Snowplow Operations and Resource Management

Final Report

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Executive Summary

The purpose of this research was to continue the development of a decision support system (DSS) to assist the Minnesota Department of Transportation (MnDOT) with snowplow operations in District 1B, operating primarily out of Virginia, and including Hibbing and Ely.

The DSS consists of three primary components: the underlying simulation model which uses ProModel®, the user interface and the output report, developed using Visual Basic®. The DSS simulates snowplow operations for selected routes under various conditions. The conditions selected by the user are length of storm, moisture content of snow, pavement temperature, and material application rate. The simulation model, which was constructed based on user input, then determines the time to achieve bare lane for each route selected, the material used, and labor and equipment costs. The model contains other information not selected by the user, including type of snowplow assigned to each route, the route length, and reloading points. These other variables can be altered by a programmer, although moving reloading points is more difficult.

The objectives of this study were to:

- Expand the existing model to include all routes that are managed by Virginia.
- Continue to work with the managers and supervisors to develop the model in order to identify the appropriate parameters to conduct "what-if" analysis.
- Include performance metrics in the output report.
- Validate the model based on actual data.

These objectives were achieved except for model validation. The model could not be verified because of lack of available accurate data. Although it was expected that automatic vehicle location (AVL) systems would be installed on selected snowplows in Virginia, that did not occur. In order to address this problem in FY 2004-2005, other types of validation efforts will be made. Although it is expected that the AVLs will be installed in the fall of 2004, total reliance on this system for validation will not be used. Two other techniques will be applied, including validation based on intermediate results, and normalizing the data.

Chapter 1
Introduction

Snowplow operations must consider a multitude of variables in order to effectively deploy the snowplows and provide an acceptable level of service to the motoring public. The specific operations, timing, and treatment applications will vary according to the weather, the road condition, characteristics of the specific route, traffic, and driver experience. Snowplow operations are fairly complex, requiring that the supervisors make decisions to deploy plows based on the weather forecast, and adjust route assignments in response to vehicle and personnel availability. Supervisors may need to split shifts, extend shift lengths, and halt plowing when plowing becomes ineffective and drivers become fatigued. Capturing the decision rules used by the supervisors and drivers in order to construct a simulation model is a challenging task due to sparse data, and the reliance on management reports and expert opinion.

The primary objective of this study is to help supervisors make decisions regarding the management of snowplow operations by providing the capability to run "what-if" scenarios. Simulation of snowplow operations requires that the interrelationships between many variables be captured in order to represent the actual system. These variables and relationships are not easily obtained from existing data for three reasons. First, the data may either not be collected, or its validity is questionable. Second, some data is simply not available, such as snowplow speed. Third, operations may change when the weather and road conditions change. For example, some plows may drive in tandem to clear the road, requiring that a plow deviate from its normal operating procedures. These variables create havoc for developing clean analytical solutions. The lack of data also creates challenges for simulation, although expert opinion may be used when data is not available.

The second objective of this study is to assess the tradeoffs associated with policy decisions. For example, simulation will help to assess the impact of fewer drivers if temporary drivers are no longer available, fewer snowplows or plows with different capacities, and shorter shifts.

Along these same lines, this study will also assess the impact of performance metrics on system performance by looking not only at the traditional measures, but also at costs of material, labor, and equipment. Two performance measures are currently used. One is the target value for reaching bare pavement by route, which differs according to highway classification (urban commuter, rural commuter, primary, and secondary). A second performance measure used by management averages these individual values together and is presented as a "dashboard". This aggregate measure, however, can mask problems such as under-serviced roads or over-serviced roads. Additional metrics will help to reveal not only service levels to the motoring public, but also the cost of maintaining specific levels of service.

Finally, an interface between the simulation model and the display of output in an Excel spreadsheet were developed serving to provide output displays that reflect the preferences of the user.

