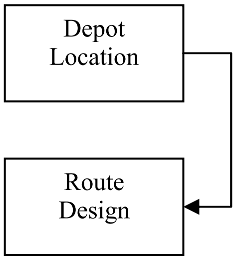


Figure 6. Influence diagram for stage 1 of the initial solution phase

The following heuristic is used to determine the initial incomplete vehicle routes based on the objectives of providing the desired level of service frequency, minimizing deadhead travel, and minimizing the number of routes, the topology of the transportation network, the potential depot locations, and the operational constraints:

Stage 1 Heuristic

(0) Initialize
  a. Initialize variables setting $i = 1$, $j = 1$, $k = 1$, and $m = 1$.
  b. Define total distance as sum of the distances of all the serviced arcs included in the current route and a_j.
  c. Define total duration as the sum of 1) the travel time on all of the arcs included in the current route (either serviced or deadheaded depending on the arc), 2) the travel time on arc a_j, 3) the average deadhead travel times of the shortest paths

from the ten nearest depots to the beginning of the current route, and 4) the average deadhead travel times of the shortest paths from of the end of arc a_j to the ten nearest depots.

   d. Define n as the number of subnetworks ($A_1 \ldots A_n$).
   e. Define the total deadhead travel time as the sum of the deadhead travel time from each depot to the beginning of each route and the deadhead travel time from the end of each route to each of the depots.

(1) For subnetwork A_i, choose a seed node v_0 and create a closed Chinese postman tour (CPT) that begins at the seed node and includes all arcs $(v_i, v_j) \in A_i$, using the program presented in Thimblebly (2003). Set P = the number of arcs in the CPT.

(2) Partition the initial CPT into routes ($R_1, R_2 \ldots R_K$) that satisfy the limits on the maximum route distance d_i and maximum allowable duration t_i by executing the following:
   a. Rank and label the arcs in the CPT from 1 to P, starting with the arc a_m and ending with the arc just prior to arc a_m. Define a_j as the arc in the j^{th} position of the CPT, where $j = 1 \ldots P$.
   b. Choose a_j and determine whether the arc is deadheaded or serviced. If the arc is serviced, add a_j to the current route and update $j = j + 1$. If $j \leq P$, proceed to step 2c, otherwise proceed to step 2f. If the arc is deadheaded, then update $j = j + 1$. If $j \leq P$, repeat step 2b; otherwise proceed to step 2f.
   c. Choose the next arc a_j in the tour that is not assigned to a route, and determine whether the arc is deadheaded or serviced. If a_j is deadheaded, move on to step 2d. If a_j is serviced, determine whether the total distance exceeds d_i. If the total distance is less than or equal to d_i, go to step 2d. If the total distance exceeds d_i, then go to step 2e.
   d. Determine whether the total duration exceeds t_i. If the total duration is less than t_i, then add a_j to the current route and set $j = j + 1$. If $j \leq P$, return to step 2c; otherwise proceed to step 2f. If the total duration exceeds t_i, then proceed to step 2e.
   e. Complete the current route R_k, set $k = k + 1$, and return to step 2b.
   f. Complete the current route R_k, and then proceed to step 2g.
   g. Check to see if any routes end with a deadheaded arc. If so, remove the arc and repeat step 2g. Otherwise, proceed to step 3.
   h. Save the set of routes as S_m. If $m < P$, set $m = m + 1$, set $j = 1$, set $k = 1$, and return to step 2a; otherwise proceed to step 3.

(3) Choose the best partitioning of the CPT, the set of routes S_m with the least total deadhead time.
   a. Calculate the total deadhead travel time for each set of routes S_m.
   b. Choose the set of routes S_m with the minimum total deadhead travel time, and set S_m equal to S_i. If i < n, update $i = i + 1$, set $j = 1$, set $k = 1$, set $m = 1$, and return to step 1; otherwise terminate.

3.4.3 Stage 2: Integrated Depot Location, Sector Design, and Route Design

The solution for the depot locations and the initial solutions for the sector design and route design are found in the second stage by solving a linear program (LP). The LP determines the depot locations and assigns the initial incomplete routes—created in the first stage—to the opened depots based on the objective of minimizing the total frequency weighted deadhead travel time between each route and its assigned depot. The assignment of the routes to the depots creates sectors and completes the routes created in the first stage. This stage closes the loop on the relationship between the depot location problem and the route design problem, and it also integrates the sector design problem; depot locations are determined simultaneously with solutions to the route design and sector design problems.

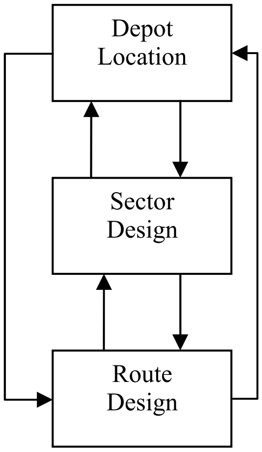


Figure 7. Influence diagram for stage 2 of the initial solution phase

The LP is a slightly modified version of the mixed-integer program (MIP) proposed in Reinart, Miller, and Dickerson (1985). The main difference is that Reinart, Miller, and Dickerson used the length of the route for weighting the objective function, while this research uses the service frequency. Using the service frequency to weight the objective function attempts to open depots near the higher priority routes. The weights correspond to the ideal service frequency of 6, 6, 2, and 1 hours for routes of class A_1, A_2, A_3, and A_4, respectively.

Although the desired solution is in integer form, Reinart, Miller, and Dickerson noticed that the LP relaxation of the MIP can be solved instead. Therefore, the modified version used in this research is formulated and solved as an LP. The objective function for the LP is to minimize the total service frequency-weighted deadhead travel time between each route and its assigned depot. As previously discussed, the initial routes found in the first stage are incomplete because they do not begin and end at a depot; this is because they have not yet been assigned to a depot.

The LP uses the following inputs: 1) the initial incomplete routes, 2) the deadhead travel time from the beginning of each route to each depot, 3) the deadhead travel time from the end of each route to each depot, 4) a predetermined set of candidate sites for depot locations, 5) a predefined number of depots to open, and 6) predefined weights for each route, based on the service frequency. The solution to the LP designates the depot locations to open and the routes assigned to each opened depot.

Once the incomplete routes are assigned to a depot, each route is completed by adding the shortest path—in terms of deadhead travel time—from the depot to the beginning of the existing incomplete route and the shortest path from the end of the existing route to the depot. The depot locations determined in this stage are final, while the solution improvement phase will attempt to improve the solutions to the sector design and route design problems.

The solutions developed in this stage can also serve the purpose of determining the appropriate number of depots to open. A comparison of the solutions for a varying number of depots gives insight into the benefit that may be gained by increasing the number of depots; this can be accomplished simply by solving the LP presented in this section for a varying number of depots. Although the solution improvement phase will determine the final solutions, the solutions determined in this phase are used as a screening process to determine the number of depots to open. The following LP (see Figure 8) was quickly and easily solved using the extended version of LINGO 8.0.

The symbol key for the LP is given below:

f_i = the required service frequency for route *i*
t_{ij} = the sum of 1) the deadhead travel time on the shortest path from depot *j* to the beginning of route *i* and 2) the deadhead travel time on the shortest path from the end of route *i* to depot *j*. (The shortest path is defined as the path which requires the least travel time.)
x_{ij} = 1 if route *i* is assigned to depot *j*; otherwise $x_{ij} = 0$
Y_j = 1 if depot *j* is opened; otherwise $Y_j = 0$
D = the maximum number of depots to open

$$\text{(1)} \qquad \text{Minimize} \quad \sum_{i \in I} \sum_{j \in J} f_i \cdot t_{ij} \cdot x_{ij}$$

subject to.

$$\text{(2)} \qquad \sum_{i \in I} x_{ij} \leq 1 \qquad \text{for all } j$$

$$\text{(3)} \qquad \sum_{j \in J} Y_j \leq D$$

$$\text{(4)} \qquad Y_j - x_{ij} \geq 0 \qquad \text{for all } i, j$$

Figure 8. Linear program for stage 2 of the initial solution phase

Figure 8 displays the objective function (1), which minimizes the total service frequency-weighted deadhead travel time between each route and its assigned depot. The first constraint (2) ensures that each route is assigned to exactly one depot. Equation (3) limits the number of depots which are opened. The solution will always result in D depots being opened, since additional depots decrease the objective function. The last constraint (4) restricts route assignments to those depots which are opened.

3.5 Solution Improvement Phase

3.5.1 Overview of Solution Improvement Phase

The third phase, the solution improvement phase, attempts to improve the quality of the initial solutions to the sector design and plow-and-spreader route design problems based on the determined depot locations. Then the solutions to the vehicle scheduling and fleet configuration problems are determined based on the final solutions to the depot location, sector design, and route design problems.

The first stage of the solution improvement phase applies an improvement heuristic to the initial solutions to the sector design and route design problems. The improvement heuristic includes two subroutines, each of which attempts to improve the solutions to the sector design and route design problems, simultaneously. The two subroutines, called “delete and insert” and “link exchange,” were developed by Qaio (1998). This research utilizes the same subroutines, the only differences being in the characteristics of the problem to which they are applied. This research studies a multi-depot routing problem with maximum service distance and maximum duration constraints, whereas Qaio (1998) developed the two subroutines for a single-depot problem with a maximum route distance constraint. The changes necessary to adapt the subroutines for a multi-depot problem with constraints on the maximum service distance and maximum duration of each route were minor.

The first subroutine attempts to improve the route by removing an arc from one route and inserting it into another. The second subroutine attempts to exchange sections between two routes; one arc is removed from each route and then inserted into the best position within the other respective route. The heuristic only allows section moves which satisfy the operational constraints and improve the objective of minimizing total deadhead travel time. Moves between two routes in the same sector improve the route design, while moves between two routes in different sectors improve both the route design and the sector design. The heuristic terminates when no more improving moves are possible. The improvement heuristic is applied to each of the four subnetworks—A_1, A_2, A_3, and A_4.

The second stage involves a manual adjustment procedure designed to remove excess u-turns from routes containing four-lane roadways. The routing procedure in subroutines 1 and 2 results in additional unnecessary u-turns for roadways with more than one lane in each direction. However, the excess u-turns can be easily removed without changing the total deadheading required for each route. In terms of the objective, this step does not affect the solution; however, it is included to provide a more practical routing solution.

In the third and final stage, vehicle scheduling and fleet configuration problems are solved using the final solutions to the depot location, sector design, and route design. The following figure shows the relationships between the problems of depot location, sector design, route design, vehicle scheduling, and fleet configuration considered in this phase.

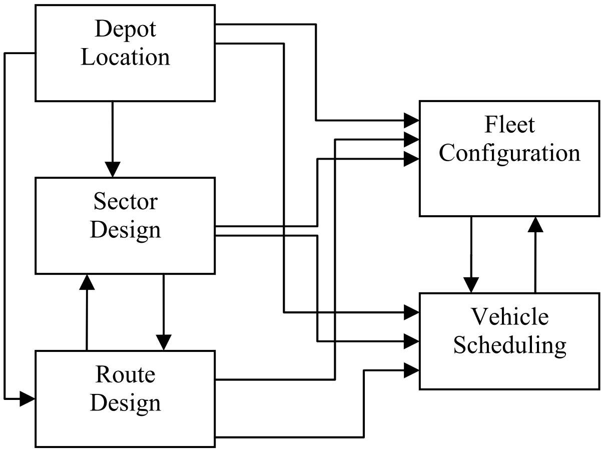


Figure 9. Influence diagram for the solution improvement phase

3.5.2 Stage 1: Improvement Heuristic

As previously mentioned, the improvement heuristic applies the delete-and-insert algorithm and the link exchange algorithm in succession, until no further solution is applied. The delete-and-insert algorithm is more flexible in that it can move one arc at a time, whereas the link exchange algorithm is forced to move two arcs, even if moving only one of them results in a better solution. However, as the distance and duration of a route approach the maximum limit, it becomes less likely that there is enough capacity to insert an additional arc; it is for this reason that the link exchange algorithm is applied. Exchanging arcs frees up enough capacity to make a move that would not be feasible using only the delete-and-insert algorithm. First, the delete-and-insert algorithm is applied, recursively, until no further improvements are found. Then the link exchange algorithm is applied, recursively, until no further improvements exist. The loop of these two algorithms is repeated until no more improvements can be found. The following sections explain the algorithms in more detail and present the algorithms in their entirety.

3.5.2.1 Delete-and-Insert Algorithm

The delete-and-insert algorithm examines moves between two routes in which an arc is removed from one route and inserted into the other. The algorithm only allows moves which satisfy the operational constraints of maximum route service distance and maximum duration and also minimize deadheading. The algorithm tries all possible moves between all of the routes, two at a time, and it is performed on each subnetwork—A_1, A_2, A_3, and A_4—separately. A brief description and illustration of the algorithm can be found in Figure 10, and the entire algorithm is included below.

