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Snowplow Operations and Resource Management

Final Report

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Executive Summary

The purpose of this research was twofold: to develop a simulation model of snowplow operations, and to develop a conceptual design for a predictive maintenance system.

The first portion of the research was concerned primarily with developing a simulation model of snowplow operations for selected routes in Virginia, MN. The purpose of this model is to assist managers with decisions related to route length, assignment of plows to routes, placement of reloading points, and the collection of labor and material cost based on “what-if” scenarios. Creating this model depended on input from experienced operators, internal management reports, and archived Road and Weather Information Systems (RWIS) data.

One important input variable to the model was plow speed. It was assumed that plow speed was affected by both snow accumulation rate and moisture content. The researchers relied on input from experienced operators to determine the effect of accumulation rates and moisture content on plow speed. For each event during the 2002-2003 winter, Mn/DOT reports were used to determine the length of each event, and the time to reach bare pavement. The archived RWIS data was then matched to each event to estimate snow accumulation rates and relative humidity, which was used as a pseudo-measure for moisture content of the snow. Using the estimated plow speeds, the simulation model was run for selected routes and the output of the model was then compared to the bare lane reports. Although the model structure, logic, and design were verified to be correct, the model could not be validated, as the results did not match the bare lane reports. This problem can be attributed to either incorrect input data, or incorrect reports that were used to validate the model. It was not possible to determine the source of the inaccuracy.

In spite of this shortcoming, other aspects of the project were successful. A user interface was developed for the simulation model, which operates from an Excel spreadsheet. The process of developing the interface was very instructive for both the researchers and the supervisors, as details of snowplow operations were articulated and the important variables affecting operations were identified. As the interface was developed, the users identified additional constraints and variables that needed to be addressed and included in the simulation model. Some variables turned out to be relatively unimportant but others turned out to be key. Key variables were pavement temperature, accumulation rate, moisture content, and material application rate, which the user can control from the interface. The supporting Excel spreadsheet were also designed with the flexibility for the user to make additional changes in the future, such as route length, and number of snowplows assigned to a route.

During the winter of 2003-2004, several snowplows in Virginia will be equipped with automatic vehicle location systems that will have the ability to determine vehicle locations. This should provide tremendous assistance with model validation by determining plow speed.

In summary, the simulation model was successful on many fronts: identifying key variables, determining the operational rules and logic, developing a user interface, and designing

model flexibility for future development through Excel spreadsheets. The only disappointment was in model validation, which should be solved when data is collected directly from the plows through the AVL system.

It is therefore recommended that data be collected from the snowplows using systems such as AVL or GIS systems. In addition to location information, data should also be collected to determine the rate and quantity of material application. In the future, systems which identify the configuration of the snowplow (e.g. wings up or down, underbelly plow up or down) should be implemented. Gathering this data using real time systems will reduce reporting errors, thereby improving any models that are used to depict snowplowing operations and also improving the reliability of internal management reports. Similar work is being conducted elsewhere. Therefore, it is also recommended that a site visit be made to Ohio, who has recently implemented software developed by Cascade International, for managing snowplow operations. It is also recommended that the researchers for this project work closely with other organizations conducting similar work, which include two private consulting firms and the Army's Cold Weather Research Labs.

The other portion of this project was to develop a conceptual model of a predictive maintenance system. The interest in predictive maintenance arose from the snowplow simulation study. It was expected that the simulation model would include snowplow breakdowns, but no data was available to characterize this type of event. Although the plows are subjected to preventive maintenance, there is no predictive maintenance program, which raised concern regarding the potential breakdowns during a snow event. This study was mostly exploratory in nature, but yielded some surprising results. The first is that the research literature on predictive maintenance for vehicles is fairly small, and tends to focus instead on industrial and manufacturing equipment and machinery. The second surprising result is how few departments of transportation have predictive maintenance programs for their vehicles. The Pennsylvania DOT stands out, as it has had a predictive maintenance program in place for several years. It has taken several years to realize the benefits of the program as historical data for each vehicle has been collected. Other DOTs, such as Michigan, conduct predictive maintenance on selected equipment. Michigan performs predictive maintenance on snowplows. Similar to Pennsylvania's experience, Michigan also realized benefits from the predictive maintenance on snowplows, reporting far fewer breakdowns and higher service levels.

It is recommended that MnDOT, through a fleet management program, categorize equipment to identify which equipment should have preventive maintenance programs. Next, it is important to determine if the organization is ready to implement a predictive maintenance program and, if so, to identify the vehicles to use for a pilot program. It is also recommended that DOTs who have successfully implemented such programs be contacted to arrange a site visit, and to contact software vendors to identify potential software that will serve not only the needs of the fleet manager, but also the decentralized shops where the maintenance is performed.

Chapter 1

Introduction

1.1 Background Information

This project is a continuation of work which was begun in fiscal year 2001. As a result of this first project, several needs for vehicle management were identified. One need was in the area of snowplow operations and resource management, which consumed 25% of the maintenance budget during the 2001-2002 winter season. The other need directly related to snowplow operations was vehicle maintenance and repair information.

Snowplow operations involve more than simply sending out a fleet of snowplows when a snowflake hits the ground. Depending on the weather forecast, snowplows may be deployed prior to an event, such as a freezing rain, to apply chemicals to the pavement and return to the shop before the rain even begins. Another event may involve a lot of blowing snow, requiring drivers to plow only the downwind shoulder of the road to allow the snow to blow off, avoiding the application of treatment (salt) which could cause snow to accumulate. A more common event, such as a light or heavy snowfall, will require that plows be deployed when the event begins, and continue after the event ends until bare pavement is achieved. One commonality between each of these scenarios is that all snowplows must undergo a pre-inspection before they leave the shop, and a post-inspection when they return. Otherwise, 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 more complex than one might initially suspect. Routing and scheduling snowplows require the consideration of numerous variables, and turns out to be more complicated than the traditional vehicle routing problem. The first year of this project proved to be a fertile learning ground, and the research conducted during 2002/2003 are a direct result of the findings from the first year of research.

