Optimizing Winter/Snow Removal Operations in MoDOT St. Louis District – Includes Outcome Based Evaluation of Operations

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16. Abstract

The objective of this project was to develop fleet location, route decision, material selection, and treatment procedures for winter snow removal operations to improve MoDOT's services and lower costs.
This work uses a systematic, heuristic-based optimization approach to integrate the winter road maintenance planning decisions, which is typically the most intensive operation in the DOT maintenance system. The application of the solution methodology developed in this research to the transportation network of St. Louis District in Missouri resulted in optimal truck allocation and route decision policies. The optimal analysis allows MoDOT to provide the most efficient snow removal services, to develop specific service routes that trucks can follow, to compute standard lane mile factors to be applied, and to develop optimal truck allocation scenarios when additional budget reduction is unavoidable. All of these can be achieved with the minimal cycle time and deadheading miles. In particular, the results show the opportunities of cost savings by closing some maintenance buildings without losing the efficiency of high level service. In addition, the survey results and our recommendations on the equipment selection and treatment procedures are presented.

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EXECUTIVE SUMMARY

Optimizing Winter/Snow Removal Operations in MoDOT St. Louis District

The objective of this project is to develop fleet location, route decision, material selection, and treatment procedures for winter snow removal operations to improve MoDOT's services and lower costs. The overall project objective is obtained via the following sub-objectives:

1) Development of a protocol for determining the desired level of service and the required constraints.
2) Development of integrated algorithms to create efficient route plans and fleet allocations
3) Development of an approach for evaluating the effects of different material treatments and equipment and determining the optimal levels of material and equipment to utilize.

This work uses a systematic, heuristic-based optimization approach to integrate the winter road maintenance planning decisions, which is typically the most intensive operation in the DOT maintenance system. The application of the solution methodology developed in this research to the transportation network of St. Louis District in Missouri resulted in optimal truck allocation and route decision policies. The optimal analysis allows MoDOT to provide the most efficient snow removal services, to develop specific service routes that trucks can follow, to compute standard lane mile factors to be applied, and to develop optimal truck allocation scenarios when additional budget reduction is unavoidable. All of these can be achieved with the minimal cycle time and deadheading miles. In particular, the results show the opportunities of cost savings by closing some maintenance buildings without losing the efficiency of high level service. In addition, the survey results and our recommendations on the equipment selection and treatment procedures are presented.

Our approach allows MoDOT to provide the best possible service with the available resources. 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 and its application focuses on the winter maintenance operations, its usage can be applied to any work building and fleet management systems. The potential cost savings to the DOTs would accrue in many areas.

Chapter 1: Introduction

Winter road maintenance operations require many complex planning decisions; the main strategic and operational problems include defining a service level policy, locating work buildings, designing sectors, routing service vehicles, configuring the vehicle fleet, scheduling vehicles, selecting equipment, and determining treatment procedures. All the activities are interrelated, in that each decision affects some or all of the other decisions and all together they impact the agency's ability to provide the desired level of service.

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 still rely in large part on assessments dictated by field experiences rather than scientific and systematic analysis. Winter road maintenance planning decisions include many complex characteristics, and it is very difficult to make these decisions solely on the basis of experience. Therefore, an opportunity exists for improving the planning process through the implementation of an optimization based methodology.

This research attempts to solve winter road maintenance problems in an integrated manner. The need for such research has been recognized for some time, but it has not been undertaken because of the complexity of each of the problems involved. The routing problem usually involves the determination of a set of routes, which are serviced by vehicles starting and ending at their respective buildings, to optimize some performance criteria. Routes are typically constrained either by maximum duration or distance. If it is possible for a vehicle to service multiple routes prior to servicing any of the routes again, then the vehicle scheduling problem must be solved as well. Determining the fleet configuration depends on whether the fleet is assumed to be homogeneous. If the fleet is assumed to be homogeneous, the problem is reduced to a fleet sizing problem. Otherwise, the problem is more complex and consists of determining the numbers of each of the types of vehicles based at each building.

Our analysis is applied to the state highway road network in St. Louis District, which is serviced by the Missouri Department of Transportation (MoDOT). We utilize the knowledge of experienced planners in MoDOT to determine the objectives, constraints, and other factors. This increases the chance that the solutions will be accepted and implemented. Our analytical results of fleet allocations and route decisions are described in Chapter 2. The results for equipment selection and treatment procedures are given in Chapter 3. In addition, mathematical models and algorithms are given in Chapter 4. Finally, conclusions are given in Chapter 5.

Ch 2: Truck Allocation and Routing Analysis

The results of the project on truck allocation and routing are presented in this section. The summary of the results is first provided and results for individual areas are described afterwards.

2.1 Analysis Summary

Figure 2.1.1 and Table 2.1.1 show the map and road information of St. Louis District included in this analysis. The continuous operation roads are marked with thicker purple lines while non-continuous operation roads are marked with thinner gray lines. It shows total 5,816 lane miles to serve in the St. Louis District, of which 76% (4,438 lane miles) are served under continuous operation and the rest (1,378 lane miles) are under non-continuous operation. The lane miles in Table 2.1.1 do not include some turn lanes, ramps, acceleration/deceleration lanes, and overpasses. The total lane miles in St. Louis District are now close to 6,200 miles. While areas such as St. Louis City and St. Louis County have mostly continuous operation roads, other areas such as Franklin County has a lot of non-continuous operation roads.

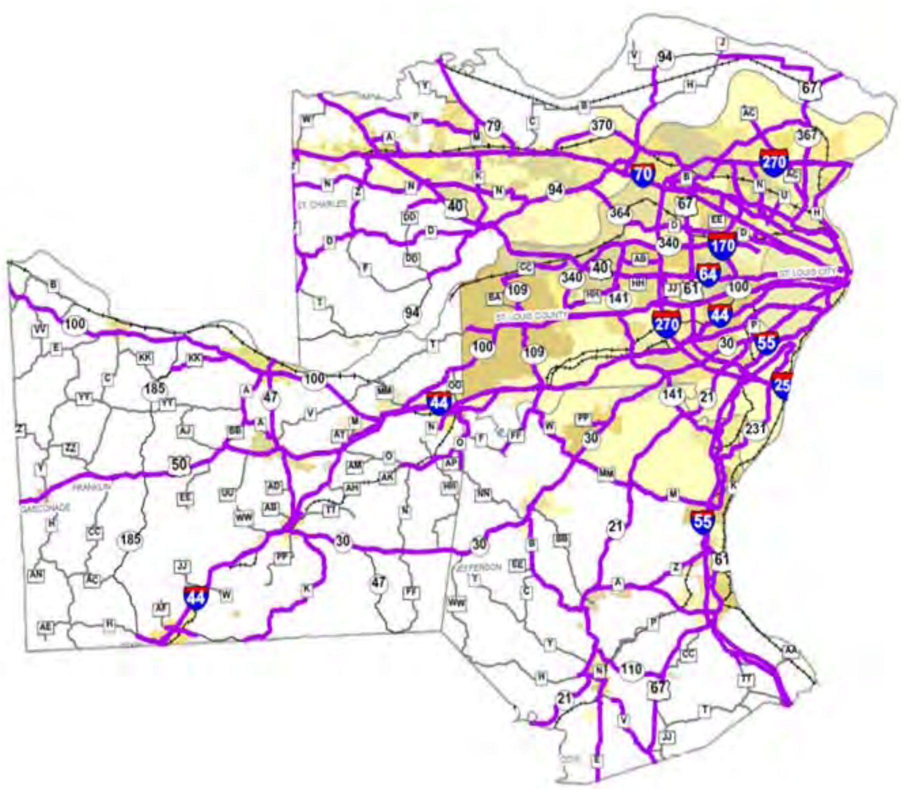


Figure 2.1.1 Road Map of St Louis District

	Continuous Operations			Non-Continuous Operations			
Area	Lane Miles	Area %	District %	Lane Miles	Area %	District %	***Area Miles***
6211	698.83	73.3%	15.7%	255.03	26.7%	18.5%	953.86
6212	620.51	92.1%	14.0%	52.95	7.9%	3.8%	673.46
6213	764.48	90.7%	17.2%	78.54	9.3%	5.7%	843.02
6214	335.92	96.9%	7.6%	10.65	3.1%	0.8%	346.57
6215	577.60	46.4%	13.0%	668.56	53.6%	48.5%	1,246.16
6216	878.55	94.2%	19.8%	54.48	5.8%	4.0%	933.03
6217	562.53	68.6%	12.7%	257.56	31.4%	18.7%	820.09
District Total	4,438.42		76.3%	1,377.77		23.7%	5,816.19

Table 2.1.1 Road Information of St. Louis District (excluding turn lanes, ramps, overpasses, etc.)

Service routes are first developed in each area, and then, trucks are assigned according to service routes. Certain parameters such as length, time, etc. are needed to develop practical service routes, and the following terms under continuous operation were assumed in the analysis.

- Up to 40 service lane-miles per route
- 80 minute service time assuming 30 mph
- 5,000 lb salt usage (75%: 100 lb/mile, 25%: 200 lb/mile)
- Average cycle time: 90 ~ 120 minutes

Average cycle time includes dead-heading and 30 minute replenishment time after one or two service routes. For example, if a truck is replenished after single route service, the cycle time could be 80 + 30 = 110 minutes. On the other hand, if a truck is replenished after every two service routes, the cycle time could be (80 + 80 + 30) / 2 = 95 minutes. For non-continuous operation, it is assumed to have up to 80 service lane-miles per route.

The following analysis focuses on continuous operation roads only. Truck allocation to non-continuous operation is discussed later. Table 2.1.2 shows the number of routes created in each area. When a route is much shorter than a full length (40 mile) route due to operational constraints, 0.5 route is used. The first column shows the number of one way lanes in each route. Again, 0.5 lane is used if the width of a route varies. For example, if a route has both 1-lane segment and 2-lane segment equally, it is designated as a 1.5 lane route. Each column of the table shows the number of routes in each area. For example, St. Charles County has a total of 8.5 full length equivalent routes, of which 3.5 routes are one-lane roads, 2 routes are 1.5-lane roads, 0.5 route is two-lane road, and 2.5 routes are three-lane roads. As the last column shows, there are total 52 full-length equivalent routes in the St. Louis district. Details of the routes are given in the following sections. From this table, it is also observed that 45% of routes are light volume routes (i.e., 1~1.5 lanes), 25% are medium volume routes (i.e., 2~2.5 lanes), and the remaining 30% are heavy volume routes (i.e., 3 lanes or more). However, in terms of lane miles, they occupy 25%, 25%, and 50% of roads, respectively. Therefore, it is necessary to focus and provide a better service on the heavy volume routes, which are only 30% of the total routes but occupy 50% lane miles.

Routes	St. Charles	STL North	STL West	STL City	Franklin	STL South	Jefferson	Total
1 lane	3.5		1		8		3.5	16
1.5 lane	2	1	1			1	2	7
2 lane	0.5		1		2.5	2	1	7
2.5 lane		1	1.5			2	1	5.5
3 lane	2.5	3	3	0.5		0.5	1	10.5
3.5 lane		1		0.5		1		2.5
4 or more			1	1		1.5		3.5
Total	8.5	6	8.5	2	10.5	8	8.5	52
Weighted Total	15	16.5	21.25	7.25	13	21.5	14	

Table 2.1.2 Number of Routes

The next step is to develop a truck assignment rule. Based on the discussions and feedbacks from field engineers and operators, Table 2.1.3 was developed. The second column shows the best truck assignment rule when there are enough resources. With the current number of trucks used in the St. Louis District, the rule in the third column, 'Current Resource', should be employed. Note that this rule favors wider multi-lane roads, which are supposed to have high ADTs. For example, consider an area with three one-lane routes. Assuming full-length (40 mile) routes, its total lane miles are 120 miles and three trucks are assigned per rule because one truck is assigned to each one-lane route. However, if there are one two-lane route and one one-lane route four trucks are assigned, even though the total lane miles are still 120 miles. If there is one three-lane route, five trucks are assigned. Lane miles are the same for all of these three scenarios, but the third case receives the largest number of trucks because it has wider roads with higher ADTs. Hence, this assignment rule allocates more trucks to urban areas than rural areas. Table 2.1.3 also provides truck assignment rules when additional resource cut is unavoidable. The fourth and fifth column show the rules when there are 10% and 20% decrease of trucks, respectively.

Routes	Best Scenario	Current Resource	10% Cut	20% Cut
1 lane	1	1	1	1
1.5 lane	2	2	2	2
2 lane	3	3	2	2
2.5 lane	5	4	4	3
3 lane	6	5	4	4
3.5 lane	7	6	6	5
4 lane	8	7	7	6

Table 2.1.3 Truck Assignment Rule

Table 2.1.4 shows the final allocation of trucks. It includes trucks allocated based on Table 2.1.3, Truck Assignment Rule, and trucks allocated considering non-continuous operation routes. The total number of 193 trucks is maintained, but some areas such as St. Louis North and St. Louis South gain trucks, while areas such as St. Louis City, Franklin, and Jefferson Counties lose some trucks. Lane mile factors computed according to the new allocation are also given in the table. They are about 28 miles per truck for urban locations and up to 55 miles per truck for rural counties. Note that the lane mile factor for St. Louis City is not accurate because the winter maintenance operation is shared between MoDOT and St. Louis City.

	Suggested Number	Current Number	Change	Lane Miles	Lane Mile Factor
St. Charles	24	25	-1	888	37.00
STL North	27	23	4	776	28.74
STL West	37	37	0	1041	28.14
STL City*	13	16	-3	510	39.23
Franklin	21	24	-3	1169	55.67
STL South	35	29	6	1010	28.86
Jefferson	20	23	-3	717	35.85
GPS	16	16			
Total	193	193	0	6111	34.53

Table 2.1.4 Truck Allocation and Lane Mile Factor

Table 2.1.5 shows the breakdown of truck allocations at the maintenance building level. Table 2.1.6 shows truck allocation to each area considering both big trucks such as XHD, HD, and Tow Plow and small trucks such as 1 Ton and Grader. The final computation shows that a big truck is allocated to every 28 ~ 40 continuous service miles or 80 ~ 120 non-continuous service miles. In addition, a small truck per 150 service miles is allocated to each area. Table 2.1.7 also shows lane mile factors with only big trucks and both big and small trucks. Lane mile factors based only on big trucks are about 28 miles per truck for urban areas and up to 55 miles per truck for rural counties. However, they become around 30 miles per truck in most areas when both big and small trucks are considered.

	Suggested #	Current #	Change
St. Charles	9	11	-2
Weldon Springs	6	6	0
Wentzville	9	8	1
Area Total	**24**	**25**	**-1**
Bellefontaine	13	10	3
Normandy	14	13	1
Area Total	**27**	**23**	**4**
Ballas	14	16	-2
Eureka	6	10	-4
Page	17	11	6
Area Total	**37**	**37**	**0**
Broadway	10	12	-2
Shreve	3	4	-1
Area Total	**13**	**16**	**-3**

	Suggested #	Current #	Change
Beaufort	6	6	0
Gray Summit	8	10	-2
St. Clair	7	8	-1
Area Total	**21**	**24**	**-3**
Barnhart	8	8	0
Lemay	12	10	2
Sunset Hills	15	11	4
Area Total	**35**	**29**	**6**
Cedar Hill	3	5	-2
Desoto	5	6	-1
Festus	12	12	0
Area Total	**20**	**23**	**-3**
GPS Team	16	16	0
District Total	**193**	**193**	**0**

Table 2.1.5 Truck Allocation – Building Level

	Big Trucks	Change	Small Trucks	Change	Total	Change
St. Charles	24	-1	6	2	30	1
STL North	27	4	5	-3	32	1
STL West	37	0	7	3	44	3
STL City*	13	-3	4	-2	17	-5
Franklin	21	-3	8	1	29	-2
STL South	35	6	6	-1	41	5
Jefferson	20	-3	6	0	26	-3
GPS	16				16	
Total	193	0	42	0	235	0

Table 2.1.6 Truck Allocation – Big and Small Trucks

	Lane Miles	Factor Big Trucks	Factor Overall
St. Charles	888	37.00	29.60
STL North	776	28.74	24.25
STL West	1041	28.14	23.66
STL City*	510	39.23	30.00
Franklin	1169	55.67	40.31
STL South	1010	28.86	24.63
Jefferson	717	35.85	27.58
Total	6111	34.53	27.90

Table 2.1.7 Lane Mile Factors

The quality of routes developed in this work can be measured by cycle times and deadheading miles. Figure 2.1.2 shows the distribution of cycle times. As seen, most cycle times are less than 100 minutes. The average cycle time is 89 minutes for all continuous service routes (shown in next sections) with the worst cycle time of 121 minutes. Figure 2.1.3 shows the distribution of deadheading miles. As seen, deadheading miles in most routes are less than 10 miles. The average deadheading mile of continuous service routes is 3.75 miles, while the worst case is 19 miles.

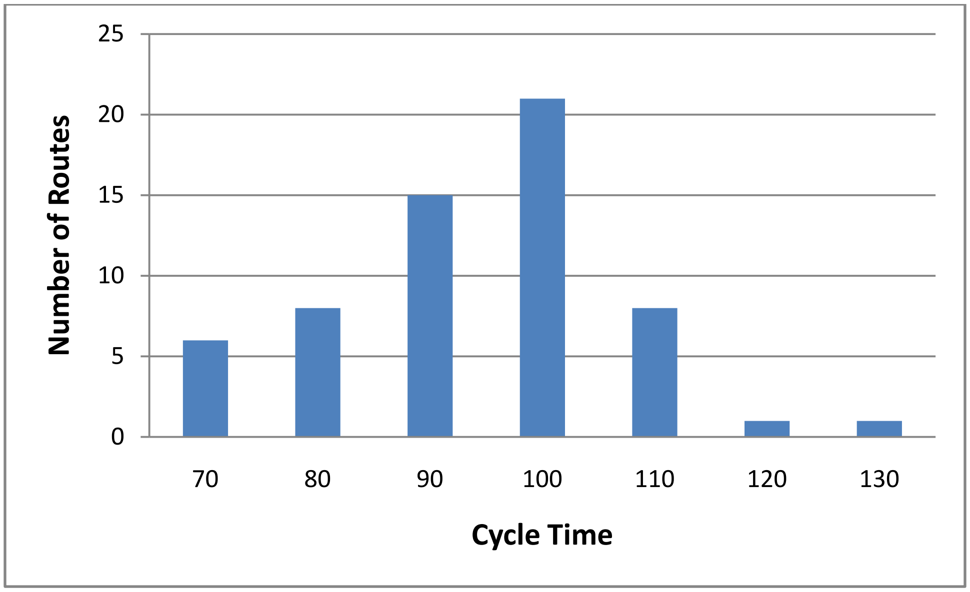


Figure 2.1.2 Cycle Time Distribution

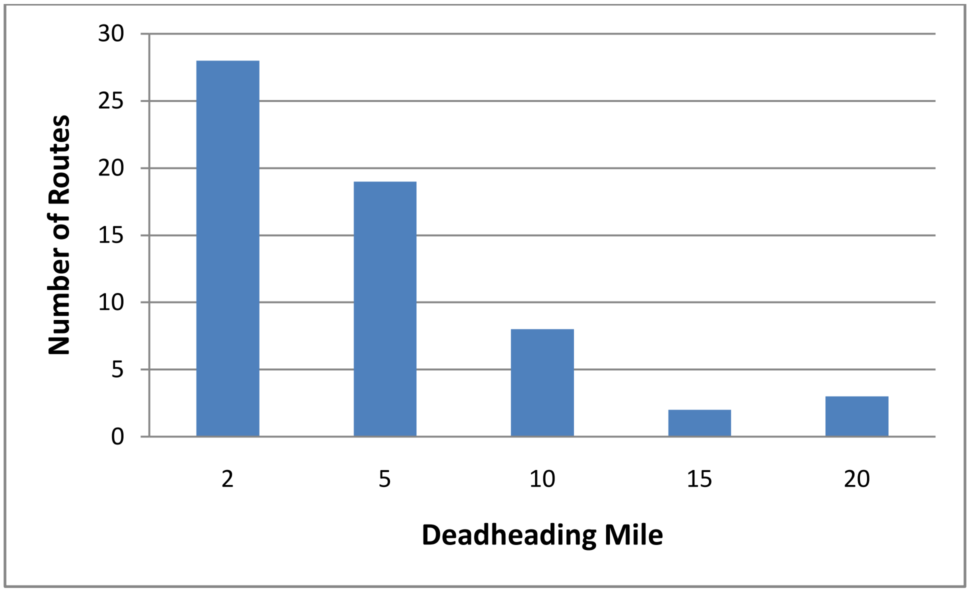


Figure 2.1.3 Deadheading Mile Distribution

Table 2.1.8 shows how to allocate trucks if additional budget and resource reduction is unavoidable. This will negatively affect the quality of snow removal services and is not recommended. Especially, snow clearing times for certain high ADT routes under heavy snow conditions may increase by up to 50%. Additionally, snow clearing times of medium ADT routes may increase by 20%.

	Currently Suggested	Additional 10% Cut	Additional 20% Cut
St. Charles	24	21	19
STL North	27	24	22
STL West	37	34	30
STL City*	13	12	11
Franklin	21	18	17
STL South	35	32	28
Jefferson	20	17	16
GPS	16	14	12
Total	193	172	155

Table 2.1.8 Truck Assignment under Additional Budget Cut

The final analysis of this project includes possible maintenance building closing scenarios. In general, maintenance building or building closure reduces administrative costs but deteriorates service efficiency such as increased deadheading times. However, there are some situations where the negative effect is minimal. Five such situations were identified and analyzed in this project. The summary of the major changes and negative effects are given below and detailed results are presented in Section 2.9.

- Weldon Springs
  - no significant change
- Shreve
  - no route change
- Barnhart
  - minimal deadheading and cycle time increase
- Eureka
  - slight decrease in St. Louis West area
  - additional work for nearby areas, but overall saving
- Page
  - 17 deadheading mile increase

2.2 St. Charles County

Figure 2.2.1 shows the existing three work buildings in Wentzville, Weldon Spring and St. Charles in St. Charles County. The roads are distinguished by their classes and number of one-way lanes. Figure 2.2.2 shows the best routes to serve the roads in Figure 2.2.1.

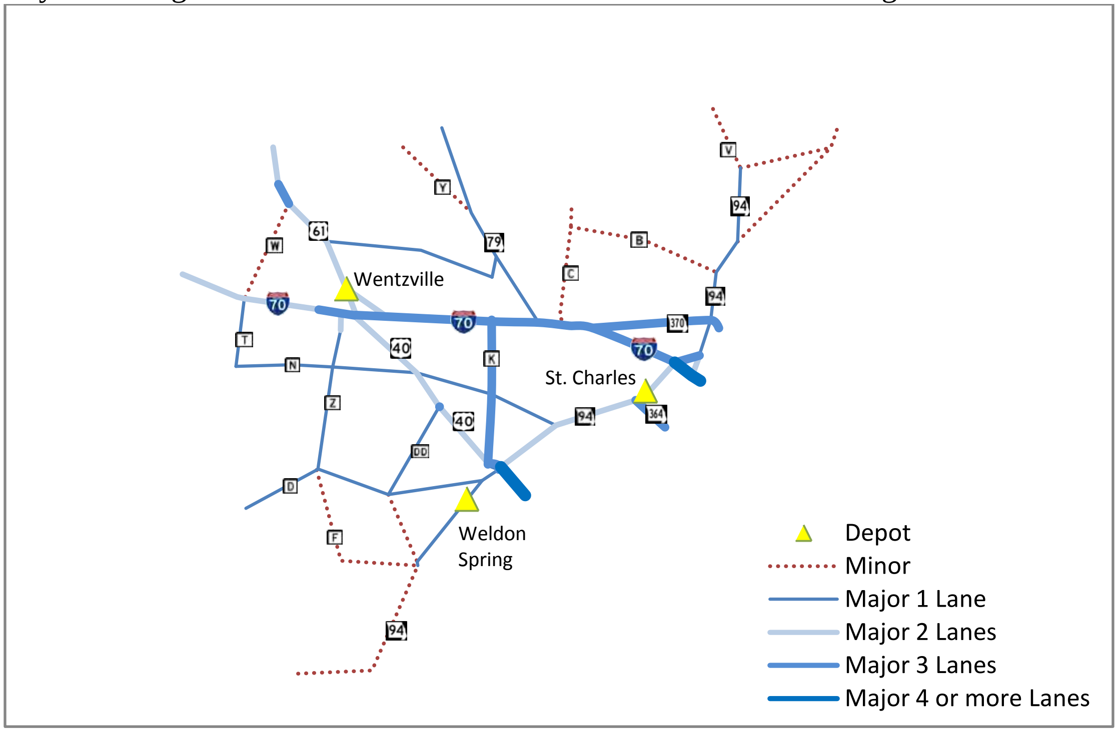


Figure 2.2.1 St. Charles County Road Map

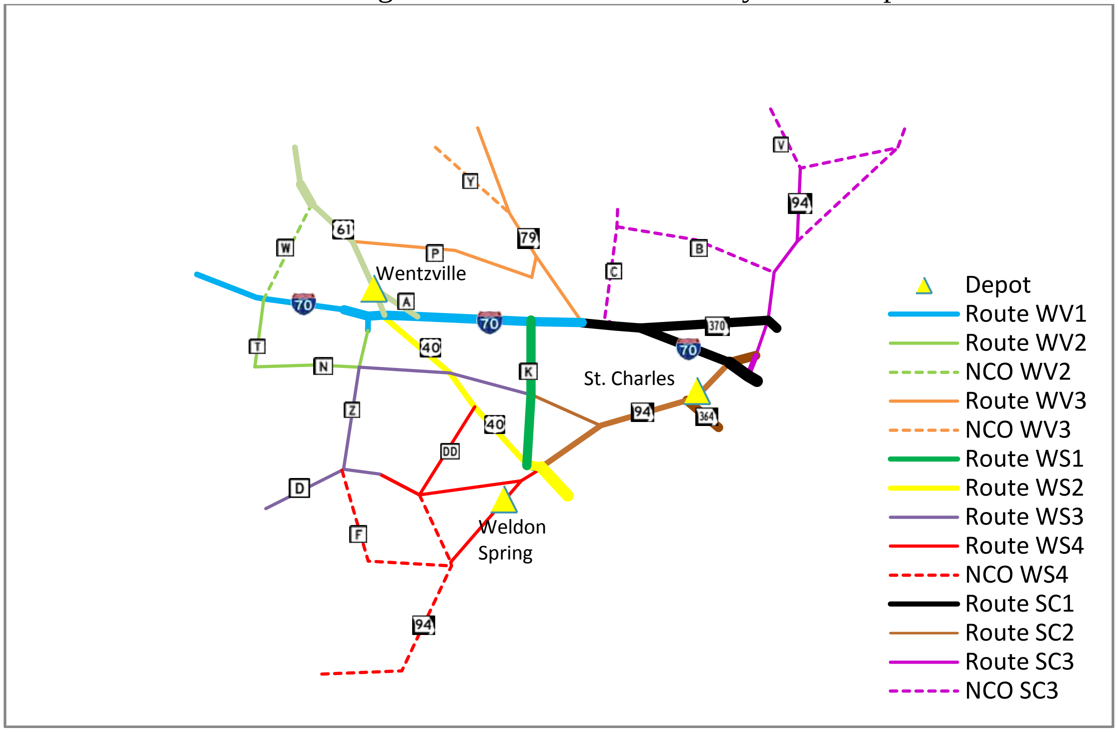


Figure 2.2.2 St. Charles County Route Map

The summary and description of the recommended routes in Figure 2.2.2 are given in Table 2.2.1 and Table 2.2.2. Table 2.2.1 shows necessary distance and time to serve each route. Route ID is a combination of building name and route number. For example, "WV1" means the first route from building Wentzville. In the Class column, "CO" and "NCO" stand for continuous operation and non-continuous operation roads, respectively. In addition, "DH" stands for deadheading. The total time represents service time plus deadheading time. Note that there are some rounding errors. The average cycle time includes dead-heading and 30 minute replenishment time after two service routes. For example, in the second row, (83 + 83 + 6 + 30) / 2 = 101 minutes.

Route ID	Class	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
WV1	CO	2~3	41	3	83	6	88	101
WV2	CO	1~2	48	0	96	0	96	111
	NCO	1	12		23			
WV3	CO	1	44	5	87	9	96	107
	NCO	1	12		24			
WS1	CO	mostly 3	15	5	29	10	39	49
WS2	CO	mostly 2	26	5	53	10	62	73
WS3	CO	1	43	19	87	38	125	121
WS4	CO	1	43	0	85	0	85	100
	NCO	1	48		96			
SC1	CO	mostly 3	36	4	73	8	81	92
SC2	CO	1~3	39	0	79	0	79	94
SC3	CO	mostly 1	21	6	42	13	55	63
	NCO	1	65		131			

Table 2.2.1 Summary of Routes

Route ID	Class	Description
WV1	CO	I70, from int. with MO79 towards west; Z with two lanes
WV2	CO	US61; A; T; N; Z, from int. with N to int. with I70
	NCO	W
WV3	CO	MO79; P; M
	NCO	Y
WS1	CO	K; OR40
WS2	CO	US40
WS3	CO	Z, from int. with N to int. with D; N, from int. with Z to int. with K; D, from 2 miles east of int. with Z towards west
WS4	CO	D, from 2 miles east of int. with Z to int. with MO94; MO94, from int. with US40 to int. with F; DD, from int. with US40 to int. with D
	NCO	F; DD, from int. with D to int. with MO94; MO94, from int. with US40 towards west
SC1	CO	I70, from int. with MO79 towards east; MO370, from int. with I70 towards east
SC2	CO	MO94, from int. with LP70 to int. with US40; N, from int. with MO94 to int. with K; MO364
SC3	CO	MO94, from int. with V to int. with LP70; LP70
	NCO	C; B; V; MO94 from int. with V towards east; H; J

Table 2.2.2 Route Description

2.3 North St. Louis County Area

Figure 2.3.1 shows the existing two buildings in Bellefontaine and Normandy in North St. Louis County Area. The roads are distinguished by their classes and number of one-way lanes. Figure 2.3.2 shows the best routes to serve the roads in Figure 2.3.1.