Step 1: Choose two routes

Route 1

Arc	From	To	Service/ Deadhead
1,2	1	2	S
2,3	2	3	S
3,5	3	5	D
5,8	5	8	D
8,2	8	2	S

Route 2

Arc	From	To	Service/ Deadhead
3,4	3	4	S
4,5	4	5	D
5,19	5	19	D
19,13	19	13	D
13,14	13	14	S

Step 2: Remove all deadhead arcs from both routes

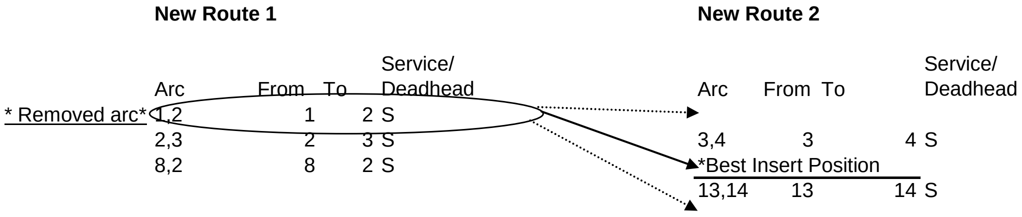
New Route 1

Arc	From	To	Service/ Deadhead
1,2	1	2	S
2,3	2	3	S
8,2	8	2	S

New Route 2

Arc	From	To	Service/ Deadhead
3,4	3	4	S
13,14	13	14	S

Step 3: Choose an arc from Route 1 to be removed and determine the best position to insert the removed arc into Route 2, based on the total deadhead distance required to reconnect Route 2



New Route 1

	Arc	From	To	Service/ Deadhead
* Removed arc*	1,2	1	2	S
	2,3	2	3	S
	8,2	8	2	S

New Route 2

Arc	From	To	Service/ Deadhead
3,4	3	4	S
*Best Insert Position			
13,14	13	14	S

Step 4 : Reconnect the two routes with the necessary deadhead arcs

New Route 1

Arc	From	To	Service/ Deadhead
2,3	2	3	S
3,5	3	5	D
5,8	5	8	D
8,2	8	2	S

New Route 2

	Arc	From	To	Service/ Deadhead
	3,4	3	4	S
	4,1	4	1	D
Inserted Arc	1,2	1	2	S
	2,13	2	13	D
	13,14	13	14	S

Step 5: Compare the total deahdead travel of (Route 1 +Route 2) with that of (New Route 1 + New Route 2) and choose the set of routes with that require the least total deadhead travel

Figure 10. Delete-and-insert algorithm example

Define

- Routes, R_1 to R_n
- D_i, as the depot to which R_i is assigned
- R_{im} as the number of arcs in route i
- For each route i, define service arcs R_iA_z where z = 1 to R_{im}
- For each arc R_iA_z, define a beginning node B(R_iA_z) and an ending node E(R_iA_z)

- LIC as the least insert cost of inserting an arc into route R_j that was removed from route R_i
- LRC as the least removal cost of removing an arc from route R_i to insert into route R_j
- LIR*i* as the route from which arc R_iA_z is removed from to get LIC
- LIR*j* as the route from which arc R_iA_z is inserted into get LIC
- TDT(R_i) as the total deadhead travel time for route R_i
- TST(R_i) as the total service time for route R_i
- MST(R_i) as the maximum time duration for the class of route R_i TSD(R_i) as the total service distance for route R_i
- MSD(R_i) as the maximum service distance for the class of route R_i
- SP[E(R_iA_z),B($R_iA_z + 1$)] as the deadhead travel time from the ending node of arc R_iA_z to the beginning node of arc $R_iA_z + 1$
- ST(R_iA_z) as the service time for arc R_iA_z
- SD(R_iA_z) as the service distance for arc R_iA_z
- CR1 to CR*n* as the current possible routes which are examined for a possible improvement to the existing solution

Initialize

(0) Set $i = 1, j = 2, k = 1, h = 1$

Delete

(1) Remove all deadhead arcs from R_i; set LIC = MT(R_j), LRC = MT(R_i), LIRi = R_i, LIR$_j$ = R_j
(2) Calculate TDT(R_i)
  a. Determine the number of arcs in R_i and set equal to Rim, then set m = Rim
  b. Add SP[D_i, B(R_iA_1)]
  c. Add the SPs for any deadhead arcs needed to connect the arcs from R_iA_1 to RiAM
    i. Set counter $z = 1$
    ii. If E(R_iA_z) = B($R_iA_z + 1$), then add 0; otherwise add the SP[R_iA_z, $R_iA_z + 1$]. Update $z = z + 1$. If $z \leq m - 1$, then repeat step 2cii; otherwise, proceed to step 2d.
  d. Add SP[E(R_iA_m), D_i]
(3) Calculate TDT(R_j)
  a. Determine the number of arcs in R_j and set equal to R_{jm}; then set $m = R_{jm}$
  b. Add SP[D_j, B(R_jA_1)]
  c. Add the *S* values for any deadhead arcs needed to connect the arcs from R_jA_1 to R_jA_m
    i. Set counter $z = 1$
    ii. If E(R_jA_z) = B($R_jA_z + 1$), then add 0; otherwise, add SP[R_jA_z, $R_jA_z + 1$]. Update $z = z + 1$. If $z \leq m - 1$, then repeat step 3cii; otherwise, proceed to step 3d.
  d. Add SP[E(R_iA_m), D_i]
(4) If $i = j$ then update $j = j + 1$
(5) Check the capacity by adding the SD(R_iA_k) to TSD(R_j) to get TSD(CR$_j$). If TSD(CR$_j$)

$\leq$ MSD(R_j), then proceed to step 6; otherwise, update $k = k + 1$. Then, if $k \leq R_{im}$, repeat step 5, Otherwise proceed to step 9.

(6) Remove R_iA_k from R_i, set $m = R_{im} - 1$, and label the new route as CR$_i$; rank and label the service arcs in order of service CR_iA_z, where $z = 1$, to m
   a. Set $z = 1$
   b. If $z < k$, set $CR_iA_z = R_iA_z$; otherwise, set $CR_iA_z = R_iA_z - 1$. Update $z = z + 1$. If $z \leq m$, repeat step 6b; otherwise, proceed to step 7.

(7) Calculate TDT($\mathrm{CR_i}$)
   a. Add SP[D_i, B(CR_iA_1)]
   b. Add the SPs for any deadhead arcs needed to connect the arcs from CR_iA_1 to CR_iA_m
      i. Set counter $z = 1$
      ii. If E(CR_iA_z) = B(CR_iA_z+1), then add 0; otherwise, add SP[CR_iA_z, $CR_iA_z + 1$]. Update $z = z + 1$. If $z \leq m - 1$, then repeat step 7bii; otherwise, proceed to step 7c.
   c. Add SP[ECR_iA_m, D_i]

Insert

(8) Calculate the LIC for inserting $\mathrm{R_iA_k}$ into $\mathrm{CR_j}$
   a. Set $m = R_{jm} + 1$
   b. Set R_iA_k equal to R_jA_h and call new route CR$_j$; rank and label the service arcs in order of service CR_jA_1 to C R_jA_m
      i. Set $z = 1$
      ii. If $z < h$, set $CR_jA_z = R_jA_z$; otherwise, set C $R_jA_z = R_jA_z + 1$. Update $z = z + 1$. If $z \leq m$, repeat step 8bii; otherwise, proceed to step 8biii.
      iii. Set $CR_jA_h = R_iA_k$ Calculate TST(CR$_j$)
      iv. Sum all of the service times for arcs CR_jA_1 to C R_jA_m
   c. Calculate TDT(CR_j)
      i. Add the SP[D_j, B(CR_jA_1)]
      ii. Add the SPs for any deadhead arcs needed to connect the arcs from CR_iA_1 to CR_iA_m
         1. Set counter $z = 1$
         2. If E(CR_jA_z) = B($CR_jA_z + 1$), then add 0; otherwise, add SP[CR_jA_z, $CR_jA_z + 1$]. Update $z = z + 1$. If $z \leq m - 1$, then repeat step 8dii2; otherwise, proceed to step 8diii.
      iii. Add the SP[E(CR_jA_m), $\mathrm{D_j}$]

(9) If TDT(CR$_j$) + TST(CR$_j$) < MST(R_j), and TDT(CR$_j$) < LIC, then set LIC = TDT(CR$_j$), LRC = TDT(CR$_i$), LIRi = CR$_i$, and LIR$_j$ = CR$_j$. Update $h = h + 1$. If $h \leq m$, return to step 8a; otherwise, update $k = k + 1$. If $k \leq R_{im}$, return to step 4; otherwise, proceed to step 10.

(10) If LRC + LIC < TDT(R_i) +TDT(R_j), then set R_i = LIR_j and R_j =LIR_j. If $j \leq n$, then update $j = j + 1$, $k = 1$, $h = 1$ and return to step 4; otherwise, update $i = i + 1$. If $i \leq n$, then update $j = 1$, $k = 1$, $h = 1$ and return to step 1. Otherwise terminate.

3.5.2.2 Link Exchange Algorithm

The link exchange algorithm is very similar to the delete-and-insert algorithm, except that both routes give up an arc, which is then inserted into the other respective route; the removed arcs are inserted into the best position within their new route. The algorithm only allows moves which satisfy the operational constraints of maximum route service distance and maximum duration and also minimize deadheading. A brief description and illustration of the algorithm is included in Figure 11. The entire link exchange algorithm follows.

Step 1: Choose two routes

Route 1

Arc	From	To	Service/ Deadhead
1,2	1	2	S
2,3	2	3	S
3,5	3	5	D
5,8	5	8	D
8,2	8	2	S

Route 2

Arc	From	To	Service/ Deadhead
3,4	3	4	S
4,5	4	5	D
5,19	5	19	D
19,13	19	13	D
13,14	13	14	S

Step 2: Remove all deadhead arcs from both routes

New Route 1

Arc	From	To	Service/ Deadhead
1,2	1	2	S
2,3	2	3	S
8,2	8	2	S

New Route 2

Arc	From	To	Service/ Deadhead
3,4	3	4	S
13,14	13	14	S

Step 3: Choose an arc from Route 1 and and arc from Route 2 to be removed

New Route 1

	Arc	From	To	Service/ Deadhead
* Removed arc*	1,2	1	2	S
	2,3	2	3	S
	8,2	8	2	S

New Route 2

Arc	From	To	Service/ Deadhead
3,4	3	4	S
13,14	13	14	S

* Removed arc*

Step 4: Determine the best positions to insert the removed arcs into the other respective route based on the objective of minimizing total deadhead travel

	Arc	From	To	Service/ Deadhead
* Removed arc* From Route 1	1,2	1	2	S

New Route 2

Arc	From	To	Service/ Deadhead
Best Insert Position			
3,4	3	4	S

New Route 1

Arc	From	To	Service/ Deadhead
2,3	2	3	S
Best Insert Position			
8,2	8	2	S

Arc	From	To	Service/ Deadhead
13,14	13	14	S

* Removed arc*
From Route 2

Step 5 : Reconnect the two routes with the necessary deadhead arcs

New Route 1

	Arc	From	To	Service/ Deadhead
	2,3	2	3	S
	3,13	3	13	D
Inserted Arc	13,14	13	14	S
	14,8	14	8	D
	8,2	8	2	S

New Route 2

	Arc	From	To	Service/ Deadhead
Inserted Arc	1,2	1	2	S
	2,3	2	3	D
	3,4	3	4	S

Step 6: Compare the total deahdead travel of (Route 1 +Route 2) with that of (New Route 1 + New Route 2) and choose the set of routes with that require the least deadhead travel

Figure 11. Link exchange example

Define

- Route R_1 to R_n
- D_i as the depot to which R_i is assigned
- R_{im} as the number of arcs in route i
- For each route i, define service arcs R_iA_z where $z = 1$ to R_{im}
- R_iA_z, define a beginning node $B(R_iA_z)$ and an ending node $E(R_iA_z)$
- LECi as the least exchange cost of removing an arc R_iA_z from route R_i and inserting an arc R_jA_z into route R_i
- LECj as the least exchange cost of removing an arc R_jA_z from route R_j and inserting an arc R_iA_z into route R_j
- LIR_i as the route R_i with R_iA_z removed and R_jA_z inserted that results in LECi
- LIR_j as the route R_j with R_jA_z removed and R_iA_z inserted that results in LECj
- TDT(R_i) as the total deadhead travel time for route R_i
- TST(R_i) as the total service time for route R_i
- MST(R_i) as the maximum time duration for the class of route R_i
- TSD(R_i) as the total service distance for route R_i
- MSD(R_i) as the maximum service distance for the class of route R_i
- SP[E(R_iA_z), B($R_iA_z + 1$)] as the deadhead travel time from the ending node of arc R_iA_z to the beginning node of arc $R_iA_z + 1$
- ST(R_iA_z) as the service time for arc R_iA_z
- SD(R_iA_z) as the service distance for arc R_iA_z
- C1 R_i and C2 R_i current possible routes which are examined for a possible improvements to R_i CLECi as the best temporary exchange cost, for improving route i
- CLIR_i as the route that results in CLEC$_i$

Initialize

(0) Set $i = 1, j = 2, k = 1, h = 1, q = 1, s = 1$, LEC$i$ = CLECi = MT(R_i), LIR_i = R_i, LECj = CLECj = MT(R_j), LIR_j = R_j

Delete

(1) Remove all deadhead arcs from R_i,
(2) Calculate TDT(R_i)
    a. Determine the number of arcs in R_i and set equal to R_{im}; then set $m = R_{im}$
    b. Add SP[D_i, B(R_iA_1)]
    c. Add the SPs for any deadhead arcs needed to connect the arcs from R_iA_1 to R_iA_m
        i. Set counter $z = 1$
        ii. If E(R_iA_z) = B($R_iA_z + 1$), then add 0; otherwise, add the SP[R_iA_z, $R_iA_z + 1$]. Update $z = z + 1$. If $z \leq m - 1$, then repeat step 2bii, otherwise, proceed to step 2c.
    d. Add SP[E(R_iA_m), D_i]
(3) Calculate TDT(R_j)
    a. Determine the number of arcs in R_j and set equal to R_{jm}; then set $m = R_{jm}$

  b. Add SP[D_j, B(R_jA_1)]
  c. Add the SPs for any deadhead arcs needed to connect the arcs from R_jA_1 to R_jA_m
    i. Set counter $z = 1$
    ii. If E(R_jA_z) = B($R_jA_z + 1$), then add 0; otherwise, add the SP[R_jA_z, $R_jA_z + 1$]. Update $z = z + 1$. If $z \leq m - 1$, then repeat step 3cii; otherwise, proceed to step 3d.
  d. Add SP[E(R_iA_m), D_i]

(4) Remove R_iA_k from R_i and label the resulting route as C1R_i; rank and label the service arcs in order of service C1R_iA_z, where $z = 1$, to m
  a. Set $z = 1$, set $m = R_{im} - 1$
  b. If z < k, set C1R_iA_z = R_iA_z; otherwise, set C1R_iA_z = $R_iA_z + 1$. Update $z = z + 1$. If $z \leq m$ repeat step 4b; otherwise, proceed to step 5.

(5) Calculate TSD(C1R_i)
  a. Set m = $R_{im} - 1$, $z = 1$
  b. Add SD(C1R_iA_z). Update $z = z + 1$. If $z \leq m$ repeat step 5b; otherwise, proceed to step 6.