This current project addressed the issue of snowplow operations, including routing and resource management. Snowplow scheduling is really fairly simplistic: when it snows, send a plow and a driver. Snowplow routing, on the other hand, is more complicated considering the numerous ways in which a route can be managed. A route may use two plows which may or may not drive in tandem. The plows may or may not perform the same activities, with one plow tending to the highway and the other plowing crossovers and turnouts. The plows may or may not go in the same direction. Depending on the weather conditions, they may or may not make a complete pass before returning to a reloading point. The route length could also vary. These variables create havoc for developing clean analytical solutions. Therefore simulation modeling will be used to capture the various activities in order to assist decision makers with route planning.

A second important finding from the first year was the need for vehicle information to assist with preventive and predictive maintenance activities. Although it was expected that data could be gathered to characterize statistical distributions for time between

failures, repair times, and cost, the existing database does not contain information necessary to perform this analysis. Specifically, it lacks hours of vehicle operation, recording only the time and date of repair and in many cases, vehicle mileage. Labor hours, labor cost, and repair times are available, but this information is tedious to extract from the system that has been used over the past year and a half. Therefore, this study proposes to develop a conceptual design for a support system for tracking vehicle maintenance information.

These two findings – the complexity of snowplow operations management, and the need for better tracking of vehicle maintenance information – are intertwined with existing information systems and other transportation information projects. Therefore, ongoing coordination with other projects within the Minnesota Department of Transportation (Mn/DOT) is essential. Specifically, these include the Safety Automated Intelligent Locator project (SAIL II), Road Weather Information System (RWIS), and the vehicle maintenance information system (M4). Additionally, other decision support systems were also be considered, such as the Surface Transportation Weather Decision Support Requirements (STWDSR) (Mitretek, 2000).

This project focused on two activities: the development of a simulation model for assisting with snowplow operations, and the development of a conceptual design for a predictive maintenance system. The simulation model was developed using ProModel®, which ran from a customized user – interface on an Excel spreadsheet (programmed in Visual Basic).

1.2 Research Goals

The goals of this research are to:

- Develop a simulation model of selected snowplow routes in District 1, which will meet the needs of the user for route planning, ultimately improving the efficiency and reducing the cost of winter road maintenance activities.
- Develop a conceptual design of a support system for vehicle maintenance which will assist with predictive and preventive maintenance.
- Coordinate with ongoing activities associated with decision support within Mn/DOT and the Federal Highway Administration (FHWA).

1.3 Previous Work

This research stems from previous work that was conducted during 2001-2002. During this time period several tasks were completed. They were:

1. Assess the needs of end-users, including snowplow drivers, dispatchers, and vehicle maintenance personnel, and the motoring public
2. Quantify the relationship between factors that affect snowplow operations

3. Develop vehicle maintenance information
4. Identify and investigate other state DOT decision support systems
5. Develop a coordination plan with similar activities on other projects
6. Investigate various modeling and software options
7. Develop a preliminary model of a decision support system

Task 2 has become an ongoing activity, as the level of detail can vary considerably depending on the approach taken to snowplow operations management. Task 3 was also not completed during the first year, as it proved to be more complex and larger in scope than originally expected, and was therefore more fully addressed during FY 2003 as a separate study, which is discussed in Chapter 3.

First and foremost, the previous work conducted during FY 2002 helped researchers to gain a much greater understanding of snowplow operations and the information needed to effectively maintain roads during the winter. The two most important results of this previous year of work are the development of a simulation model, which is a preliminary model of a decision support system, and the identification of the information needs for preventive and predictive maintenance for snowplows.

1.4 Basic Approach

For developing the simulation model, the users were interviewed, and the user-interface developed, and other modifications made. Specific tasks included:

1. Validate the simulation model.
2. Expand the model to include routes selected by Mn/DOT.
3. Incorporate costs into the simulation model.
4. Improve the user interface.
5. Perform additional simulation of scenarios identified by MnDOT.

In order to develop a conceptual design for vehicle maintenance, a thorough literature review was conducted, process maps were developed, user needs identified, and other agencies contacted. Specific tasks included:

1. Conduct a literature review.
2. Develop process maps.
3. Identify essential information for vehicle maintenance.

4. Identify user needs via interviews and surveys.
5. Develop a conceptual model for data gathered and reports generated.

1.5 Report Organization

Chapter 2 presents a more detailed discussion of the snowplow simulation model, including the model development as well as verification and validation issues.

Chapter 3 discusses the other portion of this project – preventive and predictive maintenance.

Finally, Chapter 4 presents the results, conclusions, and recommendations from both portions of this project.

Chapter 2

Simulating Snowplow Operations

2.1 Methodology and Approach to Model Development

2.1.1 Introduction

The simulation model developed to depict snowplow operations consists of two parts: a model that runs in the ProModel simulation software, and user interface driven by MS Excel's VBA. The methodologies for developing the two parts of the model are therefore the focus of this chapter. The first section discusses the steps taken during the development of the simulation model. It presents the details on each of the steps and results achieved for each step. The second section dwells on the approach to the user interface design. Again it discusses the processes that led to the design of the user interface.