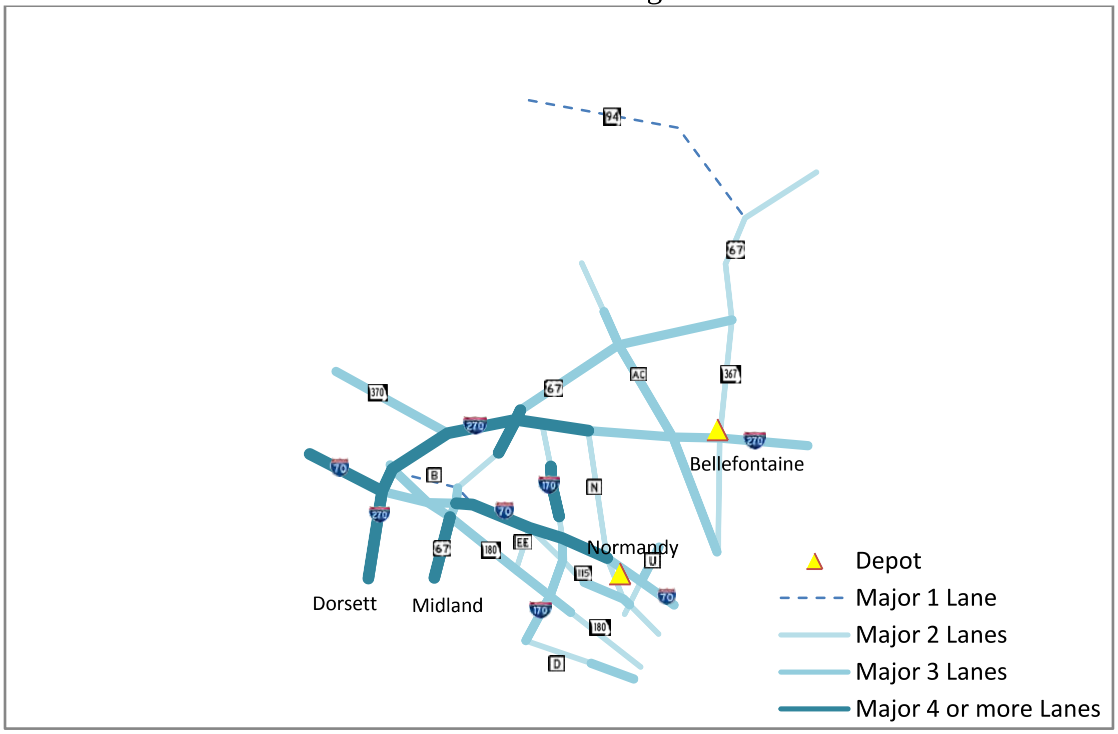


Figure 2.3.1 North St. Louis County Area Road Map

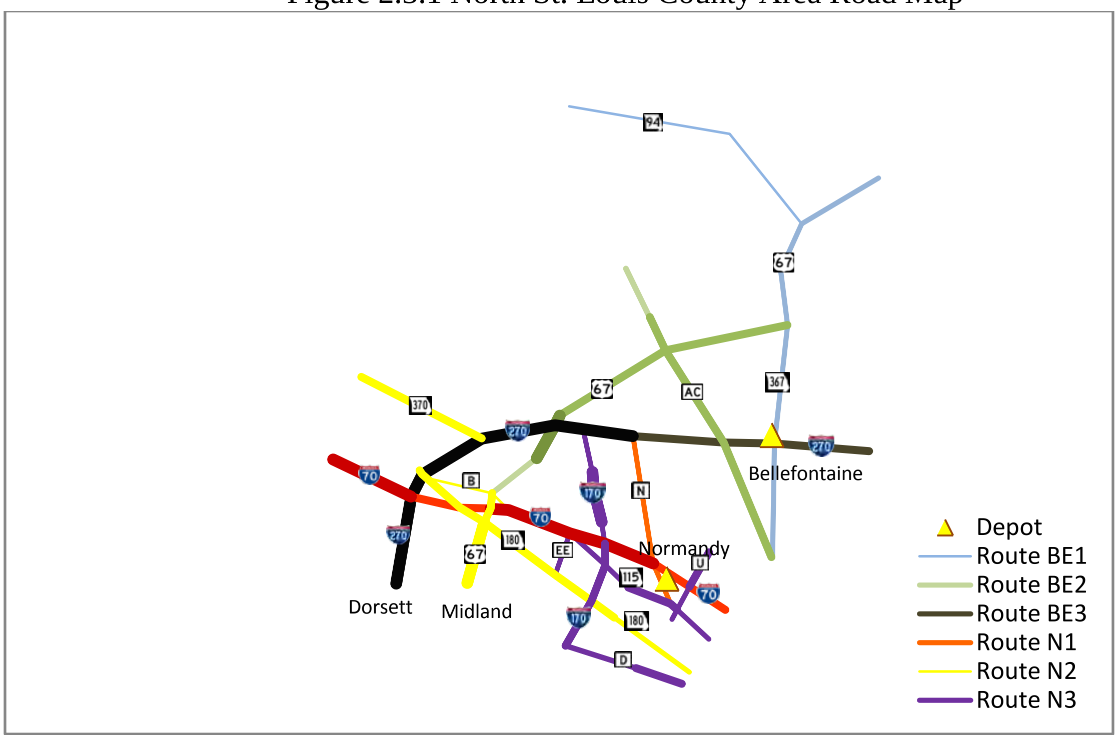


Figure 2.3.2 North St. Louis County Area Route Map

The summary and description of the recommended routes in Figure 2.3.2 is given in Table 2.3.1 and Table 2.3.2. Table 2.3.1 shows necessary distance and time to serve each route. There are only continuous operation roads in this area.

Route ID	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
BE1	1~2	44	0	87	0	87	102
BE2	mostly 3	42	3	85	6	91	103
BE3	3~4	35	0	69	0	69	84
N1	2~4	36	0	73	0	73	88
N2	mostly 3	40	10	81	20	101	106
N3	2~3	39	1	78	2	80	94

Table 2.3.1 Summary of Routes

Route ID	Class	Description
BE1	CO	MO94, from int. with US67 towards west; US67 from the int. with MO367 towards north; MO367
BE2	CO	US67, from the int. with MO367 to the int. with B; AC
BE3	CO	I270 from Dorsett towards east
N1	CO	I70; N
N2	CO	MO370;MO180; B; US67, from int. with B to Midland
N3	CO	I170 from the int. with I270 to the int. with D; D; MO115; U; EE

Table 2.3.2 Route Description

2.4 West St. Louis County Area

Figure 2.4.1 shows the existing three buildings in Page, Ballas and Eureka in West St. Louis County Area. The roads are distinguished by their classes and number of one-way lanes. Figure 2.4.2 shows the best routes to serve the roads in Figure 2.4.1.

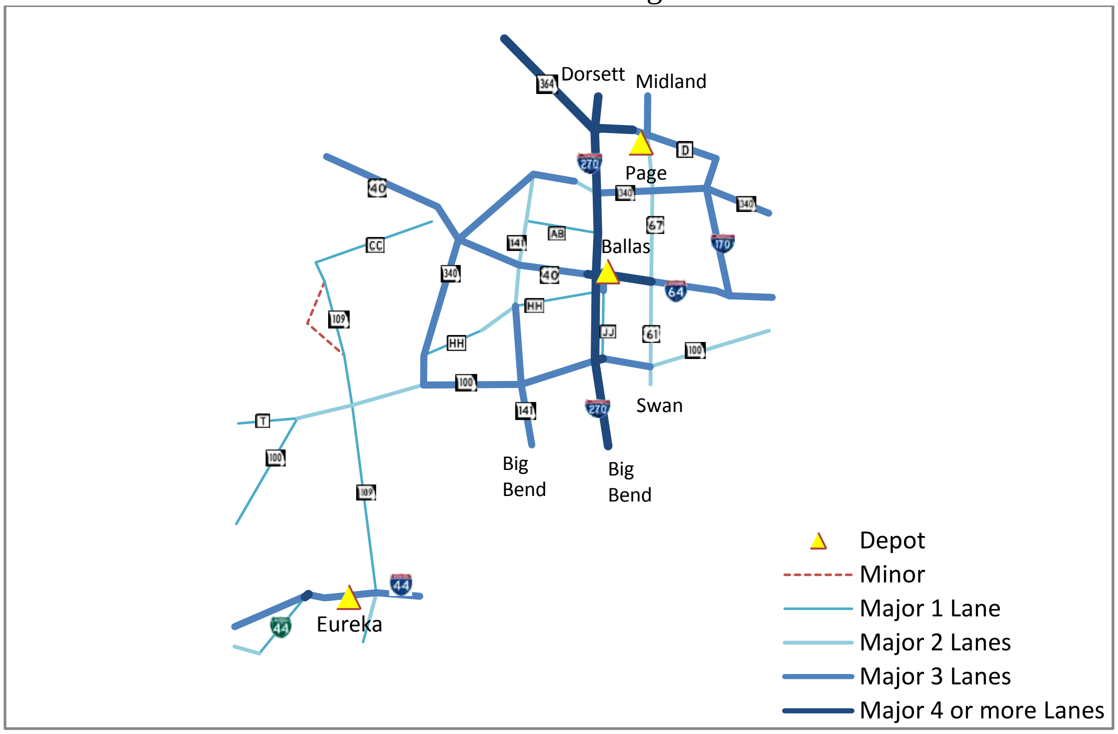


Figure 2.4.1 West St. Louis County Area Road Map

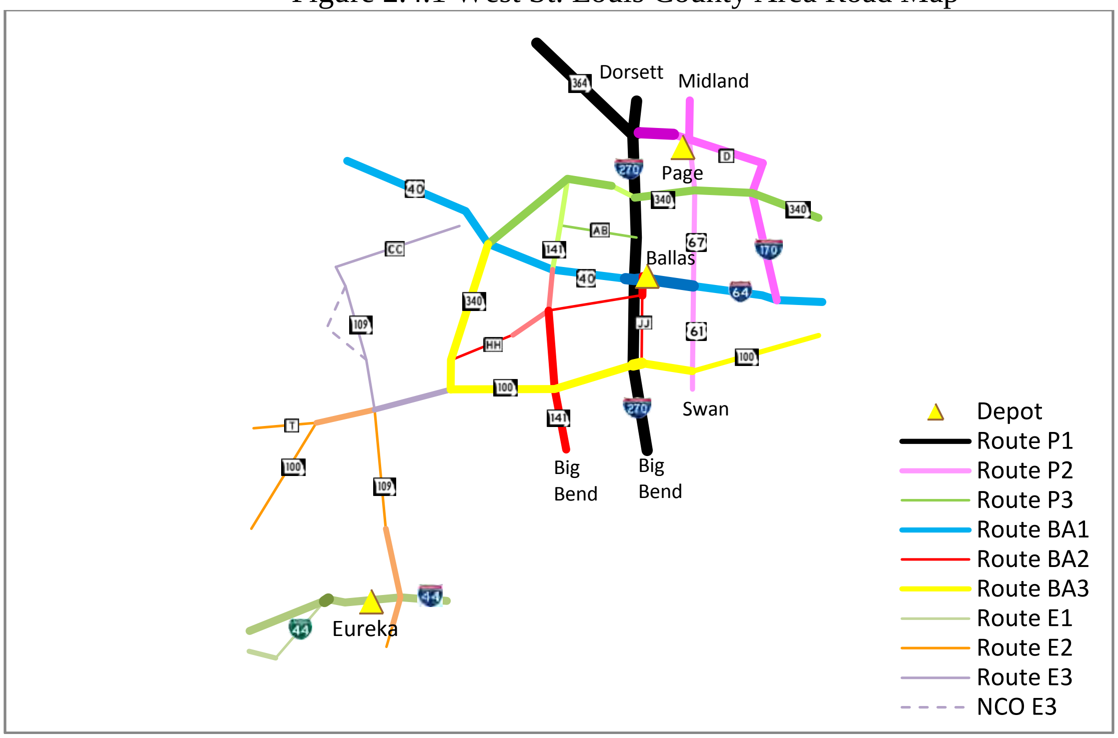


Figure 2.4.2 West St. Louis County Area Route Map

The summary and description of the recommended routes in Figure 2.4.2 are given in Table 2.4.1 and Table 2.4.2. Table 2.4.1 shows necessary distance and time to serve each route.

Route ID	Class	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
P1	CO	4	32	4	63	8	72	83
P2	CO	2~4	36	0	72	0	72	87
P3	CO	2~3	41	3	83	6	89	101
BA1	CO	mostly 3	41	0	82	0	82	97
BA2	CO	1~3	33	0	66	0	66	81
BA3	CO	mostly 3	40	5	80	10	89	100
E1	CO	1~3	25	0	49	0	49	64
E2	CO	1~2	35	5	70	9	79	90
E3	CO	1~2	27	17	55	34	89	87
	NCO	1	7		13			

Table 2.4.1 Summary of Routes

Route ID	Class	Description
P1	CO	MO364; I270 from int. with Dorsett to int. with Big Bend;
P2	CO	US67, from Midland to int. with I64; US61 from int. with I64 to Swan; D; I170 from int. with D to int. with I64;
P3	CO	MO340, from int. with I270 to int. with US40; MO141 from int. with MO340 to int. with US40; AB;
BA1	CO	US40 from int. with I64 towards west; I64 from int. with US40 towards east;
BA2	CO	MO141 from int. with US40 to Big Bend; HH from int. with MO340 to int. with JJ; JJ;
BA3	CO	MO340 from int. with US40 to int. with MO100; MO100 from int. with MO340 towards east;
E1	CO	I44; LP44;
E2	CO	MO100 from int. with MO109 towards west; MO109 from int. with MO100 towards south; T;
E3	CO	MO100 from int. with MO109 to int. with MO340; MO109 from int. with CC to int. with MO100; CC;
	NCO	BA;

Table 2.4.2 Route Description

2.5 St. Louis City Area

Figure 2.5.1 shows the existing two buildings in Shreve and Broadway in St. Louis City Area. The roads are distinguished by their classes and number of lanes. Figure 2.5.2 shows the best routes to serve the roads in Figure 2.5.1.

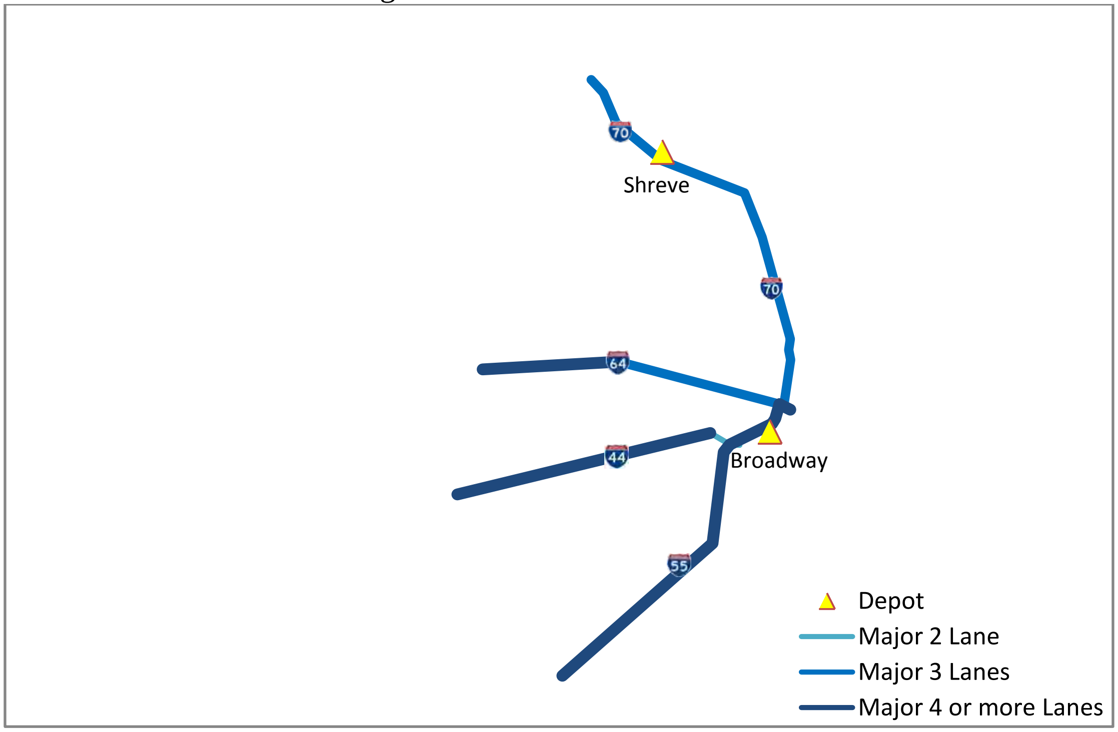


Figure 2.5.1 St. Louis City Area Road Map

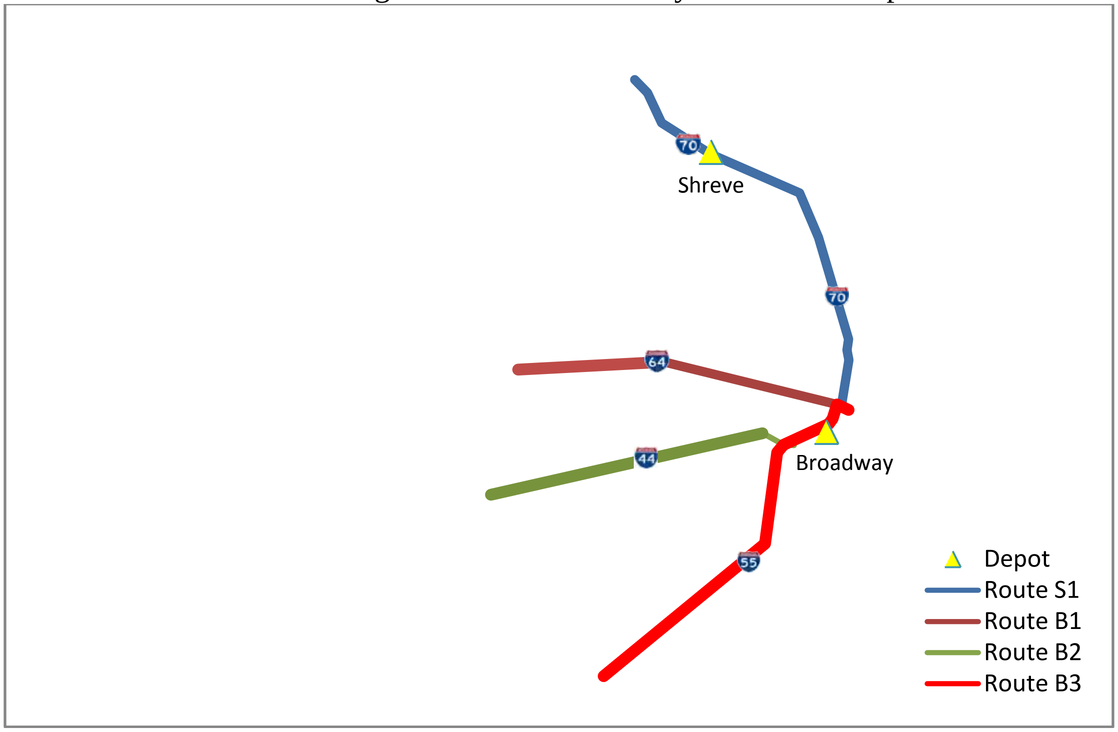


Figure 2.5.2 St. Louis City Area Route Map

The summary and description of the recommended routes in Figure 2.5.2 are given in Table 2.5.1 and Table 2.5.2. Table 2.5.1 shows necessary distance and time to serve each route. There are only continuous operation roads in this area.

Route ID	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
S1	3	17	0	33	0	33	48
B1	3~4	14	1	28	2	29	44
B2	mostly 4	14	2	28	4	32	45
B3	4	16	0	32	0	32	47

Table 2.5.1 Summary of Routes

Route ID	Class	Description
S1	CO	I70
B1	CO	I64
B2	CO	I44
B3	CO	I55

Table 2.5.2 Route Description

2.6 Franklin County

Figure 2.6.1 shows the existing three buildings in Beaufort, St. Clair and Gray Summit, and one salt site in Franklin County. The roads are distinguished by their classes and number of one-way lanes. Figure 2.6.2 shows the best continuous operation (CO) routes to serve the major roads in Figure 2.6.1. Figure 2.6.3 shows the best non-continuous operation (NCO) routes to serve the minor roads in Figure 2.6.1.

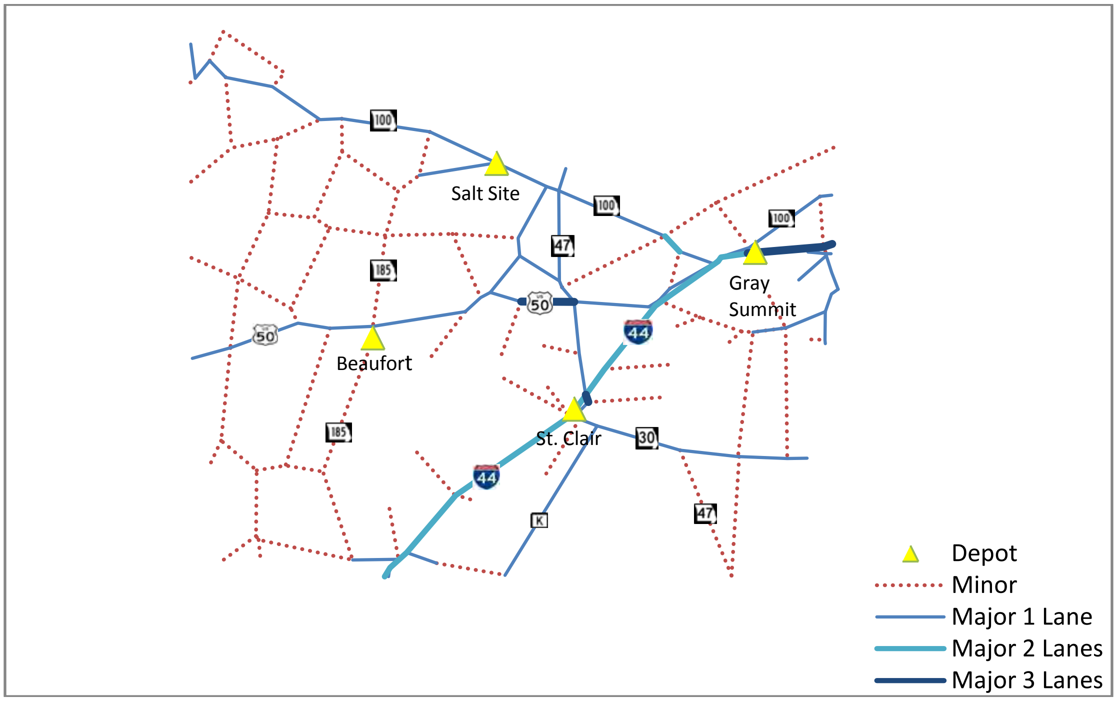


Figure 2.6.1 Franklin County Road Map

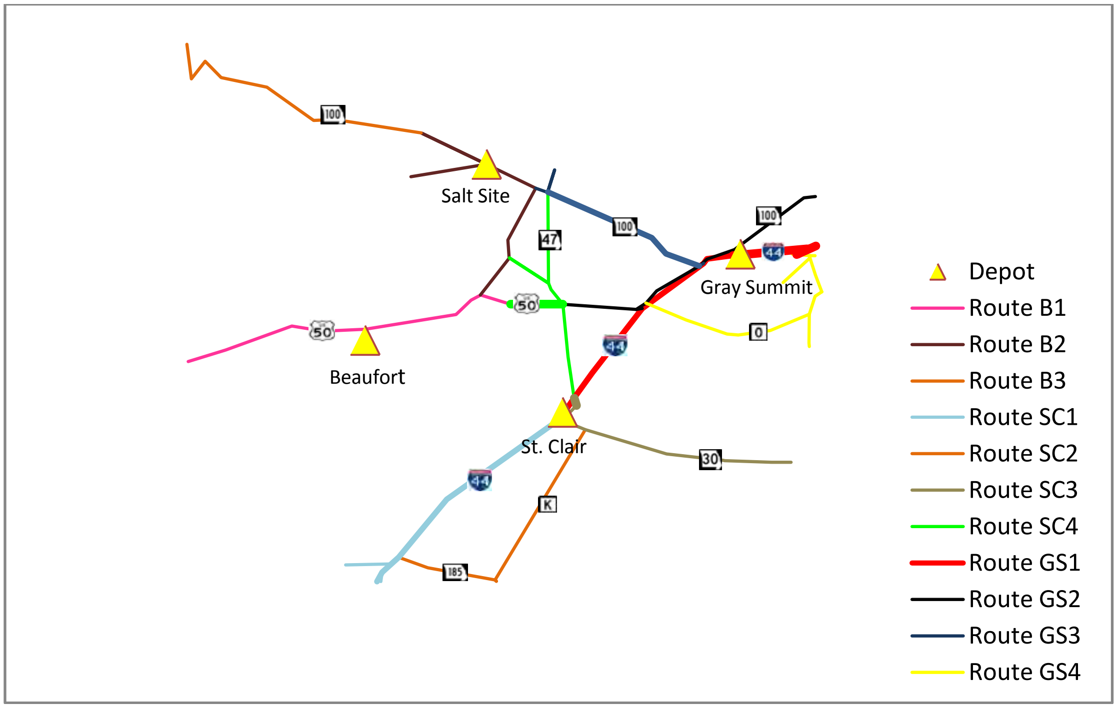


Figure 2.6.2 Franklin County CO Route Map

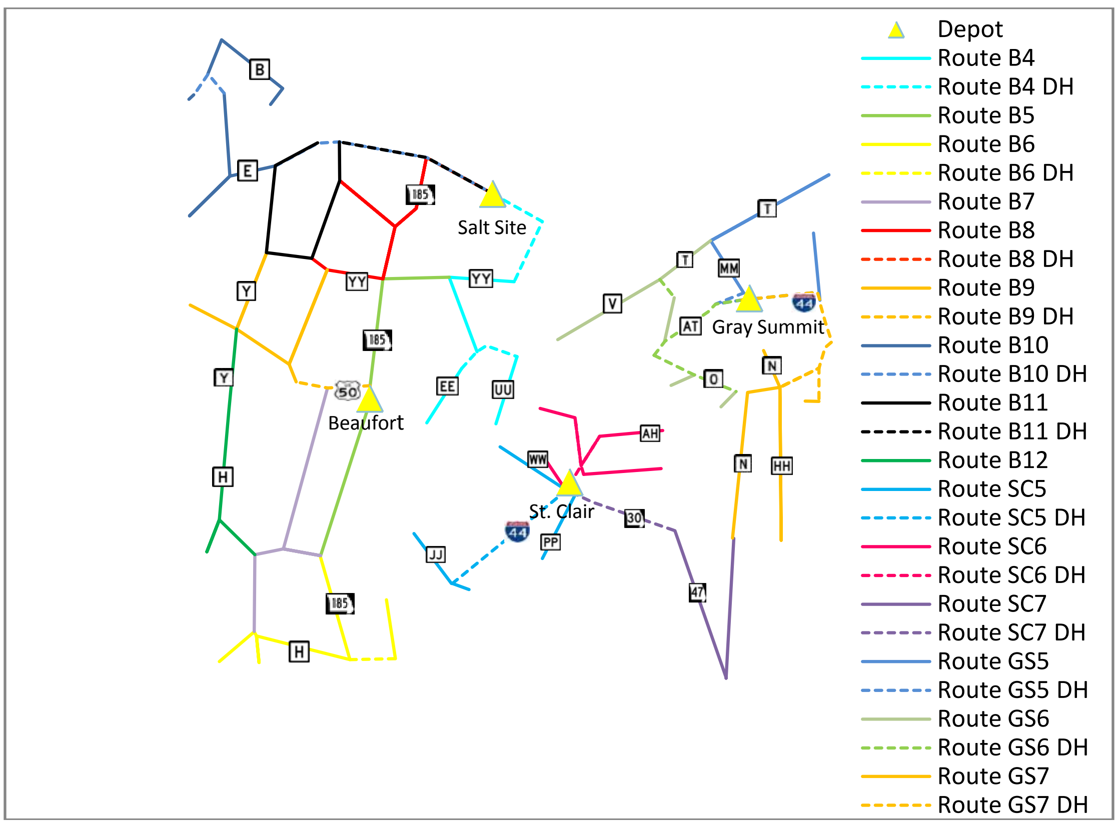


Figure 2.6.3 Franklin County NCO Route Map

The summary and description of the continuous operation routes in Figure 2.6.2 are given in Table 2.6.1 and Table 2.6.2. The summary and description of the non-continuous operation routes in Figure 2.6.3 are given in Table 2.6.3 and Table 2.6.4. Table 2.6.1 and 2.6.3 show necessary distance and time to serve each route.