(6) Remove R_iA_q from R_i and label the resulting route as C$1R_j$; rank and label the service arcs in order of service C1R_jA_z, where $z = 1$, to m
  a. Set $z = 1$, $m = R_{jm} - 1$,
  b. If $z < q$, set C1R_iA_z = R_iA_z, otherwise set C1R_iA_z = $R_iA_z + 1$. Update $z = z + 1$. If $z \leq m$ repeat step 6b; otherwise, proceed to step 7.

(7) Calculate TSD(C1R_j)
  a. Set $m = R_{jm} - 1$, $z = 1$
  b. Add SD(C1R_jA_z). Update $z = z + 1$. If $z \leq m$ repeat step 7b; otherwise, proceed to step 8.

(8) Check the capacity by adding the SD(R_iA_k) to TSD(C1R_j) to get TSD(C1R_j), and adding SD(R_jA_q) to TSD(C1R_i) to get TSD(C1R_i). If TSD(C1R_j) ≤ MSD(R_j) and TSD(C1R_i) ≤ MSD(R_i), then proceed to step 9; otherwise, update $q = q + 1$. If $q \leq R_{jm}$, then return to step 6; otherwise, update $k = k + 1$. If $k \leq R_{im}$, then set $q = 1$ and return to step 4; otherwise, proceed to step 12.

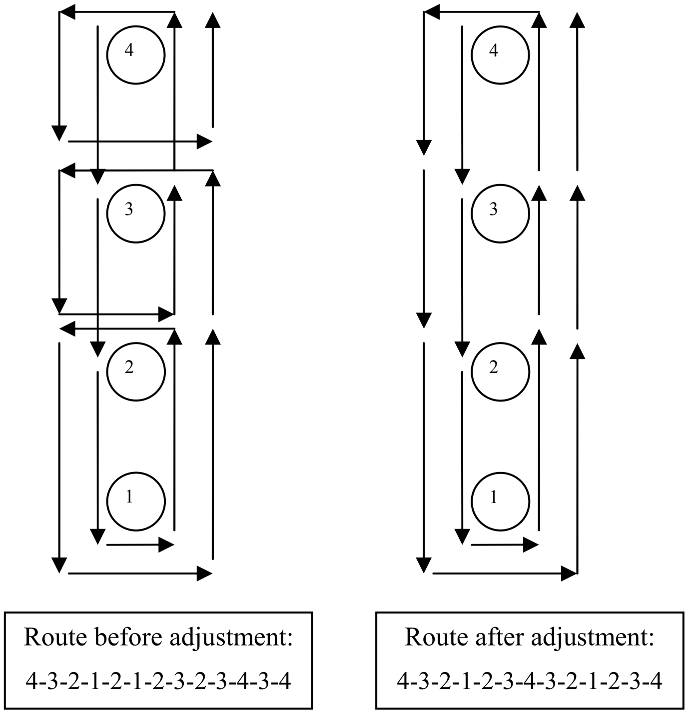
Insert

(9) Calculate the CLECj for inserting R_iA_k into CR_j
  a. Set m = R_{jm}
  b. Set R_iA_k equal to C2R_jA_h and call new route C2R_j; rank and label the service arcs in order of service C2R_jA_1 to C2R_jA_m
    i. Set $z = 1$
    ii. If $z < h$, set C2R_jA_z = C1R_jA_z; otherwise, set C2R_jA_z = C1$R_jA_z + 1$. Update $z = z + 1$. If $z \leq m$, repeat step 9bii; otherwise, proceed to step 9biii.
    iii. Set C2R_jA_h = R_iA_k
  c. Calculate TST(C2R_j)
    i. Sum all of the service times for arcs C2R_jA_1 to C2R_jA_m
  d. Calculate TDT(CR_j)
    i. Add the SP[D_j, B(C2R_jA_1)]
    ii. Add the SPs for any deadhead arcs needed to connect the arcs from C2R_jA_1 to C2R_jA_m

```
            1. Set counter $z = 1$
            2. If $E(C2R_jA_z) = B(C2R_jA_z + 1)$, then add 0; otherwise, add $SP[C2R_jA_z, C2R_jA_z + 1]$. Update $z = z + 1$. If $z \le m - 1$, then repeat step 9diib; otherwise, proceed to step 9diii.
        iii. Add the $SP[E(C2R_jA_m), D_j]$
    e. If $TDT(C2R_j) + TST(C2R_j) < MST(R_j)$ and $TDT(C2R_j) < CLECj$, then set $CLECj = TDT(C2R_j)$ and $CLIR_j = C2R_j$. Update $h = h + 1$. If $h \le R_{jm}$, then return to step 9a; otherwise, proceed to step 10.
(10) Calculate the $CLECi$ for inserting $R_jA_q$ into $CR_i$
    a. Set $m = R_{im}$
    b. Set $R_jA_q$ equal to $C2R_iA_s$ and call new route $C2R_i$; rank and label the service arcs in order of service $C2R_iA_1$ to $C2RiA_m$
        i. Set $z = 1$
        ii. If $z < q$, set $C2R_iA_z = C1R_iA_z$; otherwise, set $C2R_iA_z = C1R_iA_z + 1$. Update $z = z + 1$. If $z \le m$, repeat step 10bii; otherwise, proceed to step 10biii.
        iii. Set $C2\ R_iA_s = R_jA_q$
    c. Calculate $TST(C2R_i)$
        i. Sum all of the service times for arcs $C2\ R_iA_1$ to $C2\ R_iA_m$
    d. Calculate $TDT(C2R_i)$
        i. Add the $SP[D_j, B(C2\ R_iA_1)]$
        ii. Add the SPs for any deadhead arcs needed to connect the arcs from $C2\ R_iA_1$ to $C2R_iA_m$
            1. Set counter $z = 1$
            2. If $E(C2R_iA_z)=B(C2R_iA_z +1)$, then add 0, otherwise add $SP[C2R_iA_z, C2R_iA_z +1]$. Update $z=z+1$. If $z <= m-1$, then repeat step 10diib, otherwise proceed to step 10diii.
            3. Add the $SP[E(C2\ R_iA_m), D_j]$
    e. If $TDT(C2R_i) + TST(C2R_i) < MST(R_i)$ and $TDT(C2R_i) < CLECi$, then set $CLECi = TDT(C2R_i)$ and $CLIR_i = C2R_i$. Update $s = s + 1$. If $s \le R_{im}$, then return to step 10.a; otherwise, proceed to step 11.
    f. If $CLECi + CLECj < LECi + LECj$, then set $LECi = CLECi$, $LIR_i = CLIR_i$, $LECj = CLECj$, $LIR_j = CLIR_j$. Update $q = q + 1$. If $q \le R_{jm}$, then set $CLECi = MT(R_i)$, $CLIR_i = R_i$, $CLECj = MT(R_j)$, $CLIR_j = R_j$ and return to step 6; otherwise, update $k = k + 1$. If $k \le R_{im}$, set $q = 1$, $CLECi = MT(R_i)$, $CLECj = MT(R_j)$, and then return to step 4; otherwise, proceed to step 11.
(11) If $LECj + LECi < TDT(R_j) + TDT(R_i)$, then set Rj = LIRj and $R_i = LIR_i$. Update $j = j + 1$. If $j \le n$, then set $k = 1$, $h = 1$, $q = 1$, $s = 1$, $LECi = CLECi = MT(R_i)$, $LIR_i = R_i$, $LECj = CLECj = MT(R_j)$, $LIR_j = R_j$ and return to step 3; otherwise, update $i = i + 1$. If $i \le n - 1$, then set $j = i + 1$, $k = 1$, $h = 1$, $q = 1$, $s = 1$, $LECi = CLECi = MT(R_i)$, $LIR_i = R_i$, $LECj = CLECj = MT(R_j)$, $LIR_j = R_j$ and return to step 1; otherwise terminate.
```

3.5.3 Stage 2: Manual Route Adjustment

The second stage involves a manual adjustment procedure designed to remove excess u-turns from routes containing four lane roadways. The routing procedure above results in additional unnecessary u-turns for roadways with more than one lane in each direction. However, the excess u-turns can be easily removed without changing the total deadheading required for each route. In terms of the objective, this step does not affect the solution; however, it is included to provide a more practical routing solution. Figure 12 shows an example of a route before and after applying the procedure.



Route before adjustment:
4-3-2-1-2-1-2-3-2-3-4-3-4

Route after adjustment:
4-3-2-1-2-3-4-3-2-1-2-3-4

Figure 12. Manual route adjustment example

The procedure is performed by identifying unnecessary u-turns (as can be seen in the “route before adjustment” example in Figure 12) and reordering the arcs within the route to remove them (as seen in the “route after adjustment” example). Figure 12 illustrates that the two routes both contain the same arcs and begin and end at the same points. Since the procedure is applied to each route separately, it only removes unnecessary u-turns caused on four lane roads and does not affect the mileage or duration, either deadhead or service on the routes.

3.5.4 Stage 3: Vehicle Scheduling and Fleet Configuration

Finally, in the third stage, vehicle scheduling and fleet configuration problems are solved using the final solutions for depot location, sector design, and route design. However, the vehicle scheduling and fleet configuration problem can be solved before, after, or in parallel to stage 2. Since the manual route adjustment procedure does not affect the total deadheading, service mileage, or travel time, it will not affect the solution to the vehicle scheduling and fleet configuration problems.

The fleet configuration problem and the vehicle scheduling problem are solved simultaneously in this stage. The fleet configuration problem determines how many of each type of vehicle are needed at each of the depots, based on the routes and sectors associated with each depot, while the vehicle scheduling problem determines which vehicles service each of the routes. Figure 13 shows the relationships between the depot location, sector design, route design, fleet configuration, and vehicle scheduling considered in this stage.

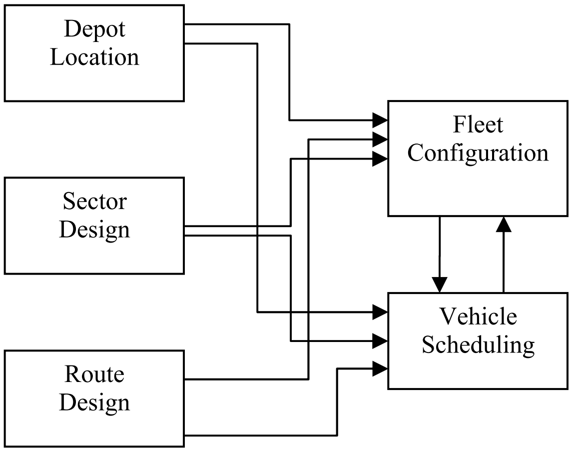


Figure 13. Influence diagram for stage 3 of the solution improvement phase

As previously discussed, MoDOT's fleet consists of heavy-duty single-axle trucks and extra heavy-duty tandem-axle trucks. The single-axle trucks have a capacity of approximately 7.5 tons of material, while the tandem-axle trucks can hold approximately 10 tons of material. The tandem-axle trucks are restricted to the roadways in class A_1 and are only scheduled to service these roadways, while the single-axle trucks are used to service the remaining class A_2, A_3, and A_4 roadways. The capacity constraints are expressed as the maximum distance for which a tandem-and single-axle truck can service 100 miles and 75 miles, respectively, without refilling.

The fleet configuration problems and vehicle scheduling problems are solved separately for each depot, since a vehicle can only service routes that are assigned to its home depot. The vehicles are scheduled for a 12-hour shift, in which it is assumed that the combined plowing and spreading operations continue for the entire shift. The fleet is composed and the vehicles are scheduled using the routes, sectors, and depot locations determined previously, as well as the operational constraints for maximum route duration (which depends on the class of the route) and maximum service distance (which depends on the type of vehicle). Once a vehicle has exhausted its capacity—represented by maximum service distance—or does not have sufficient capacity to service additional routes, it must refill prior to serving any additional routes. The ability of a vehicle to service multiple routes is also constrained by the maximum duration constraints for the highest priority roadway that it services; for class A_1, A_2, A_3, and A_4 routes, a vehicle can only be scheduled for 120, 120, 360, and 720 minutes, respectively. Once the maximum duration for each class of routes is reached, a vehicle must refill and return in order to repeat service on any assigned routes that require additional service. An average refill time of 30 minutes is factored in.

Although a vehicle servicing a route of class A_1 is restricted to only servicing A1 routes, a vehicle that services class A_2 routes can also service class A3 and A4 routes. A vehicle servicing class A_3 routes can also service class A_4 routes. The maximum duration of a vehicle servicing a class A_2 route is 120 minutes; this means that a truck servicing routes of this class must refill and repeat service on them after every 120 minute period. During a 12-hour storm it is possible for a vehicle servicing a class A_2 route to be scheduled for 5 periods of service, each with duration of 120 minutes. Any A_3 routes serviced by a vehicle that also services a class A_2 route must be scheduled during two of the periods, since they require service twice during a 12-hour storm. A truck with a class A_3 route as its highest priority route can be scheduled for two periods. The first period has a maximum duration of 360 minutes and the second has a maximum duration of 330 minutes. The reduction in duration for the second period accommodates the mandated refill after the first period. Any A_3 routes serviced in the first period must also be included in the schedule for the second period. Routes of class A_4 only require service once and would only need to be scheduled during one period if they are serviced by a vehicle which also services any A_2 or A_3 route(s).

The fleet configuration and scheduling procedure attempts to service the routes with the minimum number of vehicles. First an instance of a vehicle is created, with the type depending on the class of route being serviced. Then as many routes as the operational constraints allow are assigned to that vehicle. Once a vehicle has no remaining capacity, a new vehicle is added to the depot; the process is continued until all of the routes serviced by the depot have been assigned to a vehicle. Capacity is represented as a maximum service distance. To ensure that higher priority roadways are serviced earlier than lower priority roadways, the routes are scheduled in order of decreasing priority. From an operational standpoint, it is desirable that a vehicle exhaust its remaining capacity prior to refilling. Therefore, the procedure attempts to assign routes which do not require refill to service before those that require refilling, when comparing routes of the same class. Finally, when comparing routes of the same class that require refill, the scheduling rule is to first assign the route with the maximum duration that can be serviced by the current vehicle.