Summary of Previous Work:

Previous work conducted during 2002-2003 focused on developing a simulation model of snowplow operations using various techniques for representing weather and road conditions. This proved to be a fairly complicated task, as different variables interact to impact snowplowing operations in ways that do not affect operations in the presence of only one variable. A good example of this interaction is the moisture content of snow and the accumulation rate. Taken separately, an average accumulation rate, or high moisture content may represent a "typical" storm which requires little variation from normal operations. Taken together, however, operations can change drastically, with snowplow speeds falling to almost half of the average speed, and without the underbody or wing plows deployed due to the heavy snow. Gathering this information proved to be challenging because actual plow speeds are not recorded, only the target speeds for each route. The actual speed can vary considerably depending on the accumulation route, moisture content, and road temperature. The simulation was modified to include this interaction, and verification and validation studies will continue throughout 2002-2003 and extend into 2003-2004.

One other important aspect of the work conducted during 2002-2003 was dealing with weather forecasting. Although the simulation model is not intended to forecast weather, weather is critical in simulating operations. Therefore the most important weather characteristics were identified and used as input into the simulation model.

Another key accomplishment during the 2002-2003 year was the development of a user interface. This proved to be critical in eliciting expert opinion, as it helped in identifying the important issues that must be considered during an event.

In summary, the 2002-2003 year resulted in an improved simulation model that included an interface selected by the user, better representation of operations by capturing the interaction of key variables, and a greater understanding of the role of simulation and its benefit to Mn/DOT.

Specific tasks were to be accomplished during 2003-2004. These specific tasks and the results of these tasks are discussed in Chapter 2. Chapter 3 presents conclusions and recommendations. The simulation model and all related files are available on a CD and on a laptop computer dedicated to this project.

Chapter 2
Results

Seven tasks were planed for this project. Each are presented in their original form and the results of each are discussed.

Task 1: Validation of model using the automatic vehicle location (AVL) systems installed on snowplows.

Description: At the end of the second phase of this project in June 2003, the model was not valid. Although investigations were conducted to identify possible sources of error, none were forthcoming. Either input data was incorrect, or reporting data was incorrect. Therefore, the information from the AVL systems will be used to validate the simulation model by comparing actual performance to the performance predicted by the simulation model. Data will be gathered throughout the winter.

Deliverable: Statistically valid simulation runs, with the supporting calculations and assumptions for selected routes.

Results: Validation proved to be far more difficult than expected, in part because the AVL systems were not in place. The handwritten reports generated by the snowplow drivers were also not very helpful because information was missing, incomplete, or incorrect.

For simulation runs, it is usually required that a certain number of replications are conducted in order to generate statistically independent and unbiased observations (Harrell et al., 2000). Let e be the error between the estimated mean value $\bar{x}$ and the true mean value u, α be the probability that the difference between $\bar{x}$ and u is greater than e, and S be the standard error, then the number of replications N to satisfy the error amount e and the significance level α can be estimated as follows:

$$N = \left(\frac{t_{(N-1),\alpha/2} S}{e} \right)^2 \qquad (2.1)$$

where $t_{(N-1),\alpha/2}$ is the critical value for t distribution. However, equation 4.1 cannot be resolved for N because it exists on the both sides of the equation. Regarding this situation, Harrell et al. (2000) replace $t_{(N-1),\alpha/2}$ with the standard normal distribution $Z_{\alpha/2}$ and approximately estimate the number of replications as follows:

$$N' = \left(\frac{Z_{\alpha/2} S}{e} \right)^2 \qquad (2.2)$$

In this study, we calculate the number of replications for each route based on the following assumed scenario described in Table 2.1, choosing the largest number from the sample sizes for all 18 routes as the number of replications for the entire simulation model. In this case, a 5-hour event has snow accumulation rate between 0.5 and 1.0 inches per hour, high moisture content, pavement temperature 15 to 20 degrees Fahrenheit. The material application rate is about 600 pounds for each lane mile.