Route ID	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
B1	1	39	1	78	3	81	94
B2	1	41	16	82	31	113	112
B3	1	30	9	61	17	78	84
SC1	Mostly 2	39	1	77	1	79	93
SC2	1	39	3	79	7	86	97
SC3	Mostly 1	30	1	60	1	62	76
SC4	Mostly 1	38	2	75	5	80	93
GS1	Mostly 2	39	7	77	13	91	99
GS2	1	36	3	72	6	78	90
GS3	Mostly 2	25	4	50	7	57	68
GS4	1	42	7	83	14	97	105

Table 2.6.1 Summary of Continuous Operation Routes

Route ID	Class	Description
B1	CO	US 50, from int. with UU towards west;
B2	CO	MO 100, from int. with MO 185 to int. with A; A from int. with MO100 to int. with BB; BB; KK, from int. with MO185 to int. with MO100;
B3	CO	MO100 from int. with MO185 towards west;
SC1	CO	I44, from int. with WW towards south; D; MO185, from int. with H to int. with IS44;
SC2	CO	K;MO185, from the int. with K to the int. with I44;
SC3	CO	MO30, from int. with I44 towards east; Part of MO47, from int. with MO30 towards north;
SC4	CO	MO47, from int. with I44 to int. with MO100; US50 from int. with MO47 to int. with UU; A from int. with BB to int. with MO47;
GS1	CO	I44, from int. with MO30 towards east;
GS2	CO	US50, from int. with MO47 to int.with AT; AT; MO100 from int. with AT towards east;
GS3	CO	MO47, from int. with I44 towards north; MO100, from int. with A to int. with AT;
GS4	CO	LP 44; NN; F, from int. with LP44 to int. with O; O, from int. with F to int. with I44; N from int. with F towards south;

Table 2.6.2 Continuous Operation Route Description

Route ID	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)
B4	41	21	81	42	123
B5	40	0	79	0	79
B6	43	24	86	49	134
B7	37	6	75	13	87
B8	33	9	66	17	83
B9	39	10	78	20	98
B10	41	30	82	59	142
B11	34	18	69	37	106
B12	33	20	65	41	106
SC5	36	19	73	38	111
SC6	30	13	60	26	86
SC7	35	14	71	27	98
GS5	33	13	65	25	90
GS6	34	25	68	51	119
GS7	47	24	94	47	141

Table 2.6.3 Summary of Non-Continuous Operation Routes

Route ID	Class	Description
B4	NCO	UU; EE; AJ; YY from int. with AJ to int. with A;
B5	NCO	YY from int. with MO185 to int. with AJ; MO185 from int. with AC to int. with YY;
B6	NCO	MO185 from int. with AC to int. with H; H from int. with AE to int. with MO185; J; AE; AF;
B7	NCO	AC from int. with H to int. with MO185; CC; H from int. with AC to int. with AE;
B8	NCO	MO185 from int. with YY to int. with MO100; KK from int. with C to int. with MO185; YY from int. with C to int. with MO185; C; from east int. with YY to west int. with YY
B9	NCO	C; Y from int. with YY to int. with ZZ; ZZ
B10	NCO	VV; Z; B; E from int. with Y towards west;
B11	NCO	E from int. with Y to int. with MO100; Y from int. with E to int. with YY; YY from int. with Y to int. with C; C from int. with YY to int. with MO100;
B12	NCO	H from int. with Y to int. with AC; Y from int. with ZZ to int. with H; AN
SC5	NCO	W; JJ; PP; WW
SC6	NCO	AB; TT; AD; AH
SC7	NCO	MO47 from int. with MO30 to int. with FF; FF
GS5	NCO	MM; OO; T from int. with MM towards east;
GS6	NCO	M; AK; AM; V; T from int. with MO100 to int. with MM
GS7	NCO	N from int. with O to int. with MO30; N from int. with O to Zagreb RD; HH; AP

Table 2.6.4 Non-Continuous Operation Route Description

2.7 South St. Louis County Area

Figure 2.7.1 shows the existing three buildings in Lemay, Sunset Hills and Barnhart in South St. Louis County Area. The roads are distinguished by their classes and number of one-way lanes. Figure 2.7.2 shows the best routes to serve the roads in Figure 2.7.1.

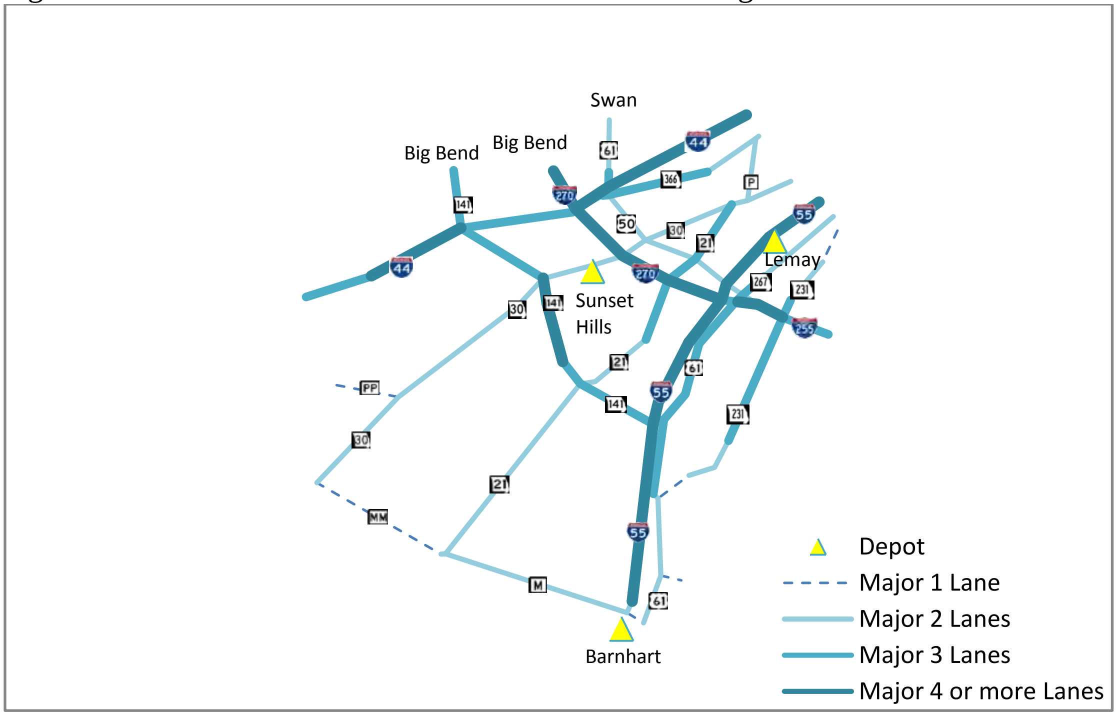


Figure 2.7.1 South St. Louis County Area Road Map

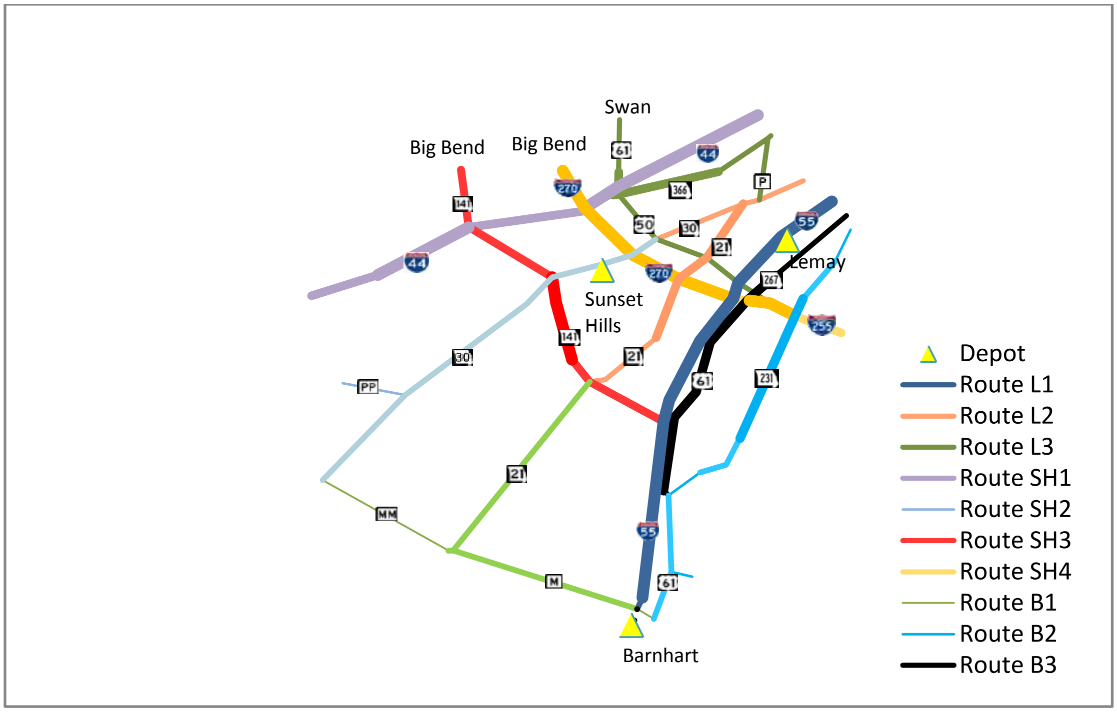


Figure 2.7.2 South St. Louis County Area Route Map

The summary and description of the recommended routes in Figure 2.7.2 are given in Table 2.7.1 and Table 2.7.2. Table 2.7.1 shows necessary distance and time to serve each route. There are only continuous operation roads in this area.

Route ID	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
L1	4	39	0	78	0	78	93
L2	2~3	28	7	57	15	71	79
L3	2~3	37	4	74	9	83	93
SH1	3~4	34	7	68	13	81	89
SH2	mostly 2	33	0	66	0	66	81
SH3	3~4	27	3	53	7	60	71
SH4	mostly 4	23	2	45	4	50	62
B1	1~2	41	1	82	3	85	98
B2	1~3	35	3	71	5	76	89
B3	mostly 3	25	12	50	24	74	77

Table 2.7.1 Summary of Routes

Route ID	Class	Description
L1	CO	I55;
L2	CO	MO30 from int. with US50 towards east; MO21 from int. with MO30 to int. with MO141
L3	CO	US61 from int. with US50 to Swan; US50, from int. with US61 to int. with I255; MO366; P;
SH1	CO	I44;
SH2	CO	MO30; PP;
SH3	CO	MO141;
SH4	CO	I270, from int. with I255 towards west; I255, from int. with I270 towards south;
B1	CO	MO21, from int. with MO141 to int. with MM; MM; M
B2	CO	MO231, from int. with US61 towards north; US61, from int. with MO231 to int. with M; K;
B3	CO	MO267; US61 from int. with MO267 to int. with MO231;

Table 2.7.2 Route Description

2.8 Jefferson County

Figure 2.8.1 shows the existing three buildings in Festus, Cedar Hill and DeSoto in Jefferson County. The roads are distinguished by their classes and number of one-way lanes. Figure 2.8.2 shows the best continuous operation (CO) routes to serve the major roads in Figure 2.8.1. Figure 2.8.3 shows the best non-continuous operation (NCO) routes to serve the minor roads in Figure 2.8.1.

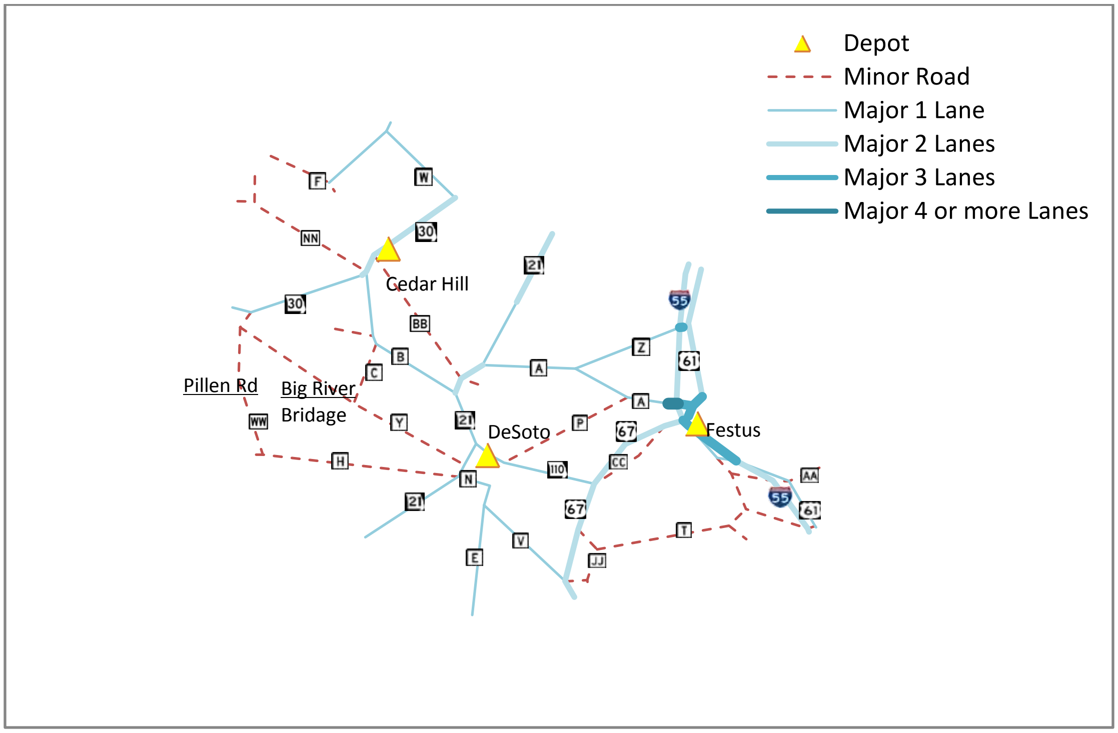


Figure 2.8.1 Jefferson County Road Map

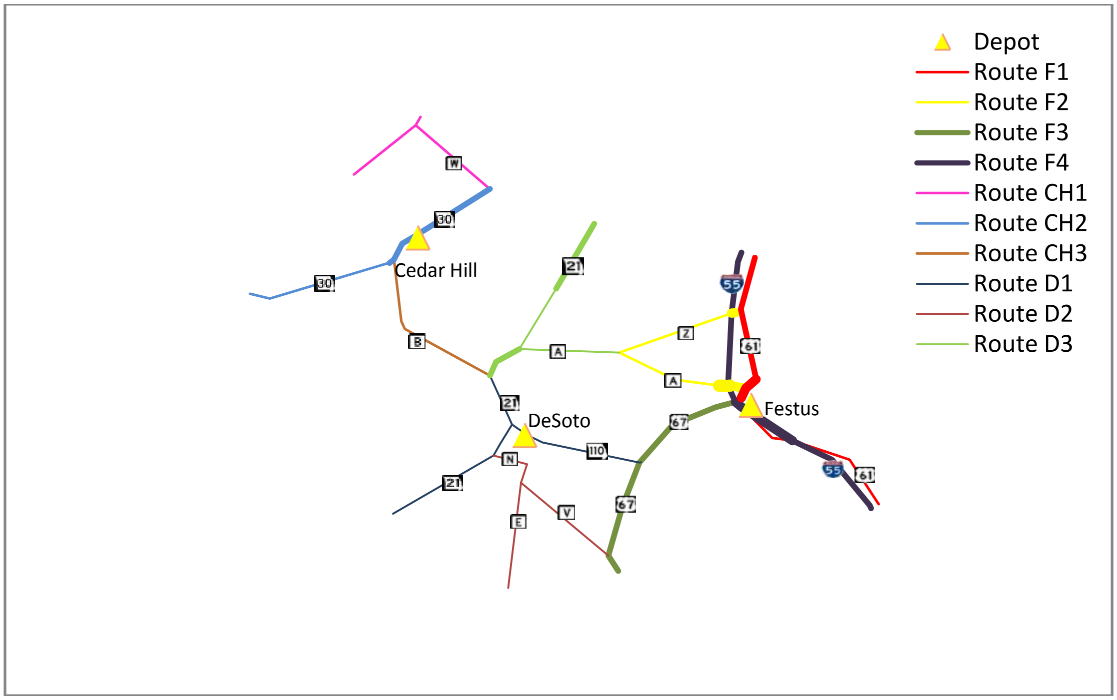


Figure 2.8.2 Jefferson County CO Route Map

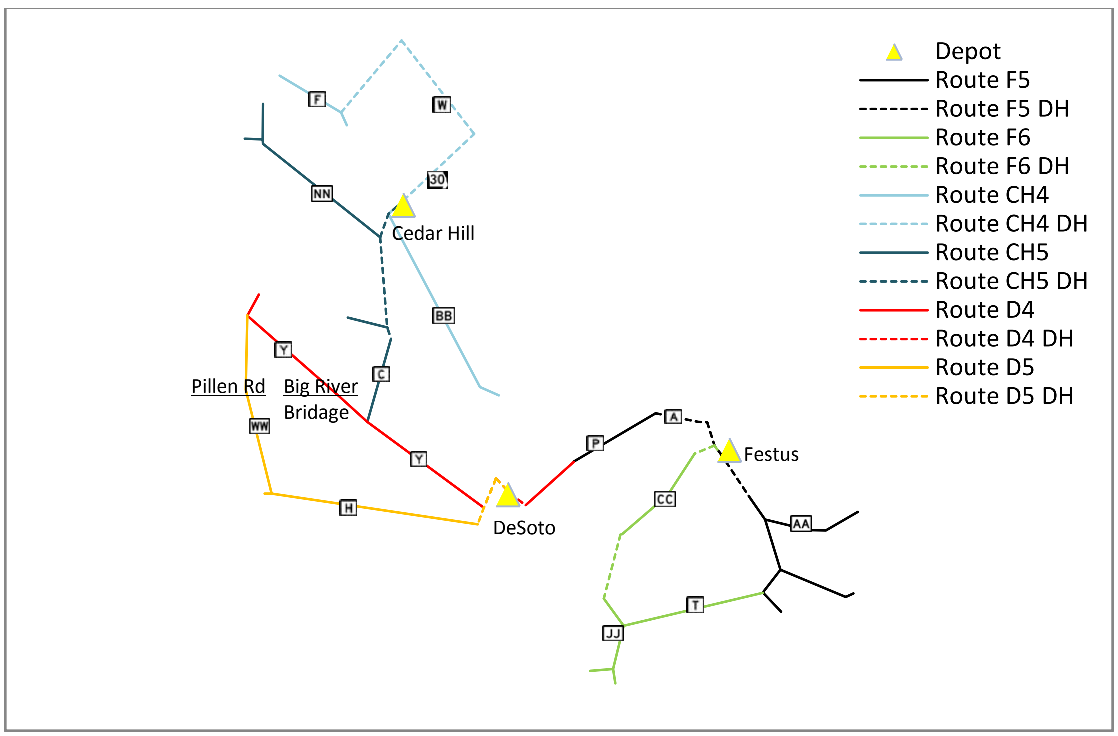


Figure 2.8.3 Jefferson County NCO Route Map

The summary and description of the continuous operation routes in Figure 2.8.2 are given in Table 2.8.1 and Table 2.8.2. The summary and description of the non-continuous operation routes in Figure 2.8.3 are given in Table 2.8.3 and Table 2.8.4. Table 2.8.1 and 2.8.3 show necessary distance and time to serve each route.

Route ID	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
F1	1~3	43	0	86	0	86	101
F2	mostly 1	24	3	49	6	55	67
F3	2	29	1	58	3	61	74
F4	2~3	41	0	81	0	81	96
CH1	1	23	10	46	19	66	71
CH2	1~2	28	0	56	0	56	71
CH3	1	22	4	43	7	51	62
D1	1	41	0	82	0	82	97
D2	1	36	5	71	10	81	91
D3	1~2	34	11	67	21	89	93

Table 2.8.1 Summary of Continuous Operation Routes

Route ID	Class	Description
F1	CO	US61;
F2	CO	Z, from int. with A to int. with US61; A, from int. with Z to int. with US61;
F3	CO	US67
F4	CO	I55
CH1	CO	MO109, from int. with W to the north; FF; W;
CH2	CO	MO30 from int. with W to the south;
CH3	CO	B, from int. with MO30 to int. with MO21;
D1	CO	MO21, from int. with B to the south; MO110, from int. with MO21 to int. with US67;
D2	CO	N; E; V, from int. with E to int. with US67;
D3	CO	MO21, from int. with B to the north; A, from int. with MO21 to int. with Z;

Table 2.8.2 Continuous Operation Route Description

Route ID	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)
F5	42	13	83	26	109
F6	37	9	73	18	92
CH4	29	33	58	66	124
CH5	35	14	70	28	99
D4	40	7	80	14	94
D5	41	10	83	19	102

Table 2.8.3 Summary of Non-Continuous Operation Routes

Route ID	Class	Description
F5	NCO	TT; AA; T, from int. with TT to int. with DD; DD; Part of P;
F6	NCO	T, from int. with DD to int. with JJ; JJ; V; CC;
CH3	NCO	F; BB;
CH4	NCO	NN; AP; EE; C;
D4	NCO	Y; Part of P;
D5	NCO	WW; H;

Table 2.8.4 Non-Continuous Operation Route Description

2.9 Building Closure Scenarios

Possible building closing situations were considered in this project. In general, maintenance building closure reduces administrative costs but deteriorates service efficiency such as increased deadheading times. However, there are some situations where the negative effect is minimal. Five such situations were identified and analyzed in this section. Specifically, those buildings are Weldon Spring in St. Charles County, Page in west St. Louis County area, Eureka in west St. Louis County area, Shreve in St. Louis City area, and Barnhart in South St. Louis County area.

2.9.1 Weldon Spring Closed in St. Charles County

If the maintenance building in Weldon Spring is closed, Wentzville and St. Charles need to serve the roads previously served by Weldon Spring. The roads served by routes WS1, WS2, WS3 and WS4 in Figure 2.2.2 are now served by routes WV4, WV5 and SC4 in Figure 2.9.1. The total number of routes is decreased from 10 to 9, and there is no increase in deadheading miles. Table 2.9.1 and Table 2.9.2 are the summary and description of the recommended routes in Figure 2.9.1 for the situation without Weldon Spring.

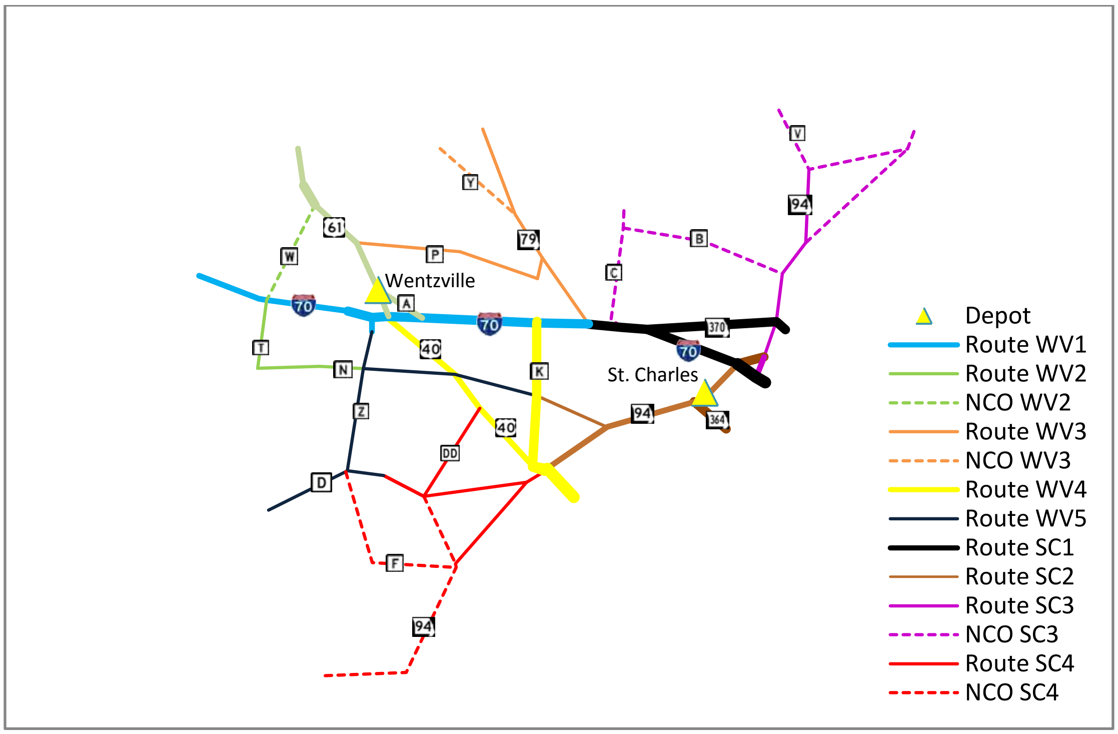


Figure 2.9.1 St. Charles County Route without Weldon Spring

Route ID	Class	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
WV1	CO	2~3	41	3	83	6	88	101
WV2	CO	mostly 2	44	0	88	0	88	103
WV2	NCO	1	12		23			
WV3	CO	1	44	5	87	9	96	107
WV3	NCO	1	12		24			
WV4	CO	2~4	41	3	82	6	87	99
WV5	CO	1	47	5	94	11	105	115
SC1	CO	mostly 3	36	4	73	8	81	92
SC2	CO	1~3	39	0	79	0	79	94
SC3	CO	mostly 1	21	6	42	13	55	63
SC3	NCO	1	65		131			
SC4	CO	1	43	18	85	36	122	118
SC4	NCO	1	48		96			

Table 2.9.1 Summary of Routes without Weldon Spring

Route ID	Class	Description
WV1	CO	I70, from int. with MO79 towards west; Z with two-lanes
WV2	CO	US61; A; T; N
WV2	NCO	W
WV3	CO	MO79; P; M
WV3	NCO	Y
WV4	CO	US40; OR40; K
WV5	CO	one-lane Z, from 2 miles north of int. with I70 to int. with D; N, from int. with Z to int. with K; D, from 2 miles east of int. with Z towards west
SC1	CO	I70, from int. with MO79 towards east; MO370, from int. with I70 towards east
SC2	CO	MO94, from int. with LP70 to int. with US40; N, from int. with MO94 to int. with K; MO364
SC3	CO	MO94 from int. with V to int. with LP70; LP70
SC3	NCO	MO94 from int. with V towards east; V; J; H; C; B
SC4	CO	D, from 2 miles east of int. with Z to int. with MO94; MO94, from int. with US40 to int. with F; DD, from int. with US40 to int. with D
SC4	NCO	MO94 from int. with DD towards west; DD from int. with D to int. with MO94; F from int. with D to int. with MO94

Table 2.9.2 Route Description without Weldon Spring

2.9.2 Page Closed in West St. Louis County Area

If Page is closed in West St. Louis County Area, Ballas and Eureka need to serve the roads previously served by Page. The roads served by routes P1, P2 and P3 in Figure 2.4.2 are now served by routes BA3, BA4 and BA5 in Figure 2.9.2. Besides, the roads served by BA2 and BA3 in Figure 2.4.2 are now served by E2 and E3 in Figure 2.9.2. Figure 2.9.2 shows the best routes to serve the roads in Figure 2.4.1 when Page is closed. These increase the total deadheading distance by 17 miles. Table 2.9.3 and Table 2.9.4 are the summary and description of the recommended routes in Figure 2.9.2 for the situation without Page.

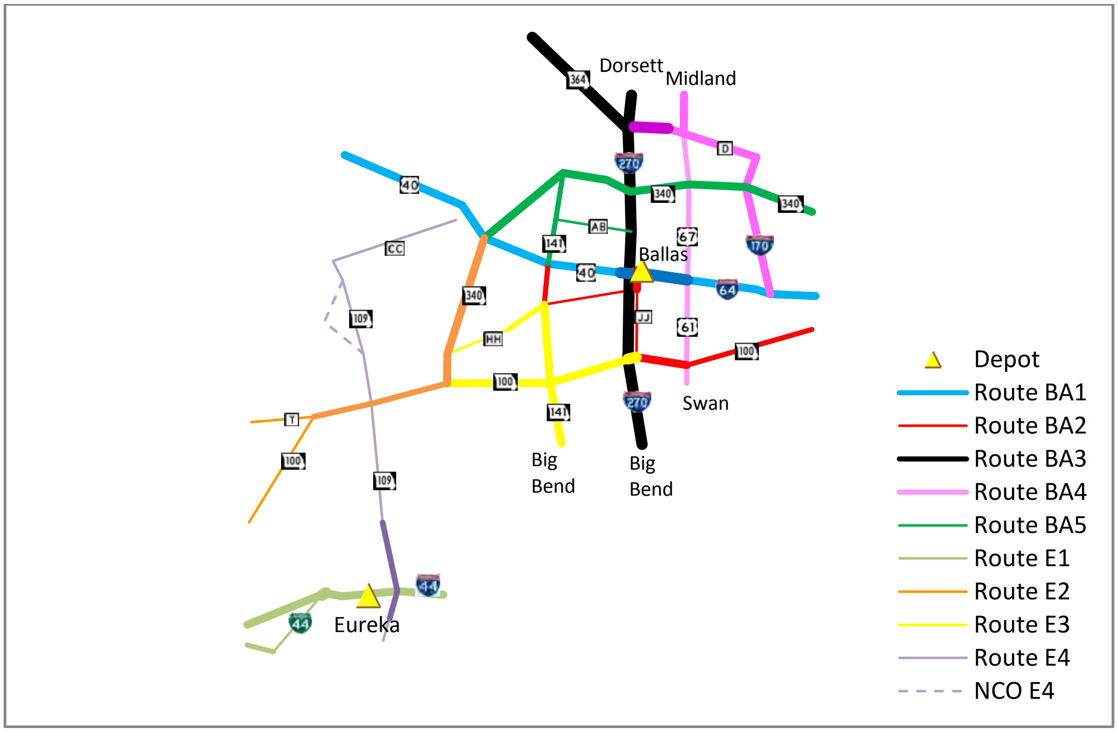


Figure 2.9.2 West St. Louis County Area Route without Page

Route ID	Class	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
BA1	CO	mostly 3	41	0	82	0	82	97
BA2	CO	1~3	31	0	61	0	61	76
BA3	CO	4	32	1	63	1	65	79
BA4	CO	2~4	36	2	72	4	76	89
BA5	CO	2~3	41	3	83	7	89	101
E1	CO	1~3	25	0	49	0	49	64
E2	CO	1~3	35	17	71	34	105	103
E3	CO	mostly 3	33	23	66	47	113	104
E4	CO	1~2	36	5	73	9	82	92
	NCO	1	7		13			

Table 2.9.3 Summary of Routes without Page

Route ID	Class	Description
BA1	CO	US40 from int. with I64 towards west; I64 from int. with US40 towards east;
BA2	CO	MO141 from int. with US40 to int. with HH; MO100 from int. with JJ towards east; HH from int. with MO141 to int. with JJ; JJ
BA3	CO	MO364; I270 from int. with Dorsett to int. with Big Bend;
BA4	CO	I170; US67, from Midland to int. with I64; US61 from int. with I64 to Swan; I170 from int. with D to int. with I64; D
BA5	CO	MO340, from int. with US40 towards east; MO141 from int. with MO340 to int. with US40; AB;
E1	CO	I44; LP44
E2	CO	MO100 from int. with MO340 towards west; MO340 from int. with MO100 to int. with US40; T;
E3	CO	MO100 from int. with MO340 to int. with JJ; MO141 from int. with HH to Big Bend; HH from int. with MO340 to int. with MO141
E4	CO	MO109 from int. with CC towards south; CC
	NCO	BA

Table 2.9.4 Route Description without Page

2.9.3 Eureka Closed in West St. Louis County Area

If Eureka is closed, its roads will be served by Ballas and Gray Summit and/or Sunset Hills in nearby areas. This will reduce the service area of West St. Louis but improve the overall efficiency. The roads served by routes E1, E2 and E3 in Figure 2.4.2 are now served by routes GS1, GS2 and BA4 in Figure 2.9.3. Table 2.9.5 and Table 2.9.6 are the summary and description of the recommended routes in Figure 2.9.3 for the situation without Eureka.