The fleet configuration and vehicle scheduling procedure is summarized below:

For each depot

(0) Define the maximum capacity of a tandem-axle truck and a single-axle truck as 100 and 75 miles, respectively. Define a vehicle's maximum duration as the maximum duration of the highest priority route that is assigned to the vehicle. The maximum durations for class A_1, A_2, and A_4 routes are 120, 120, and 720 minutes, respectively. A vehicle with a maximum duration corresponding to A_3 routes can be serviced for two periods, with a maximum duration of 360 minutes for the first period and 330 for the second; any A_3 routes must be scheduled in both periods.

(1) Rank the unassigned routes in descending order by priority, with class A_1 being the highest and A_4 being the lowest.

(2) Allot a vehicle to service the highest priority route that is still unassigned; tandem-axle trucks are used on class A1 roadways, while all other roadways are serviced by single-axle trucks.

(3) Assign as many routes as possible to the vehicle—based on the vehicle's maximum duration and maximum capacity—according to the following rules, listed in order of

precedence. Once a vehicle cannot be assigned any more routes, return to step 2.

a. Tandem-axle trucks can only service class A_1 roadways and single-axle trucks can only service class A_2, A_3, and A_4 roadways.
b. Higher priority routes are assigned before lower priority routes.
c. Routes that do not require the vehicle to refill are assigned prior to those that do.
d. Routes are assigned in order of duration, from highest to lowest.

CHAPTER 4: CASE STUDY DESCRIPTION

4.1 Overview of Problem Characteristics

This section provides an overview of the modeling environment considered for this research by briefly discussing the operations performed, the transportation network, the resources available, and other operational constraints. As previously discussed, this research integrates the winter road maintenance decisions for depot location, sector design, plow-and-spreader route design, and fleet configuration. The transportation network considered is the state highway road network in the Boone County district of Missouri, which is serviced by Missouri Department of Transportation (MoDOT). The winter road maintenance operations are extremely complex, so this section focuses only on the operational objectives and parameters which have been abstracted for the purpose of modeling the system.

4.2 Winter Road Maintenance Operations

The primary winter road maintenance operations performed by MoDOT include pre-treatment; combined spreading and plowing operations for roadways, shoulders, and bridges; and then after-storm cleanup. The response depends on the intensity of the storm and the expected weather conditions. Pre-treatment, which occurs prior to or in the early stages of a storm event, is the spreading of abrasives or chemicals over the roadway in an attempt to prevent precipitation from bonding with the road surface. Pre-treatment may be performed on all of the roadways; higher priority roadways only; or just bridges, hills, and curves, depending on the storm conditions. The most common and probably the most important procedure is the plowing-and-spreading operation; this occurs for the duration of most storm events in an attempt to keep the road surface as clear and safe as conditions allow. Combined spreading and plowing is the most time-intensive operation, since plowing is slower than spreading and spreading requires more frequent return trips to the depot than plowing. Secondary and shoulders is the process of plowing the snow from the inner and outer shoulders of highways and other major roadways; this occurs once a storm event has ended. Finally, cleanup and bridges is the process of plowing any remaining snow from the roadways and bridges that has built up as a result of previous plowing operations. All plowing and spreading operations require one service pass per lane. Since combined plowing and spreading is the bottleneck operation, it is the basis for the depot location, sector design, plow-and-spreader route design, and fleet configuration decisions, and this task is also the focal point of the model. Therefore, the discussion presented in this section focuses on the plowing-and-spreading operation.

4.3 Service Level

The objective of the winter road maintenance operations is to provide the highest level of service available, given the existing resources and annual budgetary constraints. The primary goal is to maintain safe driving conditions in order to facilitate the flow of traffic and prevent accidents. However, the quality of the service provided depends largely on the public’s perception of the service, which is based primarily on two factors: service frequency and deadheading. The frequency of service is important because 1) more frequent service results in better driving conditions and 2) frequent visual confirmation of service being performed is comforting to the public. While viewing a vehicle performing service can positively affect the public's perception of service, seeing a vehicle that is not performing service can have a significantly negative impact on the perception of service; this negative perception can arise when a vehicle is seen deadheading a roadway. On the other hand, a reduction in deadheading results in more efficient service by allowing vehicles to service more lane miles per unit of time; consequently, increased efficiency allows more frequent service. Therefore, a high level of service can be achieved by minimizing the time spent deadheading and maintaining an acceptable service frequency.

In this study, unfortunately, constraints on the resources available prevent MoDOT from providing the highest level of service to all roadways. Therefore, the response is prioritized with the objective of providing the maximum benefit to the greatest number of people; a service hierarchy is defined for the roadways based on their historical average daily traffic (ADT). The department has three levels of service hierarchy. Class 1, Class 2, and Class 3 roadways and are determined using the following ADT levels: Class 1 are greater than 5000, Class 2 are between 1700 and 5000, and Class 3 are less than 1700. While MoDOT does not have predefined time windows for servicing each class, they have developed the following targets which they are considering and which will be included in this research: Class 1, Class 2, and Class 3 roadways should be serviced within 2, 6, and 12 hours respectively per 12-hour shift. These time windows translate into an ideal service frequency of 6, 2, and 1 times serviced per shift for Class 1, Class 2, Class 3 roadways, respectively; the frequency is considered ideal because it does not factor in the time needed to refill a vehicle between service runs. Since, MoDOT assigns larger vehicles to service Interstate 70 and Highway 63 than the rest of the transportation network, the hierarchy is further subdivided into the following categories: A_1, A_2, A_3, and A_4, which represent the Class 1 highways, the Class 1 non-highway roadways, the Class 2 roadways, and the Class 3 roadways, respectively. Table 1 shows the hierarchy considered in this research and the corresponding parameters.

Table 1. Service hierarchy parameters

Class Assignment	Description	Class*	Maximum Service Distance	Maximum Duration (minutes)	Ideal Frequency**
A_1	I-70, Highway 63	Class 1	100 miles	120	6
A_2	Class 1 non-highway	Class 1	75 miles	120	6
A_3	Class 2 roadways	Class 2	75 miles	360	2
A_4	Class 3 Roadways	Class 3	75 miles	720	1

*Class is determined based on average daily traffic (ADT)
**Ideal number of times road should be serviced during a 12-hour storm.

4.4 Transportation Network

MoDOT is responsible for servicing all state roads within the state of Missouri. Since this research focuses on the Boone County district, the transportation network includes all state roadways within Boone County, Missouri. Within Boone County, MoDOT is responsible for servicing approximately 1030 lane miles consisting of an interstate highway, state highways, and other state roadways (see Figure 14). Service vehicles are restricted to the state road network while providing service and while deadheading. Since spreading-and-plowing operations require one pass per lane and some roadways have multiple lanes, the road network is modeled as a directed multi-graph. The directed arcs represent the roadways and the direction of travel on them, while the nodes correspond to the intersections and depot locations. Multiple lane roadways are represented with one arc for each traffic lane. The transportation network created to represent the state road network includes 137 nodes and 452 directed arcs. Table 2 shows the categorization of the transportation network into four defined levels of service hierarchy—A_1, A_2, A_3, and A_4.

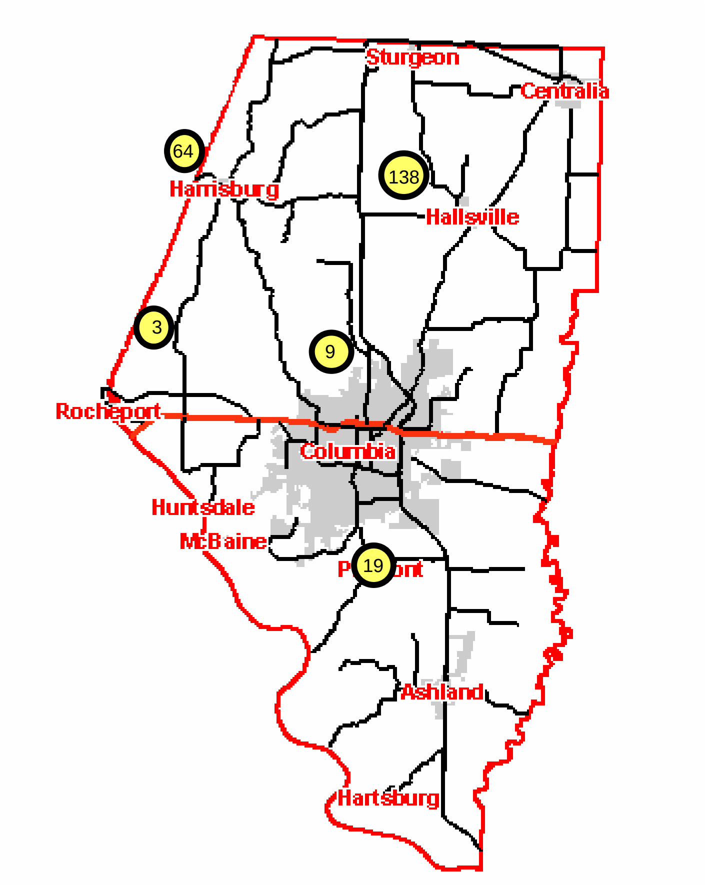


Figure 14. MoDOT Boone County transportation network with existing depots

Table 2. Transportation subnetworks in Boone County, Missouri, by class

Class Assignment	Number of Arcs Requiring Service	Total Distance (miles)
A_1	140	306.42
A_2	124	260.21
A_3	38	125.52
A_4	150	337.35

4.5 Depot Locations

MoDOT currently has five depots, each with a corresponding sector, located throughout the Boone County district (see Figure 14). Currently, MoDOT is considering combining two of the smaller depots into one larger depot and relocating another existing depot. The economic growth within Boone County has resulted in some of the current depot locations being very desirable to private parties, bringing about offers to relocate the facilities in return for new and improved facilities. The decision of whether or not to relocate is based primarily on the premise that the current level of service can be maintained or improved, as this is the purpose of the winter road maintenance operations. Unfortunately, MoDOT currently has no means for assessing the impact of these changes in depot location on the service performed, because there are no performance measures or formal methods for locating depots and designing routes in place. Rather, locations and routes have evolved as a result of annual decisions and adjustments made by MoDOT's managers and planners based on their operational experience. Currently, the main criterion for locating a depot is the proximity to the interstate or other highways and major roadways, since these roadways require the highest frequency and level of service. Additional requirements include more than one access point, easy access to the nearest roadway (preferably through an intersection with a traffic light), and enough space for the required materials and equipment.

4.6 Vehicle Routing

Currently, MoDOT does not have any predetermined routes to guide the winter road maintenance operations. There have been no previous attempts to define routes based on the service level objectives, the problem characteristics, and the topology of transportation network. Instead, a supervisor assigns each driver a set of roads to service, and the order in which they should be serviced is not defined. Once a driver has completed the assignment, he or she returns to the depot to refill the vehicle and receive another assignment. An experienced supervisor makes the operator assignments based his or her knowledge of the operating environment, the storm conditions, and the desire to service higher priority roadways prior to lower priority ones. The operator assignments vary from one storm event to another.

4.7 Fleet Configuration

MoDOT's fleet consists of heavy-duty single-axle trucks and extra heavy-duty tandem-axle trucks. The single-axle trucks have a capacity of approximately 7.5 tons of material, while the tandem-axle trucks can hold approximately 10 tons of material. Each vehicle can be fitted with a 10-, 12-, or 14-foot-wide plow, depending on the roadways to which it is assigned. All three plow sizes can clear one traffic lane by adjusting the angle of the plow. However, a larger plow tends to clear a lane more thoroughly than a smaller plow. All trucks are fitted with monitors that control the rate of material application for spreading. For most storm conditions, vehicles spread material at a rate of 200 lbs. per lane mile. During pure ice storms, material is spread at 400 lbs. per lane mile. Routes for spreading and combined spreading and plowing activities are constrained by material capacity, while pure plowing routes are constrained by fuel capacity. For combined spreading and plowing, the average speed while servicing is 40 mph on the interstate and highways and 30 mph on all other state roadways. Deadheading vehicles travel approximately 10 mph faster than they do while servicing roadways. For safety reasons, the larger vehicles are equipped with 14-foot plows and used to service the interstate and major highways, while the smaller vehicles are used on the remaining roadways and can be equipped with either a 10- or 12-foot plow.

4.8 Material Inventory

State transportation agencies spread a variety of materials on roadways to improve driving conditions. Materials typically used include the following: 1) sodium chloride (rock salt) when road temperature is above 25°F, 2) calcium chloride (brine, pellet, and flake) when road temperature is less than 25°F, and 3) sand. Since it is critical to have these materials available when winter storms occur, the common practice is to maintain an inventory of 1.5 to 2 times the expected usage. For MoDOT District 5 this amounts to having 40,000 tons of material all stored under roof. The Boone County portion of this is approximately 4,000 tons. In the event that additional material is required during the winter storm season, additional material can be obtained for a 50% premium over the preseason purchase price. Due to the necessity to be prepared for the "typical" winter season and the overriding importance of public safety, it is deemed that developing a more detailed, probabilistic inventory procedure is not warranted, nor desirable.

4.9 Operators

Each vehicle requires one operator who is responsible for driving the vehicle and refilling with material and fuel as needed. The crew tends to be very experienced, which is desirable because the situation requires them to work long 12-hour shifts in harsh and sometimes dangerous operating conditions. Operators begin with a prescribed route assignment, but they do have a radio through which changes in route assignments can be communicated, if necessary.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Overview

This section includes an illustration of the solution methodology developed in this research, in which the problems of depot location, sector design, route design, vehicle scheduling, and fleet configuration are solved for the Boone County District in Missouri. Although the characteristics of MoDOT's operations in Boone County were discussed in Chapter 4, some aspects are reiterated in this section. The problem presented in this chapter is to determine the depot locations, routes, sectors, vehicle schedules, and fleet configuration, based on the multiple objectives of minimizing deadhead travel and minimizing the number of vehicles; also included are the operational constraints for service frequency and vehicle capacity. Three different scenarios are evaluated:

- Scenario 1. Existing depots and sectors
    - New routes, vehicle schedules, and fleet configuration

- Scenario 2. MoDOT proposed depots and sectors
    - Move Columbia depot
    - Combine Hallsville and Harrisburg to one sector and depot
    - New routes, vehicle schedules, and fleet configuration

- Scenario 3. Unconstrained solution
    - Depot location, sector design, route design, vehicle scheduling, and fleet configuration problems

5.2 Scenario 1: Existing Depots and Sectors

In scenario 1, the existing depot locations and sector designs are used as the basis for determining solutions to the route design, vehicle scheduling, and fleet configuration problems. MoDOT currently utilizes five depots located on nodes 3, 9, 19, 64, and 138 of the transportation network (see Figure 15 and Appendix).