2.1.2 Simulation Model Development

Although earlier prototype simulation models were developed which depicted snowplow operations, their primary purpose was to determine future directions for development. Additionally, this model was developed with more attention to validation issues, the user, and potential expansion to include other features. The steps in developing this model are shown in Figure 2.1

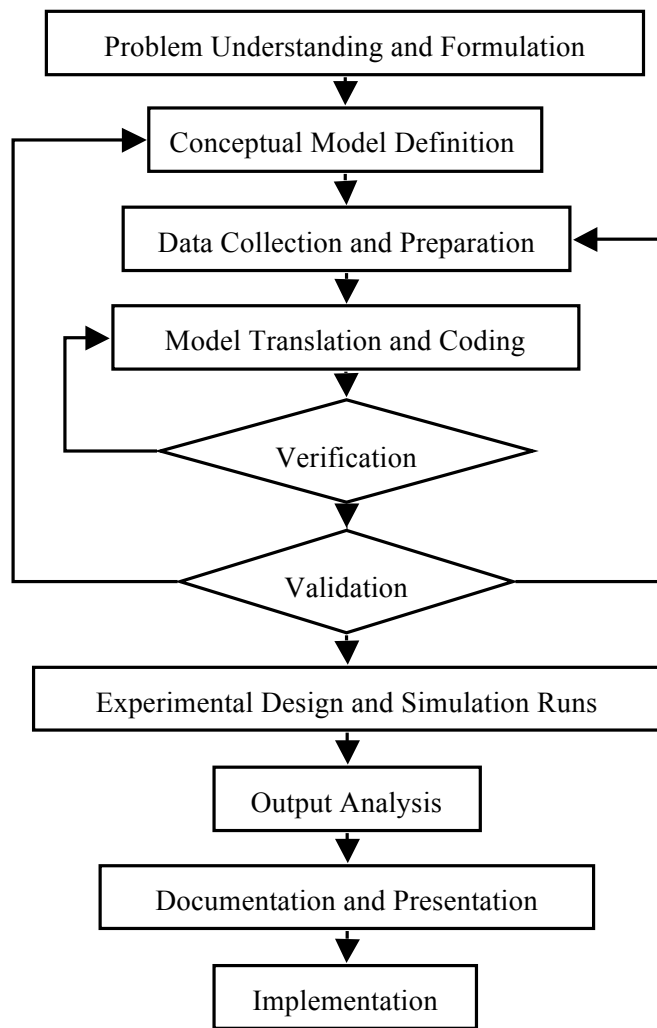


Figure 2.1.Steps in Model Development

2.1.2.1 Problem Understanding and Formulation

The overall approach to defining and formulating the problem was thus to seek the constant and active involvement of Mn/DOT personnel involved in snow and ice removal operations at the Virginia sub-district. Specific steps taken were as follows:

- i. Meetings were organized with Mn/DOT personnel (area supervisors, dispatchers and drivers) to discuss and outline possible questions that the model should be capable of solving. This was to ensure that the problems being addressed in the study met the needs of the end users and that the modeler and the end users understood and agreed on the problem formulated.

Initial meetings were used to gain a thorough understanding of the system to be simulated.

- ii. Interviews were administered to identify the needs of the potential users and benefits to be derived from use of the model. Questions asked were specific, yet open ended, which allowed for more discussion.
- iii. Key questions that the model should answer were then identified together with Mn/DOT personnel. Additional capabilities that would be desirable of the model in the future were also discussed. The approach was to limit the model to answer the most important questions thereby making it simpler from the outset. It was also to ensure that flexibility for future upgrade was built into it.
- iv. An understanding of the system was summarized and reviewed with the different personnel involved in snowplow operations and end users of model. This was to ensure that the system was defined as-is, and not misrepresented. The review also ensured that all the essential components of the system were captured.

As a result of these meetings, interviews and discussions, a better understanding of the problem and an appreciation of the operational characteristics (processing logic, operational rules, and operating schedules) of the system to be simulated was reached. This was important for setting objectives and measures of performance of the system under simulation.

Problem Definition/Objectives

Figure 2.2 presents an overview of snowplow operations at the Virginia sub-district of Mn/DOT. Area supervisors receive weather forecast information about an impending storm. Forecasted storm characteristics include its start time, duration, end time, accumulation rate, visibility, air temperature, dew point, relative humidity, wind speed and direction. They also receive forecasted information on the road conditions which include pavement temperature, surface conditions (wet, dry or frozen), sub-surface temperature, and freezing point of road surface. Snowplow drivers are called in when the chances of the storm are greater than forty percent (40%). When drivers arrive, they check to ensure that the snow plows are “road-worthy” and fit to go on the road once the storm hits. Plows are then filled with salt, sand and brine.