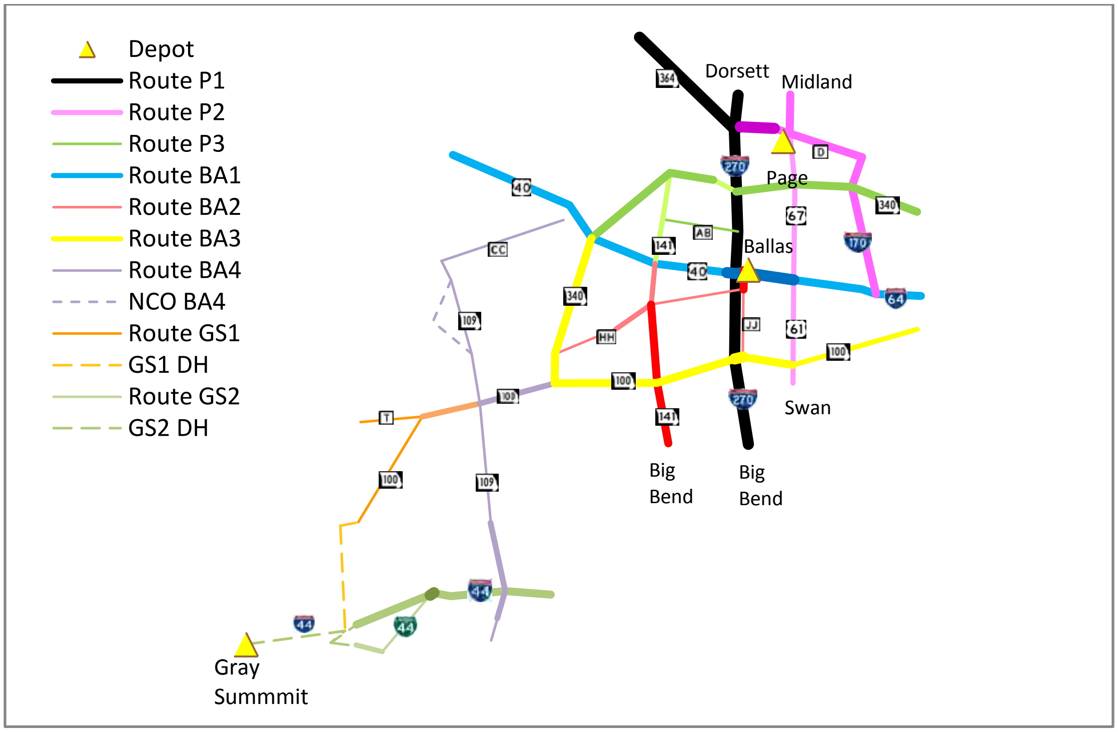


Figure 2.9.3 West St. Louis County Area Route without Eureka

Route ID	Class	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
P1	CO	4	32	4	63	8	72	83
P2	CO	2~4	36	0	72	0	72	87
P3	CO	2~3	41	3	83	6	89	101
BA1	CO	mostly 3	41	0	82	0	82	97
BA2	CO	1~3	33	0	66	0	66	81
BA3	CO	mostly 3	40	5	80	10	89	100
BA4	CO	1~2	43	21	86	41	127	121
	NCO	1	7		13			
GS1	CO	1~2	20	14	40	29	68	69
GS2	CO	mostly 3	25	9	49	19	68	74

Table 2.9.5 Summary of Routes without Eureka

Route ID	Class	Description
P1	CO	MO364; I270 from int. with Dorsett to int. with Big Bend;
P2	CO	US67, from Midland to int. with I64; US61 from int. with I64 to Swan; I170 from int. with D to int. with I64; D
P3	CO	MO340, from int. with US40 towards east; MO141 from int. with MO340 to int. with US40; AB
BA1	CO	US40 from int. with I64 towards west; I64 from int. with US40 towards east;
BA2	CO	MO141 from int. with US40 to Big Bend; HH from int. with MO340 to int. with JJ; JJ;
BA3	CO	MO340 from int. with US40 to int. with MO100; MO100 from int. with MO340 towards east;
BA4	CO	MO100 from int. with MO109 to int. with MO340; MO109 from int. with CC towards south; CC;
	NCO	BA
GS1	CO	MO100, from int. with MO109 to int. with OO; T
GS2	CO	I44; LP44

Table 2.9.6 Route Description without Eureka

2.9.4 Shreve Closed in St. Louis City Area
Even if Shreve is closed in St. Louis City Area, there will not be any change in routes. Route S1, which was served from Shreve in Figure 2.5.2, is simply served from Broadway building. Figure 2.9.4 shows the best routes to serve the roads in Figure 2.5.1 when Shreve is closed. Table 2.9.7 and Table 2.9.8 are the summary and description of the recommended routes in Figure 2.9.4 for the situation without Shreve.

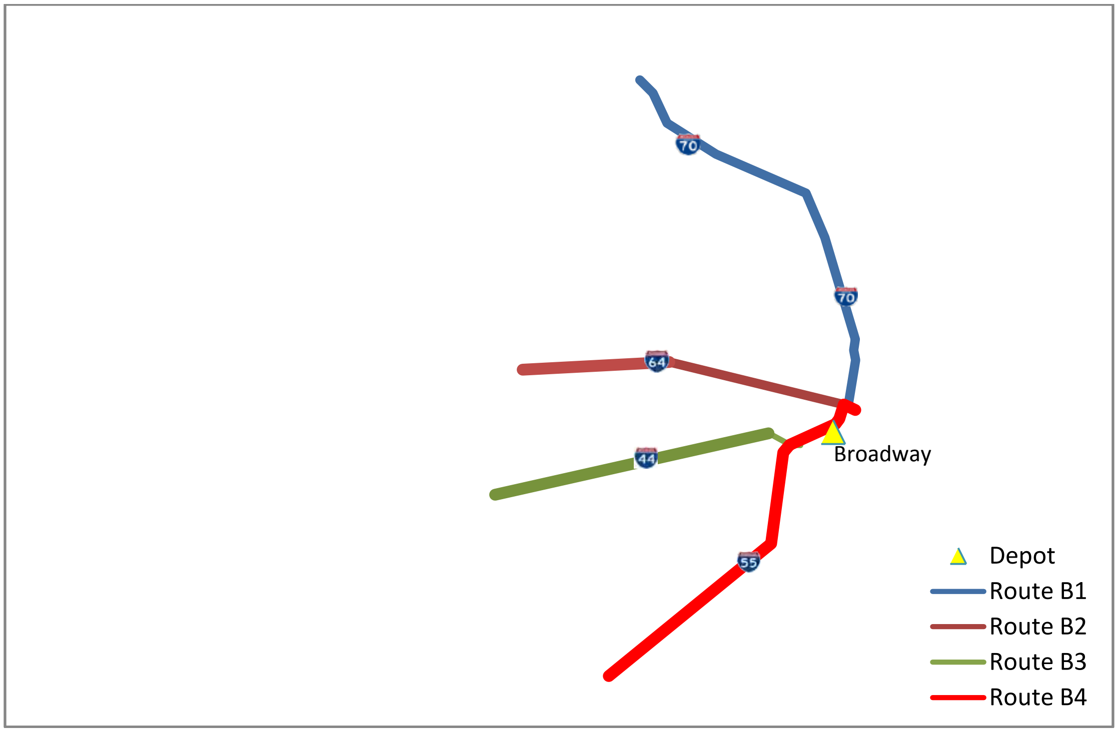


Figure 2.9.4 St. Louis City Area Route without Shreve

Route ID	Class	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
B1	CO	3	17	1	33	2	35	49
B2	CO	3~4	14	1	28	2	29	44
B3	CO	mostly 4	14	2	28	4	32	45
B4	CO	4	16	0	32	0	32	47

Table 2.9.7 Summary of Routes without Shreve

Route ID	Class	Description
B1	CO	I70
B2	CO	I64
B3	CO	I44
B4	CO	I55

Table 2.9.8 Route Description without Shreve

2.9.5 Barnhart Closed in South St. Louis County Area

If Barnhart is closed in South St. Louis County area, Lemay and Sunset Hills need to serve the roads previously served by Barnhart. The roads served by routes B2 and B3 in Figure 2.7.2 are now served by routes L4 and L5 in Figure 2.9.5. The roads served by B1 in Figure 2.7.2 is now served by part of SH2 and L2 in Figure 2.9.5. There are also some changes in the routes served by Lemay and Sunset Hills. These changes increase deadheading and cycle time only minimally. Figure 2.9.5 shows the best routes to serve the roads in Figure 2.7.1 when Barnhart is closed. Table 2.9.9 and Table 2.9.10 are the summary and description of the recommended routes in Figure 2.9.5 for the situation without Barnhart.

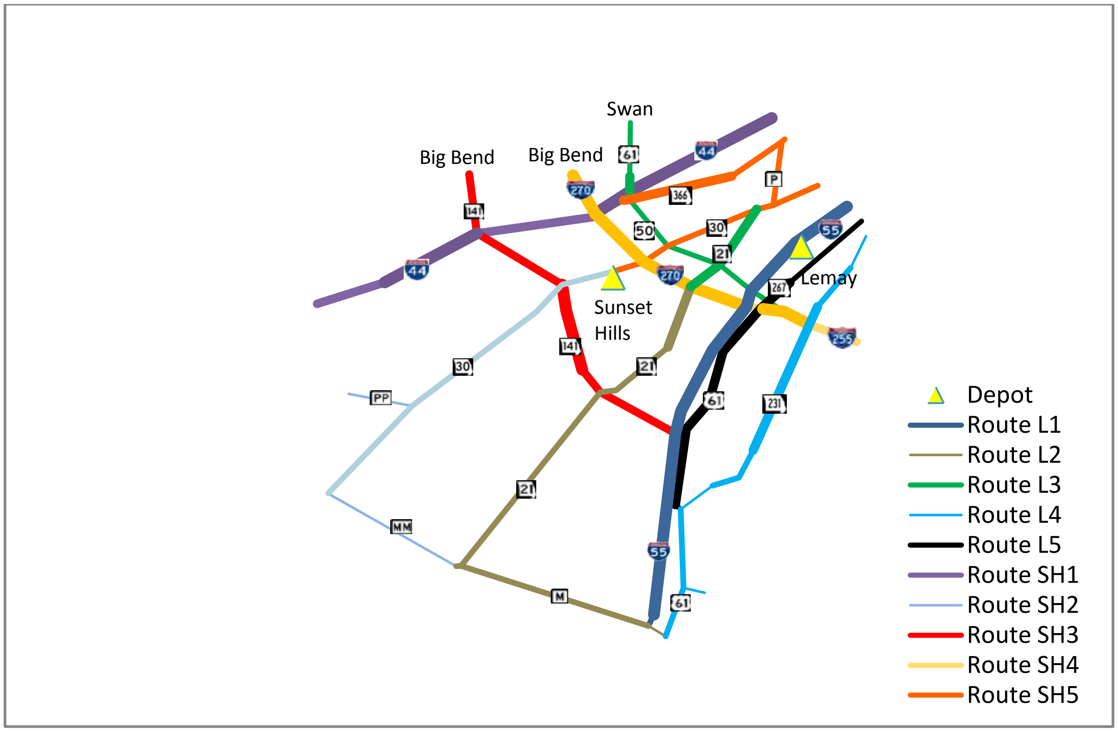


Figure 2.9.5 South St. Louis County Area Route without Barnhart

Route ID	Number of Lanes	Service Distance (mile)	DH Distance (mile)	Service Time (min)	DH Time (min)	Total Time (min)	Avg. Cycle Time (min)
L1	4	39	0	78	0	78	93
L2	mostly 2	42	8	83	17	100	107
L3	2~3	26	4	52	9	61	72
L4	1~3	35	9	71	19	90	95
L5	mostly 3	25	6	50	12	62	71
SH1	3~4	34	7	68	13	81	89
SH2	1~2	39	0	78	0	78	93
SH3	3~4	27	3	53	7	60	71
SH4	mostly 4	23	2	45	4	50	62
SH5	2~3	32	0	65	0	65	80

Table 2.9.9 Summary of Routes without Barnhart

Route ID	Class	Description
L1	CO	I55
L2	CO	MO21 from int. with M to int. with I270; M from int. with US61 to int. with MM;
L3	CO	MO21 from int. with MO30 to int. with I270; US61; US50;
L4	CO	MO231 from int. with US61 towards north; US61 from int. with MO231 towards south; K
L5	CO	US61 from int. with MO267 to int. with MO231; MO267
SH1	CO	I44
SH2	CO	MO30 from Sunset Hills to int. with MM; MM from int. with MO30 to int. with M; PP
SH3	CO	MO141 from int. with US61 towards west
SH4	CO	I255; I270
SH5	CO	MO30 from Sunset Hills towards east; MO366; P

Table 2.9.10 Route Description without Barnhart

Chapter 3: Winter Maintenance Treatment Strategy and Equipment

Winter maintenance practice is affected by the interaction of many variables and practices. The following will briefly review the climate factors and associated operational parameters. Then an overview of snow treatment materials and protocols are presented. This is synthesized into specific recommendations for MoDOT. Finally, a review of various snow blade types is conducted, followed by checklist for the complete range of snow removal equipment.

3.1 Background

3.1.1 Climate

In order to improve a strategy for the winter maintenance, a better understanding of what kind of weather environment in Missouri is needed. In this section, the historical statistics of climate have been reviewed in order to get a whole map of weather during winter in Missouri. Figures 3.1.1 and 3.1.2 illustrate the average winter temperature and snow fall for the entire state of Missouri, respectively. Figures 3.1.3 and 3.1.4 show the precipitation and snow fall, respectively, for the St. Louis area.

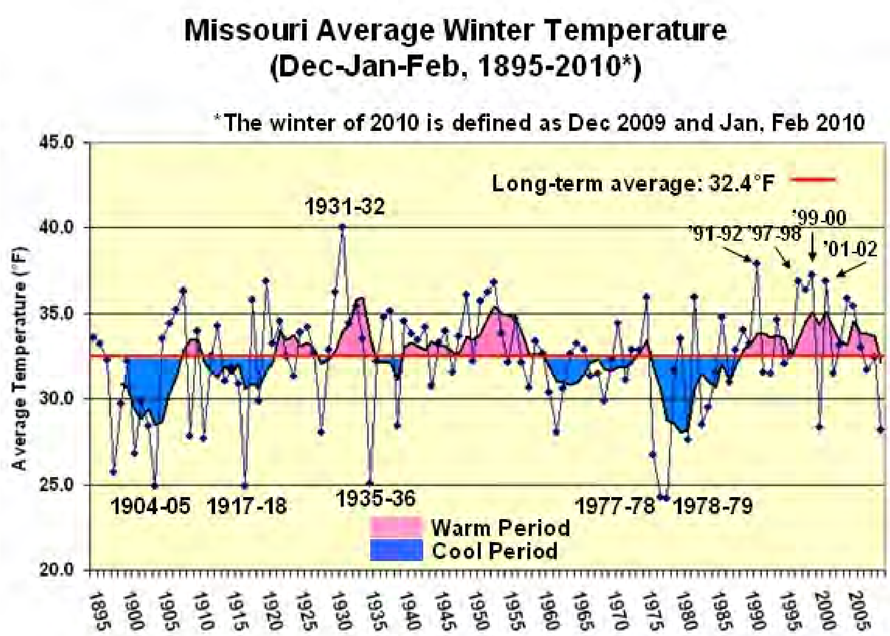


Figure 3.1.1 Missouri Winter Temperatures
(Source – Missouri Climate Center - http://climate.missouri.edu/charts/chart2.php)

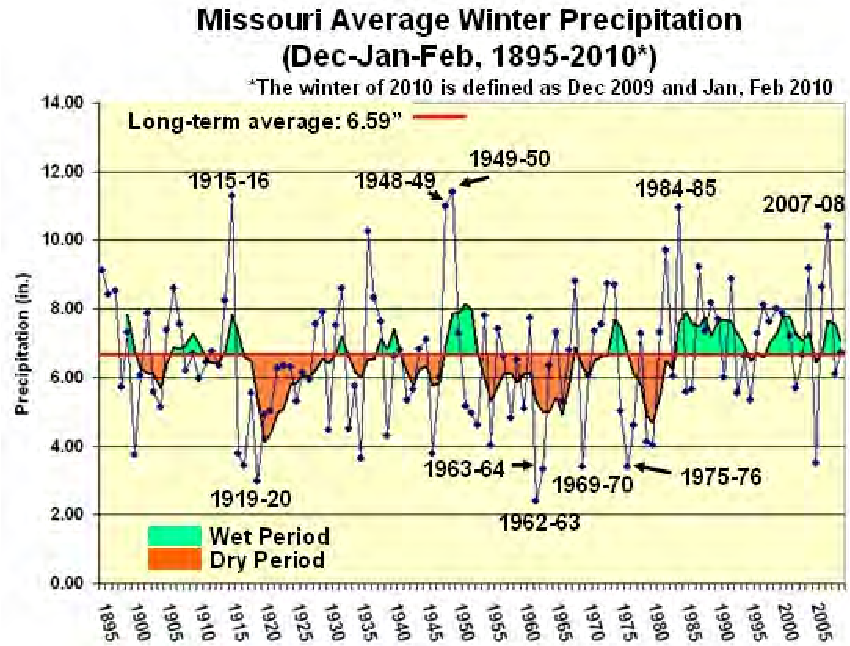


Figure 3.1.2 Missouri Winter Precipitation
(Source – Missouri Climate Center - http://climate.missouri.edu/charts/chart7.php)

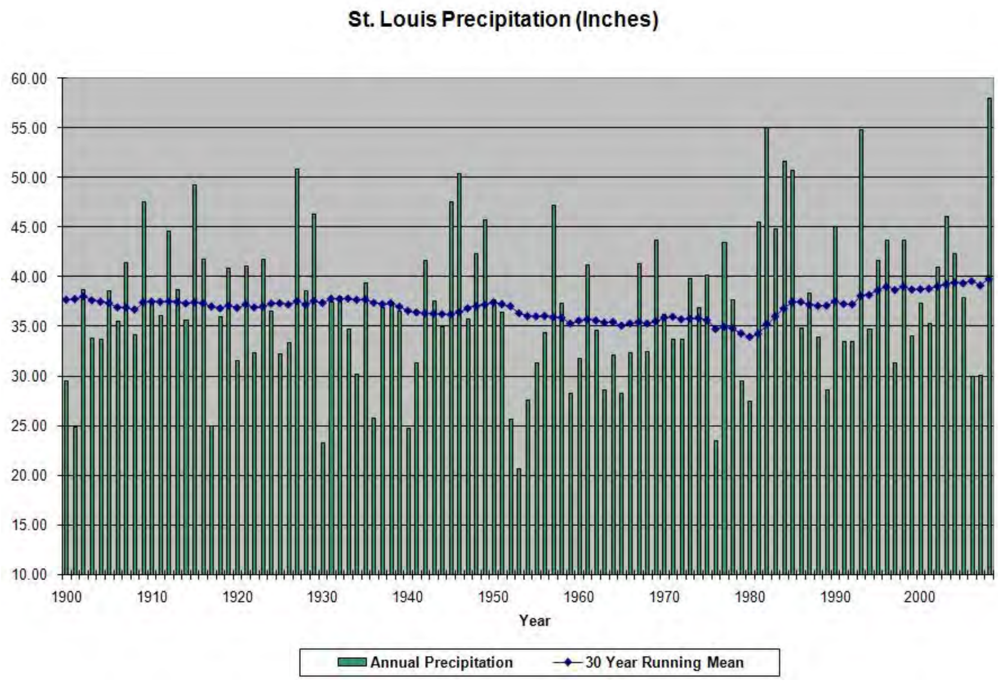


Figure 3.1.3 STL Precipitation
(Source – National Weather Service - http://www.crh.noaa.gov/lsx/?n=avgpcp)

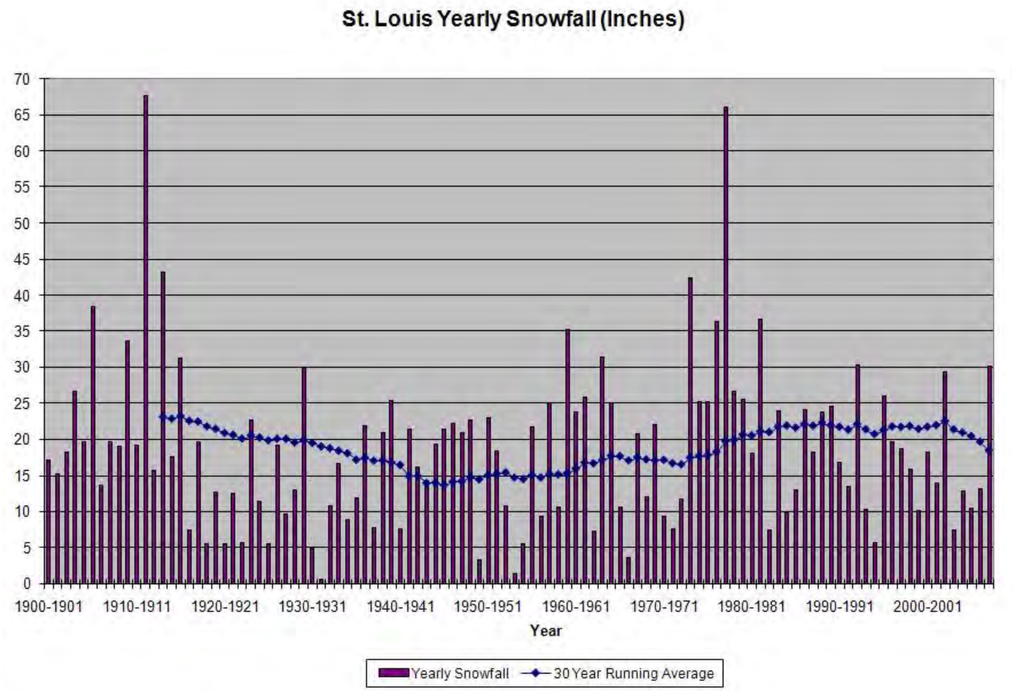


Figure 3.1.3 STL Snow Fall

(Source – National Weather Service - http://www.crh.noaa.gov/lsx/?n=avgsnow)

Based on the long-term climate data for Missouri, the average temperature is 32.4°F (0.22°C) and the average precipitation is 6.6 inches (167 mm). The long-term data for St. Louis reveals that the average precipitation of 37.5 inches is significantly higher than the overall Missouri average. The average total snowfall for St Louis is 18.6 inches during the winter.

3.2 Winter maintenance operation parameters

The following presents three different winter maintenance parameters that can be used to assess conditions and formulate action plans (Norem, 2009).

3.2.1 Winter Severity Index, Wsev

The winter severity index is the number of hours with recorded road surface temperatures below 18.6°F (−8°C) divided by the total hours in the period investigated. For instance, Wsev=0.1 means that 10% of the recordings are below 18.6°F (−8°C). Wsev tells the proportion of time when salting with NaCl is no longer an alternative for friction control.

3.2.2 Winter Stability Index, Wstab

The winter stability index, Wstab, describes the frequency of periods favorable for use of the warm-wetted sand method. A period favorable for warm-wetted sand is defined as a period lasting for 24 hr when the road surface temperatures in the whole period has been below 30.2°F (−1°C) and the precipitation is less than 0.12 inches (3 mm) within a 6-hr period. The winter stability index is then defined as the proportion of the number of favorable 24-hr periods divided by the number of days. Wstab=1 means that all road surface temperatures in the given period are below 30.2°F (−1°C) and there is only light snowfall. When Wstab is below 1, this might be the result of either road surface temperatures above 30.2°F (−1°C) or precipitation exceeding 0.12 in (3 mm) WE within 6 hr. Figure 3.2.1 illustrates calculation of the winter stability index where the first 15 hr the road surface temperatures have been below 30.2°F (−1°C) and the accumulated precipitation is less than 0.12 inches (3 mm) WE in a 6-hr period. During the next period the road surface temperature has been below 30.2°F (−1°C) all time, but the precipitation exceeded 0.12 inches (3 mm) WE within a 4-hr precipitation period and 8-hr after the start of the cold period.

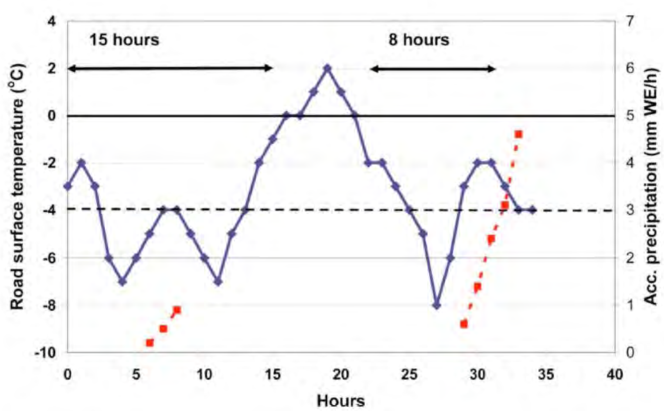


Figure 3.2.1 Illustration of how the hours favorable for using the warm-wetted sand method are counted (Source: Norem, 2009, p. 119)

3.2.3 Winter Instability Index, Winst

The winter instability index, Winst, is defined as the number of fluctuations around 32.0°F (0°C) divided by the number of days. For instance, if the road surface temperature every day has one period with temperatures above 32.0°F (0°C) and one period below 32.0°F (0°C), Winst will be equal 2. When Winst is 0, the road surface temperatures might have been either above or below

32.0°F (0°C) the whole period. Winst thus does not describe if it has been a warm or cold period, but only the frequency of fluctuations around 32.0°F (0°C).

3.3 Overview of snow treatment materials and protocols

3.3.1 Snow treatment materials

There are a range of different snow melting materials, each with different characteristics. Table 3.3.1 illustrates the eutectic temperature (the lowest temperature at which the chemical can depress the freezing point of water) of each material and Table 3.3.2 gives the eutectic temperature of selected commercial deicers.

Table 3.3.1 Snow Melting Material Eutectic Temperatures

Chemical	Concentration	Eutectic Temperature	
		°C	°F
Sodium Chloride	23%	-21	-5.8
Calcium Chloride	29.80%	-51	-59.8
Magnesium Chloride	21.60%	-33	-27.4
Calcium Magnesium Acetate	32.50%	-27	-16.6
Potassium Acetate	49%	-60	-76

(Source: Cuelho, et al., 2010, California DOT, Report CA10-1101)

Table 3.3.2 Eutectic Temperatures of Selected Deicers

Deicer	Concentration	Eutectic Temperature (°F)	Reference
Caliber™ M1000	27% magnesium chloride	-85	Product Specification Sheet
CMA® (anhydrous)	32.6% calcium magnesium acetate	-18	K. Johnson, Cryotech, personal communication
CMA25® (25% aqueous solution)	100% calcium magnesium acetate	+1	K. Johnson, Cryotech, personal communication
CMAK™ (50:50 blend of CMA25 and CF7)	100% CMAK	-25	K. Johnson, Cryotech, personal communication
FreezGard-Zero® with Shield LS®	22% magnesium chloride	-27	Envirotech Product Information Sheet
Ice Ban M50™	30% magnesium chloride + Ice Ban (ratio 1:1)	-78	M. Duran, Envirotech, personal communication
Ice Slicer®	92-98% sodium chloride	-6	G. Liest, Envirotech, pers. communication
Ice-Stop™CI	21.6% magnesium chloride	-28	Product Specification Sheet
Liquidow* Armor*	30% calcium chloride	-59	Product Information Sheet
NAAC® (anhydrous)	27% sodium acetate	-7	K. Johnson, Cryotech pers. communication
Potassium Acetate (CF7®) (50% aqueous solution)	100% potassium acetate	-76	K. Johnson, Cryotech, personal communication
Sodium Chloride	23% sodium chloride	-6	Dow Chemical Product Information Document[1]

[1] – Dow Chemical Company – Manual of Good Practice for Snow and Ice Control with Dow Calcium Chloride Products (no date).