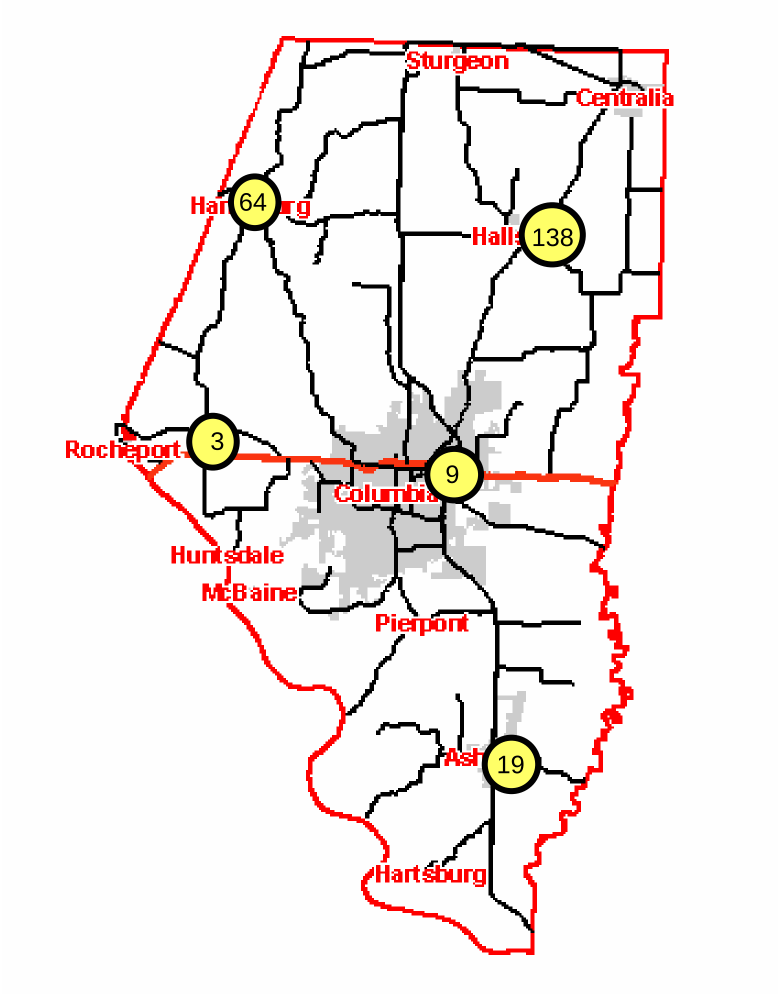


Figure 15. Current solution for depot locations

Since MoDOT does not currently have predefined service routes, they are determined using a slightly modified version of the route first–cluster second method, utilized in the solution methodology developed in this research. For each class of arcs, a Chinese postman tour (CPT) is created that starts at the depot and services all of the arcs of that class within the sector. Then the tour is partitioned into feasible routes based on the operational constraints, and finally, the solution improvement algorithm is applied to the routes. The improvement algorithm considers inter-sector moves between routes in each class but does not consider intra-sector moves to preserve the existing sectors. Although MoDOT has an existing fleet of 23 vehicles, it was suspected that the routes developed would decrease the number of required vehicles. Therefore, the fleet configuration and vehicle scheduling problems were solved using the existing depots and sectors and the new routes.

The results show that that the routes and corresponding vehicle schedules for each of the existing sectors did decrease the total number of required vehicles from the current MoDOT level of 23 vehicles to only 18 vehicles. The decrease in the number of required vehicles suggests a successful solution to the route design problem. The required fleet consists of 6 tandem-axle and 12 single-axle vehicles. The total weighted deadheading for all of the required service routes is

813 minutes. Table 3 summarizes the solutions to the depot location, sector design, fleet configuration, and vehicle scheduling problems.

Table 3. Summary of final results for scenario 1

Depot	Route	Class	Truck	Type*	Weighted Deadhead (min)
3	6	A_1	1	T	0.0
3	13	A_2	2	S	19.4
3	24	A_4	2	S	5.0
9	2	A_1	1	T	54.1
9	3	A_1	2	T	39.5
9	7	A_2	3	S	5.4
9	8	A_2	4	S	30.4
9	9	A_2	5	S	8.7
9	10	A_2	6	S	0.0
9	15	A_3	7	S	63.3
9	19	A_4	8	S	91.3
19	1	A_1	1	T	0.0
19	14	A_3	2	S	19.2
19	18	A_4	2	S	32.6
64	5	A_1	1	T	118.8
64	12	A_2	2	S	0.0
64	17	A_3	3	S	81.9
64	22	A_4	3	S	0.0
64	23	A_4	3	S	21.2
138	4	A_1	1	T	57.3
138	11	A_2	2	S	49.0
138	21	A_3	2	S	59.1
138	16	A_4	3	S	56.8
138	20	A_4	3	S	0.0
Total Weighted Deadhead (min)					**813**
Number of Vehicles					**18**
Tandem Axle					6
Single Axle					12

*T = tandem-axle truck; S = single-axle truck

5.3. Scenario 2: MoDOT Proposed Depots and Sectors

In scenario 2, a modification to the existing depot locations and sector designs is used as the basis for determining solutions to the route design, vehicle scheduling, and fleet configuration problems. MoDOT wanted to evaluate the impact of reducing the number of Boone County depots from five to four. This would be accomplished by combining two rural depots (locations 64 and 138) into a single depot (location 33), plus moving the large Columbia depot (location 9) to a specified location (location 29) while leaving depots 3 and 19 as they were originally (see Figure 16).

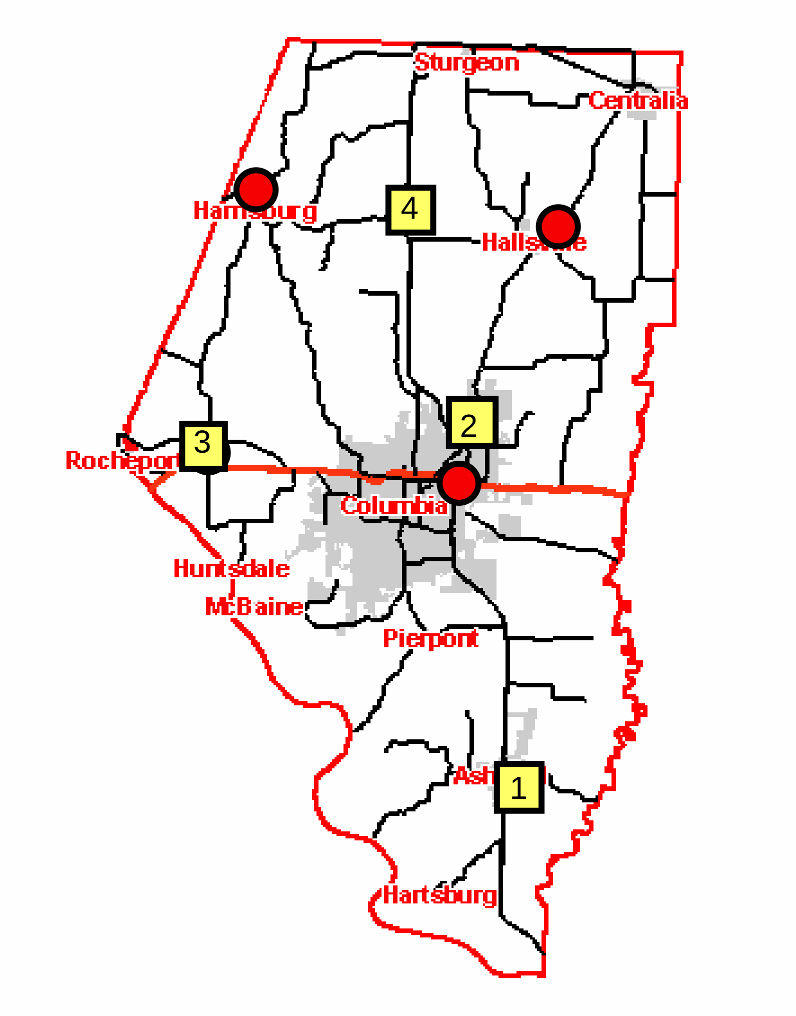


Figure 16. MoDOT proposed depot locations

The results show that that the routes and corresponding vehicle schedules for each of the existing sectors decreased the total number of required vehicles from the 18 vehicles obtained in Scenario 1 (for the original depot locations) to 17 vehicles. The resulting fleet consists of 5 tandem-axle and 12 single-axle vehicles. However, the total weighted deadheading for all of the required service routes increases to 1031 minutes. This was not surprising, as the modified solution still maintained the existing sector designs, so there is effectively a larger area for the single depot to cover as a result of combining two sectors. Table 4 summarizes the solutions to the depot location, sector design, fleet configuration, and vehicle scheduling problems.

Table 4. Summary of final results for scenario 2

Depot	Route	Class	Truck	Type*	Weighted Deadhead (min)
3	5	A_1	1	T	0.0
3	12	A_2	2	S	19.4
3	21	A_4	2	S	5.0
19	1	A_1	1	T	0.0
19	13	A_3	2	S	19.2
19	16	A_4	2	S	32.6
29	2	A_1	1	T	65.4
29	3	A_1	2	T	7.3
29	6	A_2	3	S	47.0
29	7	A_2	4	S	80.7
29	8	A_2	5	S	0.0
29	9	A_2	6	S	0.0
29	14	A_3	7	S	74.3
29	17	A_4	8	S	96.8
33	4	A_1	1	T	0.0
33	10	A_2	2	S	226.1
33	11	A_2	3	S	106.4
33	15	A_3	4	S	116.7
33	20	A_4	4	S	42.7
33	18	A_4	5	S	64.2
33	19	A_4	5	S	27.6
Total Weighted Deadhead (min)					**1031**
Number of Vehicles					**17**
Tandem Axle					5
Single Axle					12

*T = tandem-axle truck; S = single-axle truck

5.4 Scenario 3: Unconstrained Solution

5.4.1 Initial Depot Location Solution

In Scenario 3, the integrated solution methodology is applied to the depot location, sector design, route design, vehicle scheduling, and fleet configuration problems for Boone County, Missouri. In addition to the previously discussed problem characteristics, a set of potential depot locations is also needed to develop the new solution. MoDOT provided the following set of potential depot locations to be considered (numbers correspond to the nodes in the transportation network): 3, 4, 5, 9, 11, 18, 19, 23, 26, 27, 29, 33, 36, 60, and 64 (see Figure 17). The potential depot locations include only three of the five current depot locations; while this may impact the comparison between the existing operations and the proposed solution, the decision was made because of a desire to move depots nearer to the highest-priority roadways.

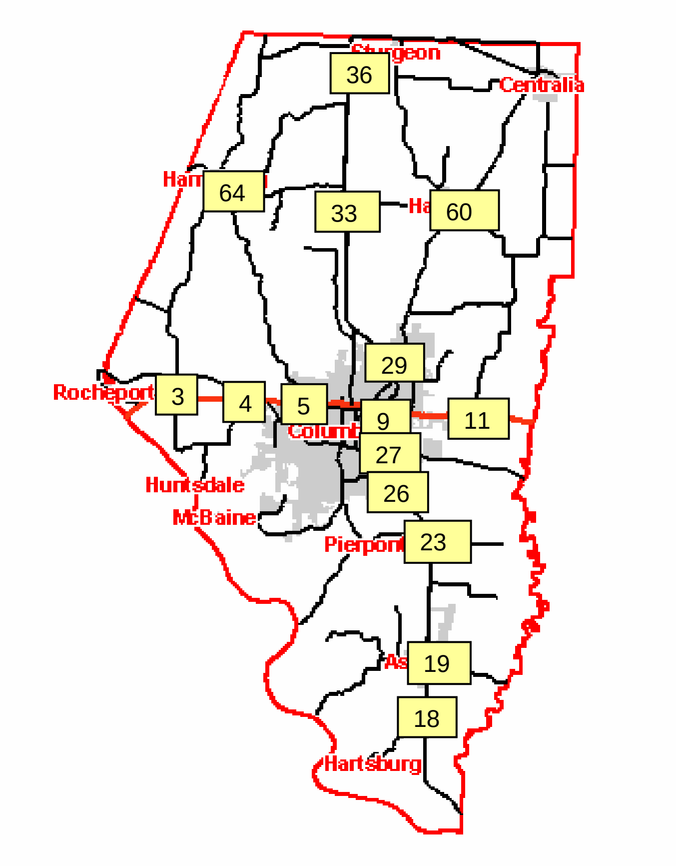


Figure 17. Potential depot location sites proposed for scenario 3

Since MoDOT is interested in knowing the number of depots to open in addition to their existing locations, the initial solutions are compared to gain some insight into the number of depots that should be opened. Initial solutions were found for an increasing number of depots, from one to eight, and the results are shown in Figure 18 and Table 5.