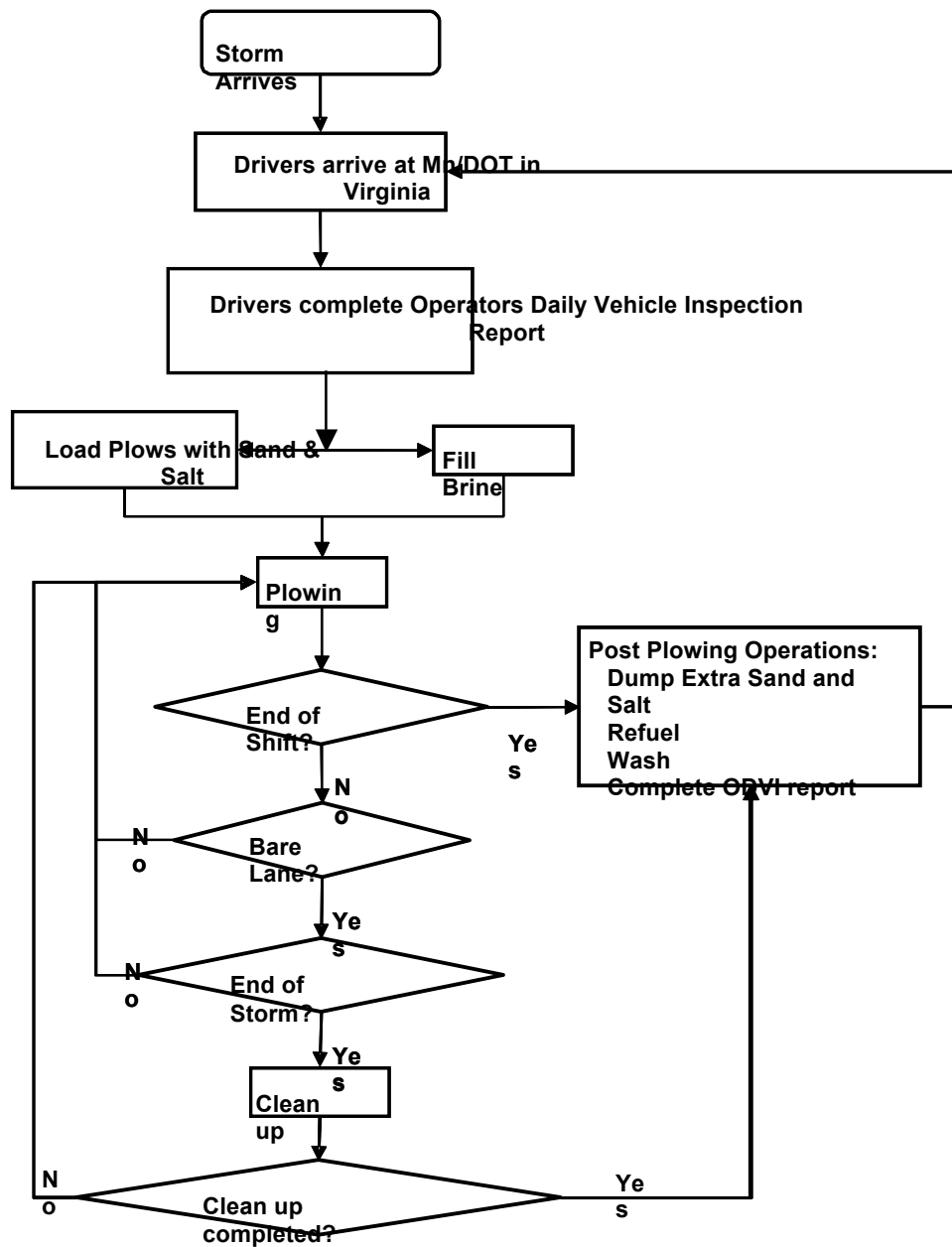


Figure 2.2. Overview of Snowplow Operations

Plows start plowing their assigned routes when snow accumulation on the road exceeds the critical depths. However to ensure a high degree of public safety, and also for a better public image, plows may start plowing immediately a storm hits. Plowing of the roads continues during and after the storm is ended. The first task is to clear the roads so that bare lane or bare pavement is achieved. A plow may go to a re-loading point to load sand and salt. Clean-up passes on crossovers, shoulders and bridge decks are then undertaken to ensure that these areas are clear of any snow accumulation. This is done after bare lane has been achieved and maintained, and when the storm has ended.

If a storm continues after a shift has ended, the driver returns to the garage where they dump extra salt, refuel, wash the plows and complete the operator's daily vehicle inspection report (ODVI).

Problem Formulation

Based on the problem description, the problem for this simulation study was formulated as follows:

- i. The plowing process was identified as the sub-system to be simulated. The plowing process refers to the actual plowing of the routes during and after a storm event.
- ii. The goal was to simulate plowing operations from the time a storm starts until it ends, and until bare lane or bare pavement has been achieved. Plowing starts immediately a storm event starts. When the storm ends, plows make an average of two (2) passes to achieve bare lane.
- iii. Specific questions to be answered were:
 - a. For a given storm, how many passes are made to get to bare lane?
 - b. How long does it take to clear a route until bare pavement is achieved?
 - c. How much material is used for a given storm, and at what cost?
 - d. How much labor is used, and at what cost?
- iv. Performance measures are outlined in Mn/DOT guidelines for winter maintenance operations. The output of the simulation will be evaluated against the primary performance measure, time to bare lane.
- v. The model was to be validated using historical storm events with known answers to the questions posed in (iii) above.
- vi. The model has the capability of simulating 5 routes with varying weather conditions which include rate of snow accumulation, moisture content, and pavement temperature.

The above processes and results lead to the definition of a conceptual model.

2.1.2.2 Conceptual Model Definition

This phase of the study is characterized by four steps, each of which is elaborated in greater detail in the next section.

- i. The elements that drove the system were determined. The entities which flow through the system were defined. Stations or locations where something was done to or for the entities were also identified.
- ii. The basic flow patterns of entities through the stations were defined using flow diagrams.
- iii. A process flow chart was developed to show the routing logic.
- iv. The interrelationship between the elements and the various factors that affect operations were discussed and identified. Tables and concept maps were developed to depict these relationships.

Elements of the Snowplowing System

The elements that define the system are shown in Figure 2.3. The elements defined represent the entire range for the snow plowing system at the Virginia sub-district of Mn/DOT. However, the model developed in this study focuses primarily on plowing activities on routes.