(Source: CDOT – DTD-R-2001-15, (http://www.coloradodot.info/programs/research/pdfs/2001/deicers.pdf)

3.3.1.1 Rock Salt (Sodium Chloride NaCl)

Rock salt has the following characteristics (Helmenstine):

- Lowest practice temperature: 15°F (-9°C)
- Use: Chemical used to either break the bond of ice to the pavement or used to prevent it from forming by lowering the freezing point of water.
- Advantage: Inexpensive. Very effective. Readily available.
- Disadvantage: Impact on the Environment. Corrosive. Doesn't work at low temperatures. damages concrete & vegetation

Salt is used to avoid the formation of compacted snow and ice on roads. The use of salt has three aims: 1) to melt snow and ice on the road, 2) to lower the freezing point to prevent moisture freezing on the roads, or 3) to take the advantage of the effect of the salt to reduce the bonds between the snow grains. When these bonds are reduced by the salt, it is impossible to compact the snow, and the snow hardly sticks to the road surface. The snow cover then changes to a loose snow slush. The amount of salt used for keeping the roads free of snow and ice is thus highly dependent on the amount of snow falling each winter and on the winter temperatures. A study for two roads in Oslo (Norem 2009) in 2003/2004 showed that 63% of the salt consumption was used during snowfalls and 31% as preventive actions and only 6% for melting ice already formed on the road. The consumption of salt in relation to the weather conditions has also been studied in Sweden (Johansson 2002). The salt consumption per day and kilometer was recorded and compared in relation to temperature, humidity, and precipitation. The highest consumption was found on cold days with precipitation, approximately 4–5 times higher compared to humid days with the same temperature. The use of salt has important limitations in harsh climates. At temperatures below 18.6°F (−8°C) it is difficult to keep sufficient salt concentrations to prevent the formation of ice film, therefore, the Scandinavian guidelines operate with a lower limit of 42.8°F (6°C) to 18.6°F (−8°C) for using salt (NaCl). Therefore, spreading of salt in very low temperatures should be avoided.

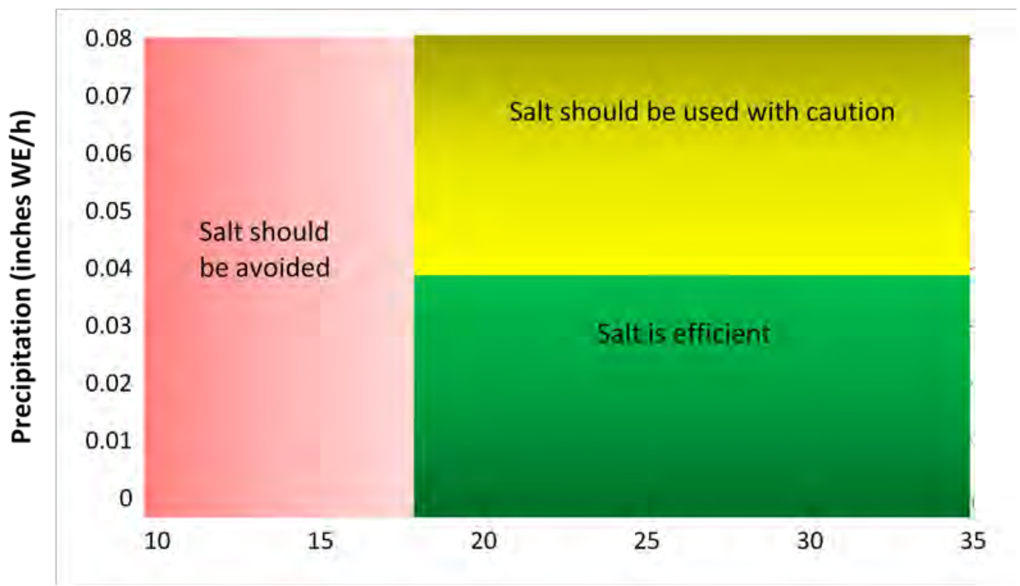


Figure 3.3.1 Weather situations and salt usage ((Source: Norem, 2009, p. 115)

The kind of weather situations where salt is favorable or has limited effect is shown graphically in Figure 3.3.1. The figure indicates that the best efficiency is found at temperatures down to 18.6°F (−8°C) and with only modest snow fall (around 0.04 inches (1 mm) water equivalent WE per hour). At higher intensities, salt should be used with caution. The limit of snow fall intensity of 0.04 inches (1 mm) WE/h is close to the findings of the “winter model” for intensities that cause salted roads to be packed with snow (Norem, 2009).

3.3.1.2 Sand

Sand has the following characteristics (MassDOT Road Treatment Materials):

- Use: Used only in Reduced Salt Zones and at very low temperatures when Rock Salt will not work effectively.

- Advantage: Inexpensive. Works at low temperatures. Availability.

- Disadvantage: Impact on the Environment. Does not melt snow and ice. Clogs drainage structures. Expenses to sweep and dispose of.

Sand or crushed rock has traditionally been spread out on ice and compacted snow surfaces to improve the road friction. The effect of dry sand is limited, the improvement in the friction coefficient is usually considered to be 0.05–0.1 and the improved friction lasts for a limited time period. On roads with traffic speeds of 50 mph and a high percentage of trucks, the improved friction will only last for approximately 50 cars (Vaa 2006).

At the 10th PIARCWinter Road Congress in Luleå in 1998, the Swedish Road Administration presented equipment for wetting the sand with hot water, termed “the warm-wetted sand method.” The spreader equipment used can handle both salt and sand. The spreaders are equipped with water tanks that make it possible to heat the water to 203.0°F (95°C) and the hot water is mixed with the sand at the spreading disk (Vaa 2006). The warm-wetted sand method needs to have road surface temperatures below 32.0°F (0°C) in order for the sand grains to freeze to the ice or the compacted snow. When the climatic conditions are favorable, the effect of the gritting has been recorded up to one week with an AADT exceeding 1,000 (Vaa 2006). In this instance, 200 g/m2 sand has been used, and the road surface temperatures have been well below 32.0°F (0°C) and no precipitation.

3.3.1.3 Pre-Mix (Sodium Chloride/Calcium Chloride blend)

Pre-mixed sodium chloride / calcium chloride has the following characteristics (MassDOT Road Treatment Materials):

- Use: The material is used in "reduced-salt areas" and elsewhere when air temperature is very low.

- Advantage: Less harmful to the environment. Works at a lower temperature. Quicker.

- Disadvantage: Expensive. Must be stored and kept dry.

3.3.1.4 Liquid Calcium Chloride ($CaCl_2$)

Liquid calcium chloride has the following characteristics (MassDOT Road Treatment Materials):

- Use: The material works by attracting moisture and releasing heat. When mixed with salt it melts up to eight times as much ice as using salt alone.

- Lowest practice temperature: -20°F (-29°C)

- Advantage: Very effective for pre-treatment or direct liquid application. Works at low temperatures.
- Disadvantage: Expensive. Applications must be timed correctly.

3.3.1.5 Magnesium Chloride ($MgCl_2$)

Magnesium chloride has the following characteristics (MassDOT Road Treatment Materials):

- Lowest practice temperature: 5°F (-15°C)
- Use: Used as pre-treatment to prevent snow and ice from sticking to pavement.
- Advantage: Less harmful to the environment. Works at low temperatures. Less harmful to equipment. Melts ice faster than sodium chloride
- Disadvantage: Expensive. Application must be timed correctly.

3.3.1.6 Potassium Acetate (CH3COOK)

Potassium acetate has the following characteristics (Helmenstine):

- Lowest practice temperature: 15°F (-9°C)
- Use: Potassium acetate is used in liquid form as a chemical snow melt. The chemical is melts snow and ice up to -15°F. It also has a build-up effective requiring fewer applications should snow continue to fall. This also means that when the snowy season ends the built-up potassium acetate must be cleaned from the surfaces it was applied to.
- Advantage: Biodegradable
- Disadvantage: Corrosive

3.3.1.7 Calcium magnesium acetate

Calcium magnesium acetate has the following characteristics (Helmenstine):

- Formula: Calcium Carbonate CaCO3, magnesium carbonate MgCO3, and acetic acid CH3COOH
- Lowest practice temperature: 15°F (-9°C)
- Advantage :Safest for concrete & vegetation, Works better to prevent re-icing than as ice remover
- Disadvantage: Expensive: 60 times greater than Sodium Chloride.

3.3.2 Chemical Additions

There are two main types of chemical additives: solid and liquid chemical. Usually, liquid chemicals are preferred over solid, because (Chollar, 1996):

- Liquids do not get blown away like dry chemicals.
- The agents do not form a cake in the application vehicle.
- The chemicals do not corrode the truck.
- There is not any need for abrasives.

So usually, the solid chemicals will be prewetted when it is used.
Advantages of prewetting are (Ketcham and Minsk, 1996):

- Salt is spread homogeneously.
- Salt granules adhere to the surface better.
- Long lasting effect compared to solid chemicals.
- Spreading speed is faster.
- Since lower application rate is used compared to solid chemicals, one truck load covers more lane miles resulting in reduction in resources.
- Deadhead reduction (salt finishing quickly and returning to the garage empty)

Prewetting can be done by either of three methods: 1) a prewetting chemical can be injected into a material stock pile at a specific dosage, (2) a liquid chemical can be sprayed onto a loaded spreader or on the material as it is being loaded into the spreader, or (3) an on-board spray system mounted on the spreader and/or dump body can add a liquid chemical to the dry chemical at the time of spreading. (Salt Brine – NSC Minerals)

3.3.3 Comparison of different snow treatment materials

3.3.3.1 Calculations of the amount of melting materials required

The essential issue for melting materials for the highways is not to melt the snow and ice, but to lower the freezing point of the materials. Schneider (1960) gave a standard way to calculate the amount of salt required to melt ice and snow on highways in 1960. Figures 3.3.2 and 3.3.3 are based on Schneider's work.

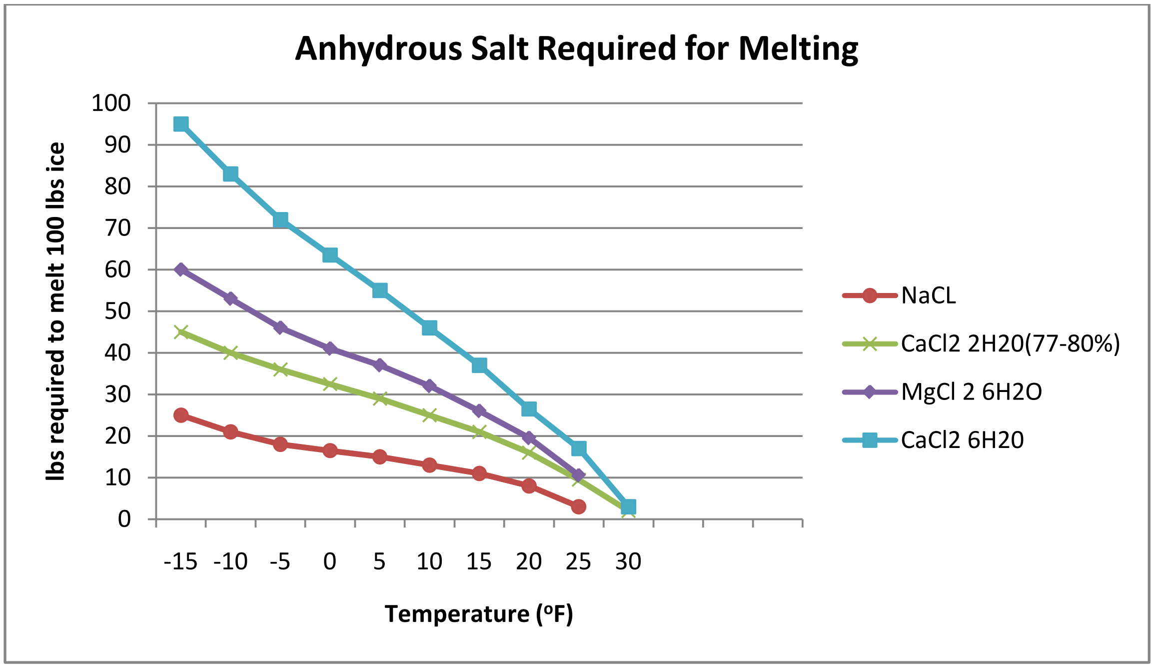


Figure 3.3.2 Salt required for melting 100 lb ice

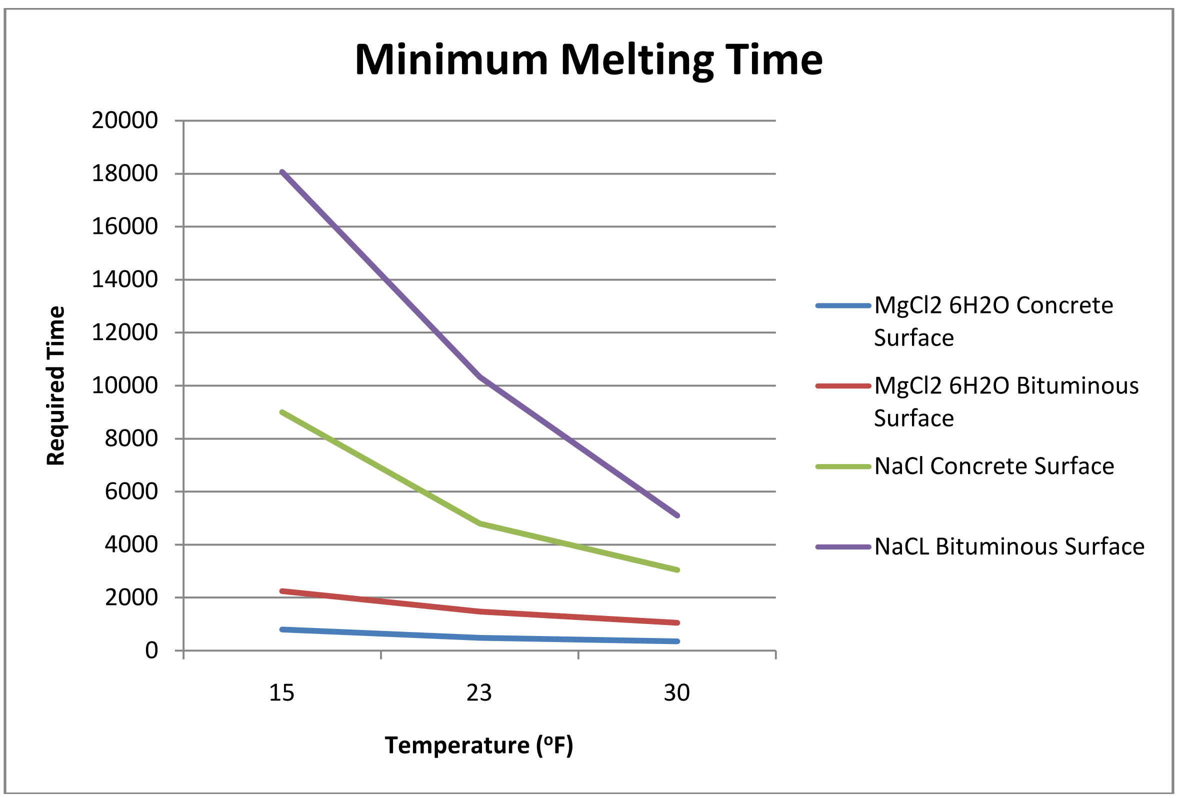


Figure 3.3.3 Minimum melting time

3.3.4 Material application protocols

The following presents several different snow / ice control material application guidelines.

3.3.4.1 Mass DOT

MATERIAL APPLICATION GUIDELINES (PER LANE MILE)

Current Pavement Temperature Range (°F)	**Anticipated Pavement Temp. Change (Higher or Lower)**	**Severity/ Precipitation Type**	**Application rate 240lb Per Ln/mile**	**Recommended Treatment**	**Comments**
Above 32	Higher	Light-Rain, Sleet or Wet Snow	240	Initial application, reapply as needed	Pre-wet salt application Do not Pre-treat roadway
	Lower	Moderate to Heavy-Rain, Sleet or Wet Snow	240		Pre-Wet initial Salt application Pre-treat roadway with Calcium Chloride @ 20-30 gals per lane mile
25 to 32	Higher	Light Freezing-Rain, Sleet, Dry Snow or Wet Snow	240	Initial application plow and reapply as needed	Pre-wet Salt with Calcium Chloride @ 8-10 gals per ton Pre-treat roadway with Calcium Chloride @ 20-30 gals per lane mile or Pre-Wet Salt with Calcium Chloride @ 8-10 gal per ton.
		Moderate to Heavy Freezing Rain, Sleet, Dry Snow or Wet Snow	240		
	Lower	Light-Freezing Rain, Sleet, Dry Snow or Wet Snow	240		
		Moderate to Heavy-Freezing Rain, Sleet, Dry Snow or Wet Snow	240		

20 to 25	Higher	Light-Sleet, Dry Snow or Wet Snow	240	Initial application, plow/reapply as needed	Pre-treat roadway with Calcium Chloride @ 20-30 gals per ton Pre-wet Salt with Calcium Chloride @ 8-10 gal per ton
		Moderate to Heavy-Sleet, Dry Snow or Wet Snow	240		
	Lower	Light-Sleet, Dry Snow or Wet Snow	240	Initial application, plow/reapply as needed	
		Moderate to Heavy-Sleet, Dry Snow or Wet Snow	240		
15 to 20	Higher	Light-Sleet or Dry Snow	240	Initial application, plow/reapply as needed	Pre-treat roadway with Calcium Chloride @ 20-30 gals per lane mile Pre-wet Salt with Calcium Chloride @ 8-10 gals per ton
		Moderate to Heavy-Sleet or Dry Snow	240		
	Lower	Light-Sleet or Dry Snow	240	Initial application, plow/reapply as needed	
		Moderate to Heavy-Sleet or Dry Snow	240		
15 or Below				Apply sand if necessary, plow as needed	Monitor pavement temperature. Switch to wetted salt if rising above 15°F

Source: MassDOT Material Application Guidelines (per lane mile) http://www.mhd.state.ma.us/default.asp?pgid=snowandice/applicationGuide&sid=dtable

3.3.4.2 City of Toronto

ROAD CLASSIFICATION – SALTING CHART

ROAD CLASSIFICATION	TYPICAL	WINTER* SERVICE	DEICER	APPLICATION RATE KG/LANE-KM	TIME FRAME TO COMPLETE DE-ICER OPERATIONS
Expressways	DVP / FGGE	Bare Pavement	100% Rock Salt	70 / 140 / 180	2-3 cm snow & continuing 1-2 hrs
Arterials (minor / major)	Yonge St. / Sheppard Ave.	Bare Pavement	100% Rock Salt	70 / 140 / 180	5 cm snow 2-3 hrs
Collectors	Main Streets through sub-division	Centre Bare Pavement	100% Rock Salt	70 / 90	8 cm of snow & stopped 4-6 hrs
Locals	Residentials (including dead end streets and industrial roads <2500 AADT**)	Safe and Passable Pavement	100% Rock Salt	70 / 90	8 cm of snow + stopped 8-12 hrs
Laneways		Safe and Passable Pavement	100% Rock Salt	180	24 hrs

* This is the desired condition of the pavement surface. However, it is necessary to have sufficient traffic volumes to activate and improve the characteristics or the de-icer, the time to achieve this condition will vary with the time, duration and intensity of each storm event.

** Local roads > 2500 AADT under review.

(Source: City of Toronto – Salt Management Plan http://www.toronto.ca/transportation/snow/pdf/02smp.pdf)

3.3.4.3 MAINE DOT - Salt Application Rates

Current Pavement Temperature Range (F)	Anticipated Pavement Temperature Change (Higher or Lower)	Precipitation: Type / Severity	Application Rate: Pounds per Lane Mile	Recommended Treatment	Comments
ABOVE 32	Higher	4, 6, 8 / Light	None		
	Lower	4, 6, 8/Moderate to Heavy	100 to 200	Initial Application, reapply as needed	Use Pre-wet System
25 to 32	Higher	5, 6, 7, 8 / Light	200 to 300	Initial Application, Plow / Reapply as needed	Pre-wet @ 6 gals per ton
	Higher	5, 6, 7, 8/ Moderate to Heavy	200 to 300		
	Lower	5, 6, 7, 8 / Light	200 to 400		
	Lower	5, 6, 7, 8/ Moderate to Heavy	200 to 400		
20 to 25	Higher	6, 7, 8 / Light	300 to 500	Initial Application, Plow / Reapply as needed	Pre-wet @ 8 gals per ton
	Higher	6, 7, 8/ Moderate to Heavy	300 to 500		
	Lower	6, 7, 8 / Light	400 to 600		
	Lower	6, 7, 8/ Moderate to Heavy	400 to 600		
15 to 20	Higher	6, 7 / Light	500 to 700	Initial Application, Plow / Reapply as needed	Pre-wet @ 10 gals per ton
	Higher	6, 7/ Moderate to Heavy	500 to 700		
	Lower	6, 7 / Light	700 to 800		
	Lower	6, 7/ Moderate to Heavy	700 to 800		
15 or Below				Apply sand and plow as needed	Monitor pavement temperature Switch to Salt if rising above 15 F

If snow is blowing off roadway and no hard pack exists, do not apply.

Weather Conditions

- 4 = Rain
- 5 = Freezing Rain
- 6 = Sleet
- 7 = Dry Snow
- 8 = Wet Snow

(Source: MaineDOT – Salt Application rates - http://www.maine.gov/mdot/community-programs/csd/saltapprates.php)

3.3.4.4 ColoradoDOT

Maintenance Section	Contact	Location	Deicers and Other Materials Used	Application Rates	Advantages	Disadvantages	Comments
MS 5	Chuck Loerwald	Aurora	$MgCl_2$ w/inhibitor and Caliber M1000; Sand	Start at 40 GPLM, higher as needed.	The deicers remove the snowpack and ice off the road, so do not have to use as much sand.	Sand has to be picked up.	MgCl2 works well in spring and fall before it gets too cold. Caliber M1000 works well when it is cold. Caliber M1000 works better than MgCl2.
MS 6	Bernard Lay	Craig	FreezGard Zero, Caliber M1000, Ice Slicer, Sand	40 GPLM	Get roads back to a non-icy safer condition much quicker.	Sand very costly to clean up.	Use sand/salt everywhere except Steamboat Springs and Rabbit Ears Pass, where use sand/salt impregnated with Freezgard.
MS 7	Frank Holman	Alamoso	$MgCl_2$ and Caliber M1000	80 GPLM (pretreatment); 40-80 GPLM depending on conditions.	Less sand use; less snow pack; fewer inconveniences for motorists.	Problems with electricals systems on our trucks; cost, complaints from motorists.	Do not use liquid deicers in combination with sand.
MS 8	Randy Jensen	Denver	MgCl2 (30%), sand/salt, Ice Slicer, Caliber M1000	40 GPLM	Helped reduce salt and sand usage as required by Regulation 16, air pollution regulation.		Maintenance staff likes Ice Slicer, but it is more costly ($58/ton).
MS 9	Michael Solomon	Eisenhower/ Johnson Memorial Tunnels	Sand/salt around the tunnels				Section 9 does not have direct responsibility for any of the roadways. Section 5 is responsible for treating I-70 through the tunnel.

[1] – Personal communication with CDOT Maintenance Supervisors [2] - GPLM = gallons/lane-mile

(Source: CDOT – DTD-R-2001-15, (http://www.coloradodot.info/programs/research/pdfs/2001/deicers.pdf)

3.3.4.5 Iowa DOT Salt Application Rate

Salt Application Rate Guidelines

Prewetted salt @ 12' wide lane (assume 2-hr route)							
Surface Temperature (º Fahrenheit)		**32-30**	**29-27**	**26-24**	**23-21**	**20-18**	**17-15**
lbs of salt to be applied per lane mile	Heavy Frost, Mist, Light Snow	50	75	95	120	140	170
	Drizzle, Medium Snow 1/2" per hour	75	100	120	145	165	200
	Light Rain, Heavy Snow 1" per hour	100	140	182	250	300	350
Prewetted salt @ 12' wide lane (assume 3-hr route)							
Surface Temperature (º Fahrenheit)		**32-30**	**29-27**	**26-24**	**23-21**	**20-18**	**17-15**
lbs of salt to be applied per lane mile	Heavy Frost, Mist, Light Snow	75	115	145	180	210	255
	Drizzle, Medium Snow 1/2" per hour	115	150	180	220	250	300
	Light Rain, Heavy Snow 1" per hour	150	210	275	375	450	525

(Source: Iowa Highway Research Board Technical Report #463, 2007 - http://www.iowadot.gov/operationsresearch/reports/reports_pdf/hr_and_tr/reports/tr471.pdf)

3.3.5 Summary comparison of different protocols

Figure 3.3.4 provides a synthesis of the different material protocols.

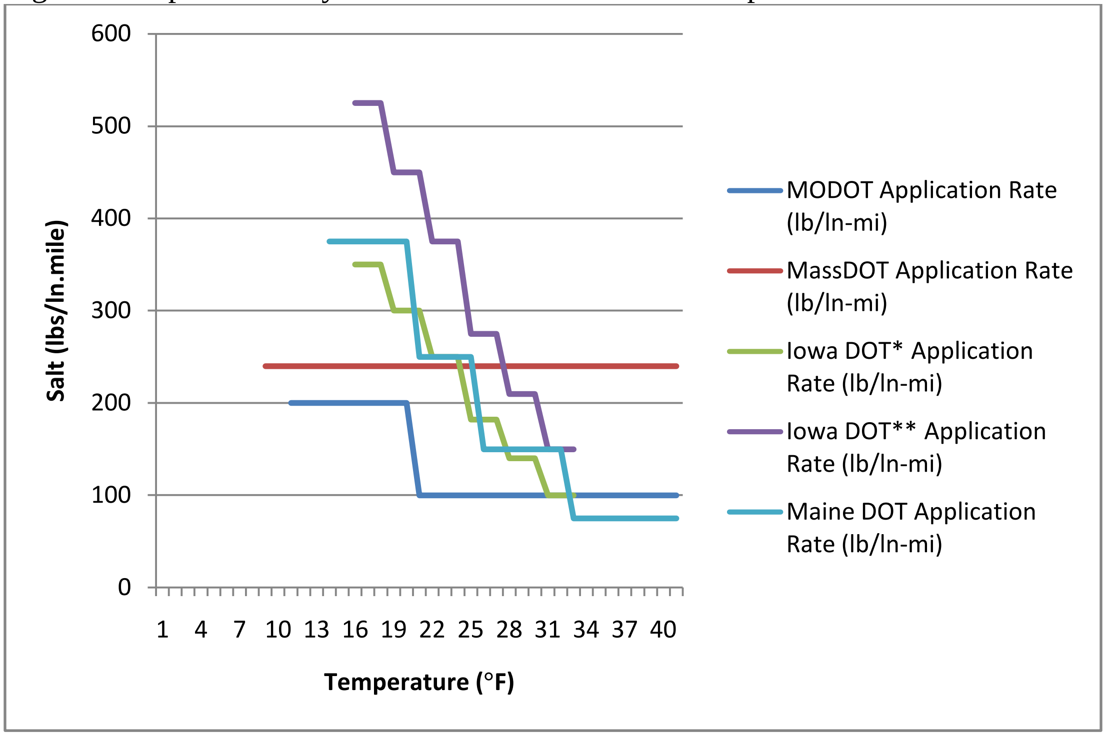


Figure 3.3.4 Comparison of Application Rate at Condition 2

Note: Iowa DOT*: Application Rate for Trucks with 2hr routes
Iowa DOT**: Application Rate for Trucks with 3hr routes

3.4 Recommended MoDOT snow and ice control strategy

The following are the study's recommendations regarding snow and ice control strategy that takes into account the range of different DOT strategies and unique conditions that MoDOT encounters.

3.4.1 Pavement snow and ice conditions

The pavement snow and ice conditions define the type of winter weather event and the type of response needed. The following provides seven different conditions and the corresponding approach to addressing each one.

Condition 7:

Condition of Pavement: All snow and ice are prevented from bonding and accumulating on the road surface. Bare/wet pavement surface is maintained at all times

Weather Environment: Frost, Flurries, Freezing Fog, Drifting Snow & Refreeze

Traffic: No weather-related delays

Condition 6:

Condition of Pavement: Bare/wet pavement surface is the general condition. There are occasional areas having snow or ice accumulations resulting from drifting, sheltering, cold spots, frozen melt-water, etc.

Weather Environment: Moderate Rain, light snow, Ice pellet, and light intensity of sleet

Traffic: Prudent speed reduction

Condition 5:

Condition of Pavement: Accumulations of loose snow or slush ranging up to 2" are found on the pavement surface. Packed and bond snow and ice are not present.

Weather Environment: Dusting to 1'' inch of SNOW/SLEET, (Other Frozen Precipitation), Moderate intensity of sleet, freezing rain

Traffic: Moderate delays

Condition 4:

Condition of Pavement: The pavement surface has continuous stretches of packed snow with or without loose snow on top of the packed snow or ice

Weather Environment: 1'' inch of SNOW, Frozen Precipitation to 6'' inches, and ¼'' inch of ice, heavy intensity of sleet

Traffic: Reduced capacity, reduction traveling speed, the road is passable.

