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

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Abstract

Winter road maintenance operations require many complex strategic and operational planning decisions; the main problems include locating depots, designing sectors, routing service vehicles, vehicle scheduling, 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. This report 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.

1.0 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 that each decision has on some or all of the other decisions, impacts the agency's ability to provide the desired level of service. Figure 1.1 presents an influence diagram for the complex interactions between the different winter road maintenance planning decisions.

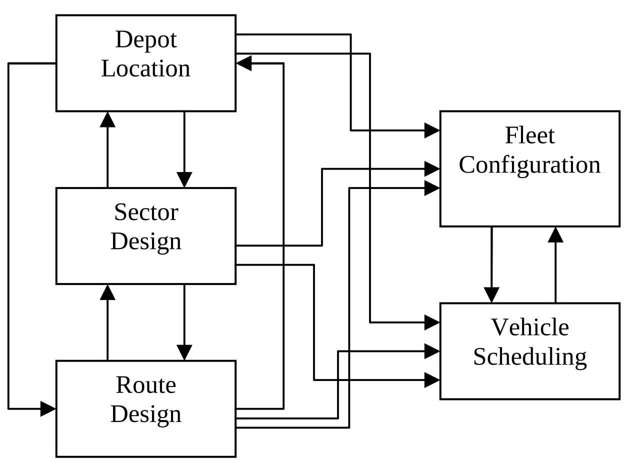

Figure 1.1 – Influence diagram

1.2 The Research Objective

A systematic optimization based approach allows planners to deal with discontinuities between past and current operational requirements, which may result in new decision making challenges.

This research develops a more integrated and less sequential approach to the main winter road maintenance planning decisions to attempt to provide higher quality solutions by avoiding the sub-optimization that may occur in treating each problem individually. Additionally, an integrated approach provides planners with a means for assessing the impact of the strategic decision of depot locations 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 winter road maintenance operations and planning for Boone County, Missouri, and therefore focuses on public-sector winter road maintenance planning for a rural transportation network. 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.

2.0 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 decisions for depot location, sector design, vehicle route design, vehicle scheduling, and fleet configuration, within the scope defined for this research.

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, et al. 2005). Rahja and Korhonen (1994) discussed a decision support tool, which assists planners in locating storage facilities for abrasives used in spreading operations and designating the sectors or demand zones assigned to each depot.

2.3 Combined depot location, sector design, and fleet sizing

Hayman and Howard (1972), Reinert, Miller and Dickerson (1985) have developed models that combine the decisions for depot location, sector design and capacity of storage depots with the assignment of pre-defined winter road maintenance routes to each depot. 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.

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. Liebling (1973), Cook and Alprin (1976) developed cluster-first, route-second heuristic and a simple construction algorithm to create vehicle routes for spreading. Lemieux and Campagna (1984) modeled a single plow routing problem with hierarchical service constraints and U-turn restrictions. In 1990, students from universities across the U.S. participated in a competition to design service routes for two snow plows in Wicomico County, Maryland. Atkins, et al. (1990), Chernak, et al. (1990), Robinson, et al. (1990), Hartman, et al. (1990) proposed several methods for service routes for snow plows.

Haslam and Wright (1991), Wang and Wright (1994) developed a decision support system for planners to develop snow plow routes for the Indiana Department of Transportation (INDOT). Kandula and Wright (1997) developed an interactive bounds based heuristic for winter road maintenance routing in the state of Indiana. Campbell and Langevin (2000), Haghani and Qiao (2001), Salim et al. (2002) also developed decision systems related to winter road maintenance operations.

2.5 Combined depot location and routing

Lotan et al. (1996) discussed a systematic location routing problem for spreading operations in Antwerp, Belgium. Kandula and Wright (1997) described a modified version of the combined sector design, depot location, and fleet sizing model previously described. And Gupta (1998) developed a decision support system which aids planners in estimating the economical impacts

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.

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, et al. (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 incorporates the new aspects of multiple depot vehicle routing, fleet configuration, and vehicle scheduling.

3.0 Case Study Description

3.1 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. 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).