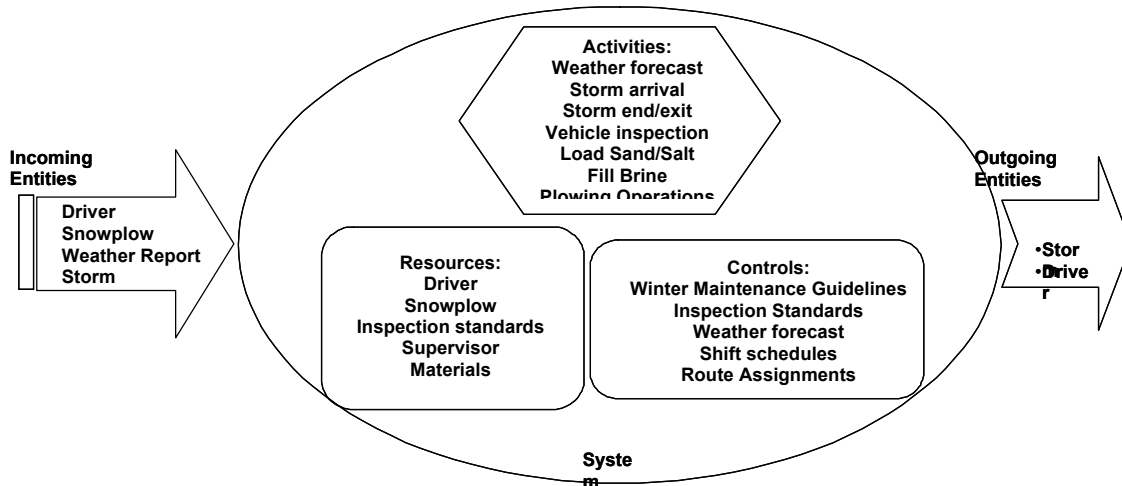


Figure 2.3. Elements of the Snowplow System

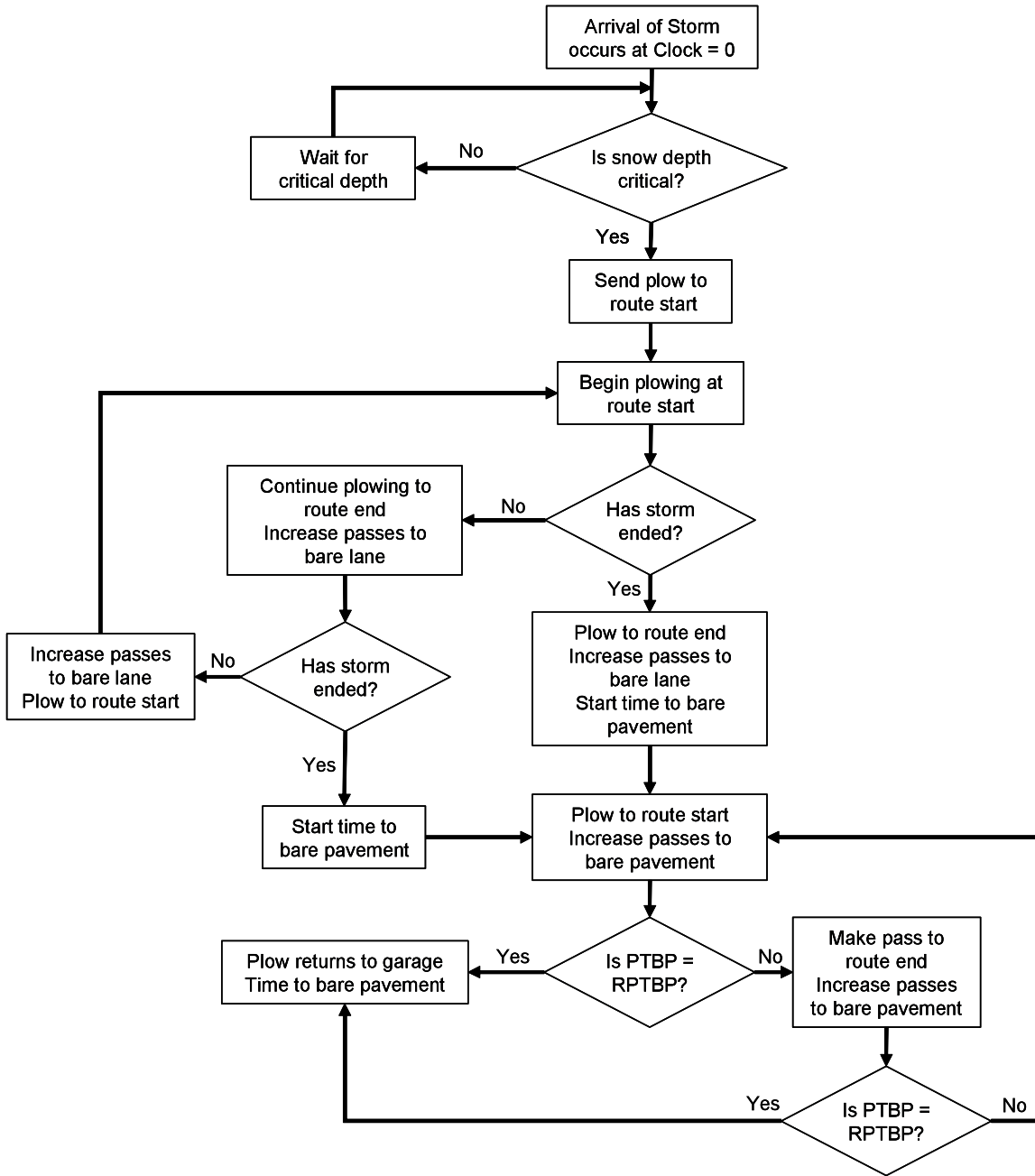
The elements that drive the route plowing system were categorized into entities, activities, resources and controls. Table 2.1 also presents the objects identified for the above system in simulation terminology.

Table 2.1. System Objects Presented in Simulation Terminology

System	Entities	Attributes	Activities	Events	State Variables
Plowing System	Driver	Particular route; shift	Vehicle inspection Plowing Damp sand and salt Fill brine	Arrival at Mn/DOT garage; depart to plow route; return to Mn/DOT garage	
	Snowplow	Particular route; speed; capacity	Plowing to bare lane Plowing to bare pavement Spreading sand/salt	Leave garage to assigned route; Plow assigned route; return to garage	Number of passes to bare lane; time to bare pavement; cost of materials used
	Storm	Start time; duration,		Arrival; departure/end	
	Weather Report	Storm event		Arrival	

Logic for a Storm Event

Figure 2.4 shows an event diagram for a storm arrival and exit, with plowing operations at the beginning and end of a typical route.