Table 2.1: Scenario for Initial Sample of Observation

Storm Duration	300 minutes
Snow Accumulation Rate	0.5-1.0 inches per hour
Moisture Content	High
Pavement Temperature	15 – 20 ^{0}F
Material Application Rate	600 lbs per lane mile

Because the sample size of 5 was determined for the prototype simulation model in the previous work, we ran the simulation for 5 times as an initial sample of observations to obtain the average value and the standard error S . The results for route 301 are presented as follows:

Average Time to Bare Lane 301 = 378.72 min

Standard Deviation 301 = 11.52 min

Thus if we take $e = \pm 10\% \bar{x}$, then e_{301} can be computed as:

$$e_{301} = \pm 10\% \times 378.72 = 37.87 \qquad (2.3)$$

And let $\alpha = 0.05$, from equation 4.2 and value of e_{301} obtained from 4.3, the number of replications for route 301 can be estimated as:

$$N'_{301} = \left(\frac{Z_{\alpha/2} S}{e} \right)^2 = \left(\frac{1.96 \times 11.52}{37.87} \right)^2 = 0.4 \qquad (2.4)$$

therefore, we choose 1 as the sample size for route 301. The same approach applies for other 17 routes and the results of all 18 routes are presented in following Table 2.2.

Table 2.2: Number of Replications for Each Route

Route	**Avg. Time to Bare Lane**	S **(min)**	e **(min)**	N'	**Sample Size**
301	378.72	11.52	37.87	0.4	1
302	225.61	32.93	22.56	8.1	9

303	349.79	64.89	34.98	13.2	14
304	400.06	67.94	40.01	11.1	12
305	385.52	20.75	38.55	1.1	2
306	306.95	19.57	30.70	1.6	2
307	359.56	36.44	35.96	3.9	4
308	679.45	39.49	67.94	1.3	2
311	409.01	25.74	40.90	1.5	2
312	289.92	75.77	29.00	26.2	27
313	167.19	55.70	16.72	42.6	43
314	354.98	65.16	35.50	14.4	15
315	588.37	17.25	58.84	0.3	1
316	674.78	70.62	67.48	4.2	5
321	417.07	29.55	41.71	1.9	2
322	645.56	28.04	64.56	0.7	1
323	67.60	21.17	6.76	37.7	38
324	384.79	21.44	38.48	1.2	2

The above table shows that the number of replications for the routes vary from 1 to 43, which indicates that we should choose the sample size of 43 to be able to believe with 95 percent confidence that the results from the simulation system have no larger than 20 percent error against those of the actual system

The output of the simulation model includes time to bare lane, amount and the cost of the material applied on each route, labor cost and equipment cost on each route. This section mainly focuses the analysis on time to bare lane as it is the most essential performance measure in the snowplow operations. The statistical tests are conducted upon the simulated time to bare lane and the available historical data. The data of weather and road conditions during these historical storm events is acquired from Mn/DOT's RWIS website. The historical time to bare lane is obtained from the Bare Pavement Work Record (BPWR) filled out by the plow drivers during the past snowplow services. Totally we have 59 sets of data from 13 routes available, however only 27 sets of data are usable because of input error, missing information and poor legibility. The detailed counts of failed data are shown in Table 2.3.

Table 2.3: Failed BPWR Data

	Poor legibility	**Input Error**	**Missing Info**
Number	1	17	14
Percentage of Total	1.7%	28.8%	23.7%

Based on the 27 sets of usable data, null hypothesis tests were conducted to compare the simulated results and the recorded historical values. As discussed in section 3.3, let the hypothesis be:

$$H_0 : E[x] = \mu$$

$$H_1 : E[x] \neq \mu$$

$$t = \frac{\bar{x} - \mu}{\frac{s}{\sqrt{N}}}$$

where sample size N is 43 in this case. Let α be 0.05, reject H_0 when $|t| > t_{N-1,\alpha/2} = t_{42,0.025}$. Because of unavailability of the historical data on route 301, 321, 322, 323 and 324, 13 routes were tested based on the actual time to bare lane from the BPWR reports and the storm scenarios gained from RWIS website. The test results are shown in Table 2.4.