3.2 Winter road maintenance operations

The main winter road maintenance operations performed by MODOT include pre-treatment, combined spreading and plowing, secondary and shoulders, and clean up and bridges. Combined plowing and spreading is the most time intensive and the bottleneck operation, it is the basis for other decisions and the focal point of the model. Therefore the following discussion presented in this section is focused on the combined spreading and plowing operation.

3.3 Service level

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. Therefore, a high level of service can be achieved by minimizing the time spent deadheading and maintaining an acceptable service frequency.

Constraints on the resources available prevent MODOT from proving the highest level of service to all roadways. A service hierarchy is defined for the roadways based on the historical average daily traffic on them. Table 3.1 shows the hierarchy considered in this research and the corresponding parameters.

Class Assignment	Description	Class (ADT)	Maximum Service Distance	Maximum Duration	Ideal Frequency (12 hour storm)
A1	I-70, Highway 63	Class 1	100 miles	120 minutes	6
A2	Class 1 non-highway	Class 1	75 miles	120 minutes	6
A3	Class 2 roadways	Class 2	75 miles	360 minutes	2
A4	Class 3 Roadways	Class 3	75 miles	720 minutes	1

Table 3.1 – Service hierarchy parameters

3.4 Transportation network

Within Boone County, MODOT is responsible for servicing approximately 1030 lane miles consisting of an interstate highway, state highways, and other state roadways (Figure 3.1). The road network is modeled as a directed multi-graph. Table 3.2 shows the decomposition of the transportation network into the four defined levels of service hierarchy, A1, A2, A3, and A4.

Class Assignment	Number of Arcs Requiring Service	Total Distance (miles)
A1	140	306.42
A2	124	260.21
A3	38	125.52
A4	150	337.35

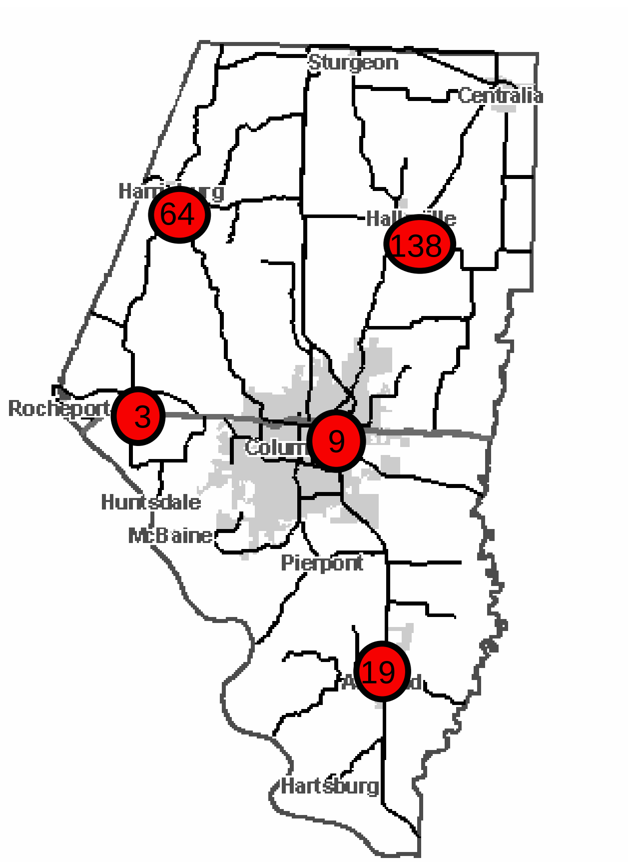

Figure 3.1 – MoDOT Boone County transportation network with existing depots

3.5 Depot locations

MODOT currently has five depots, each with a corresponding sector, located throughout the Boone County district (Figure 3.1). Currently, MODOT is considering combining two of the smaller depots into one larger depot, and relocating another existing depot. 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.

3.6 Vehicle routing

Currently, MODOT does not have any predetermined routes to guide the winter road maintenance operations. 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.

3.7 Fleet configuration

MODOT's fleet consists of heavy duty single axle trucks and extra heavy duty tandem axle trucks. Spreading and combined spreading and plowing routes 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. While deadheading vehicles travel approximately 10 mph faster than they do while servicing, combined spreading and plowing.

3.8 Operators

Each vehicle requires one operator, who is responsible for driving the vehicle and refilling with either material or fuel as needed. The operators are required to work 12 hour shifts. The crew tends to be very experienced, which is desirable because the work requires them to work long hours 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.