Legend

PTBP = passes to bare pavement or bare lane

RPTBP = required passes to bare pavement or bare lane

Figure 2.4. Logic for a Storm Event

Concept Map

The concept of the model was developed around the speed of the plow during a plowing operation. To do this the various factors that affect the plow speed were determined. The interactions and interrelationships are depicted in Figure 2.5.

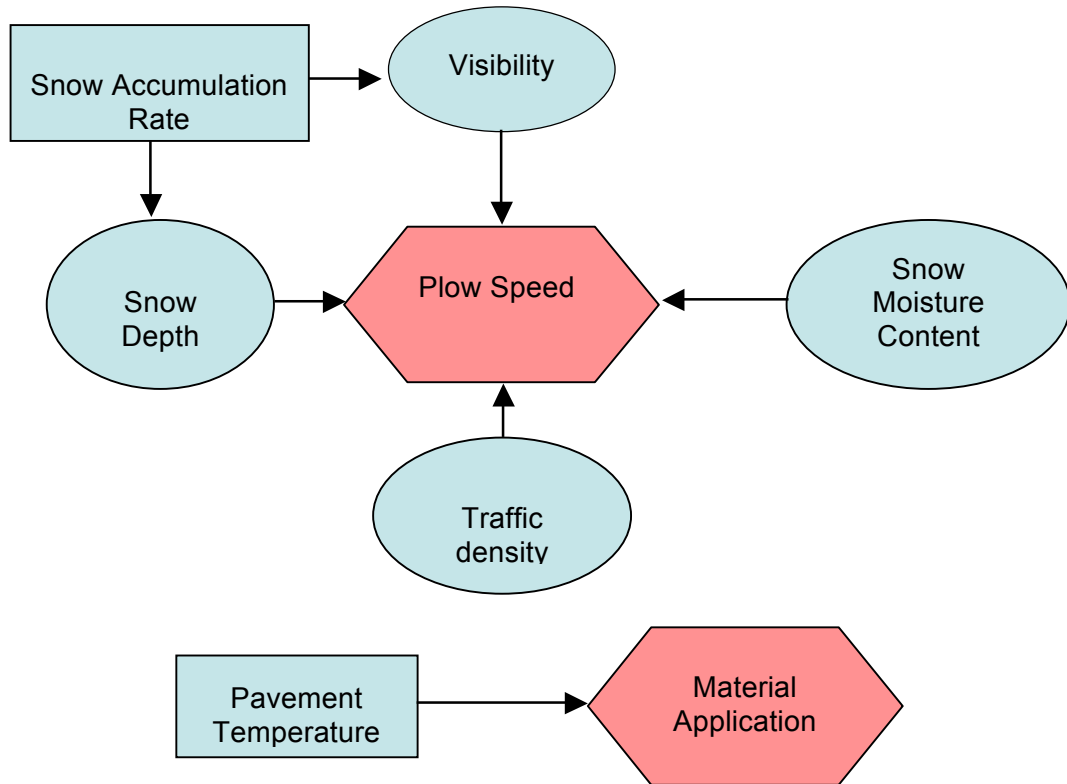


Figure 2.5. Concept Map of Factors Affecting Plow Speed and Material Application

The key factors that affect plow speed were traffic density, snow depth, visibility, and moisture content of falling snow. Other variables affecting snow and ice removal from the surface were snow accumulation rate, humidity, air temperature, pavement temperature, wind speed and direction, time of day, and the sun. Details of how these affect plow speed are provided in Table 2.2 below.

During the plowing process, the speed at which the plow moves is determined by the moisture content of falling snow. Dry, fluffy and low moisture-laden snow can be easily plowed off the road. This is based on the assumption that the wind is either not strong enough to blow the snow to create visibility problems or it's blowing parallel to the plowing operation, thereby not having any effect on the speed at which the plow is moving. The snow accumulation rate affects both depth and visibility which, in turn, affect plow speed. The traffic density will also determine how fast the plow can clear the snow of the road. Essentially, the pavement temperature governs how much chemicals are applied onto the roadway.

Table 2.2. Relationship Between Weather Conditions and Plowing Operations

Variable	Conditions & Levels	Operations		Effects (e.g. on plow speed)
		Material Application	Other activity	
Moisture Content	Low	See Table 2.4		Plow speed not greatly reduced
	High	See Table 2.4		Plow speed is reduced
Snow Depth	Accumulating faster than plowing rate	Apply chemicals before onset. Sand if snow is hard and dry		Impedes plow speed
Type of storm	<ul style="list-style-type: none"> ▪ Heavy wet snow ▪ High moisture content. 	Keep chemicals at critical spots. Keep plowing.	Require plow working in tandem.	Reduces plow speed if accumulating faster than plowing rate.
	<ul style="list-style-type: none"> • High winds • Light snow • Low moisture content 	Sand may be applied if snow is dry and hard	Do nothing or allow winds to blow off snow.	Plow speed slowed by snowdrift and impaired visibility.
	Freezing Rain (Sleet formation)	Anti-icing applied before or just at the start of the storm.	Plow when salt reacts and snow/ice becomes mushy	Reduces plow speed
Air Temperature	< 0 ⁰ F and falling; freezing rain, sleet formation, accumulation of snow and ice.	Apply salt (see Table 2.4)	Plowing required when snow becomes mealy and slushy	Heavy packed snow/ice reduce plow speed
	0 – 15 ⁰ F	See Table 2.4		
	> 15 ⁰ F and rising	See Table 2.4		Plowing speed may increase when snow starts to melt
Pavement temp	> 32 ⁰ F	See Table 2.4		
	< 32 ⁰ F	See Table 2.4 Must have chemicals on pavement to prevent freezing and sleet formation		
Road Surface	Wet and sticky	Apply salt.		
	Dry	Sand		
Wind direction (drifting)	Crossing			Visibility problems may slow down plowing
	Parallel			May facilitate plowing
Wind speed	Low (< 10miles/hr)			May promote good visibility.
	High (> 10 miles/hr)			Visibility may be impaired with blowing snow. Plowing may be aided by drifting snow.
Humidity	Low			Encourages melting and may facilitate plowing.
	High			Prevents melting and slush formation. Packed snow may be difficult to plow.
Traffic volume	6:00am – 6:00pm	More material application (20% loss of chemicals)		Speeds slower due to high traffic volumes.
	6:00pm – 6:00am			Best times to operate (low traffic volumes)