Condition 3:

Condition of Pavement: The pavement surface is completely covered with packed snow and ice that has been treated with abrasives or abrasive/chemical mixtures. There may be loose snow of up to 2" on top of the packed surface.

Weather Environment: Heavy snow, 6'' – 12" inches of SNOW in 24 hrs or ¼'' to ½" inch ice

Traffic: The use of snow tires is required. Chains and/or four-wheel drive may also be required. Traveling speed is significantly reduced and there are general moderate delays with some incidental severe delays. The use of snow tires is required. Chains and/or four-wheel drive may also be required.

Condition 2:

Condition of Pavement: The pavement surface is covered with a significant buildup of packed snow and ice that has not been treated with abrasives or abrasives/chemical mixtures. There may be 2" of loose or wind-transported snow on top of the packed surface due to high snowfall rate and/or wind. There may be deep ruts in the packed snow and ice that may have been treated with chemicals, abrasives, or abrasives/chemical mixtures.

Weather Environment: Blowing Snow, 12'' or greater of SNOW in 24 hrs or ½'' inch ice or greater

Traffic: Not recommend for passing. The use of snow tires is the minimum requirement. Chains and snow tire equipped four-wheel drive are required in these circumstances. Travelers experience severe delays and low travel speeds due to reduced visibility, unplowed loose, or wind-compacted snow, or ruts in the packed snow and ice.

Condition 1:

Condition of Pavement: This may be the result of severe weather (low visibility, etc.) or road conditions (drifting, excessive unplowed snow, avalanche potential or actuality, glare ice, accidents, vehicles stuck on the road, etc.).

Weather Environment: Severe weather

Traffic: The road is temporarily closed.

3.4.2 Strategies and tactics

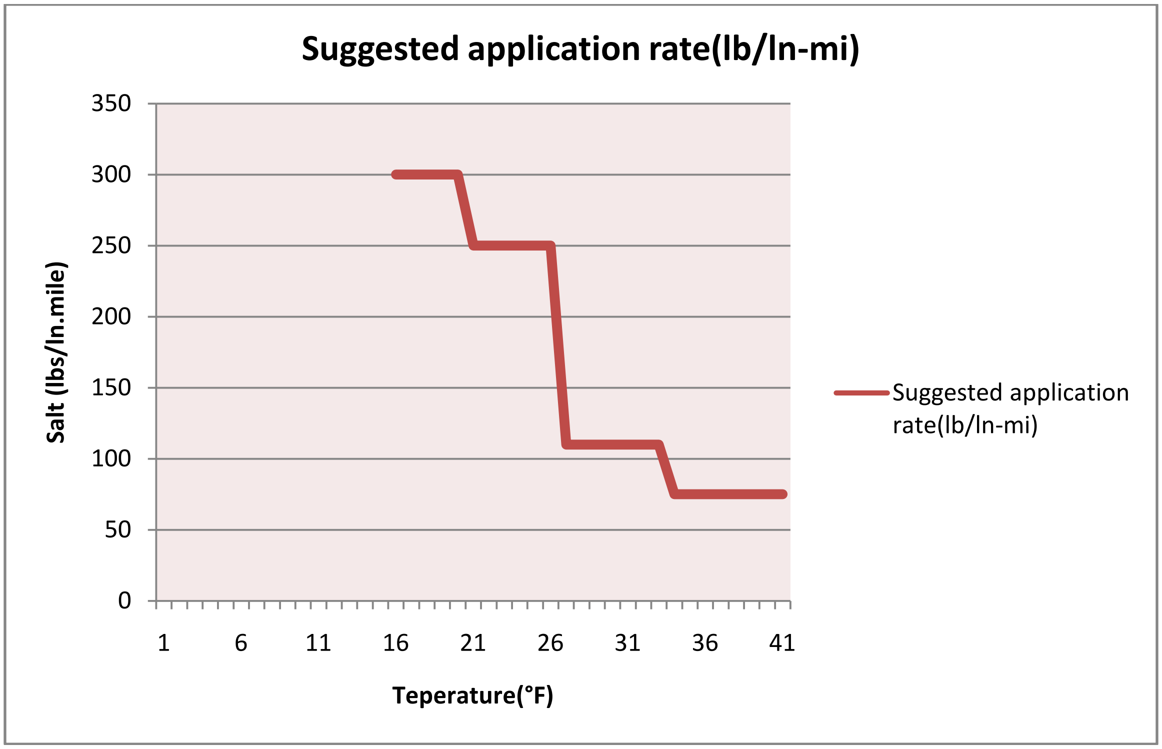
PSIC	Pavement Temperature	AADT	Strategies and Tactics									
			Anti-Icing	Deicing	Mechanical	Mech & Abrasives	Mech & Anti-icing	Mech & Deicing	Mech & Prewetted Abrasives	Anti-icing for Frost / Icing protection	Mech & abrasives containing > 100 lb/LM of chemical	Chemical treatment early, Mech removal during, Deicing at end
	above 32 ^{o}F		X									
	20 - 32 ^{o}F	> 2500	X									
	below 20 ^{o}F			X								
7	above 32 ^{o}F		X									
	20 - 32 ^{o}F	< 2500	X									
	below 20 ^{o}F			X								
	above 32 ^{o}F		X									
	20 - 32 ^{o}F	> 2500	X									
6	below 20 ^{o}F			X								
	above 32 ^{o}F		X									
	20 - 32 ^{o}F	< 2500	X									
	below 20 ^{o}F			X								
	above 32 ^{o}F		X									
	20 - 32 ^{o}F	> 2500					X					
5	below 20 ^{o}F							X				
	above 32 ^{o}F		X									
	20 - 32 ^{o}F	< 2500	X									
	below 20 ^{o}F								X			
	above 32 ^{o}F		X									
	20 - 32 ^{o}F	> 2500					X					
4	below 20 ^{o}F							X				
	above 32 ^{o}F		X									

	20 - 32 ^{o}F	<							X			
	below 20 ^{o}F	2500				X						

			Strategies and Tactics									
PSIC	**Pavement Temperature**	**AADT**	**Anti-Icing**	**Deicing**	**Mechanical**	**Mech & Abrasives**	**Mech & Anti-icing**	**Mech & Deicing**	**Mech & Prewetted Abrasives**	**Anti-icing for Frost / Icing protection**	**Mech & abrasives containing > 100 lb/LM of chemical**	**Chemical treatment early, Mech removal during, Deicing at end**
	above 32 ^{o}F				X							
	20 - 32 ^{o}F	>									X	
	below 20 ^{o}F	2500									X	
3	above 32 ^{o}F				X							
	20 - 32 ^{o}F	<				X						
	below 20 ^{o}F	2500				X						
	above 32 ^{o}F								X			X
	20 - 32 ^{o}F	>								X	X	
2	below 20 ^{o}F	2500								X	X	
	above 32 ^{o}F									X	X	
	20 - 32 ^{o}F	<								X	X	
	below 20 ^{o}F	2500								X	X	
	above 32 ^{o}F								X			X
	20 - 32 ^{o}F	>								X	X	X
1	below 20 ^{o}F	2500								X	X	X
	above 32 ^{o}F									X	X	X
	20 - 32 ^{o}F	<								X	X	X
	below 20 ^{o}F	2500								X	X	X

3.4.3 Materials and Application Rates

According to the literature and the condition scenarios given above, it is recommended that the application rate be based on the condition and the temperature of the pavement as noted in Figure 3.4.1. The application of chemical material is performed in conjunction with plow vehicles to remove the snow and ice from the pavement.



3.5 Equipment for Snow Removal

3.5.1 Existing research

According to the test done by Nixon and Potter (1997), two parameters were detected in the experiments which are scraping effectiveness, and force angle which is based on the blade angle. The scraping effectiveness is defined as the horizontal force experienced by the cutting edge and the $\text{Force Angle} = \tan^{-1}[\frac{\text{Vertical Force}}{\text{Horizontal Force}}]$. Nixon and Potter noted that there are two failure zones – zone 1 and 2 as noted in Figure 3.5.1.

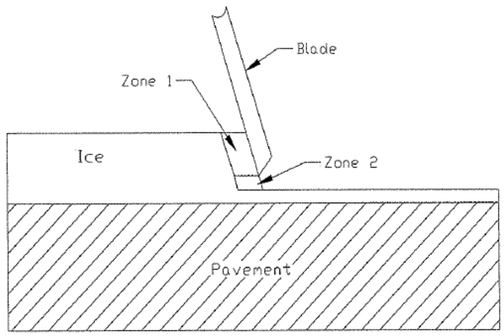


Figure 3.5.1 Blade Forces

Table 3.5.1 provides a detailed comparison of snow plow cutting edges that was conducted by the South Dakota DOT in 1994 (SD89-04X) and Table 3.5.2 provides a summary of common material specifications to tungsten carbon inserts for snowplow blades.

Table 3.5.1 Snow Plow Cutting Edge Comparison

	Plow number Location Plow length/type Surface Plowed	RC093/RC554 Pierre 10' One Way Asphalt	RC089/RC254 Pierre 10' One Way Asph/Conc	RD706 Murdo 12' Rev. Asph/Conc	RD739 Presho 10' Rev. Asph/Conc Concrete	RD721 Sisseton 11' Rev
CAT Without Frontal blade Blade cost/foot $9.86 Usable Height 5" Width 3/4"	Miles Plowed Edge Height Used Plow Length Cost per mile Condition Plowed	620 3.5 10 .111 43% Ice/Snow Covered 36% Dry/Ice 21% variable	554 5 10 .178 43% snow covered 57% ice/snow pack	100 4.375 12 1.035 100% dry to snow cover with finger drifts	259 4 10 .305 *Estimated miles* 100% dry or wet or snow covered 46.2% snow cover/pack/slush	558 4.667 11 .181 53% snow packed/ice
Pacal without Frontal Blade Blade cost/foot $10.91 Useable Height 5" Width 3/4"	Miles Plowed Edge Height Used Plow Length Cost per mile Condition Plowed	528 4.75 10 .196 95.3% snow packed 4.7% snow covered	242 3.375 10 .304 60.3% snow covered 39.7% variable	95 4.4375 12 1.223 100% dry with snow covered areas	176 4.8125 10 .597 27.8% dry to wet with snow cover 72.2% snow cover/pack 100% dry with finger drifts	250 4.0417 11 .388
CAT With 1/2" Frontal Blade Blade cost/foot $16.54 Usable Height 5" Width 3/4"	Miles Plowed Edge Height Used Plow Length Cost per mile Condition Plowed	999 4.875 10 .161 60% Ice/slush 30% wet/slush 10% dry/snow covered	857 5 10 .193 45% ice/snow pack 32% slush 23% snow covered	265 5 12 .749 54.7% dry/snow pack 45.3% snow pack	185 4.5 10 .805 *Estimated miles* 100% dry or wet or snow covered 6% dry/snow cover	810 4.125 11 .185 62% ice snowpack 32% wet/slush
Pacal with 1/2" Frontal Blade Blade Cost/foot $17.59 Usable Height 5" Width 3/4"	Miles Plowed Edge Height Used Plow Length Cost per mile Condition Plowed	907 3.875 10 .150 49% dry/snow pack 24.7% Ice/snow pack 26.3% variable	1323 4 10 .106 48% dry/snow covered 33% snow/slush 19% ice/snow pack	159 4.6875 12 1.245 100% dry to snow covered with finger drifts	426 4.6875 10 .387 40% dry/snow covered 23% dry/slush 37% variable 32.7% snow covered/ice	450 4.7708 11 .410 67.3% dry w/ finger drifts
Kennametal with 1/2" Frontal Blade Blade Cost/foot $24.39 Usable Height 0.635" Width 3/4"	Miles Plowed Edge Height Used Plow Length Cost per mile Condition Plowed	5897 0.635 10 .041 47% dry/snow covered 31% wet/slush 22% ice/snow pack	Incomplete test Plow was sold	917 0.635 12 .319 48% dry/snow covered 20% snow packed 32% variable	1194 0.635 10 .204 57% dry/snow covered 43% snow pack/covered 13% ice/snow covered	6335 0.635 11 .042 65% dry/snow covered 22% slush/snow covered
CPL with 1/2" Frontal Blade Blade cost/foot $47.96 Usable Height 1.5" Width 3/4"	Miles Plowed Edge Height Used Plow Length Cost per mile Condition Plowed	Incomplete test Plow was sold	3765 1.5 10 .127 51% snow/slush 49% snow/ice pack	636 1.5 12 .905 25% slush 33% ice/snow pack 42% dry/snow covered	1226 1.5 10 .337 * 30% dry/snow packed 67% snow covered 3% wet/slush 68% dry/snow covered	2825 1.5 11 .187 32% snow/slush

* Cost/mile based on $41.28 price w/o frontal blade.

(Source: Snow Plow Cutting Edge Cost Effectiveness, South Dakota DOT, SD89-04 Final Report)

Table 3.5.2 Summary of Common Material Specifications for Purchase of Tungsten Carbine Inserts for Snowplow Blades

REQUIREMENT	SPECIFICATION or TEST METHOD	RANGE OF ACCEPTABLE LIMITS
Percent Cobalt Content	Not indicated	11 to 13 percent
Density	ASTM B311 or not indicated	14.1 to 14.6
Hardness	ASTM B294 Rockwell Hardness "A" Scale	87.5 to 89.0 "A" Scale
Transverse Rupture Strength	Not indicated	300,000 to 400,000 psi
Porosity	ASTM B276	A06 B02 C00
Certification		Vendor shall furnish "certification" that carbide inserts meet the required specifications.
Material Source		No recycled or reprocessed carbide may be used.

(Source: ClearRoads, 2010).

3.5.2 Snow Plow Blade Options

There are 5 main alternatives for snow plow blades: carbide-tipped, high carbons-steel, steel blades, rubber and urethane. A study conducted in 1995 compared carbide tipped, rubber and urethane blades to determine if urethane blades could be an alternative to rubber so that pavement markings would experience less degradation during snow removal operations (Roosevelt, 1995). The studies found that urethane blades cleaned the roadway surface better than rubber blades, but are not anymore durable. The rapid disintegration of the blades within a single snow event results in a life-cycle cost for the urethane blades that was 6.5 times greater than that of rubber blades.

	Carbide Blade	**Rubber Blade**	**Urethane Blades**
Labor Cost	22.5	22.5	22.5
Material	100	26	296
Total	122.50 x 1.25 changes/year $153.13	48.50 x 3 changes/year $145.50	
		48.50 x 5 changes/year $242.50	318.50 x 5 changes/year $1,592.50

Roosevelt, D. S., 1995,Evaluation of Urethane Snow Plow Blades as an Alternative to Rubber Blades, Virginia Transportation Research Council (VTRC 96-R2), (http://www.virginiadot.org/vtrc/main/online_reports/pdf/96-r2.pdf).

3.5.3 Carbide Inserts

Tables 3.5.2 provides the results of a study on the application of carbine insert snowplow blades.

Table 3.5.2 Factors Affecting Carbide Insert Snowplow Blade Wear and Fracturing

CATEGORY	FACTOR	COMMENT/ASSUMPTIONS
Blade Material Composition and Specifications	Carbide insert: Density Porosity Hardness Grain Size Impact Resistance Brittleness Fracture Toughness	*Some or all may relate to wear resistance (or rate of wear) and the degree that carbide inserts extend the service life over that of regular or hardened steel blades.*
	Steel blade material: Tensile strength Yield strength Percent of elongation Chemical Analysis	*The degree of fracture is related to the strength of the steel substructure holding the insert.*
Blade Attributes	Degree or amount of fracture	*Fracturing reduces the surface area touching the road surface, expediting the rate of wear.*
	Design of blade with insert: Brazing method Manufacturing Temperature	*The better the connection at the interface of the insert and the substructure, the less fracturing.* *The manufacturing temperature may affect the connection.*
	Back blade, presence/absence: Rigidity Wearing capability Thickness of blade	*The presence of a back up blade adds to the surface area wearing on the roadway as well as providing a higher resistance to fracture of carbide insert.*

CATEGORY	FACTOR	COMMENT/ASSUMPTIONS
Blade Configuration In Relation To Pavement Surface	Surface area touching the pavement surface	*The greater the surface area on the road, the slower the rate of wear*
	Down pressure of plow: Weight of plow Hydraulic down pressure Fulcrum of hitch (distance pivot point to blade)	*The greater the pressure of the blade against the road, the greater the friction and the greater the impact causing fracture.* *Surface area touching the pavement surface determines the pressure per square inch.*
	Vertical angle to pavement surface	*Theoretically, "scraping of ice" causes more wear to the blade then "slicing ice off"*
	Horizontal angle to road centerline	*The greater the angle from "bulldozing position", the less the impact to obstructions and high spots on the pavement*
	Reversible Plow vs. One-way	*Wear varies from leading edge of blade compared to middle as compared to trailing edge.* *Can assume reversible plows have consistent angles due to operators reversing to full stops (except when" bulldozing").*
Pavement Surface Properties	Pavement material type: Concrete Bituminous Gravel	*It is common knowledge that concrete wears blades out faster than bituminous, especially the first two to three years of new concrete pavement* *Exposure to gravel shoulders can wear the steel portion of the blade, thus increasing risk of carbide inserts fracturing or falling out..*
	Oil on surface	*Although slight, oil could serve as lubricant, extending service life.*
	Pavement rutting	*The greater the rutting, the less surface of the blade is on the pavement and the faster the rate of wear on the portion of the blade in contact with the surface.*
	Skid resistance	*Relates to presence of sharp and asperities properties on the surface; The higher the skid resistance, the higher the abrasive qualities of the pavement, thus expediting wear.*
	Obstruction on road surface: Raised manhole Raised pavement markers Bridge expansion joints Raised pavement panels Raised shoulders	*Presence or absence of obstruction relate to fracturing; fracturing relates to surface area subject to wear; reduced surface area leads to more rapid wear.*

CATEGORY	FACTOR	COMMENT/ASSUMPTIONS
Blade Configuration In Relation To Pavement Surface	Surface area touching the pavement surface	*The greater the surface area on the road, the slower the rate of wear*
	Down pressure of plow: Weight of plow Hydraulic down pressure Fulcrum of hitch (distance pivot point to blade)	*The greater the pressure of the blade against the road, the greater the friction and the greater the impact causing fracture.* *Surface area touching the pavement surface determines the pressure per square inch.*
	Vertical angle to pavement surface	*Theoretically, "scraping of ice" causes more wear to the blade then "slicing ice off"*
	Horizontal angle to road centerline	*The greater the angle from "bulldozing position", the less the impact to obstructions and high spots on the pavement*
	Reversible Plow vs. One-way	*Wear varies from leading edge of blade compared to middle as compared to trailing edge.* *Can assume reversible plows have consistent angles due to operators reversing to full stops (except when" bulldozing").*
Pavement Surface Properties	Pavement material type: Concrete Bituminous Gravel	*It is common knowledge that concrete wears blades out faster than bituminous, especially the first two to three years of new concrete pavement* *Exposure to gravel shoulders can wear the steel portion of the blade, thus increasing risk of carbide inserts fracturing or falling out..*
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	Skid resistance	*Relates to presence of sharp and asperities properties on the surface; The higher the skid resistance, the higher the abrasive qualities of the pavement, thus expediting wear.*
	Obstruction on road surface: Raised manhole Raised pavement markers Bridge expansion joints Raised pavement panels Raised shoulders	*Presence or absence of obstruction relate to fracturing; fracturing relates to surface area subject to wear; reduced surface area leads to more rapid wear.*

CATEGORY	FACTOR	COMMENT/ASSUMPTIONS
Operational Issues	Distance plowed (plow in down position)	*Obviously, wearing only occurs in "plow down" position, not during total plowing distance, which is what operators normally record/report in accomplishment reporting.* *Note that some operators are known to keep plow down even when plowing is not necessary, thus causing unnecessary wear and shortened service life, unrelated to quality of the blade itself.*
	Speed of plowing	*The faster the plowing speeds, the higher the impact to obstruction and skid resistance.*
	Impact of blade lowered onto pavement: Dropped Gradual, more gentle	*The greater the impact of the plow being placed on and off the pavement, the greater chance of fracturing.*
Operating Temperature	Air temperature Surface temperature Carbide Insert temperature	*The lower the temperature of carbide inserts, the higher the brittleness.* *Low air and surface temperature will lower carbide insert temperature.* *Friction can raise temperature of carbide insert to a higher level than air and surface.*
Snow & Ice Characteristics	Material being plowed: Snow Loose vs compacted Ice Black Ice Slush	*Rate of wear would depend on whether water is in form of liquid, loose snow, compacted snow, ice, black ice, etc* *Slush means presence of liquid water which serves as a lubricant, reducing wear.* *Slush and heavy snow are "harder to push" but this probably does not relate to blade wear, except when vertical blade angle to pavement deviates from 90 degrees.* *Heavy snow, black ice and regular ice need to be scrapped off, perhaps affecting wear.* *Slush and loose snow lead to blade having more contact with the abrasive pavement surface.*
	Anti-icing vs de-icing mode	*Anti-icing lead to less ice to remove, thus more wear (increase friction surface).*
	Density of snow: Natural Compaction wind Compacted by traffic	*Harder snow is harder to remove and causes more wear than soft fluffy snow.* *Traffic compacted snow can become as hard on blades wear as solid ice.*

CATEGORY	FACTOR	COMMENT/ASSUMPTIONS
Snow & Ice Materials	Abrasives: Sand (natural) Sand (recycled) Grit (crushed)	*Presence or absence may relate to rate of wear.* *Gradation of sand/grit may be a factor.* *Loose sand as opposed to sand imbedded in ice or compacted snow may be a factor.* *Recycled sand (like from street sweepings) has reduced abrasive power.*
	Chemicals: Corrosive salts Less corrosive alternatives	*Corrosive materials may cause surface corrosion, but probably insignificant to rate of wear.* *Chemicals melt snow & ice into liquid, which is a lubricant, thus affecting rate of wear.*

(Source: ClearRoads, 2010).

3.5.4 JOMA Blades VS Steel Blades

In 2010, the Ohio Department of Transportation conducted a research study in order to evaluate JOMA blades and compare them with traditional steel blades (JOMA Plow Blade Evaluation, Ohio Dept of Transportation, June 28, 2010).
The "JOMA 6000" is a snow plow blade that utilizes carbine inserts that are brazed into a segmented steel blade that is finally encapsulated in rubber. There have been a wide range of benefits of JOMA blades mentioned in the literature, including:

- No metal-to-metal contact causing a shock-absorbing function between the road, plow and drivers.
- Reduced noise and vibration which improves driver experience and can reduce truck maintenance.
- More effective cleaning due to blade conforming to contour of road.. a "squeegee effect".
- Reduced removal of pavement markings.
- Easier maintenance due to lighter weight blade sections. Potentially less blade change time.

3.5.4.1 JOMA Blade Experience

There are several reports of using JOMA blades over the past 5-6 years. The following summarizes their findings.

Lake County (ODOT) – 16 trucks with JOMA Blades (2006-2008) vs. Steel Blades (2000-2005)

	Steel Blades	JOMA Blades	Difference
plowing miles before maintenance	1000 - 1500	6000	4X more miles
average repair time (hr/yr)	58.5	8.5	7X less time

Franklin County Engineering's Office Experience with 16 trucks with JOMA blades (2006-2008)

	Steel Blades	JOMA Blades	Difference
# blade changes (# changes/# trucks)	44 changes / 17 trucks = 2.6	8 changes / 16 trucks = 0.5	5X less changes

Pennsylvania Department of Transportation Experience with JOMA Blades
PADOT found a material cost saving (excluding labor) due to using JOMA blades of $1025 when comparing an 11' traditional carbide blade with an 11' JOMA blade. This assumes that a normal winter would require 3 sets of carbine blades or 1 set of JOMA blades.
And in the research, some other feedback from the company is also analyzed. Generally speaking, JOMA has more advantages comparing with the traditional blades from the experience of other companies and organizations.

Cost versus Life Cycle
One of the most important factors for choosing blades is the cost. The Ohio DOT performed a cost comparison between JOMA and traditional blades, which can then be combined with the lifecycle experience of several DOTs and the other more intangible benefits.

Cost Comparison (based on 2009/2010 pricing)

	JOMA Blades (3*4')	**Regular Blades (12')**	**Hardened Blades w/ guards (12')**
Cost ($)	$556*3=$1668	$133 (13X less)	$440 (4X less)

Based on this comparison, the cost of a JOMA blade is obviously higher that for traditional blades. But JOMA blades have a longer useful life.

Life Cycle

	JOMA Blades	**Regular Blades**	**Difference**
Utah DOT	116 hours	21 hours	6X longer
Iowa DOT	6	1	6X longer
Penn DOT	3000 miles	650 miles	5X longer
Lake County ODOT	4	1	4X longer
Franklin County	5	1	5X longer

3.5.4.2 Benefit / Cost Summary

- JOMA blades last 4-6X longer
- JOMA blades require less blade, and potentially truck, maintenance
- JOMA blades reduce pavement marking repairs
- JOMA blades provide a cleaner road

- JOMA blades provide a better driver ride experience
- JOMA blades cost between 4-13X more than regular blades

A similar list of cost and benefits was presented by Tatkenhorst [2009] with respect to rubber blades in general:

Advantages: quieter, easier on chip seals, less vibration, fits contour of road, Squeegee-type effect, 5 to 7 times life of steel, increased in productivity, reduced plow weld failures, kinder to pavement markings, require less de-icing material, light weight for easy installation, less down-time for blade changes, reduced plow damage from road hazards
Disadvantages: high initial cost, difficult to cut snow pack, can get caught in bridge expansion joints

3.5.5 Kuper Tuca Composite Blades versus Standard Carbide-Insert Blades

MaineDOT started evaluating composite plow blades in the winter of 2006-2007. They evaluated the Kuper Tuca SX blade which is manufactured in Germany**.** The blade consists of tungsten carbide inserts that are vulcanized in rubber and then laminated between steel. The manufacturer claims that the cutting edges reduce vibration, minimize noise, reduce fuel consumption and provide extended blade life over standard cutting edges.

For the 2008-2009 winter season, two sets of the Tuca SX blades were compared to seven sets of standard carbide-insert edges and four sets of carbide insert underbody blades that were worn to termination (all from Valk Manufacturing Company, New Kingston, PA) (Technical Brief 09 – 03). One of the two sets of composite blades was damaged from an impact with a bridge expansion joint and the second set had some wear life remaining at the end of the 2008-2009 winter season. To complete the study, in the winter of 2009-2010, the MaineDOT experimented with three sets of the Kuper – Tuca SX36 blades (Technical Brief 10 – 02). Comparisons were made using the data collected for the standard carbide plow blades from the 2008-2009 evaluation.

3.5.5.1 Results

3.5.5.1.1 Standard Carbide-Insert Cutting Edges

Seven sets of standard carbide-insert blades were evaluated and lasted an average of 1, 933 miles. Blades on secondary roadways had an average of 2,124 miles, blades on interstate roadways had an average of 1,711 miles. Factors such as speed, frequency of scraping nearly bare pavement and road surface conditions were cited as the reason for difference between secondary and interstate route length. The 11 foot blades cost $531.52, resulting in an overall, average cost per mile of $0.28.

3.5.5.1.2 Carbide-Insert Underbody Scraper Cutting Edges

Four sets of carbide-insert underbody blades were evaluated and lasted an average of 2,558 miles. On secondary roadways the underbody blades averaged 3,611 miles, however, one of those sets lasted a reported 5,021 miles. The two sets used on the Interstate routes lasted an average of 1,505 miles. The 11 foot underbody blades cost $569.03, therefore, the average overall per mile cost for the underbody blades was $0.33 (adjusted for the outlier).

3.5.5.1.3 Tuca SX Composite Cutting Edges

For the 2007-2008 winter season no mileage was collected, but it was observed that the set of composite blades lasted three times as long as conventional carbide-insert cutting edges. Based on these results the evaluation of Tuca blades was continued in 2008-2009. Two sets of Tuca SX cutting edges were installed in January 2009 and cost per mile calculations were based on a quoted price of $1,134.00 per blade.

When the winter season ended in early March 2009, one set of the composite blades had plowed 3,324 miles with some wear life remaining. Using the actual miles plowed the cost per mile was $0.34. The manufacturer indicates that perhaps as much as 50 percent more life remained on the Tuca SX blades. The second set of blades was removed from the truck because of damage sustained from an impact with a bridge expansion joint. At the point they were removed the blades had been used for 2,248 miles.

The Maine DOT operators commented on the quietness of the Tuca SX blades. Therefore, in order to validate how much quieter the Tuca SX blades are compared to standard carbide blades an inside truck cab noise test was conducted. Plows were run at 25 miles per hour on bare, dry pavement in both the up and down positions, then sound readings were compared. Decibel levels increased 3.85% when using the standard carbide blades and by 0.65% with the Tuca SX blades. Drivers also indicated that the experimental blades seemed to clear and scrape the road as well as standard blades.

In 2009-2010 Tuca SX blades were installed on two different routes. The first set of blades was used on a two lane road considered to be in fair to good condition. These blades were worn to termination and removed from service with a total distance plowed of 1,239 miles. Excessive wear on the left end of the plow may have indicated that the crown of the road played caused the early failure. The second set of blades were utilized on an interstate route. Once again, the early end to the winter season did not allow the blades to be worn to termination, but they had 1,408 miles of service recorded. It was estimated that the blades had approximately one half of their life remaining. This year there was a mixed opinion concerning whether the blades cleaned the road as well as standard blades. It was felt that Kuper blades are better suited to roadways in good condition and that they are more susceptible to impact damage than the standard carbide blade.