4.0 Solution Methodology

4.1 Solution with deadhead travel time minimization objective

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 to see if 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. Finally four strongly connected sub networks, one for each hierarchical class of roadway, are created from the original transportation sub network.

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. First a CPT is found for each of the four sub networks 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 sub network, 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 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. 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 chooses the one that results in the least total deadheading between all of the routes and all of the depots.

Then the completed initial routes, sectors, and depot location are determined, simultaneously. 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 the 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 they are 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 combined plow and spreader route design problems based on the determined depot locations. The improvement heuristic attempts to improve the quality of the sector and route designs by making two different types of moves: to remove an arc from one route, then insert it into another route and to exchange 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 sub networks. Then, once the routes are designed the second phase determines the fleet configuration and vehicle schedules necessary to service the routes. The following diagram outlines the three phase solution methodology.

4.2 Alternative solution with cycle time minimization objective

The integrated solution for the depot locations, sector design, and route design, are found based on the objective of minimizing cycle times of routes, or equivalently, route service times. It is clear that the cycle time of any (partial) route is smaller if the route is located near a depot because a service truck should start and end at a depot. Hence, a depot should be located at a place where many streets are quickly accessible. In this research, a greedy type heuristic is employed to locate depots in the middle of clusters of streets to service. Note that we start with total 452 directed arcs and 15 potential depots.

The nearest depot is first determined for every arc and the weighted distance between the depot and the assigned arc is calculated. Because some streets, based on their classes, should be served more often, we use weights to appropriately represent their service frequency. The weights correspond to the target service frequency of 6, 6, 2, and 1 during a 12-hour continuous storm for routes of class A1, A2, A3, and A4, respectively. Using the service frequency to weight the objective function attempts to keep depots near the higher priority routes.

Next, we determine a depot that has the smallest impact in terms of the weighted distance when it is removed from the list of potential depots. In other words, we measure the increase of the weighted distance by re-assigning arcs to the next nearest depot. The sum of these increases for all the arcs assigned to a depot represents the potential impact of the selected depot when it is removed. This value is mainly affected by the number of originally assigned arcs as well as the distance to the next nearest depot. That is, a depot which has many arcs assigned to it and does not have another depot around it, has the larger impact, and hence, should not be removed from the list of potential depots. On the other hand, a depot with smaller number of arcs assigned to it and/or has other depots around it has the smaller impact. The overall weighed distance will not be increased much even though this depot does not exist.

After removing a depot with the smallest impact, we repeat this procedure until we have the right number of depots we are looking for. An initial sector is automatically determined through this process by simply constructing a sector with a depot and arcs assigned to it. This completes the depot selection and initial sector division. The same route creation and improvement methods discussed previously are applied to the initial depots and sectors. Note that sectors can be changed through the route improvement process.

5.0 Results and Discussion

5.1 Overview

This section includes an illustration of the solution methodology developed in this research. The problem presented here is to determine the depot locations, routes, sectors, vehicle schedules, and fleet configuration, based on the multiple objectives of minimizing deadhead travel or minimizing cycle times, and minimizing the number of vehicles; also included are the operational constraints for service frequency and vehicle capacity. Three different scenarios are evaluated as listed below:

- Solution to minimize total deadhead travel time
  - Scenario 1: Existing depots and sectors
    - ❑ New routes, vehicle schedules, and fleet configuration
  - Scenario 2: Unconstrained solution
    - ❑ Depot location, sector design, route design, vehicle scheduling, and fleet configuration problems
- Solution to minimize cycle times
  - 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 5 depots located on nodes 3, 9, 19, 64, and 138 of the transportation network (Figure 3.1).

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. Although, MODOT has an existing vehicle fleet of 23 vehicles, it was suspected that the routes developed would decrease the number of required vehicles.