2.1.2.3 Data Collection and Preparation

Data collection is the most crucial and time-consuming stage in the model building process [1] [2]. Robinson and Perera [3] explain that this is because of the influence that the data has over the level of accuracy attainable by the model. Having good data to drive the model is just as important as having a sound model logic and structure [4]. It is therefore important that effort is expended after the model conceptualization stage to accurately determine the data requirements. There is a constant interchange between model construction and input data collection. Thus the data collection process and the construction of the model is an iterative process. As further insight is gained during the model development, and the complexity of the model changes, the required data elements may also change [5]. Several guidelines and steps for collecting specific data for a simulation study have been discussed by Harrell et al. [6] and Vincent [7] for cases where simulation data is available. Where data is not available, expert knowledge of actual or expected behavior and established operational guidelines may be used to make educated guesses [5] [7]. However, because of the highly subjective nature of this type of data collection, the simulation model could be error-prone and may require further input modeling techniques to ensure that an appreciably “good” model has been developed. Some of these techniques include performing a sensitivity analysis of the input model on output results. Where possible, guidelines given in operations manuals may be used in fixing central values around which deviations may revolve.

The process of data gathering involved several visits to the Virginia Sub-district office. Interviews were held at the start of the study with area supervisors to determine the needs of Mn/DOT employees involved in the snow and ice removal process, including snowplow drivers, dispatchers and maintenance personnel. Specific steps to collecting essential data for the simulation model therefore included the following:

- i. Data needed was determined. The conceptual model, entity flow diagrams and the description of operations developed above provided the scope and level of detail required. Data requirements were then presented to and discussed with Mn/DOT personnel.
- ii. Existing databases of Mn/DOT were examined and required data extracted where possible.
- iii. Expert opinions were used to gather estimates for various activities where data was not available. This took the form of interviews and discussions with key Mn/DOT personnel in the presence of others who could serve as a check on estimates provided by each other.
- iv. Other external sources were examined for data relevant to snowplow operations in the district. Such data was to serve to fill any gaps that might exist as well as provide a check on data gathered from Mn/DOT.

- v. Spreadsheet templates were developed to summarize essential input data for the model from all these data sources.
- vi. Data collected were used to specify operating procedures and transformed into probability distributions for the random variables that were used in the model. Appropriate input probability distributions were then selected for each stochastic input variable and corresponding parameters estimated.

Expert opinion and the personal experiences of Mn/DOT personnel were used to ensure data accuracy, reliability and validity.

Input Data Preparation

Data collected and prepared for the simulation model are presented below. Table 2.3 contains the five routes that were selected for simulation. It shows their length in lane miles, type of route classification, number of ramps and the number of re-loading points of each route. Ramps introduce a delay in the time it takes to plow a route. Similarly, the re-loading activity also introduces an additional time delay in plowing operations. Ramps and re-loading can therefore be modeled as delays in the processing logic of plowing operations if time estimates for plowing ramps and re-loading can be obtained.

Table 2.3. Route Characteristics

Route Number	Route Length (lane-miles)	Route Type	Number of Ramps	Number of Reloading Points
201	81.92	Rural Commuter		2
202	51.54	Urban Commuter	1	1
207	26.42	Rural Commuter		
213	34.06	Rural Commuter		1
215	53.04	Rural Commuter		1

Table 2.4 contains the pre-wet material application rates used by the Virginia sub-district. This will be used in the simulation model when material has to be applied. Where the application rate is a range, the average application rates are used. However, probability density functions can be developed for these ranges in order to capture such stochastic application rates. The values have been generated partly from the recommendations of the Salt Institute and partly from the experiences of area superintendents in the district. Table 2.5 presents the general recommendations of the Salt

Institute for material application. The Salt Institute values are provided in the model as an option so that districts within the state which use these guidelines can easily use the model.

Table 2.4. Material Application Rates used at Virginia, Minnesota

Pavement Temperature (°F)	Weather Conditions	Pounds/Two lane mile		Application Frequency
		100% Salt	50% Salt	
Above 30	Snow	200 - 400	400 - 800	As needed
	Freezing Rain	200	400	As needed
25 – 30	Wet Snow	400 – 500	800 – 1000	As needed
	Freezing	300	600	Initial
	Snow	200	400	Repeat
20 – 25	Wet Snow	500 – 600	1000 – 1200	Initial
		250	500	Repeat
	Freezing Snow	400	800	Initial
		300	600	Repeat
15 – 20	Dry Snow	400	800	Sand Hazard Area
	Wet Snow	600 - 800	1200 - 1600	Sand as needed
Below 15	Dry Snow			Sand Hazard Area

Table 2.5. Material Application Rates Recommended by the Salt Institute

Pavement Temperature (°F)	Road Surface	Pounds/Two lane mile
		Salt
Near 30	Wet	500
Below 30 or Falling	Wet or Sticky	400 – 500
Below 20 and Falling	Dry	500 – 600
Below 20	Wet	400
Below 10	Packed ice or snow	800

Source: Salt Institute, 1999

Table 2.6 also contains plow speeds generated as a result of the combined effect of moisture content and snow accumulation rates. These are values based on expert opinion. The three categories of moisture content are low (less than 10% water content), medium (water content above 10% but less than 90%), and high (water content above 90%). Relative humidity values were used as surrogates for the moisture content because the moisture content of the falling snow for storm events were not available. The relative humidity value associated with a storm event was therefore assumed as an estimate of the moisture content. Details of how these values are used are discussed under section 4.2.