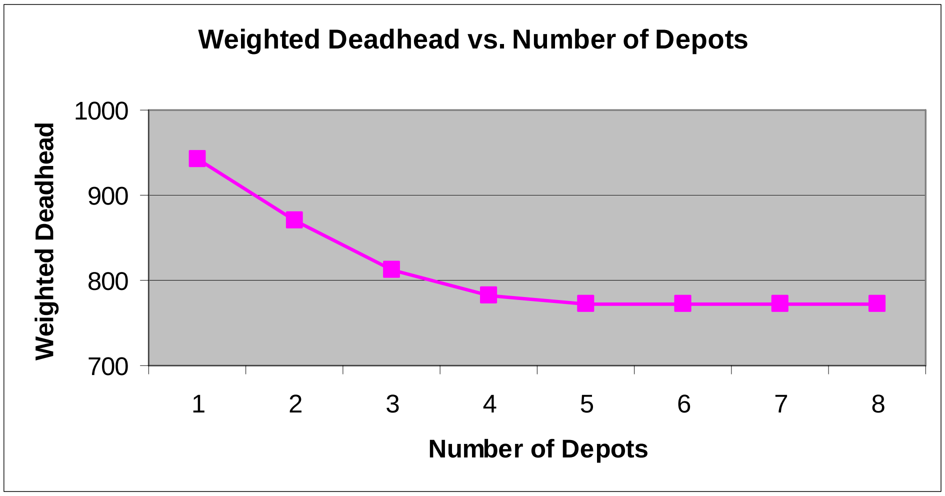


Figure 18. New solution: Weighted Deadhead vs. number of depots

Table 5. New solution: Initial solution vs. number of depots

Number of Depots	Weighted Deadhead	Improvement
1	942.3	
2	869.5	7.73%
3	812.3	6.57%
4	782.1	3.72%
5	772.8	1.18%
6	772.4	0.06%
7	772.4	0.00%
8	772.404	0.00%

The results from the initial solution phase indicate that the benefit to the objective function—total weighted deadhead travel between each route and its assigned depot—gained by opening an additional depot beyond four is marginal. Additionally, results indicate that five is probably the maximum number of depots needed to service Boone County, Missouri. The number of depots to open at this stage of the solution methodology is a judgment call; however, MoDOT is interested in knowing the effects of a decreased number of possibly relocated depots on their ability to maintain or exceed their current high level of service. Since the results to the initial solution phase indicate that a four-depot solution may provide similar results to a five-depot solution, the four-depot initial solution is chosen.

5.4.2 Final Integrated Solution

The improvement heuristic was then applied to the initial solutions for the sector design and the route design to determine the final solutions to these problems. Since the improvement heuristic proved to be computationally demanding for networks of the size required for this research, the number of iterations of each subroutine within the heuristic and the total number of iterations for the entire heuristic were limited to five. For all of the subnetworks, the heuristic converged on a solution before five iterations of the improvement heuristic. Once the final solutions for the depot locations, sector design, and route design problems were obtained, they were utilized to determine the corresponding solutions to the vehicle scheduling and fleet configuration problems. The deadhead travel time for each route was weighted based on the ideal service frequency (number of times a route is served every 12 hours) corresponding to each class of route; therefore, for a 12-hour shift, the weights are 6, 6, 2, and 1 for routes of class A_1, A_2, A_3, and A_4, respectively. The weights used in this stage were the same weights used to determine the initial solution. The total weighted deadhead travel time for all of the routes is 801 minutes. The fleet required to service these routes consists of 16 total vehicles, with 5 tandem-axle trucks and 11 single-axle trucks. Table 6 summarizes the solutions to the depot location, sector design, fleet configuration, and vehicle scheduling problems. Figure 19 shows the locations of the four depots for scenario 3.

Table 6. Summary of final results for scenario 3

Depot	Route	Class	Truck	Type*	Weighted Deadhead (min)
5	1	A_1	1	T	14.6
5	5	A_1	2	T	36.0
5	8	A_2	3	S	8.3
5	9	A_2	4	S	55.5
9	4	A_1	1	T	30.1
9	6	A_2	2	S	5.4
9	7	A_2	3	S	36.7
9	10	A_2	4	S	13.5
9	12	A_3	5	S	80.2
9	13	A_3	6	S	75.3
9	14	A_4	7	S	48.1
9	17	A_4	7	S	77.5
27	2	A_1	1	T	154.6
27	3	A_1	2	T	0.0
27	11	A_2	3	S	14.4
27	18	A_4	4	S	58.1
36	15	A_4	1	S	43.0
36	16	A_4	1	S	50.2
Total Weighted Deadhead (min)					**801**
Number of Vehicles					**16**
Tandem Axle					5
Single Axle					11

*T = tandem-axle truck; S = single-axle truck

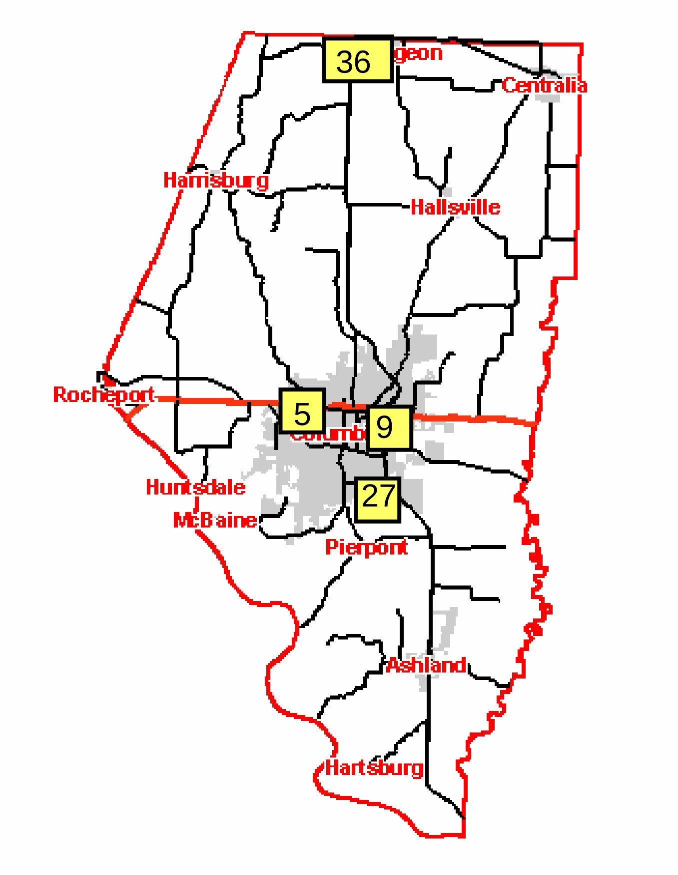


Figure 19. Final integrated solution for the depot location problem

5.5 Discussion of results

The application of the integrated solution methodology proposed in this research to the problems of depot location, sector design, route design, vehicle scheduling, and fleet configuration for Boone County, Missouri, has resulted in a very promising solution (see Table 7). The routing approach that was applied in scenario 1 was able to reduce the number of vehicles required from the existing level of 23 to 18, a fleet reduction of 20%. The depot locations, sectors, and routes for the integrated solution (scenario 3) would allow MoDOT to provide the same high level of service with significantly fewer resources. The integrated solution (scenario 3) required one fewer depot (four depots) and two fewer vehicles (16 vehicles, a 10 % reduction) than the improved routing solution developed in scenario 1. The weighted deadhead travel time required by the scenario 3 is slightly less than that for scenario 1.

Table 7. Comparison between scenarios with respect to vehicle requirements

	Existing Operations	Scenario 1	Scenario 2	Scenario 3
Number of Depots	5	5	4	4
Number of Vehicles	23	18	17	16
Tandem-axle	9	6	5	5
Single-axle	14	12	12	11
Total Weighted Deadhead Travel (min.)	**NA**	**813**	**1031**	**801**

A comparison of the deadhead travel time (see Table 8) required by scenarios 1 and 3 shows that the scenario 3 solution requires less deadhead travel on the higher priority routes, with the exception of class A_2 where the deadhead travel time is only slightly higher; the lowest priority routes, class A_4, absorb more of the deadhead travel in this solution. This is because the scenario 3 solution chooses depot locations closer to the higher priority roads. Both solutions share one depot location, located at node 9 on the transportation network.

Table 8. Comparison between solutions with respect to weighted deadhead travel time

	Total Weighted Deadhead Travel (min.)		
Class	Scenario 1 existing depots	Scenario 2 MoDOT proposed depots	Scenario 3 unconstrained solution
A_1	269.7	72.7	235.3
A_2	112.9	479.6	133.8
A_3	223.7	210.2	155.5
A_4	206.9	268.9	276.8
Total	**813**	**1031**	**801**

The promising results from the real-world test problem in Boone County, Missouri support the relevance of a more integrated approach to the winter road maintenance problems studied in this research. The integrated approach bases the number of open depots on insight gained from the interrelated route and sector design problems. This solution methodology is designed to aid winter road maintenance planners in making decisions regarding the interrelated problems studied in this research—decisions that will impact the agency's ability to achieve a desired level of service. Based on the solution methodology's ability to solve the winter road maintenance planning problems included in this research in a more integrated manner, the optimization approach herein should also be able to provide planners with the ability to make more informed, successful decisions.

CHAPTER 6: CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

6.1 Summary and Conclusions

The objective of this research was to develop a systematic, heuristic-based optimization approach to integrate the winter road maintenance planning decisions for depot location, sector design, vehicle route design, vehicle scheduling, and fleet configuration. The solution methodology achieves the objective of a more integrated and less sequential approach to the problems considered. When applied to the real-world winter road maintenance planning problems for Boone County, Missouri, the methodology delivered very promising results (i.e., the integrated solution would allow MoDOT to maintain the same high level of service with significantly fewer resources). Although there is much opportunity for further integrating the decisions studied in this research, the proposed methodology shows progress from the traditional sequential approach towards the eventual goal of a fully integrated approach to winter road maintenance planning problems.

Additionally, the research achieved the goal of considering practical, real-world objectives, constraints, and problem characteristics; this was made possible by working with MoDOT to identify the necessary aspects of each of the planning problems studied. To consider the problems of depot location, sector design, and route design simultaneously, it was necessary to develop a multiple-depot route design and improvement methodology; the results indicate that this methodology is a successful step towards solving realistic multiple-depot problems. The inclusion of a heterogeneous fleet provided a better representation of MoDOT’s current operations. Finally, the inclusion of the vehicle scheduling problem supports the idea that, when service frequency and vehicle capacity are considered, it is possible for a vehicle to service multiple routes. When a vehicle can service multiple routes, then the problem of vehicle scheduling must be considered in addition to fleet sizing.

6.2 Directions for Future Research

Since the solution methodology proposed in this research is heuristic-based, there is no guarantee that an optimal or near-optimal solution will be achieved. Overall solution quality is left for future research. Additionally, the size and sparseness of the transportation network may have played a significant role in the success of the solution achieved in this study. Further research is necessary to determine the effect of the specific characteristics of the transportation network on the quality of the solution.

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APPENDIX: TRANSPORTATION NETWORK

# ID	Alpha ID	From	To	Centerline miles	Service Time (min.)	Road and Direction	Class	Depot*
1,2	70E01	1	2	4.050	6.075	70E	1	R
1,2	70E02	1	2	4.050	6.075	70E	1	R
2,3	70E03	2	3	1.999	2.999	70E	1	R
2,3	70E04	2	3	1.999	2.999	70E	1	R
3,4	70E05	3	4	3.939	5.909	70E	1	R
3,4	70E06	3	4	3.939	5.909	70E	1	R
4,5	70E07	4	5	2.789	4.184	70E	1	R
4,5	70E08	4	5	2.789	4.184	70E	1	R
5,6	70E09	5	6	1.147	1.721	70E	1	C
5,6	70E10	5	6	1.147	1.721	70E	1	C
6,7	70E11	6	7	1.001	1.502	70E	1	C
6,7	70E12	6	7	1.001	1.502	70E	1	C
7,8	70E13	7	8	0.457	0.685	70E	1	C
7,8	70E14	7	8	0.457	0.685	70E	1	C
8,9	70E15	8	9	1.886	2.829	70E	1	C
8,9	70E16	8	9	1.886	2.829	70E	1	C
9,10	70E17	9	10	2.099	3.149	70E	1	C
9,10	70E18	9	10	2.099	3.149	70E	1	C
10,11	70E19	10	11	2.657	3.986	70E	1	C
10,11	70E20	10	11	2.657	3.986	70E	1	C
11,12	70E21	11	12	4.050	6.075	70E	1	C
11,12	70E22	11	12	4.050	6.075	70E	1	C
12,11	70W01	12	11	4.050	6.075	70W	1	C
12,11	70W02	12	11	4.050	6.075	70W	1	C
11,10	70W03	11	10	2.657	3.986	70W	1	C
11,10	70W04	11	10	2.657	3.986	70W	1	C
10,9	70W05	10	9	2.100	3.150	70W	1	C
10,9	70W06	10	9	2.100	3.150	70W	1	C
9,8	70W07	9	8	1.878	2.817	70W	1	C
9,8	70W08	9	8	1.878	2.817	70W	1	C
8,7	70W09	8	7	0.458	0.687	70W	1	C
8,7	70W10	8	7	0.458	0.687	70W	1	C
7,6	70W11	7	6	1.025	1.538	70W	1	C
7,6	70W12	7	6	1.025	1.538	70W	1	C
6,5	70W13	6	5	1.118	1.677	70W	1	C
6,5	70W14	6	5	1.118	1.677	70W	1	C
5,4	70W15	5	4	2.974	4.461	70W	1	R
5,4	70W16	5	4	2.974	4.461	70W	1	R
4,3	70W17	4	3	3.755	5.633	70W	1	R
4,3	70W18	4	3	3.755	5.633	70W	1	R
3,2	70W19	3	2	2.174	3.261	70W	1	R