Table 2.4: Actual and Simulated Time to Bare Lane

Route	**Event**	**Actual Time (min)**	**Simulated Time (min)**		**Test Statistic**	$t_{42,0.025}$	**Test Conclusions**
			Avg.	**Std. Dev.**			
302	1	210	202.04	14.69	-3.55	2.021	Reject H_0
	2	330	449.20	9.07	86.18	2.021	Reject H_0
	3	120	389.20	9.07	194.63	2.021	Reject H_0
303	1	360	371.93	37.15	2.10	2.021	Reject H_0
	2	1410	496.51	24.40	-245.50	2.021	Reject H_0
304	1	90	676.04	17.45	220.22	2.021	Reject H_0
	2	1650	436.04	17.45	-456.19	2.021	Reject H_0

305	1	180	490.42	21.15	96.24	2.021	Reject H_0
	2	300	677.17	22.14	111.71	2.021	Reject H_0
306	1	960	291.41	47.64	-92.03	2.021	Reject H_0
307	1	1410	326.35	14.40	-493.47	2.021	Reject H_0
308	1	1380	606.24	60.59	-83.74	2.021	Reject H_0
	2	1830	625.23	23.06	-342.60	2.021	Reject H_0
311	1	1035	158.97	20.64	-278.32	2.021	Reject H_0
	2	540	565.23	12.46	13.28	2.021	Reject H_0
	3	1410	525.29	14.83	-391.20	2.021	Reject H_0
312	1	1050	162.42	12.91	-450.83	2.021	Reject H_0
	2	540	358.53	6.37	-186.81	2.021	Reject H_0
	3	1440	319.43	8.26	-889.60	2.021	Reject H_0
313	1	1020	209.95	22.55	-235.56	2.021	Reject H_0
314	1	1845	357.21	49.45	-197.30	2.021	Reject H_0
	2	270	603.00	17.74	123.10	2.021	Reject H_0
	2	1440	423.00	17.74	-375.92	2.021	Reject H_0
315	1	1020	638.43	33.90	-73.81	2.021	Reject H_0
316	1	1230	682.59	56.08	-64.01	2.021	Reject H_0
	2	270	982.30	23.35	200.03	2.021	Reject H_0
	3	1650	805.60	21.52	-257.30	2.021	Reject H_0

The above table shows that hypotheses were rejects for all event scenarios, indicating that there are significant different between the actual time to bare lane and the simulated time to bare lane.

The analysis indicates that the model is not able to generate the outputs that are equivalent to the data recorded from the previous snow events. However, it is not sufficient to conclude that the simulation model is not proper to reflect the actual snowplow operations because the model has fair face validity according to the experts who are experienced with the actual operations. We believe the reasons the simulated data didn't pass the hypothesis tests mainly come from the following aspects:

- The recorded time to bare lane data is not the real mean μ of the actual system. Instead, it is only one sample under a certain event condition. However, it is impossible to conduct a number of experiments regarding one set of specific event conditions due to the impossibility of replicating the same weather condition and the road conditions. It is a trade-off to replace the real mean with the recorded data. However, we believe it is where the major error comes from.

- For each route, there are only very limited historical data available for statistical testing. These data could be the few samples in a population with a great deal of variance. Thus the unavailability of the sufficient sample size could be another major source of error.

- The reliability of the time to bare lane data and the material application rate recorded by the drivers is questionable, which directly introduced the significant unsoundness to the conduction of the hypothesis tests. In addition, we are not confident at the accountability of RWIS weather data either because there are noticeable holes. For example, the snow accumulation rate shows as 0 when snow precipitation truly happened at the corresponding time. These two errors greatly weakened the reliability of the recorded time to bare lane data and the simulated data, shown by event 1 on route 304 and event 2 on route 314.

- In the practical snowplow operations, there is a certain amount of time for drivers to switch shifts when the actual plowing is paused. Therefore, the recorded time to bare lane could contain such break time especially during those snow events happened at night. Unfortunately, the break time can not be simulated in the model. Consequently, the simulated results sometimes differ from the actual results, shown by event 2 on route 303, event 2 on route 304, and event 1 on route 307.

- For most routes, there are no exact sensors on the routes to record the data of weather and road conditions. Instead, data from the adjacent sensors has to be applied as an approximation of the sought data. However, this is absolutely another important source of error for the simulation.