3.5.5.3 Conclusions

This study of Kuper Tuca SX36 plow blades was hindered by two factors: a small sample size and short winter seasons. However, based on the data collected between 2007 through 2009, and assuming the interstate roadway blade set had approximately 50% of its life remaining, the Tuca SX36 plow blade provides an estimated wear life of 3,500 to 4,500 miles. Compared to the average wear life of 1,500 to 2,000 miles for a set of standard carbide blades, the Tuca SX last 2.25 times as long as a standard blade. Since the cost of a set of standard carbide blades is $352.99 compared to $1,134 per set for Tuca SX blades, the Tuca would have to last at least 3.5 times as long as the standard blade to be cost effective. Therefore, Maine DOT based on their four year evaluation concluded that the Kuper Tuca SX36 plow blade does not provide a cost effective alternative to standard carbide blades.

3.5.6 Recommendations for selecting snow removal equipment

The following consists of seven different check lists of factors to consider when selecting snow removal equipment.

3.5.6.1 Checklist for trucks

- Hydraulic system
- Gear ratios in transmission
- Single or double axle
- 2 or 4 –wheel drive
- Gross weight
- Mirrors (heated) and lighting package for snow plowing
- Frame (particularly if using wing plows)
- Gear ration in rear differential
- Electrical system
- Tires and rims
- Axle weight rating
- Suspension system
- Cold and wet weather operation
- Diagnostic and information systems
- Engine horsepower
- Corrosion protection
- Automatic or manual transmission
- Power windows
- Comfortable, adjustable driver's seat
- Quality heaters and defoggers
- Heated wiper blades
- Heated windshields
- Ergonomic cab features and controllers
- Wiper blade vibrators

3.5.6.2 Checklist for wheel loaders

- Reach
- Capacity
- Cold and wet weather operation
- 2 or 4- wheel drive
- Transmission type
- Attachment capability
- Articulation or straight frame
- Electrical system
- Weight and horsepower
- Power takeoff

3.5.6.3 Checklist for material spreaders

- Type - liquid, granular or combination
- Ground speed control
- Capacity
- Spread containment system
- Application rate and speed ranges
- Pre-wetting capability and method
- Uniformity of application rate & speed ranges
- Tie-down/connect/disconnect requirements
- Transverse spread pattern capability
- Lights & airfoils (if applicable)
- Zero velocity
- Hopper insert or bed
- Front, side, or tailgate applications
- Side, tailgate or insert prewet tanks
- Belt, chain, or auger system
- Stainless steel construction
- Offloading capability and ease of cleaning
- Liquid/solid mix ratio capability
- Spread data and download capabilities
- Ease of calibration

3.5.6.4 Checklist for liquid anti-icing equipment

- Tailgate tank
- Side mount
- Hopper tanks
- Prewetting support
- Trailer mount
- Tanker truck
- Nozzle type
- Discharge pattern and controls
- Overspray protection
- Low to high application flow rate
- Ground speed control
- Poly or steel tank
- Frame mount or slide in
- Off-truck storage method
- Multiple tanks for different liquids Off season usage
- Spread data and download capabilities
- Ease of calibration
- Ease of cleaning

3.5.6.5 Checklist for plows

- Length
- Tripping mechanism
- Type (reversible, one way, "V")
- Height and location of wing mount
- Hitching mechanism
- Vertical and horizontal angle adjustments
- Moldboard material, thickness, reinforcing
- Cutting edge composition (steel, carbide insert, rubber, etc.)
- Height & geometry [1 (SHRP H-206)]
- Shoes (if required)
- Laser guidance
- Underbody
- Type/brand of plow controls
- Hydraulic extension and variable shape of Tow plow
- Weight loading on truck
- Hydraulic down pressure and weight management system
- Ease and speed for cutting edge replacement o Casting distance

3.5.6.6 Checklist for snow blowers

- Production rate
- Protection systems
- Number of steering axles
- Electrical system
- Safety systems
- Chute configuration(s) and height
- Number of drive axles
- Casting distance
- Horsepower
- Road speed
- One or two engines or One or two stage
- Drive system
- Speed control

3.5.6.7 Checklist for snow sweepers

- Capacity (for discharge)
- Personnel protection systems
- Dump configuration
- Pressurized cab, air filtration/conditioning
- Operating speed of sweeping path width
- Transmission and drive mechanisms
- Broom bristle characteristic
- Dust control systems

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Chapter 4: Solution Methodology and Algorithm Implementation

The goal of our approach to the winter maintenance problem is to provide frequent service satisfying the target cycle times with a smaller number of trucks, if possible. We achieve this goal through initial route construction and the nested iterations of route improvement procedures until a better solution cannot be found. Each procedure is described in the following sections, and the implementation of the complete algorithm is given afterwards.

4.1 Solution Methodology

Since the service for the roadways must be provided according to priority rather than geography, route construction is performed separately for each class of roadways in each sector. This is done by creating four subnetworks per sector from the existing transportation network. Note that it may be necessary to add additional arcs from the other classes to each subnetwork to make it strongly connected. The original arcs are treated as service arcs for the purpose of routing, while any arcs added for connectivity are considered deadhead arcs for that subnetwork.

The initial routes are constructed based on the route-first, cluster-second method suggested by Marks and Stricker (1971) that includes additional constraints. In this approach, the CPT for a given subnetwork is determined first, and then the resulting tour is partitioned into routes based on operational constraints such as vehicle capacity and service frequency.

At the first construction of initial routes, the CPT is simply divided into feasible routes. This generates an upper bound of the number of feasible routes needed to serve the network. In subsequent iterations, some initial routes are combined to create one route, which reduces the number of total routes. This may cause initial routes to be infeasible, but they often become feasible after the solution improvement phase. The iterative process, which gradually reduces the number of total routes, stops when the final routes after solution improvement are still infeasible.

The solution improvement procedure attempts to improve the quality of initial routes. The procedure uses two heuristics: 1) one arc-position movement, and 2) one arc-position exchange. The arc movement heuristic removes a set of arcs in the same location, and then inserts them into other positions. The arc exchange heuristic attempts moves among multiple routes, where one arc position is removed from each route, and then inserted into the best position within the other respective route. The arc movement is more flexible, in that it can move one arc at a time while the arc exchange algorithm is forced to move at least two arcs. As the distance and duration of a route approach their maximum limits, it becomes less likely that there is enough capacity to add an additional arc. Exchanging arcs frees up enough capacity to make a move, which was not feasible in the movement algorithm.

These are similar to one arc movement and exchange heuristics in a single-depot problem by Qaio (1999), but in our multi-depot application, a set of arcs located in the same position sharing the same two end nodes, might need to be moved simultaneously because of the sector requirement. For example, consider a segment of four-lane roadway connecting nodes A and B. This segment is considered as four arcs with two heading west and the other two heading east in our network, and they should belong to the same sector because these four arcs are placed in the same location. Thus, our algorithm must move four arcs simultaneously if they are moved to another sector.

The heuristics only allow moves that improve the route time without further violating operational constraints. That is, the moves must decrease the route time of the routes involved. In addition, both the truck capacity constraint and the cycle time constraint should either be met or improved.

During our iterative process, the arc movement heuristic is first applied recursively, until no further improvement is found. Then, the arc exchange heuristic is applied recursively, until no further improvement exists. The loop of these two algorithms is repeated, first for intra-sector improvement and next for inter-sector improvement, until no more improvement can be found. Moves within the same sector improve the route design, while moves between different sectors improve both route and sector designs.

As an illustrative example, the subroutine of the one arc-position movement between two sectors is given below. The movement within a sector is a special case with the parameter $f_a = 1$ in the subroutine. The arc exchange subroutine can be constructed similarly. These subroutines are applied repeatedly in the heuristic to find a better solution. In the subroutine, a service arc represents an arc that is actually served through spreading and plowing operations while a deadhead arc is used to connect service arcs. Assume that $T(R)$ and $D(R)$ compute the route time and the spreading and plowing distance of route *R*, respectively.

Step 1.0: Let S_1 and S_2 be the collection of routes of the same class in two different sectors and let *t* and *d* be the maximum route time and service distance of a feasible route in the given class, respectively.

Step 1.1: Select a service arc a_1 in a route in S_1, and let $\{a_1, a_2, \ldots, a_{f_a}\}$ be the collection of service arcs that share the same end nodes with a_1, where f_a represents the number of service arcs (i.e., lanes of a roadway).

Step 1.2: Suppose that $a_i, 1 \le i \le f_a$, is a service arc of route R_i. Note that routes R_i and R_j can be the same for $i \neq j$. Replace a_i with deadhead arc(s) and call the new route $\tilde{R}_i$.

Step 2.1: Select a route in S_2. Call it Q_i and find the best location to insert a_i. Note that deadhead arcs may need to be added to make Q_i connected. Call the resulting route $\tilde{Q}_i$.

Step 2.2: If none of the following four statements is true, go to **Step 2.3**. Otherwise, select a new route in S_2 and go to **Step 2.1**. If all the routes in S_2 were tested, go to **Step 3.1**.

(1) $T(Q_i) \le t$ and $T(\tilde{Q}_i) > t$,

(2) $T(Q_i) > t$ and $T(\tilde{Q}_i) > T(Q_i)$,

(3) $D(Q_i) \le d$ and $D(\tilde{Q}_i) > d$, and

(4) $D(Q_i) > d$ and $D(\tilde{Q}_i) > D(Q_i)$.

Step 2.3: If $i = f_a$ continue. Otherwise, Set $i = i + 1$ and go to **Step 1.2**.

Step 2.4: If $\max_{1\le i\le f_a}\{T(\tilde{R}_i),T(\tilde{Q}_i)\} < \max_{1\le i\le f_a}\{T(R_i),T(Q_i)\}$, accept $\tilde{R}_i$ and $\tilde{Q}_i$, $1 \le i \le f_a$, as new routes in S_1 and S_2, respectively.

Step 3.1: Select a new service arc in S_1 and go to **Step 1.1**. If the iterations of this step do not find routes with smaller route times, stop.

4.2 Algorithm Implementation

In this section, we show step by step procedures implemented in this project using a sample scenario.

4.2.1 Service Hierarchy

The service hierarchy is defined for the roadways based on their historical average daily traffic (ADT). There are two levels of service hierarchy. Continuous Operation and Non-Continuous Operation roadways are determined by the following ADT standards:

Class	**ADT**
Continuous Operation (CO)	ADT>2500
Non-Continuous Operation (NCO)	ADT<2500

Table 4.2.1 Service Hierarchy Parameters

Based on the given service hierarchy, the original data set in one county is divided into two classes.

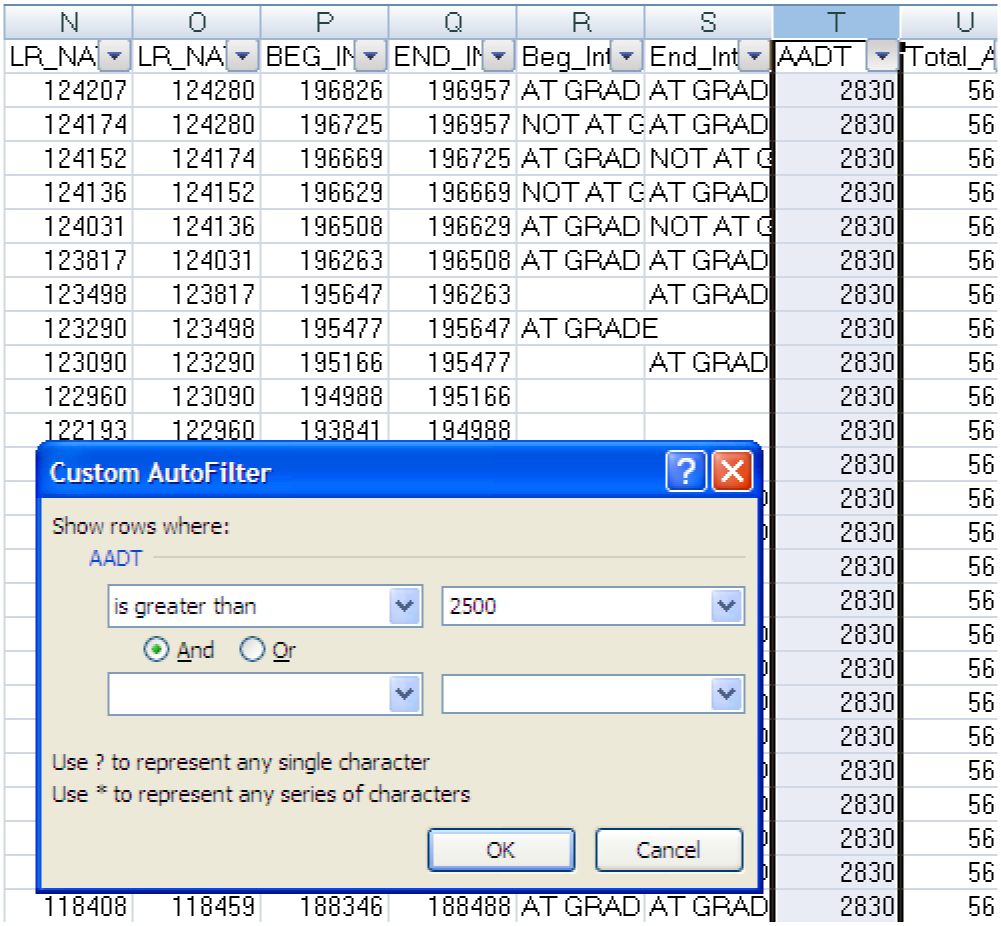


Figure 4.2.1 Classification of Roadways

4.2.2 Road Map

According to the classified data file, the longitudes and altitudes of the node points are used to graph all the nodes in one county.

U	V	W	X	Y
Total_AAI	Speed_L	Beg_Node_xy	End_Node_xy	Number_l
5660	70	-92.78248213,38.93547508	-92.77691358,38.93504149	1
5660	70	-92.77641789,38.93557727	-92.77691358,38.93504149	1
5660	70	-92.77629782,38.93569456	-92.77641789,38.93557727	1
5660	70	-92.77620642,38.93578162	-92.77629782,38.93569456	1
5660	50	-92.77562501,38.93641423	-92.77620642,38.93578162	1
5660	50	-92.77433941,38.93767868	-92.77562501,38.93641423	1
5660	50	-92.77270037,38.93944435	-92.77433941,38.93767868	1
5660	50	-92.77186022,38.9406535	-92.77270037,38.93944435	1
5660	50	-92.77126973,38.94216597	-92.77186022,38.9406535	1
5660	50	-92.77106498,38.94295864	-92.77126973,38.94216597	1
5660	50	-92.76972184,38.94781299	-92.77106498,38.94295864	1
5660	50	-92.76889615,38.94895759	-92.76972184,38.94781299	1
5660	50	-92.76700003,38.95079867	-92.76889615,38.94895759	1
5660	50	-92.76354585,38.9539211	-92.76700003,38.95079867	1
5660	50	-92.76109276,38.95611112	-92.76354585,38.9539211	1
5660	50	-92.75611789,38.96165702	-92.76109276,38.95611112	1
5660	40	-92.75513264,38.96256379	-92.75611789,38.96165702	1
5660	40	-92.75259043,38.96469295	-92.75513264,38.96256379	1
5660	40	-92.74922046,38.96667129	-92.75259043,38.96469295	1
5660	30	-92.74818372,38.96684472	-92.74922046,38.96667129	1
5660	30	-92.74762589,38.96695102	-92.74818372,38.96684472	1
5660	30	-92.74702306,38.96704922	-92.74762589,38.96695102	1
5660	30	-92.74464721,38.96747016	-92.74702306,38.96704922	1

Figure 4.2.2 Longitude and Altitude Data

The road junction points in the node map are selected and numbered. Then, the road map is drawn using straight lines to represent the road between two junction points.

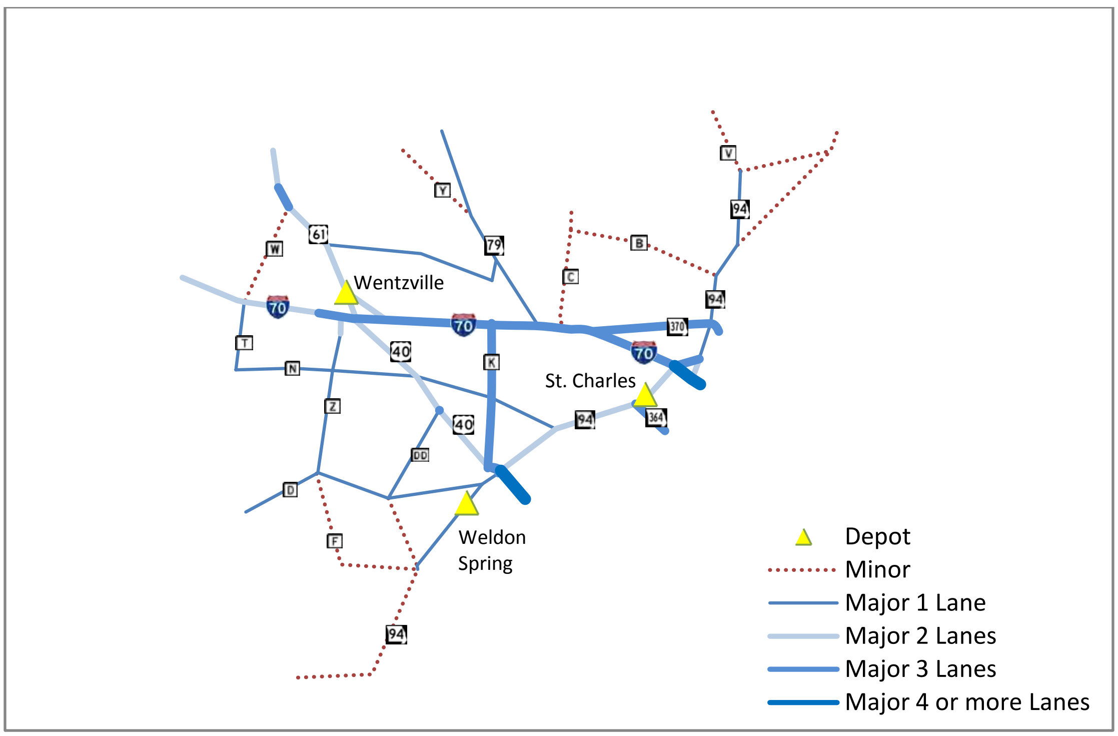


Figure 4.2.3 Road Map

4.2.3 Data Formulation

The original node information data (Excel files) are formulated into network information data (Text file), so that it can be used in the computer programs.

# ID	Alpha ID	From	To	Centerline miles	Service Time (min)	Road / Direction	Class
1, 2	50W01	1	2	1.161	1.7415	50W	A1
2, 3	50W02	2	3	1.42	2.13	50W	A1
3, 4	50W03	3	4	4.101	6.1515	50W	A1
4, 51	50W04	4	51	2.86	4.29	50W	A1
4, 51	50W05	4	51	2.86	4.29	50W	A1
51, 5	50W06	51	5	2.46	3.69	50W	A1
51, 5	50W07	51	5	2.46	3.69	50W	A1
5, 10	179S01	5	10	3.014	4.521	179S	A1
5, 12	179S02	5	12	2.338	3.507	179S	A1
12, 13	CW01	12	13	1.626	2.439	CW	A1
12, 14	179S03	12	14	1.064	1.596	179S	A1
14, 15	BS01	14	15	4.678	7.017	BS	A1
14, 16	54W01	14	16	1.899	2.8485	54W	A1
14, 16	54W02	14	16	1.899	2.8485	54W	A1
16, 17	54W03	16	17	2.098	3.147	54W	A1

Figure 4.2.4 Network Information Data (Excel file)

```
File  Edit  Format  View  Help
"1,2"    50w01   1    2    1.161   1.7415   50w    A1
"2,3"    50w02   2    3    1.42    2.13     50w    A1
"3,4"    50w03   3    4    4.101   6.1515   50w    A1
"4,51"   50w04   4    51   2.86    4.29     50w    A1
"4,51"   50w05   4    51   2.86    4.29     50w    A1
"51,5"   50w06   51   5    2.46    3.69     50w    A1
"51,5"   50w07   51   5    2.46    3.69     50w    A1
"5,10"   179s01  5    10   3.014   4.521    179s   A1
"5,12"   179s02  5    12   2.338   3.507    179s   A1
"12,13"  cw01    12   13   1.626   2.439    cw     A1
"12,14"  179s03  12   14   1.064   1.596    179s   A1
"14,15"  bs01    14   15   4.678   7.017    bs     A1
"14,16"  54w01   14   16   1.899   2.8485   54w    A1
"14,16"  54w02   14   16   1.899   2.8485   54w    A1
"16,17"  54w03   16   17   2.098   3.147    54w    A1
"16,17"  54w04   16   17   2.098   3.147    54w    A1
"17,18"  54w05   17   18   3.157   4.7355   54w    A1
```

Figure 4.2.5 Network Information Data (Text file)

4.2.4 Program Running Procedure

We use jGRASP to run the Java programs. jGRASP can be downloaded from the following website: http://www.jgrasp.org/. The typical interface of jGRASP is shown in Figure 4.2.6. It takes six steps to get the recommended routes.

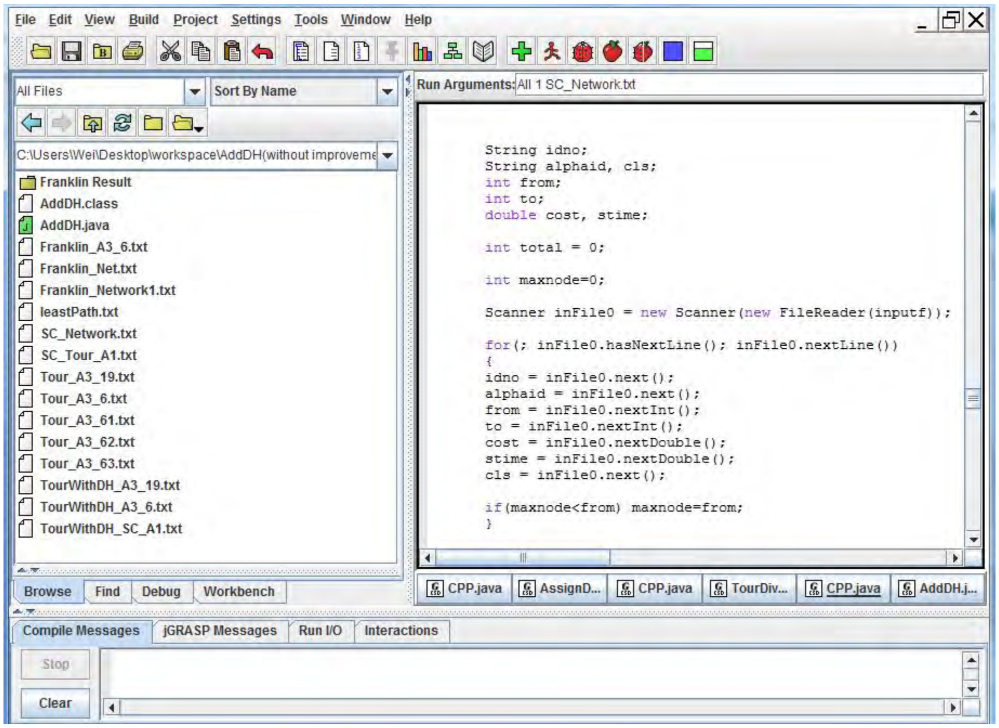


Figure 4.2.6 jGRASP Interface

Step 1: Run CPP.java to get the LeastNtime.txt and LeastDistance.txt;

To run a Java program with jGRASP, both Java program (.java) and data (.txt) files need to be placed in the same folder. For example, both "CPP.java" and "Network.txt" are placed in the same folder. We run "CPP.java" by the following argument: "All 1 Network.txt". Figure 4.2.7 shows the interface of running "CPP.java". After running "CPP.java", we get a file "leastCost.txt" in the same folder, which contains the information of the shortest distance between any two nodes in map. We change the name of the "leastCost.txt" file to "LeastDistance.txt" and generate the "leastNTime.txt".

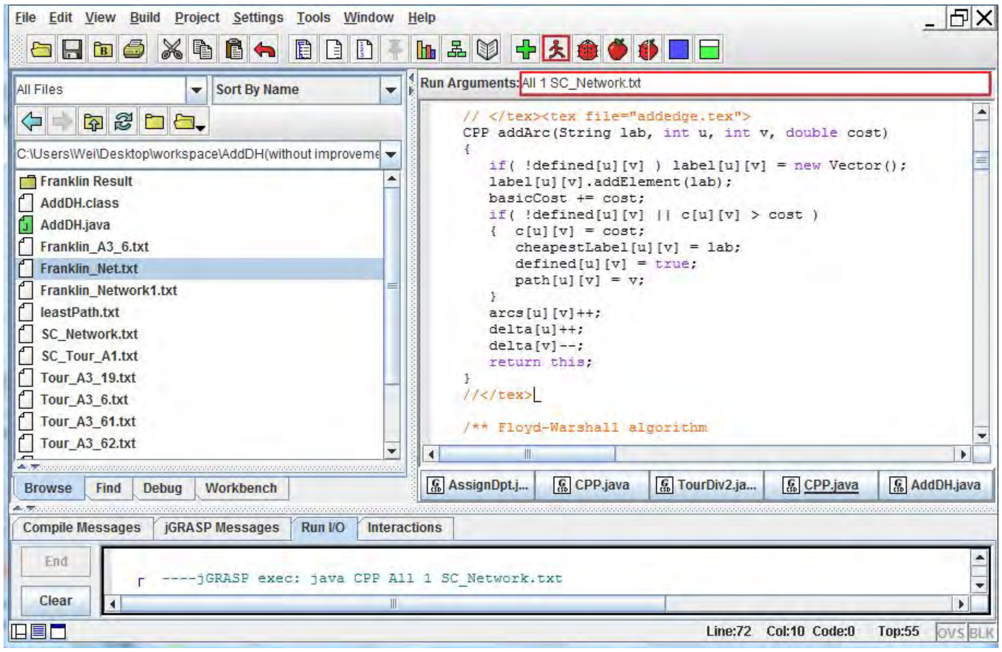


Figure 4.2.7 CPP Interface

Step 2: Run AssignDpt.java to assign the roads in the same class to the nearest depot;
Put “Network.txt” and “LeastDistance.txt” in the same folder that contains “AssignDpt.java”. To run “AssignDpt.java”, we first need to change the “ARCNO” value in the java file to the number of rows in the network file, so that we can run the program by the argument: “Network.txt Number of Depots”. Besides, when we click the run button, we need to input the location of the depot. Figure 4.2.8 shows the interface of running “AssignDpt.java”. After running “AssignDpt.java”, we get a file “Arc00.txt”. If we open it by Excel, then we can find the nearest depot for each arcs in the fifth column (Figure 4.2.9). We need to add this column to “Network,txt” file, so that each arc is assigned to a nearest depot.

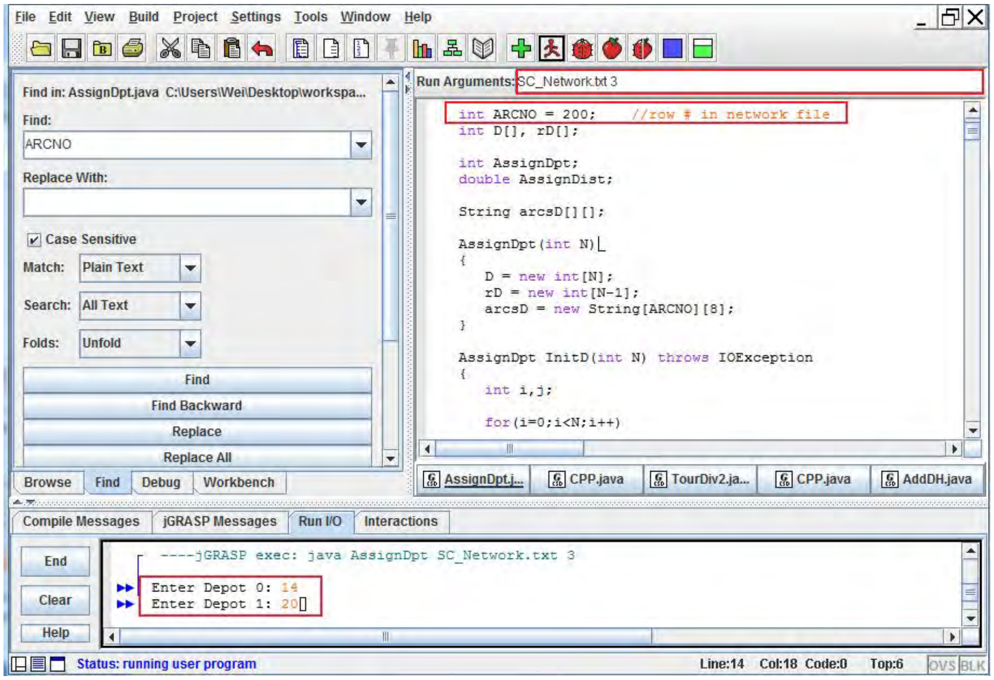


Figure 4.2.8 AssignDpt Interface

	A	B	C	D	E	F	G	H	I
1	# ID	Alpha ID	Service F	Arc Leng	Nearest Depot	Distance	Weighted	Weighted Distance	
2	1, 2	MO364E01	8	2.162	46	3.616	17.296	14.464	
3	3, 4	MO370E01	8	7.885	46	12.689	63.08	50.756	
4	4, 5	MO370E02	8	0.572	46	11.94	4.576	47.76	
5	6, 7	US40E01	8	4.3	22	8.372	34.4	33.488	
6	7, 8	US40E02	8	1.944	22	14.616	15.552	58.464	
7	8, 9	US40E03	8	3.719	42	9.933	29.752	39.732	
8	9, 10	US40E04	8	0.739	42	5.6	5.912	22.4	
9	10, 11	US40E05	8	2.451	42	7.437	19.608	29.748	
10	12, 13	US61S01	8	1.048	22	18.24	8.384	72.96	
11	13, 14	US61S02	8	2.713	22	14.479	21.704	57.916	
12	14, 15	US61S03	8	2.322	22	9.444	18.576	37.776	
13	15, 16	US61S04	8	1.397	22	5.725	11.176	22.9	
14	17, 18	US67S01	8	2.686	46	55.774	21.488	223.096	
15	18, 19	US67S02	8	1.456	46	54.544	11.648	218.176	
16	20, 21	IS70E01	8	0.402	22	9.064	3.216	36.256	
17	21, 22	IS70E02	8	4.331	22	4.331	34.648	17.324	
18	22, 23	IS70E03	8	1.328	22	1.328	10.624	5.312	
19	23, 6	IS70E04	8	0.708	22	3.364	5.664	13.456	
20	6, 16	IS70E05	8	0.128	22	4.2	1.024	16.8	
21	16, 24	IS70E06	8	1.699	22	6.027	13.592	24.108	
22	24, 25	IS70E07	8	5.815	22	13.541	46.52	54.164	

Figure 4.2.9 Arc00 file

The “Network.txt” file needs to be divided into the smaller files based on the nearest depots and road classes. For example, the St. Charles county network file can be divided into three files: “SC_A1_22.txt”, “SC_A1_42.txt” and “SC_A1_46.txt”, where “A1” means the CO class, “22”, “42” and “46” are the three depots.