# ID	Alpha ID	From	To	Centerline miles	Service Time (min.)	Road and Direction	Class	Depot
3,2	70W20	3	2	2.174	3.261	70W	1	R
2,1	70W21	2	1	4.050	6.075	70W	1	R
2,1	70W22	2	1	4.050	6.075	70W	1	R
13,14	63N01	13	14	5.900	8.850	63N	1	A
13,14	63N02	13	14	5.900	8.850	63N	1	A
14,15	63N03	14	15	1.200	1.800	63N	1	A
14,15	63N04	14	15	1.200	1.800	63N	1	A
15,16	63N05	15	16	0.500	0.750	63N	1	A
15,16	63N06	15	16	0.500	0.750	63N	1	A
16,17	63N07	16	17	2.300	3.450	63N	1	A
16,17	63N08	16	17	2.300	3.450	63N	1	A
17,18	63N09	17	18	2.300	3.450	63N	1	A
17,18	63N10	17	18	2.300	3.450	63N	1	A
18,19	63N11	18	19	3.013	4.520	63N	1	A
18,19	63N12	18	19	3.013	4.520	63N	1	A
19,20	63N13	19	20	1.681	2.522	63N	1	A
19,20	63N14	19	20	1.681	2.522	63N	1	A
20,21	63N15	20	21	2.324	3.486	63N	1	A
20,21	63N16	20	21	2.324	3.486	63N	1	A
21,22	63N17	21	22	2.043	3.065	63N	1	C
21,22	63N18	21	22	2.043	3.065	63N	1	C
22,23	63N19	22	23	0.487	0.731	63N	1	C
22,23	63N20	22	23	0.487	0.731	63N	1	C
23,24	63N21	23	24	1.334	2.001	63N	1	C
23,24	63N22	23	24	1.334	2.001	63N	1	C
24,25	63N23	24	25	0.218	0.327	63N	1	C
24,25	63N24	24	25	0.218	0.327	63N	1	C
25,26	63N25	25	26	2.378	3.567	63N	1	C
25,26	63N26	25	26	2.378	3.567	63N	1	C
26,27	63N27	26	27	1.331	1.997	63N	1	C
26,27	63N28	26	27	1.331	1.997	63N	1	C
27,28	63N29	27	28	0.991	1.487	63N	1	C
27,28	63N30	27	28	0.991	1.487	63N	1	C
28,29	63N31	28	29	3.500	5.250	63N	1	C
28,29	63N32	28	29	3.500	5.250	63N	1	C
29,30	63N33	29	30	0.465	0.698	63N	1	HL
29,30	63N34	29	30	0.465	0.698	63N	1	HL
30,31	63N35	30	31	1.735	2.603	63N	1	HL
30,31	63N36	30	31	1.735	2.603	63N	1	HL
31,32	63N37	31	32	3.269	4.904	63N	1	HL
31,32	63N38	31	32	3.269	4.904	63N	1	HL
32,33	63N39	32	33	4.587	6.881	63N	1	HL
32,33	63N40	32	33	4.587	6.881	63N	1	HL

# ID	Alpha ID	From	To	Centerline miles	Service Time (min.)	Road and Direction	Class	Depot
33,34	63N41	33	34	0.791	1.187	63N	1	HR
33,34	63N42	33	34	0.791	1.187	63N	1	HR
34,35	63N43	34	35	4.440	6.660	63N	1	HR
34,35	63N44	34	35	4.440	6.660	63N	1	HR
35,36	63N45	35	36	2.027	3.041	63N	1	HR
35,36	63N46	35	36	2.027	3.041	63N	1	HR
36,37	63N47	36	37	1.471	2.207	63N	1	HR
36,37	63N48	36	37	1.471	2.207	63N	1	HR
37,36	63S01	37	36	1.515	2.273	63S	1	HR
37,36	63S02	37	36	1.515	2.273	63S	1	HR
36,35	63S03	36	35	2.023	3.035	63S	1	HR
36,35	63S04	36	35	2.023	3.035	63S	1	HR
35,34	63S05	35	34	4.425	6.638	63S	1	HR
35,34	63S06	35	34	4.425	6.638	63S	1	HR
34,33	63S07	34	33	0.832	1.248	63S	1	HR
34,33	63S08	34	33	0.832	1.248	63S	1	HR
33,32	63S09	33	32	4.605	6.908	63S	1	HL
33,32	63S10	33	32	4.605	6.908	63S	1	HL
32,31	63S11	32	31	3.260	4.890	63S	1	HL
32,31	63S12	32	31	3.260	4.890	63S	1	HL
31,30	63S13	31	30	1.735	2.603	63S	1	HL
31,30	63S14	31	30	1.735	2.603	63S	1	HL
30,29	63S15	30	29	0.471	0.707	63S	1	HL
30,29	63S16	30	29	0.471	0.707	63S	1	HL
29,28	63S17	29	28	3.263	4.895	63S	1	C
29,28	63S18	29	28	3.263	4.895	63S	1	C
28,27	63S19	28	27	1.011	1.517	63S	1	C
28,27	63S20	28	27	1.011	1.517	63S	1	C
27,26	63S21	27	26	1.313	1.970	63S	1	C
27,26	63S22	27	26	1.313	1.970	63S	1	C
26,25	63S23	26	25	2.387	3.581	63S	1	C
26,25	63S24	26	25	2.387	3.581	63S	1	C
25,24	63S25	25	24	0.146	0.219	63S	1	C
25,24	63S26	25	24	0.146	0.219	63S	1	C
24,23	63S27	24	23	1.391	2.087	63S	1	C
24,23	63S28	24	23	1.391	2.087	63S	1	C
23,22	63S29	23	22	0.515	0.773	63S	1	C
23,22	63S30	23	22	0.515	0.773	63S	1	C
22,21	63S31	22	21	2.004	3.006	63S	1	C
22,21	63S32	22	21	2.004	3.006	63S	1	C
21,20	63S33	21	20	1.995	2.993	63S	1	A
21,20	63S34	21	20	1.995	2.993	63S	1	A
20,19	63S35	20	19	2.020	3.030	63S	1	A
20,19	63S36	20	19	2.020	3.030	63S	1	A

# ID	Alpha ID	From	To	Centerline miles	Service Time (min.)	Road and Direction	Class	Depot
19,18	63S37	19	18	3.005	4.508	63S	1	A
19,18	63S38	19	18	3.005	4.508	63S	1	A
18,17	63S39	18	17	2.273	3.410	63S	1	A
18,17	63S40	18	17	2.273	3.410	63S	1	A
17,16	63S41	17	16	2.821	4.232	63S	1	A
17,16	63S42	17	16	2.821	4.232	63S	1	A
16,15	63S43	16	15	0.500	0.750	63S	1	A
16,15	63S44	16	15	0.500	0.750	63S	1	A
15,14	63S45	15	14	1.200	1.800	63S	1	A
15,14	63S46	15	14	1.200	1.800	63S	1	A
14,13	63S47	14	13	5.900	8.850	63S	1	A
14,13	63S48	14	13	5.900	8.850	63S	1	A
38,39	40E01	38	39	3.986	7.972	40E	1	R
39,4	40E02	39	4	4.108	8.216	40E	1	R
4,39	40W01	4	39	3.686	7.372	40W	1	R
39,38	40W02	39	38	3.365	6.730	40W	1	R
6,40	LP70E01	6	40	0.958	1.916	LP70E	1	C
6,40	LP70E02	6	40	0.958	1.916	LP70E	1	C
40,41	LP70E03	40	41	0.687	1.374	LP70E	1	C
40,41	LP70E04	40	41	0.687	1.374	LP70E	1	C
41,42	LP70E05	41	42	0.517	1.034	LP70E	1	C
41,42	LP70E06	41	42	0.517	1.034	LP70E	1	C
42,43	LP70E07	42	43	0.650	1.300	LP70E	1	C
42,43	LP70E08	42	43	0.650	1.300	LP70E	1	C
43,9	LP70E09	43	9	0.600	1.200	LP70E	1	C
43,9	LP70E10	43	9	0.600	1.200	LP70E	1	C
9,43	LP70W01	9	43	0.600	1.200	LP70W	1	C
9,43	LP70W02	9	43	0.600	1.200	LP70W	1	C
43,42	LP70W03	43	42	0.650	1.300	LP70W	1	C
43,42	LP70W04	43	42	0.650	1.300	LP70W	1	C
42,41	LP70W05	42	41	0.517	1.034	LP70W	1	C
42,41	LP70W06	42	41	0.517	1.034	LP70W	1	C
41,40	LP70W07	41	40	0.687	1.374	LP70W	1	C
41,40	LP70W08	41	40	0.687	1.374	LP70W	1	C
40,6	LP70W09	40	6	0.958	1.916	LP70W	1	C
40,6	LP70W10	40	6	0.958	1.916	LP70W	1	C
5,44	740E01	5	44	0.987	1.974	740E	1	C
5,44	740E02	5	44	0.987	1.974	740E	1	C
44,45	740E03	44	45	2.964	5.928	740E	1	C
44,45	740E04	44	45	2.964	5.928	740E	1	C
45,46	740E05	45	46	0.681	1.362	740E	1	C
45,46	740E06	45	46	0.681	1.362	740E	1	C
46,27	740E07	46	27	1.649	3.298	740E	1	C

# ID	Alpha ID	From	To	Centerline miles	Service Time (min.)	Road and Direction	Class	Depot
46,27	740E08	46	27	1.649	3.298	740E	1	C
27,46	740W01	27	46	1.639	3.278	740W	1	C
27,46	740W02	27	46	1.639	3.278	740W	1	C
46,45	740W03	46	45	0.681	1.362	740W	1	C
46,45	740W04	46	45	0.681	1.362	740W	1	C
45,44	740W05	45	44	2.964	5.928	740W	1	C
45,44	740W06	45	44	2.964	5.928	740W	1	C
44,5	740W07	44	5	0.987	1.974	740W	1	C
44,5	740W08	44	5	0.987	1.974	740W	1	C
46,41	763N01	46	41	2.030	4.060	763N	1	C
46,41	763N02	46	41	2.030	4.060	763N	1	C
41,8	763N03	41	8	0.519	1.038	763N	1	C
41,8	763N04	41	8	0.519	1.038	763N	1	C
8,47	763N05	8	47	3.308	6.616	763N	1	C
8,47	763N06	8	47	3.308	6.616	763N	1	C
47,32	763N07	47	32	2.761	5.522	763N	1	C
47,32	763N08	47	32	2.761	5.522	763N	1	C
32,47	763S01	32	47	2.696	5.392	763S	1	C
32,47	763S02	32	47	2.696	5.392	763S	1	C
47,8	763S03	47	8	3.308	6.616	763S	1	C
47,8	763S04	47	8	3.308	6.616	763S	1	C
8,41	763S05	8	41	0.519	1.038	763S	1	C
8,41	763S06	8	41	0.519	1.038	763S	1	C
41,46	763S07	41	46	2.030	4.060	763S	1	C
41,46	763S08	41	46	2.030	4.060	763S	1	C
49,50	163N03	49	50	1.236	2.472	163N	1	C
49,50	163N04	49	50	1.236	2.472	163N	1	C
50,55	163N05	50	55	0.237	0.474	163N	1	C
50,55	163N06	50	55	0.237	0.474	163N	1	C
55,45	163N07	55	45	1.801	3.602	163N	1	C
55,45	163N08	55	45	1.801	3.602	163N	1	C
45,40	163N09	45	40	1.872	3.744	163N	1	C
45,40	163N10	45	40	1.872	3.744	163N	1	C
40,7	163N11	40	7	0.302	0.604	163N	1	C
40,7	163N12	40	7	0.302	0.604	163N	1	C
7,40	163S01	7	40	0.302	0.604	163S	1	C
7,40	163S02	7	40	0.302	0.604	163S	1	C
40,45	163S03	40	45	1.872	3.744	163S	1	C
40,45	163S04	40	45	1.872	3.744	163S	1	C
45,55	163S05	45	55	1.626	3.252	163S	1	C
45,55	163S06	45	55	1.626	3.252	163S	1	C
55,50	163S07	55	50	0.412	0.824	163S	1	C
55,50	163S08	55	50	0.412	0.824	163S	1	C
50,49	163S09	50	49	1.236	2.472	163S	1	C

# ID	Alpha ID	From	To	Centerline miles	Service Time (min.)	Road and Direction	Class	Depot
50,49	163S10	50	49	1.236	2.472	163S	1	C
28,9	63CN01	28	9	1.671	3.342	63CN	1	C
28,9	63CN02	28	9	1.671	3.342	63CN	1	C
9,29	63CN03	9	29	2.000	4.000	63CN	1	C
9,29	63CN04	9	29	2.000	4.000	63CN	1	C
29,9	63CS01	29	9	2.000	4.000	63CS	1	C
29,9	63CS02	29	9	2.000	4.000	63CS	1	C
9,28	63CS03	9	28	1.671	3.342	63CS	1	C
9,28	63CS04	9	28	1.671	3.342	63CS	1	C
50,26	ACE01	50	26	2.382	4.764	ACE	1	C
50,26	ACE02	50	26	2.382	4.764	ACE	1	C
26,50	ACW01	26	50	2.384	4.768	ACW	1	C
26,50	ACW02	26	50	2.384	4.768	ACW	1	C
9,51	PPN01	9	51	6.047	12.094	PPN	1	C
51,9	PPS01	51	9	6.047	12.094	PPS	1	C
52,53	TTE01	52	53	1.778	3.556	TTE	1	C
53,44	TTE02	53	44	1.341	2.682	TTE	1	C
44,54	TTE03	44	54	0.492	0.984	TTE	1	C
54,44	TTW01	54	44	0.492	0.984	TTW	1	C
44,53	TTW02	44	53	1.341	2.682	TTW	1	C
53,52	TTW03	53	52	1.778	3.556	TTW	1	C
56,57	WWE01	56	57	0.477	0.954	WWE	1	C
56,57	WWE02	56	57	0.477	0.954	WWE	1	C
57,28	WWE03	57	28	0.471	0.942	WWE	1	C
57,28	WWE04	57	28	0.471	0.942	WWE	1	C
28,58	WWE05	28	58	7.923	15.846	WWE	1	C
58,28	WWW01	58	28	7.951	15.902	WWW	1	C
28,57	WWW02	28	57	0.471	0.942	WWW	1	C
28,57	WWW03	28	57	0.471	0.942	WWW	1	C
57,56	WWW04	57	56	0.477	0.954	WWW	1	C
57,56	WWW05	57	56	0.477	0.954	WWW	1	C
42,29	BN01	42	29	2.190	4.380	BN	1	HL
42,29	BN02	42	29	2.190	4.380	BN	1	HL
29,59	BN03	29	59	3.687	7.374	BN	1	HL
29,59	BN04	29	59	3.687	7.374	BN	1	HL
59,60	BN05	59	60	6.278	12.556	BN	1	HL
60,59	BS01	60	59	6.278	12.556	BS	1	HL
59,29	BS02	59	29	3.687	7.374	BS	1	HL
59,29	BS03	59	29	3.687	7.374	BS	1	HL
29,42	BS04	29	42	2.190	4.380	BS	1	HL
29,42	BS05	29	42	2.190	4.380	BS	1	HL
60,68	124E10	60	68	8.363	16.726	124E	1	HL
68,60	124W01	68	60	8.363	16.726	124W	1	HL
5,64	EN01	5	64	13.544	27.088	EN	1	HR