Task 2: Expand the capability of the simulation model to simulate any selection of routes from Virginia, enabling the user to run any combination of routes. The completion of this task will enable the user to look at the entire subdistrict in order to assess tradeoffs

Description: Currently the model can run either one or 5 routes in Virginia, and will not allow the user to select anywhere between 1 and 5. The purpose of this task is twofold: Extend the 5 routes to include all routes in Virginia, and allow the user to select combinations besides "all or one". The purpose for this feature is to allow the user to simulate the operations on adjacent routes to determine the effect of changing route lengths or breakdowns.

Deliverable: A simulation model which includes this enhancement

Results: This task was accomplished.

Task 3: Modify the simulation model so that it can handle the following tasks: changes in route length, relocation of reloading point, operations at reloading points, responses to an equipment breakdown.

Description: Mn/DOT wanted to be able to look at changes in route length, relocating reloading points, more detailed inclusion of operations at reloading points, and responses to equipment breakdowns.

Deliverable: Inclusion in the simulation model and a report describing the results of this inclusion.

Results: Route lengths can be changed by the programmer, but not the user. The change is easy to make, but requires knowledge of the structure of the spreadsheets used in the model. Because route lengths tend to change at the beginning of the year, and not throughout the year, it was determined that it would be simpler to remove this option from the user and make it simple to change for the programmer.

Modifying the location of reloading points was very difficult because of the logic that needed to be programmed into the simulation model for determining whether or not a plow must stop to obtain more material. These reloading points cannot be easily changed by the programmer, although it is possible, and the user cannot change these points.

Operations at reloading points were included and vary according to truck capacity.

Equipment breakdowns were not included because there is not data available through the M4 maintenance system on the distribution of breakdowns.

Task 4: Modify the simulation model (and/or the accompanying Excel spreadsheets) to include various performance metrics, including target values, and labor and equipment cost.

Description: It was brought to our attention that the dashboards that are currently used by MnDOT do not capture the overall picture of snowplow operations performance. For example, averaging the time to reach bare pavement among all the routes in a district can obfuscate consistently poor (or superior) performance on one route. Also, labor and equipment costs are not included as performance metrics, so it would be interesting to look at some of these trends as well.

Deliverable: Report

Results: This modification was made to the output report, and works very well. The output report consists of three different spreadsheets. One spreadsheet shows the values that were input by the user. We found that it was very common for the user to put values into the program and not be able to recall what they had recorded. Another spreadsheet shows the results. The third spreadsheet plots the performance of the snowplow. Figures 2.1 through 2.3 show these spreadsheets.

Figure 2.1 Output Report: Input Values

Parameter:	Value
Material Applied (lbs)	500
Storm Duration (minutes):	120
Accumulation Rate (inches):	0.0 - 0.25
Moisture Content:	Low
Pavement Temperature (Degree F):	Above 30
Simulation Date:	6/10/2004

Figure 2.2a on the next page is a portion of the screen capture for output results. The results are listed by truck station. These results indicate that the user selected four routes based from the Virginia truck station. Had the user selected routes from Hibbing and Ely, those portions of the report would be filled in.

Figure 2.2a. Output Report: Results

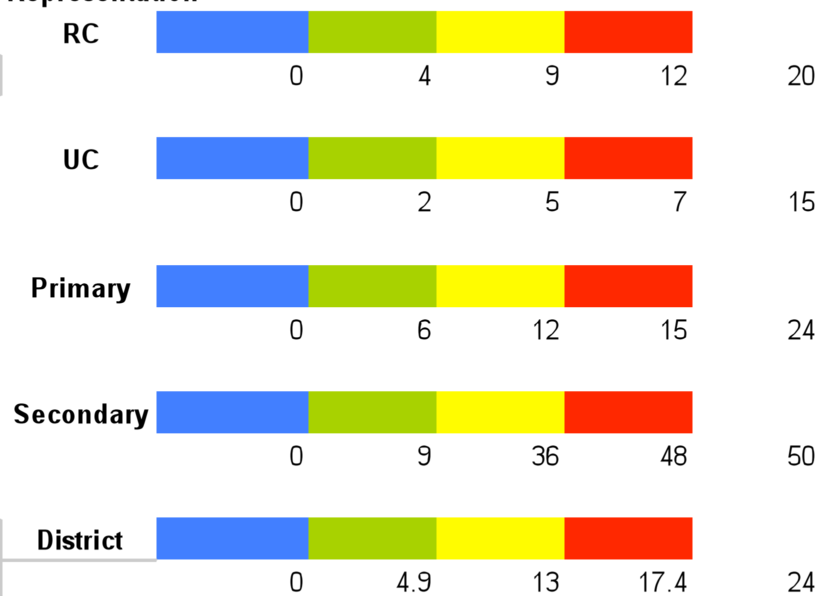
Route	Time To Bare Lane (hrs)	Material Applied (lbs)	Material Cost ($)	Labor Cost ($)	Equipment Cost ($)		Class	ROC Color
Virginia Truck Station								
301	10.74	40,960.00	$162.20	$80.28	$637.59		R.C	10.74
302	8.99	22,660.00	$89.73	$44.41	$389.77		U.C	8.99
303	10.67	31,448.00	$124.53	$61.64	$293.77		R.C	10.67
304	11.19	43,854.00	$173.66	$85.95	$349.16		R.C	11.19
Hibbing Truck Station								
Ely Truck Station								