Depot	Route	Class	Truck	Type	Weighted Deadhead (min)
3	6	A1	1	T	0.00
3	13	A2	2	S	19.44
3	24	A4	2	S	5.01
9	2	A1	1	T	54.07
9	3	A1	2	T	39.52
9	7	A2	3	S	5.39
9	8	A2	4	S	30.38
9	9	A2	5	S	8.69
9	10	A2	6	S	0.00
9	15	A3	7	S	63.33
9	19	A4	8	S	91.30
19	1	A1	1	T	0.00
19	14	A3	2	S	19.25
19	18	A4	2	S	32.56
64	5	A1	1	T	118.84
64	12	A2	2	S	0.00
64	17	A3	3	S	81.94
64	22	A4	3	S	0.00
64	23	A4	3	S	21.16
138	4	A1	1	T	57.32
138	11	A2	2	S	49.03
138	21	A3	2	S	59.14
138	16	A4	3	S	56.85
138	20	A4	3	S	0.00
Total Weighted Deadhead (min)					**813**
Number of Vehicles					**18**
Tandem Axle					6
Single Axle					12

Table 5.1 – Scenario 1: Summary of final results

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 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 5.1 summarizes the solutions to the depot location, sector design, fleet configuration, and vehicle scheduling problems.

5.3 Scenario 2: Unconstrained solution - minimizing total deadhead travel time

5.3.1 Initial depot location solution

In scenario 2 the integrated solution methodology is applied without designated depots. MODOT provided the following set of potential depot locations to be considered, the numbers correspond to the nodes in the transportation network: 3,4,5,9,11,18,19,23,26,27,29,33,36,60,64 (Figure 5.1). The decision was made because of a desire to move depots nearer to the highest priority roadways.

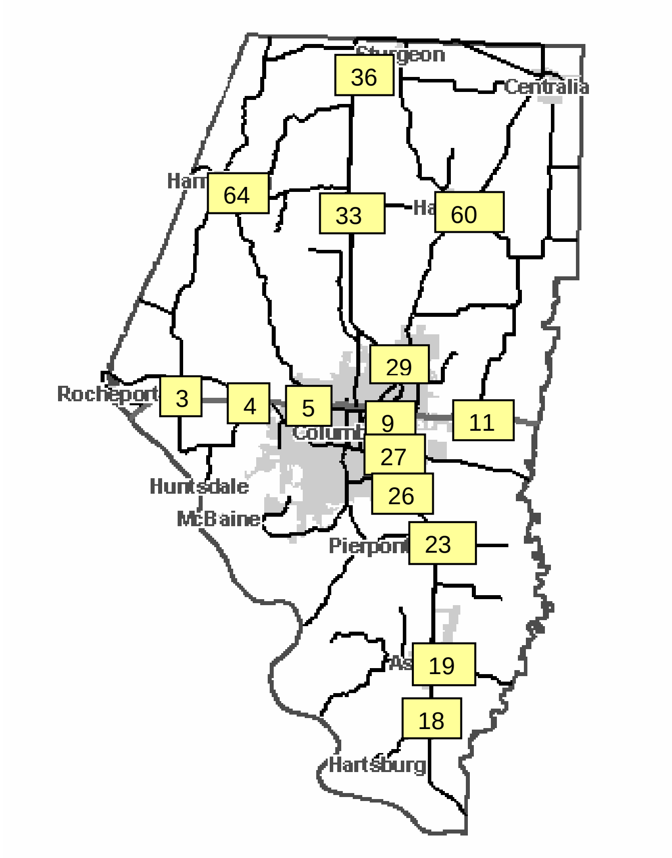

Figure 5.1 - Potential Depot Location Sites

Since MODOT is interested in knowing the number of depots to open in addition to their 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, and the results are shown in Figure 5.2 and Table 5.2.

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.

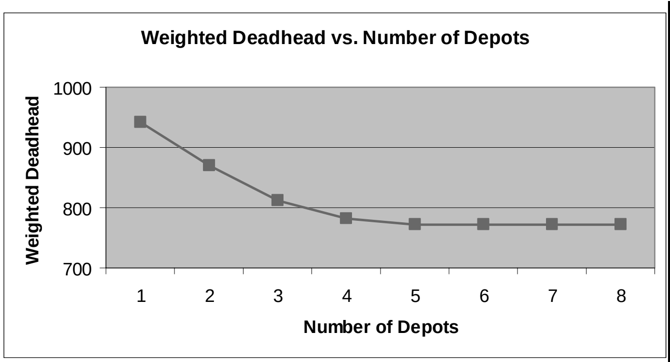

Figure 5.2 – New Solution: Initial solution vs. number of depots

Number of Depots	Weighted Deadhead	Improvement
1	942.38	
2	869.54	7.73%
3	812.368	6.57%
4	**782.127**	**3.72%**
5	772.893	1.18%
6	772.425	0.06%
7	772.404	0.00%
8	772.404	0.00%