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64,5	ES01	64	5	13.544	27.088	ES	1	HR
5,6	70SO4E01	5	6	1.200	2.400	70SO4E	1	C
6,5	70SO4W01	6	5	1.300	2.600	70SO4W	1	C
9,10	70SO6E01	9	10	2.300	4.600	70SO6E	1	C
10,9	70SO6W01	10	9	2.300	4.600	70SO6W	1	C
23,48	163N01	23	48	3.579	7.158	163N	2	C
48,49	163N02	48	49	2.655	5.310	163N	2	C
49,48	163S11	49	48	2.655	5.310	163S	2	C
48,23	163S12	48	23	3.579	7.158	163S	2	C
69,70	VN01	69	70	7.133	14.266	VN	2	HL
70,71	VN02	70	71	0.998	1.996	VN	2	HL
71,72	VN03	71	72	1.306	2.612	VN	2	HL
72,71	VS01	72	71	1.306	2.612	VS	2	HL
71,70	VS02	71	70	0.998	1.996	VS	2	HL
70,69	VS03	70	69	7.133	14.266	VS	2	HL
11,73	ZN01	11	73	6.670	13.340	ZN	2	C
73,74	ZN02	73	74	2.765	5.530	ZN	2	HL
74,75	ZN03	74	75	2.433	4.866	ZN	2	HL
75,76	ZN04	75	76	3.814	7.628	ZN	2	HL
76,68	ZN05	76	68	4.490	8.980	ZN	2	HL
68,76	ZS01	68	76	4.490	8.980	ZS	2	HL
76,75	ZS02	76	75	3.814	7.628	ZS	2	HL
75,74	ZS03	75	74	2.433	4.866	ZS	2	HL
74,73	ZS04	74	73	2.765	5.530	ZS	2	HL
73,11	ZS05	73	11	6.670	13.340	ZS	2	C
77,78	KN01	77	78	1.580	3.160	KN	2	C
78,49	KN02	78	49	5.750	11.500	KN	2	C
49,78	KS01	49	78	5.750	11.500	KS	2	C
78,77	KS02	78	77	1.580	3.160	KS	2	C
21,79	HE01	21	79	4.071	8.142	HE	2	A
79,21	HW01	79	21	4.071	8.142	HW	2	A
47,80	VVN01	47	80	7.117	14.234	VVN	2	HR
80,47	VVS01	80	47	7.117	14.234	VVS	2	HR
96,5	70SO3E01	96	5	2.300	4.600	70SO3E	2	C
5,96	70SO3W01	5	96	2.300	4.600	70SO3W	2	C
10,11	70SO7E01	10	11	2.800	5.600	70SO7E	2	C
11,10	70SO7W01	11	10	2.800	5.600	70SO7W	2	C
110,5	70NO2E01	110	5	2.100	4.200	70NO2E	2	C
5,111	70NO2E02	5	111	0.100	0.200	70NO2E	2	C
111,5	70NO2W01	111	5	0.100	0.200	70NO2W	2	C
5,110	70NO2W02	5	110	2.100	4.200	70NO2W	2	C
112,9	70NO3E01	112	9	1.100	2.200	70NO3E	2	C
9,112	70NO3W01	9	112	1.100	2.200	70NO3W	2	C
61,62	124E01	61	62	1.517	3.034	124E	3	HR

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62,63	124E02	62	63	0.282	0.564	124E	3	HR
63,64	124E03	63	64	1.225	2.450	124E	3	HR
64,65	124E04	64	65	1.734	3.468	124E	3	HR
65,66	124E05	65	66	1.424	2.848	124E	3	HR
66,34	124E06	66	34	3.444	6.888	124E	3	HR
33,67	124E08	33	67	4.777	9.554	124E	3	HL
67,60	124E09	67	60	1.132	2.264	124E	3	HL
60,67	124W02	60	67	1.132	2.264	124W	3	HL
67,33	124W03	67	33	4.777	9.554	124W	3	HL
34,66	124W05	34	66	3.444	6.888	124W	3	HR
66,65	124W06	66	65	1.424	2.848	124W	3	HR
65,64	124W07	65	64	1.734	3.468	124W	3	HR
64,63	124W08	64	63	1.225	2.450	124W	3	HR
63,62	124W09	63	62	0.282	0.564	124W	3	HR
62,61	124W10	62	61	1.517	3.034	124W	3	HR
38,81	S240E01	38	81	1.000	2.000	S240E	3	R
81,38	S240W01	81	38	1.000	2.000	S240W	3	R
22,82	ABE01	22	82	3.827	7.654	ABE	3	C
82,22	ABW01	82	22	3.827	7.654	ABW	3	C
81,2	BBE01	81	2	2.277	4.554	BBE	3	R
2,81	BBW01	2	81	2.277	4.554	BBW	3	R
36,71	CCE01	36	71	2.699	5.398	CCE	3	HL
71,70	CCE02	71	70	0.998	1.996	CCE	3	HL
70,68	CCE03	70	68	8.098	16.196	CCE	3	HL
68,70	CCW01	68	70	8.098	16.196	CCW	3	HL
70,71	CCW02	70	71	0.998	1.996	CCW	3	HL
71,36	CCW03	71	36	2.699	5.398	CCW	3	HL
83,75	DE01	83	75	1.581	3.162	DE	3	HL
75,83	DW01	75	83	1.581	3.162	DW	3	HL
84,85	EEE01	84	85	1.974	3.948	EEE	3	R
85,84	EEW01	85	84	1.974	3.948	EEW	3	R
76,86	FFE01	76	86	1.594	3.188	FFE	3	HL
86,76	FFW01	86	76	1.594	3.188	FFW	3	HL
59,73	HHE01	59	73	5.766	11.532	HHE	3	HL
73,59	HHW01	73	59	5.766	11.532	HHW	3	HL
78,87	KKE01	78	87	2.556	5.112	KKE	3	C
87,78	KKW01	87	78	2.556	5.112	KKW	3	C
88,89	ME01	88	89	5.637	11.274	ME	3	A
89,90	ME02	89	90	0.897	1.794	ME	3	A
90,19	ME03	90	19	1.532	3.064	ME	3	A
19,90	MW01	19	90	1.532	3.064	MW	3	A
90,89	MW02	90	89	0.897	1.794	MW	3	A
89,88	MW03	89	88	5.637	11.274	MW	3	A
90,91	DDN01	90	91	2.875	5.750	DDN	3	A

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91,90	DDS01	91	90	2.875	5.750	DDS	3	A
92,89	MME01	92	89	4.452	8.904	MME	3	A
89,92	MMW01	89	92	4.452	8.904	MMW	3	A
65,35	NNN01	65	35	8.496	16.992	NNN	3	HR
35,65	NNS01	35	65	8.496	16.992	NNS	3	HR
60,74	OON01	60	74	4.630	9.260	OON	3	HL
74,60	OOS01	74	60	4.630	9.260	OOS	3	HL
93,4	UUE01	93	4	4.573	9.146	UUE	3	R
4,93	UUW01	4	93	4.573	9.146	UUW	3	R
94,93	ON01	94	93	2.013	4.026	ON	3	R
93,3	ON02	93	3	4.480	8.960	ON	3	R
3,93	OS01	3	93	4.480	8.960	OS	3	R
93,94	OS02	93	94	2.013	4.026	OS	3	R
95,66	YYN01	95	66	2.324	4.648	YYN	3	HR
66,95	YYS01	66	95	2.324	4.648	YYS	3	HR
53,96	ZZN01	53	96	1.114	2.228	ZZN	3	HR
96,53	ZZS01	96	53	1.114	2.228	ZZS	3	HR
97,18	AE01	97	18	4.191	8.382	AE	3	A
18,97	AW01	18	97	4.191	8.382	AW	3	A
63,98	FN01	63	98	7.709	15.418	FN	3	HR
98,37	FN02	98	37	5.083	10.166	FN	3	HR
37,98	FS01	37	98	5.083	10.166	FS	3	HR
98,63	FS02	98	63	7.709	15.418	FS	3	HR
3,39	JN01	3	39	1.080	2.160	JN	3	R
39,85	JN02	39	85	3.605	7.210	JN	3	R
85,62	JN03	85	62	8.081	16.162	JN	3	R
62,85	JS01	62	85	8.081	16.162	JS	3	R
85,39	JS02	85	39	3.605	7.210	JS	3	R
39,3	JS03	39	3	1.080	2.160	JS	3	R
98,99	TN01	98	99	1.249	2.498	TN	3	HR
99,98	TS01	99	98	1.249	2.498	TS	3	HR
48,100	NN01	48	100	5.801	11.602	NN	3	C
100,48	NS01	100	48	5.801	11.602	NS	3	C
67,69	UN01	67	69	2.503	5.006	UN	3	HR
69,101	UN02	69	101	0.951	1.902	UN	3	HR
101,69	US01	101	69	0.951	1.902	US	3	HR
69,67	US02	69	67	2.503	5.006	US	3	HR
19,102	YE01	19	102	4.892	9.784	YE	3	A
102,19	YW01	102	19	4.892	9.784	YW	3	A
103,3	70SO1E01	103	3	1.000	2.000	70SO1E	3	R
3,104	70SO1E02	3	104	1.400	2.800	70SO1E	3	R
104,3	70SO1W01	104	3	1.400	2.800	70SO1W	3	R
3,103	70SO1W02	3	103	1.000	2.000	70SO1W	3	R
105,4	70SO2E01	105	4	0.400	0.800	70SO2E	3	R

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4,106	70SO2E02	4	106	0.400	0.800	70SO2E	3	R
106,4	70SO2W01	106	4	0.400	0.800	70SO2W	3	R
4,105	70SO2W02	4	105	0.400	0.800	70SO2W	3	R
43,107	70SO5E01	43	107	0.200	0.400	70SO5E	3	C
107,43	70SO5W01	107	43	0.200	0.400	70SO5W	3	C
11,108	70SO8E01	11	108	2.400	4.800	70SO8E	3	C
108,11	70SO8W01	108	11	2.400	4.800	70SO8W	3	C
4,109	70NO1E01	4	109	1.000	2.000	70NO1E	3	R
109,4	70NO1W01	109	4	1.000	2.000	70NO1W	3	R
11,12	70NO4E01	11	12	4.000	8.000	70NO4E	3	C
12,11	70NO4W01	12	11	4.000	8.000	70NO4W	3	C
113,11	70NO5E01	113	11	1.600	3.200	70NO5E	3	C
11,113	70NO5W01	11	113	1.600	3.200	70NO5W	3	C
31,114	63EO1N01	31	114	0.500	1.000	63EO1N	3	HL
114,31	63EO1S01	114	31	0.500	1.000	63EO1S	3	HL
115,30	63EO2N01	115	30	0.100	0.200	63EO2N	3	HL
30,115	63EO2S01	30	115	0.100	0.200	63EO2S	3	HL
27,116	63EO3N01	27	116	0.400	0.800	63EO3N	3	C
116,27	63EO3S01	116	27	0.400	0.800	63EO3S	3	C
117,26	63EO4N01	117	26	1.600	3.200	63EO4N	3	C
26,117	63EO4S01	26	117	1.600	3.200	63EO4S	3	C
25,118	63EO5N01	25	118	0.600	1.200	63EO5N	3	C
118,25	63EO5S01	118	25	0.600	1.200	63EO5S	3	C
24,119	63EO6N01	24	119	0.100	0.200	63EO6N	3	C
119,24	63EO6S01	119	24	0.100	0.200	63EO6S	3	C
23,120	63EO7N01	23	120	0.500	1.000	63EO7N	3	C
120,23	63EO7S01	120	23	0.500	1.000	63EO7S	3	C
121,21	63EO8N01	121	21	1.500	3.000	63EO8N	3	A
21,122	63EO8N02	21	122	0.500	1.000	63EO8N	3	A
122,21	63EO8S01	122	21	0.500	1.000	63EO8S	3	A
21,121	63EO8S02	21	121	1.500	3.000	63EO8S	3	A
19,123	63EO9N01	19	123	0.300	0.600	63EO9N	3	A
123,19	63EO9S01	123	19	0.300	0.600	63EO9S	3	A
124,18	63EO10N01	124	18	0.600	1.200	63EO10N	3	A
18,124	63EO10S01	18	124	0.600	1.200	63EO10S	3	A
125,17	63EO11N01	125	17	0.400	0.800	63EO11N	3	A
17,125	63EO11S01	17	125	0.400	0.800	63EO11S	3	A
15,126	63EO12N01	15	126	0.400	0.800	63EO12N	3	A
126,15	63EO12S01	126	15	0.400	0.800	63EO12S	3	A
14,127	63EO13N01	14	127	0.300	0.600	63EO13N	3	A
127,14	63EO13S01	127	14	0.300	0.600	63EO13S	3	A
47,128	63WO1N01	47	128	0.700	1.400	63WO1N	3	HR
128,47	63WO1S01	128	47	0.700	1.400	63WO1S	3	HR
129,26	63WO2N01	129	26	2.200	4.400	63WO2N	3	C

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26,129	63WO2S01	26	129	2.200	4.400	63WO2S	3	C
130,24	63WO3N01	130	24	1.300	2.600	63WO3N	3	C
24,130	63WO3S01	24	130	1.300	2.600	63WO3S	3	C
20,131	63WO4N01	20	131	0.300	0.600	63WO4N	3	A
131,20	63WO4S01	131	20	0.300	0.600	63WO4S	3	A
132,16	63WO5N01	132	16	0.500	1.000	63WO5N	3	A
16,132	63WO5S01	16	132	0.500	1.000	63WO5S	3	A
14,133	63WO6N01	14	133	0.300	0.600	63WO6N	3	A
133,14	63WO6S01	133	14	0.300	0.600	63WO6S	3	A
134,55	163WON01	134	55	2.300	4.600	163WON	3	C
55,134	163WOS01	55	134	2.300	4.600	163WOS	3	C
135,55	163EON01	135	55	1.900	3.800	163EON	3	C
55,135	163EOS01	55	135	1.900	3.800	163EOS	3	C
136,57	WWSON01	136	57	2.400	4.800	WWSON	3	C
57,136	WWSOS01	57	136	2.400	4.800	WWSOS	3	C
57,137	WWNON01	57	137	0.500	1.000	WWNON	3	C
137,57	WWNOS01	137	57	0.500	1.000	WWNOS	3	C

* R = Rocheport; C = Columbia; A = Ashland; HL = Hallsville; HR = Harrisburg