Figure 2.2b is the remainder of the output report, and shows the average performance for each type of route. The color coding indicates whether or not the targets were met, with blue indicating possible over service and red indicating a problem area that needs more service. As this case demonstrates, the urban commuter route 302 takes much longer to achieve bare lane than is acceptable. The others are within acceptable limits, although there is room for improvement.

Figure 2.2b Output Report: Results

Key:	
R.C:	Rural Commuter
U.C:	Urban Commuter
Primary:	Primary Collector
Secondary:	Secondary Collector

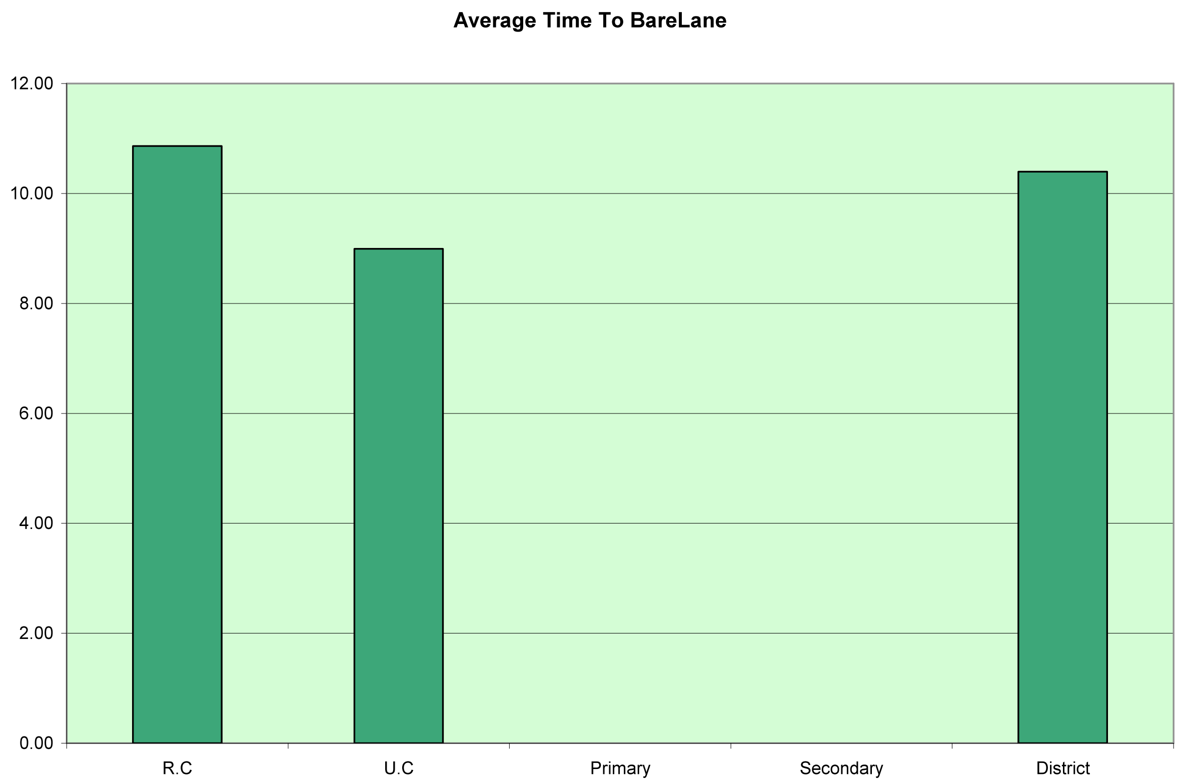
ROC Dash Board Color Representation



Class	Average
R.C	10.86
U.C	8.99
Primary	0
Secondary	0
District	10.4

Figure 2.3 on the next page shows this output presented in a slightly different way, using graphics to show the performance.