Table 5.2 – New Solution: Initial solution vs. number of depots

5.3.2 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. The deadhead travel time for each route is weighted based on the ideal service frequency, corresponding to each class of route, for a 12 hour shift; the weights are 6, 6, 2, 1 for routes of class A1, A2, A3, and A4, respectively. 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 of the tandem axle trucks and 11 single axle trucks. Table 5.3 summarizes the solutions to the depot location, sector design, fleet configuration, and vehicle scheduling problems and Figure 5.3 shows the locations of the 4 depots.

Depot	Route	Class	Truck	Type	Weighted Deadhead (min)
5	1	A1	1	T	14.58
5	5	A1	2	T	36.00
5	8	A2	3	S	8.26
5	9	A2	4	S	55.54
9	4	A1	1	T	30.07
9	6	A2	2	S	5.39
9	7	A2	3	S	36.68
9	10	A2	4	S	13.52
9	12	A3	5	S	80.19
9	13	A3	6	S	75.35
9	14	A4	7	S	48.11
9	17	A4	7	S	77.46
27	2	A1	1	T	154.63
27	3	A1	2	T	0.00
27	11	A2	3	S	14.41
27	18	A4	4	S	58.11
36	15	A4	1	S	43.01
36	16	A4	1	S	50.16
Total Weighted Deadhead (min)					**801**
Number of Vehicles					**16**
Tandem Axle					5
Single Axle					11

Table 5.3 – Scenario 2: Summary of final results

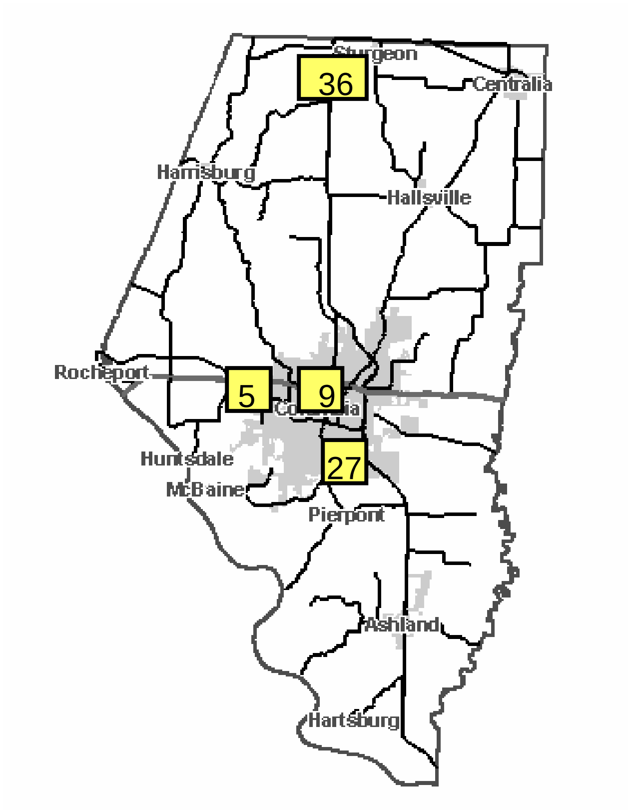

Figure 5.3 – Final integrated solution – depot location

5.4 Discussion of results for solution of minimizing total deadhead travel time

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. 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 2) would allow MoDOT to provide the same high level of service with significantly fewer resources. The integrated solution (scenario 2) 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 2 is slightly less than that for scenario 1.

	Current	Scenario 1	Scenario 2
Number of Depots	5	5	4
Number of Vehicles	23	18	16
Tandem axle	9	6	5
Single axle	14	12	11
Total Weighted Deadhead Travel (min)	-	813	801

Table 5.4 – Comparison between scenarios with respect to vehicle requirements

5.5 Scenario 3: Unconstrained solution - minimizing cycle time

5.5.1 Initial solution

The integrated solution methodology is similarly applied to the depot location, sector design, route design, vehicle scheduling, and fleet configuration problems for Boone County, Missouri. An alternative solution minimizing cycle times instead of deadhead times is proposed.