Step 3: Run CPP1.java to generate the Chinese Postman Tour for each depot and class;
Run the program by the argument: “Class Depot Network.txt”, where “Class” and “Depot” are associated with the “Network.txt” that we got in the last step. For example, the argument is “A1 46 SC_A1_46.txt” as shown in Figure 4.2.10. After running”CPP1.java”, we can find the

file”CPT.txt” generated in the same folder. We need to delete the “virtual” rows in this file and save it as “CPT_Class_Depot.txt”. For example, “CPT_A1_22.txt” is shown in Figure 4.2.11.

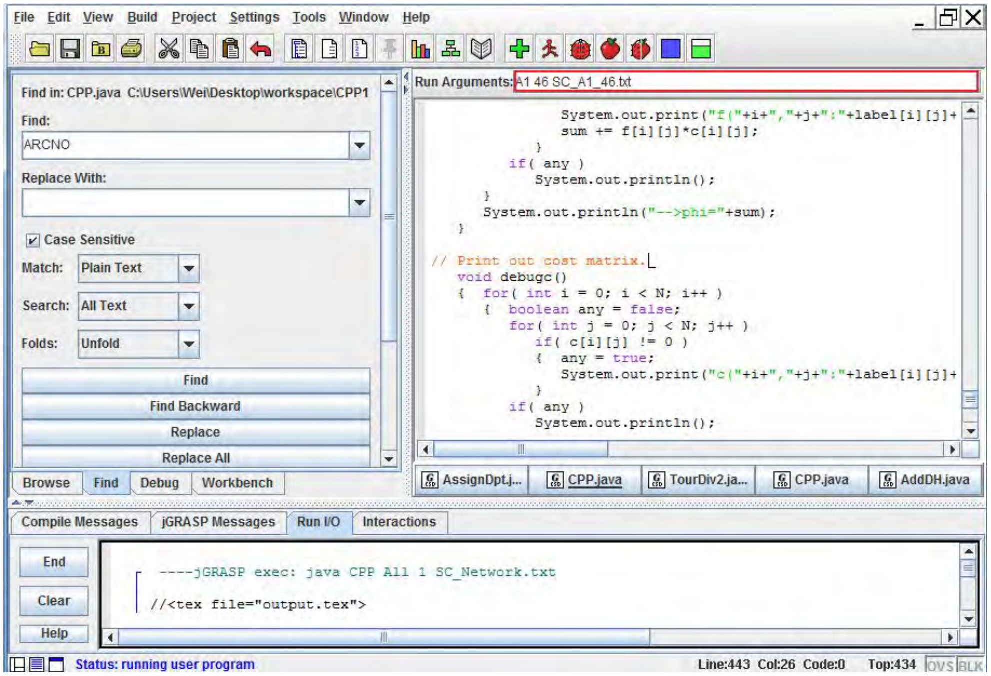
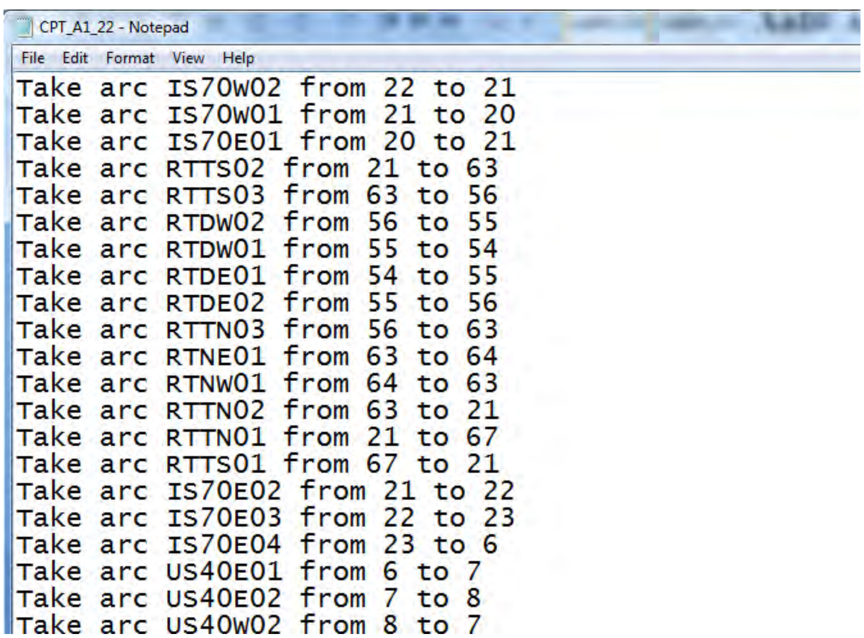


Figure 4.2.10 CPP1 Interface




```
Take arc IS70W02 from 22 to 21
Take arc IS70W01 from 21 to 20
Take arc IS70E01 from 20 to 21
Take arc RTTS02 from 21 to 63
Take arc RTTS03 from 63 to 56
Take arc RTDW02 from 56 to 55
Take arc RTDW01 from 55 to 54
Take arc RTDE01 from 54 to 55
Take arc RTDE02 from 55 to 56
Take arc RTTN03 from 56 to 63
Take arc RTNE01 from 63 to 64
Take arc RTNW01 from 64 to 63
Take arc RTTN02 from 63 to 21
Take arc RTTN01 from 21 to 67
Take arc RTTS01 from 67 to 21
Take arc IS70E02 from 21 to 22
Take arc IS70E03 from 22 to 23
Take arc IS70E04 from 23 to 6
Take arc US40E01 from 6 to 7
Take arc US40E02 from 7 to 8
Take arc US40W02 from 8 to 7
```

Figure 4.2.11 CPT_A1_22 File

Step 4: Run TourDiv2.java to divide the big Chinese Postman Tour into smaller ones based on the service time and vehicle capacity limit;

First, put “Network.txt”, “leastNTime.txt” and “CPT_Class_Depot.txt” in the same folder that contains “Run TourDiv2.java”. Then we run the program by the argument: “Class # of Arcs

MaxMile MaxTime # of Depots CPT.txt Network.txt”. For example, in Figure 4.2.12, the argument is “A1 56 45 120 3 CPT_A1_46.txt SC_A1_46.txt”, where “A1” means CO, “56” means there are 56 arcs in the network file, “45” means the maximum cycle distance is 45 miles, “120” means the maximum cycle time is 2 hours, “3” denotes the number of depot in the region, and the last two files are for the CO roads with nearest depot 46. After running this Java program, we get one file named “Final.txt”, which contains the final numbers as shown in Figure 4.2.13. Therefore, we can get the file “final number DTour.txt” as shown in Figure 4.2.14, and rename it as “Tour_Class_Depot.txt”.

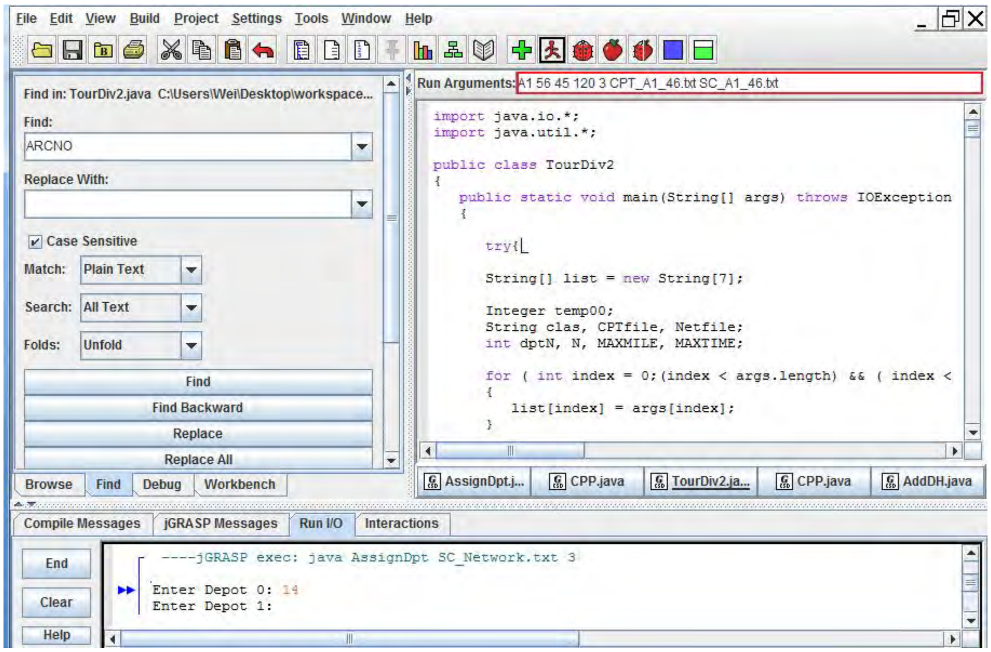
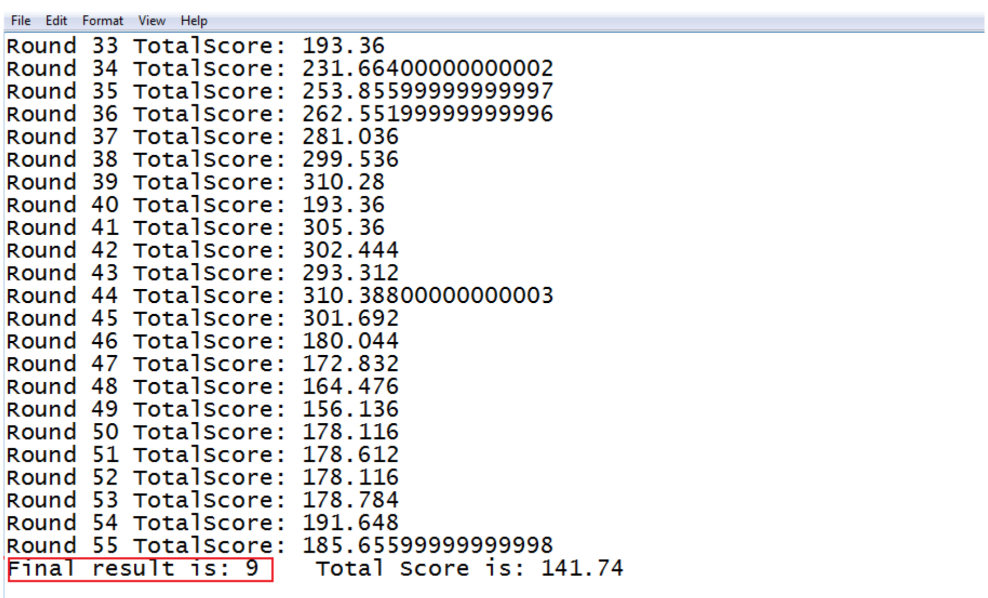


Figure 4.2.12 TourDiv2 Interface



File Edit Format View Help

```
Round 33 TotalScore: 193.36
Round 34 TotalScore: 231.66400000000002
Round 35 TotalScore: 253.85599999999997
Round 36 TotalScore: 262.55199999999996
Round 37 TotalScore: 281.036
Round 38 TotalScore: 299.536
Round 39 TotalScore: 310.28
Round 40 TotalScore: 193.36
Round 41 TotalScore: 305.36
Round 42 TotalScore: 302.444
Round 43 TotalScore: 293.312
Round 44 TotalScore: 310.38800000000003
Round 45 TotalScore: 301.692
Round 46 TotalScore: 180.044
Round 47 TotalScore: 172.832
Round 48 TotalScore: 164.476
Round 49 TotalScore: 156.136
Round 50 TotalScore: 178.116
Round 51 TotalScore: 178.612
Round 52 TotalScore: 178.116
Round 53 TotalScore: 178.784
Round 54 TotalScore: 191.648
Round 55 TotalScore: 185.65599999999998
Final result is: 9   Total Score is: 141.74
```

Figure 4.2.13 Final File

Route	Arc	From	To	Miles	Time	Class
1	MO370W01	4	3	7.885	15.77	A1
1	IS70W10	3	27	1.273	2.546	A1
1	IS70W09	27	26	1.718	3.436	A1
1	MO79N03	26	35	4.027	8.054	A1
1	MO79N02	35	34	2.342	4.684	A1
1	MO79N01	34	33	4.034	8.068	A1
1	MO79S01	33	34	4.034	8.068	A1
1	MO79S02	34	35	2.342	4.684	A1
1	RTMS01	35	62	1.004	2.008	A1
1	RTMN01	62	35	1.004	2.008	A1
1	MO79S03	35	26	4.027	8.054	A1
1	MO79S04	26	36	0.108	0.216	A1
1	MO79N04	36	26	0.108	0.216	A1
1	IS70E09	26	27	1.718	3.436	A1
1	IS70E10	27	3	1.273	2.546	A1
1	IS70E11	3	28	4.904	9.808	A1
1	IS70E12	28	29	1.106	2.212	A1
1	IS70E13	29	30	0.724	1.448	A1
1	IS70W13	30	29	0.724	1.448	A1
2	LP70W01	29	31	0.963	1.926	A1
2	MO94E14	31	4	2.085	4.17	A1
2	MO370E02	4	5	0.572	1.144	A1
2	MO370W02	5	4	0.572	1.144	A1
2	MO94E15	4	47	2.089	4.178	A1

Figure 4.2.14 9DTour File

Step 5: Run CPP(for least path).java to generate the shortest path matrix.
The argument is the same as the third step for each depot. And we can get the “leastPath.txt” as shown in Figure 4.2.15.

```
,        ,Vitual,        ,Vitual,MO364E01,
,Vitual,MO94E11,MO94E12,IS70W11,
,Vitual,MO94E11,MO94E12,MO94E13,MO94E14,
,Vitual,MO94E11,MO94E12,MO94E13,MO94E14,MO370E02,
,Vitual,MO94W10,RTNW05,RTNW04,US40W01,  ,Vitual,MO94W10,RTNW05,RTNW04,
,Vitual,MO94W10,MO94W09,US40W04,US40W03,
,Vitual,MO94W10,MO94W09,US40W04,        ,Vitual,MO94W10,MO94W09,
,Vitual,MO94W10,MO94W09,US40E05,
,Vitual,MO94W10,RTNW05,RTNW04,US40W01,IS70E05,US61N04,US61N03,US61N02,
US61N01,
,Vitual,MO94W10,RTNW05,RTNW04,US40W01,IS70E05,US61N04,US61N03,US61N02,
,Vitual,MO94W10,RTNW05,RTNW04,US40W01,IS70E05,US61N04,US61N03,
,Vitual,MO94W10,RTNW05,RTNW04,US40W01,IS70E05,US61N04,
,Vitual,MO94W10,RTNW05,RTNW04,US40W01,IS70E05,
,Vitual,MO94E11,MO94E12,MO94E13,MO94E14,MO94E15,MO94E16,RTHE01,MO94E19
,MO94E20,US67N01,
,Vitual,MO94E11,MO94E12,MO94E13,MO94E14,MO94E15,MO94E16,RTHE01,MO94E19
,MO94E20,
,Vitual,MO94E11,MO94E12,MO94E13,MO94E14,MO94E15,MO94E16,RTHE01,MO94E19
,MO94E20,US67S02,
,Vitual,MO94W10,RTNW05,RTNW04,US40W01,IS70W04,IS70W03,IS70W02,IS70W01,
,Vitual,MO94W10,RTNW05,RTNW04,US40W01,IS70W04,IS70W03,IS70W02,
,Vitual,MO94W10,RTNW05,RTNW04,US40W01,IS70W04,IS70W03,
,Vitual,MO94W10,RTNW05,RTNW04,US40W01,IS70W04,
,Vitual,MO94W10,RTNW05,RTKN02,IS70W07,  ,Vitual,MO94W10,RTNW05,RTKN02,
```

Figure 4.2.15 leastPath file

Step 6: Run AddDH.java to add deadheading roads into the smaller tour to make the round route complete.
Put “Network.txt”, “Tour_Class_Depot.txt” and “leastPath.txt” in the same folder that contains “AddDH.java”. Run “AddDH.java” using the argument “#of Routs #of Arcs Tour_Class_Depot.txt Network.txt”. For instance, the argument is “6 56 Tour_A3_19.txt

Franklin_Network.txt" in Figure 4.2.16, where "6" shows the number of routes in the file "Tour_Class_Depot.txt", "56" is the maximum number of arcs allowed in a single route. Besides, we need input the location of the depot. The program will generate the "TourWithDH.txt" file in the end as shown in Figure 4.2.17.

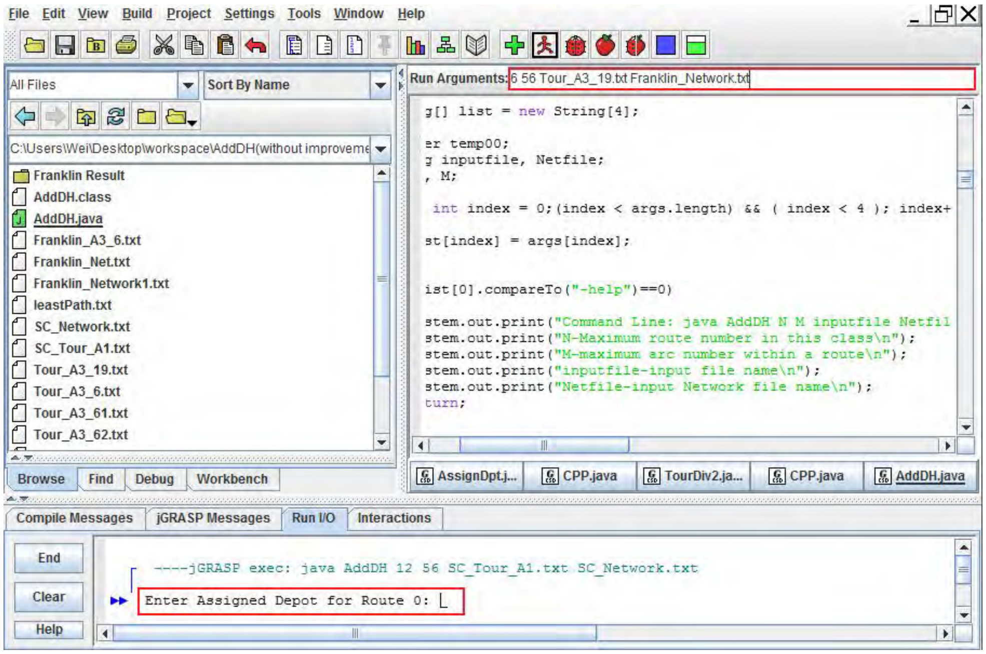


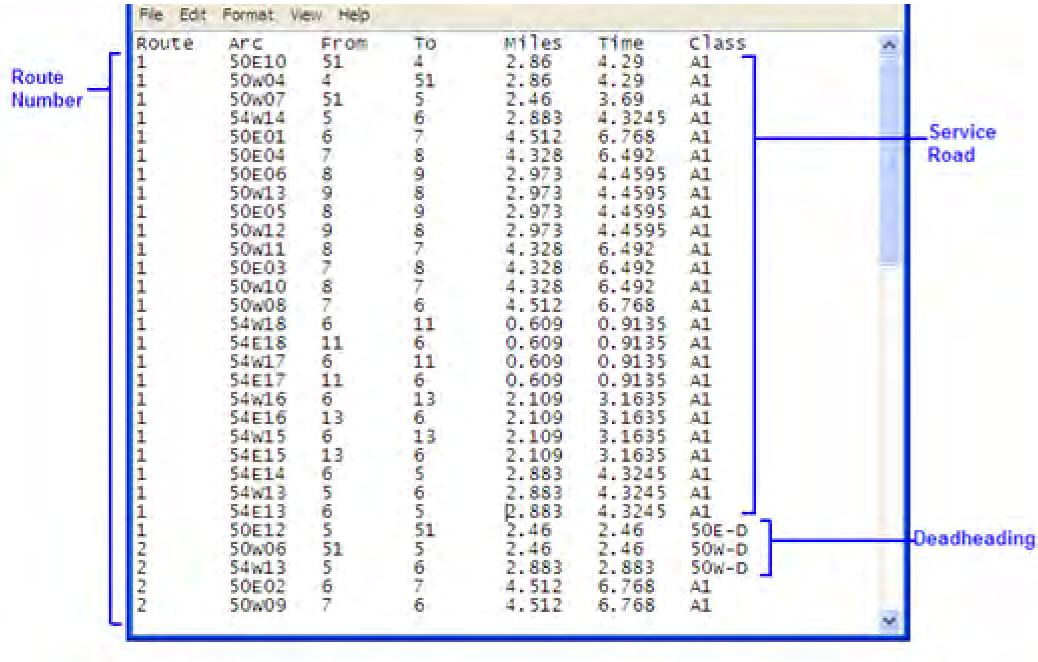
Figure 4.2.16 AddDH Interface

Route	Arc	From	To	Miles	Time	Class
1	MO185N08	19	18	0.702	0.702	185N-D
1	US50E05	18	41	5.325	5.325	50E-D
1	US50E06	41	42	1.206	1.206	50E-D
1	US50E07	42	43	0.605	0.605	50E-D
1	US50E08	43	44	1.763	1.763	50E-D
1	UUS01	44	101	4.949	9.898	A3
1	UUN01	101	44	4.949	9.898	A3
1	US50W08	44	43	1.763	1.763	50W-D
1	US50W07	43	42	0.605	0.605	50W-D
1	AJN01	42	100	6.187	12.374	A3
1	YYE04	100	71	3.765	7.53	A3
1	YYW04	71	100	3.765	7.53	A3
1	YYW03	100	17	3.87	7.74	A3
1	MO185S07	17	18	6.146	12.292	A3
1	MO185S08	18	19	0.702	1.404	A3
1	MO185S09	19	20	9.133	18.266	A3
1	MO185S10	20	21	6.199	12.398	A3
1	HN05	21	93	5.841	11.682	A3
1	HS05	93	21	5.841	11.682	A3
1	MO185N10	21	20	6.199	12.398	A3
1	MO185N09	20	19	9.133	9.133	185N-D
2	MO185S09	19	20	9.133	9.133	185S-D
2	ACW02	20	98	3.026	6.052	A3
2	CCN01	98	40	9.699	19.398	A3

Figure 4.2.17 TourWithDH file

4.2.5 Route Result Modification and Route Map Generation

The desired routes are generated after running all the programs sequentially. The route result of the computer program should be modified to minimize the deadheading time and distance, and to make the tour more reasonable. For example, if two lanes of the same road are served by different routes, we should combine them together. Or, if one road is treated both as service road and deadheading in the same route, we should consider whether it is possible to replace the deadheading by service road, etc. Finally, we need to make a graph showing the routes for each class as shown below.



Route	Arc	From	To	Miles	Time	Class
1	50E10	51	4	2.86	4.29	A1
1	50w04	4	51	2.86	4.29	A1
1	50w07	51	5	2.46	3.69	A1
1	54w14	5	6	2.883	4.3245	A1
1	50E01	6	7	4.512	6.768	A1
1	50E04	7	8	4.328	6.492	A1
1	50E06	8	9	2.973	4.4595	A1
1	50w13	9	8	2.973	4.4595	A1
1	50E05	8	9	2.973	4.4595	A1
1	50w12	9	8	2.973	4.4595	A1
1	50w11	8	7	4.328	6.492	A1
1	50E03	7	8	4.328	6.492	A1
1	50w10	8	7	4.328	6.492	A1
1	50w08	7	6	4.512	6.768	A1
1	54w18	6	11	0.609	0.9135	A1
1	54E18	11	6	0.609	0.9135	A1
1	54w17	6	11	0.609	0.9135	A1
1	54E17	11	6	0.609	0.9135	A1
1	54w16	6	13	2.109	3.1635	A1
1	54E16	13	6	2.109	3.1635	A1
1	54w15	6	13	2.109	3.1635	A1
1	54E15	13	6	2.109	3.1635	A1
1	54E14	6	5	2.883	4.3245	A1
1	54w13	5	6	2.883	4.3245	A1
1	54E13	6	5	2.883	4.3245	A1
1	50E12	5	51	2.46	2.46	50E-D
2	50w06	51	5	2.46	2.46	50W-D
2	54w13	5	6	2.883	2.883	50W-D
2	50E02	6	7	4.512	6.768	A1
2	50w09	7	6	4.512	6.768	A1

Fig.4.2.18 Route Result Details

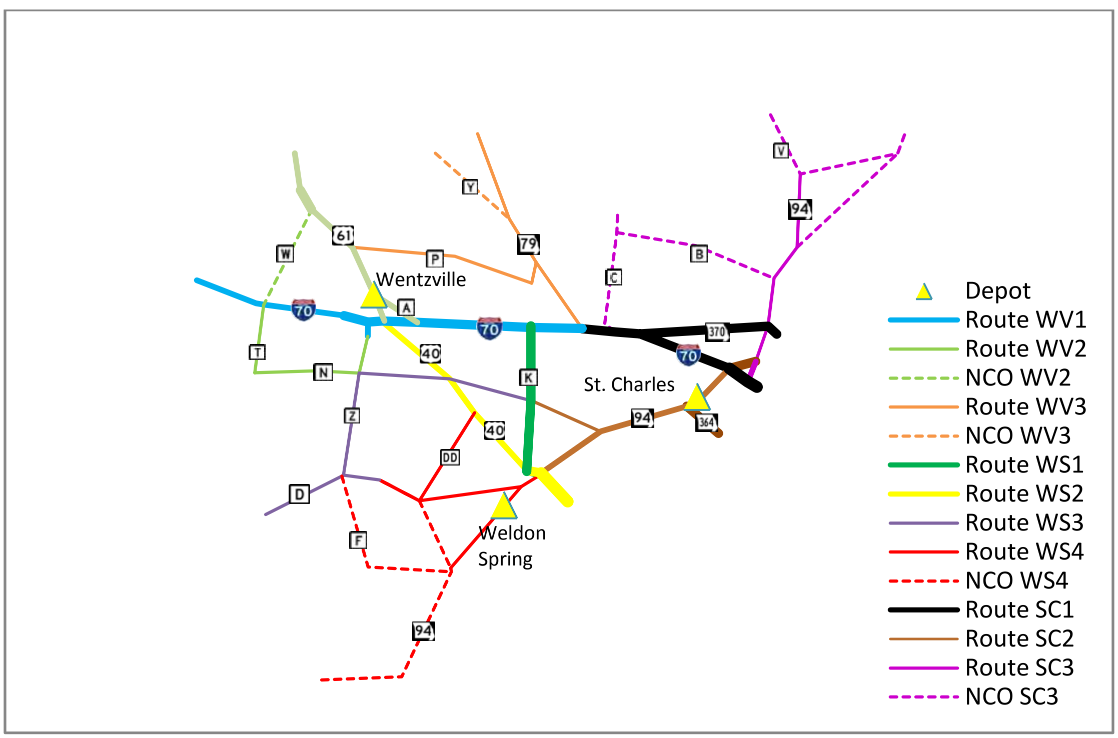


Figure 4.2.19 Route Map

Chapter 5: Conclusions

The objective of this research was to develop a systematic, heuristic-based optimization approach to integrate the winter road maintenance planning decisions for vehicle route design, fleet configuration, and equipment and treatment selection. The solution methodology that we developed achieves the objective of a more integrated approach to the problems considered. 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.

The solution applied to the transportation network of St. Louis District, Missouri, is very promising. The results indicate that our solution would allow MoDOT to maintain the same high level of service with current resources. The solutions also provide cost saving opportunities by closing maintenance buildings.

An extensive literature review of the current state-of-the-art for material treatments was conducted. Based on this review and MoDOT's current treatment objectives a recommended treatment strategy was developed that accounts for pavement and weather conditions. A literature review was also conducted for snow removal equipment, with particular attention given to blade type. It was found that the JOMA blade has many promising characteristics compared to traditional carbon steel blades.

The comprehensive scope of this project should provide winter road maintenance planners with the ability to make more informed, economically beneficial, and successful decisions.

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