Figure 2.3 Output Report: Performance Plot



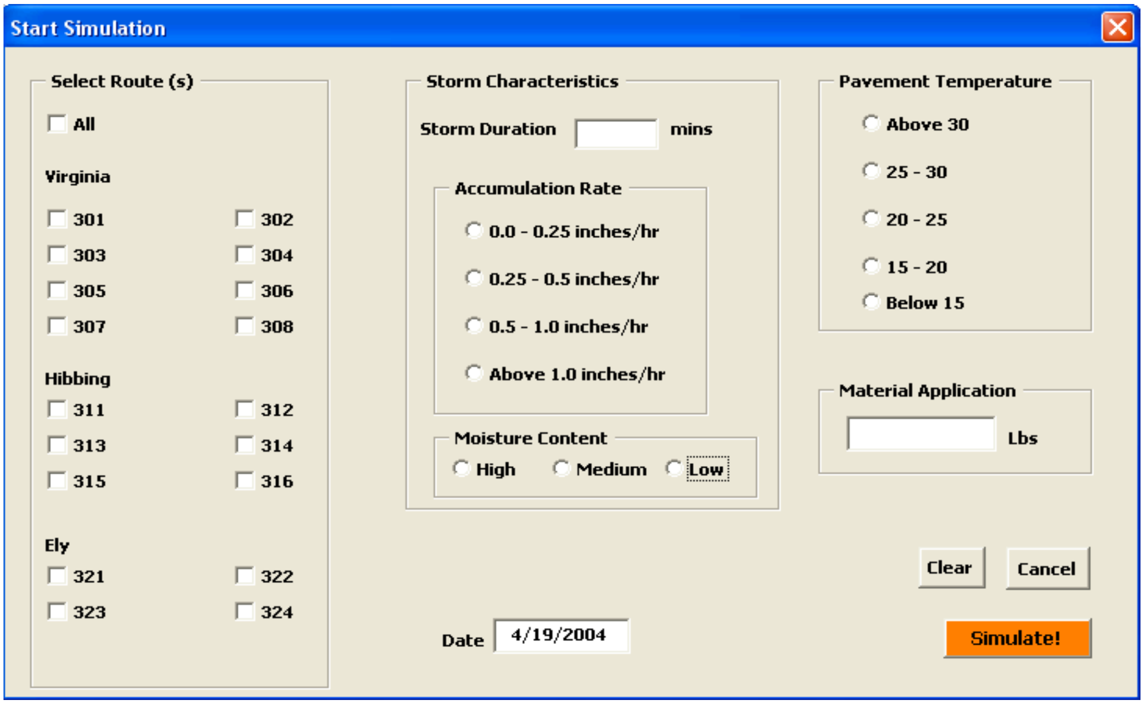
Task 5: Modify the user interface for input as required

Description: As enhancements are made to the model, the input user interface will be modified.

Deliverable: Modified user interface

Results: Figure 2.4 on the next page is a snapshot of the final user interface.

Figure 2.4 Input User Interface



Task 6: Develop an interface for output data.

Description: Output reports will be generated that will print directly to Excel. These reports will be formatted using Visual Basic to make them easy to be used.

Deliverable: Report

Results: As it turned out, this task and task 4 were combined. It made sense to make one output report that included performance metrics and costs. These figures are shown in Figures 2.1 through 2.3.

Task 7: Coordinate with other agencies conducting similar research.