The results from the initial solution phase indicate that the benefit to the objective function, total weighted distance between each route and its assigned depot, gained by opening an additional depot is significant up to five depots and somewhat important up to nine depots. However, the benefit is marginal beyond nine depots. 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.

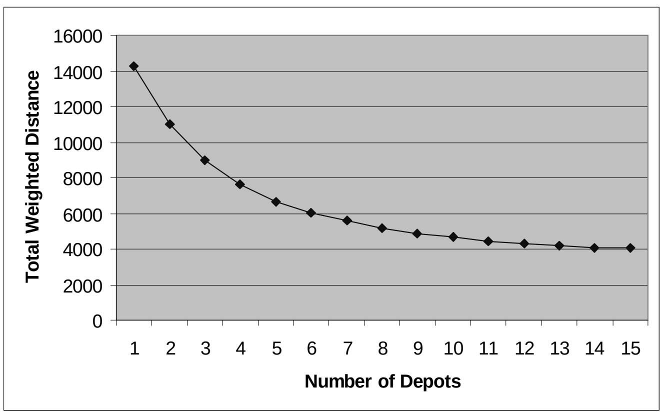

Figure 5.5 – Alternative Solution: weighted distance vs. number of depots

# of Depots	Total Weighted Distance	Improvement
1	14285	
2	10995	23.03%
3	8956	18.55%
4	7634	14.76%
5	6623	13.24%
6	6018	9.14%
7	5574	7.38%
8	5171	7.24%
9	4881	5.61%
10	4660	4.52%

Table 5.6 – Alternative Solution: weighted distance vs. number of depots

5.5.2 Final solution

The improvement heuristic was 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 the 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 sub networks, 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 can be utilized to determine the corresponding solutions to the vehicle scheduling and fleet configuration problems.

Next table presents a recommended solution when there are four depots. There are total 22 routes. These routes are determined to minimize the maximum route service time satisfying time and capacity constraints. The fourth column of the table shows necessary time to serve each route. Total 16 trucks are assigned to serve these routes. One truck is assigned to one route of A1 and A2 classes, while another truck at each depot can serve all the A3 and A4 routes without violating time constraints. The sixth column of the table shows route schedule of a truck if multiple routes are assigned to one truck. If one route is assigned to one truck, the truck will service the route continuously. Based on this schedule, the cycle time of the route is given in the last column. Note that if one route is assigned to a truck, then the route service time is the same as the cycle time. Based on the table, the maximum cycle times of A1 and A2 class routes are 90 and 99 minutes, respectively, which are well below the current target cycle time of 120 minutes. The maximum cycle times of A3 and A4 class routes are also much smaller than their respective target cycle times of 360 and 720 minutes.

Depot	Route #	Class	Route Time	Truck #	Route Schedule	Cycle Time
5	1	A1	90	1		90
	2	A2	99	2		99
	3	A2	96	3		96
	4	A3	120	4	4-5-4-6	289
	5	A4	160	4		449
	6	A4	169	4		449
9	7	A1	89	5		89
	8	A1	86	6		86
	9	A2	99	7		99
	10	A3	121	8	10-11	290
	11	A4	169	8		290
18	12	A1	85	9		85
	13	A1	74	10		74
	14	A2	99	11		99
	15	A2	98	12		98
	16	A3	123	13	16-17	294
	17	A4	171	13		294
33	18	A1	90	14		90
	19	A2	98	15		98
	20	A3	120	16	20-21-20-22	274
	21	A4	154	16		414
	22	A4	140	16		414

Table 5.7 – Proposed alternative solution: Summary of final results

The promising results from the real world test problem in Boone County, Missouri, support the assertion of the importance of a more integrated approach to the winter road maintenance problems studied in this research. 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 included in this research in a more integrated manner should provide planners with the ability to make more informed, successful decisions.

6.0 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 to winter road maintenance planning problems towards the eventual goal of a fully integrated approach.

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 would indicate that this was a success and a step towards more 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 has supported 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. 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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