Description: This task was not in the original proposal. After the original proposal was submitted, two private consulting firms doing similar work were identified and contacted. They are interested in meeting to discuss our work.

Deliverable: Report discussing similarities and differences.

Results: Dakota County and the State of Ohio are involved in work similar to this study.

The State of Ohio uses a system called WinterPlan®, which is distributed by Cascade International.[1] The system uses GIS data to develop maps of the road network, which are then converted to links and nodes with various attributes assigned to each road section and selected locations.

Ohio has developed snow and ice route plans which have evolved over the years, delivering the desired level of service for the available resources. The evolution of Ohio's snow and ice route plans seem to be very similar to the State of Minnesota's plans, with continual improvements being made over time.

The implementation of WinterPlan has not altered the basic snow and ice route plan, but has served as an additional tool that can provide performance metrics. For example, Ohio uses WinterPlan to generate the best route based on available resources. They will specify manual routing information, which includes the number of trucks, capacity, speeds, material type, and application rates. Next the manual routing solution is compared to the mathematical analysis performed by WinterPlan. These two results are then compared to each other. In this way, WinterPlan serves as a benchmarking tool, and Ohio can more easily gage improvement in their performance. Although WinterPlan can provide optimal routing information, it can also generate infeasible routes, making total reliance on the system unrealistic.

Ohio also uses WinterPlan to create electronic versions of the current system, reporting lane miles covered and plow and recovery times, other internal performance metrics. WinterPlan assists with both short- and long-term planning, and Ohio has used it to look at the feasibility of closing or opening facilities and locating stockpiles.

Another study on snowplow operations was conducted by SRF Consulting, Inc. for Dakota County.[2] They installed AVL systems on three vehicles and gather data for two seasons in order to assist the county in resource management. The systems used GPS data from which speed and time could be computed. Additionally, they recorded plow blade status, temperature, and spreader status. Both hardware and software were configured to gather and store data for analysis. Note that this project was not used for routing snowplows, but only for studying and improving the operation of the snowplows on a specific route.

One of the most interesting findings from this study was the substantial amount of time that plows were moving without actively plowing or sanding. The percentage of time spent by the trucks in this "passive" plowing was more than 50%. This value could be high, however, as the indicator switch for "plow-on, plow-off" may have been inaccurate.

This apparent level of inactivity is also influenced by deadheading, and the possibility that a very low spreader rate could result in "spreader-off" condition.

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[1] The contact for Cascade International is Ken LaBeau, 1.800.892.3338
[2] The contact for SRF Consulting, from Minneapolis, MN was Mark Gallagher.

One of the "lessons learned" by SRF Consulting had to do with installation. Essentially, the vehicle environment must be clearly understood in order to identify the type of sensors that should be used for the various components. Additionally, a good system is necessary for downloading and managing data.

The systems used by the State of Ohio and Dakota County are both aimed at improving operations, but each use quite different means to achieve it. Ohio is focusing on statewide routing and facilities planning, whereas Dakota County was focusing on the individual snowplow.

This study is doing both, to some extent. It is assumed that the existing snow and ice plan, although not "optimal", provide an acceptable level of service with the available resources. Additionally, it is also assumed that the snowplow operators are following the state guidelines for snow and ice removal. Given this information, this study is looking at the impact of reassigning plows, changing routes, moving stockpile locations, and effectively using resources.

Chapter 3
Conclusions and Recommendations

This year was successful in terms of the progress made on the simulation model, and the development of the input user interface and the creation of useful output reports. Less success was achieved in validating the model. Nevertheless, the year ended with some new ideas for validating the model in the upcoming year, and parties who lie outside the State of Minnesota continue to express interest.

The primary recommendation from this study is to collect accurate data . Without accurate data, it will be difficult to validate the model.

Another important recommendation from this study is to use other validation methods, relying not only on the time to achieve bare lane, but to also look at intermediate simulation results, and to consider the effect of normalizing the data.

Other recommendations are to identify tradeoffs associated with operational and policy decision such as route assignments and reduced budgets. More specifically, the simulation model needs to be modified to incorporate unavailable plows or drivers.