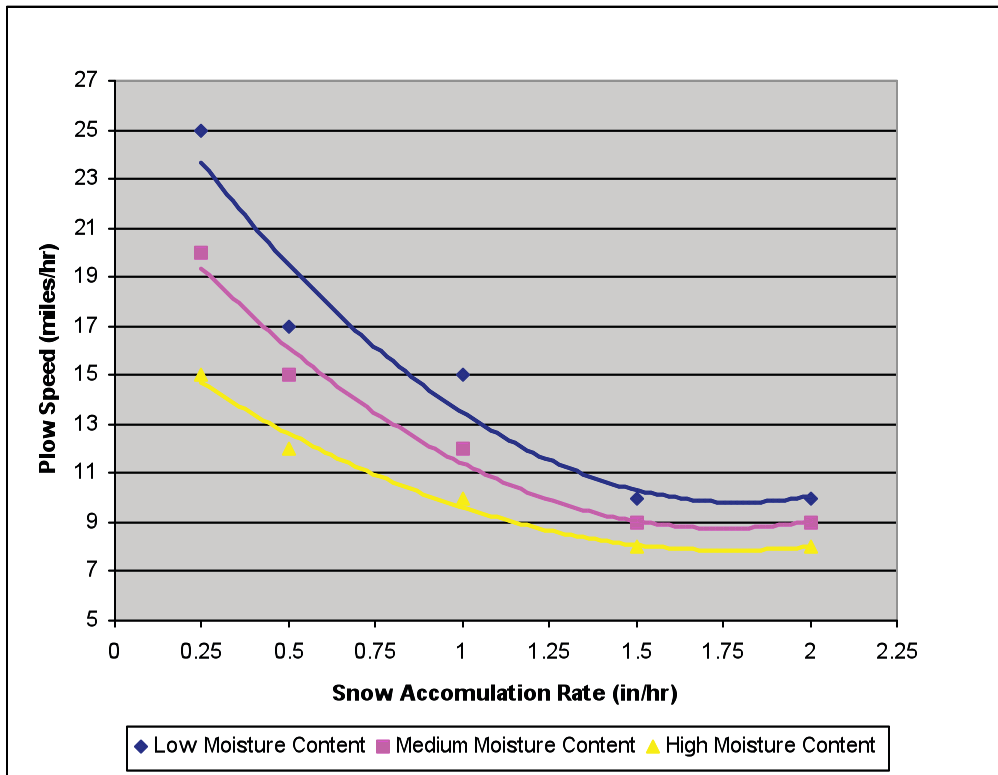
The maximum plow speed of 25 miles per hour is what is recommended and not to be exceeded when the moisture content is low (that is over 90% dry content) and during sanding. Plow speed of 8 miles per hour is the lowest that plowing operation can be undertaken against high moisture content and accumulation rates above 1.0 inches per hour. Below such speeds, gang plowing may be used or plow driver will have to lift parts of the snowplow in order to generate additional speed. Such operations are not covered within the scope of this thesis.

Table 2.6. Plow Speeds Based on Moisture Content and Snow Accumulation Rates

Moisture Content	Accumulation Rate (inches/hr)	Plow Speed (miles/hr)
Low	0.0 - 0.25	25
Low	0.25 - 0.5	17
Low	0.5 - 1.0	15
Low	Above 1.0	10
Medium	0.0 - 0.25	20
Medium	0.25 - 0.5	15
Medium	0.5 - 1.0	12
Medium	Above 1.0	9
High	0.0 - 0.25	15
High	0.25 - 0.5	12
High	0.5 - 1.0	10
High	Above 1.0	8

Figure 2.6 shows the patterns of plow speeds against different moisture conditions and accumulation rates. The trend is that plow speeds decrease with increasing accumulation rates. For a given accumulation rate however, speeds increase with decreasing moisture content. This holds true if the wind direction is parallel to plowing and does not cause visibility problems.

Figure 2.6. Plow Speed vs. Accumulation Rate by Moisture Content



Though the plow speeds given in Table 2.6 are deterministic, the reality is that these speeds may vary during the plowing operation. The deviations or variations have not yet been determined. If the deviations were known, then the plow speeds could be stochastically modeled to reflect what will pertain in the real snowplow system. Discrete-event simulation models usually have random components that mimic the probabilistic nature of the system under consideration [8].

Input Data Modeling

Because it was not possible to capture the variation in speed, the model was tested using a triangular distribution with minimum and maximum speeds of +/- 10%, shown in Table 2.7

Table 2.7. Plow Speeds and Parameters using a Triangular Distribution

Moisture Content	Accumulation Rate (inches/hr)	Plow Speed (miles/hr)		
		minimum	mode	maximum
Low	0.0 - 0.25	23.5	25	27.5
Low	0.25 - 0.5	15.3	17	18.7
Low	0.5 - 1.0	13.5	15	16.5
Low	Above 1.0	9	10	11
Medium	0.0 - 0.25	18	20	22
Medium	0.25 - 0.5	13.5	15	16.5
Medium	0.5 - 1.0	10.8	12	13.2
Medium	Above 1.0	8.1	9	9.9
High	0.0 - 0.25	13.5	15	16.5
High	0.25 - 0.5	10.8	12	13.2
High	0.5 - 1.0	9	10	11
High	Above 1.0	7.2	8	8.8

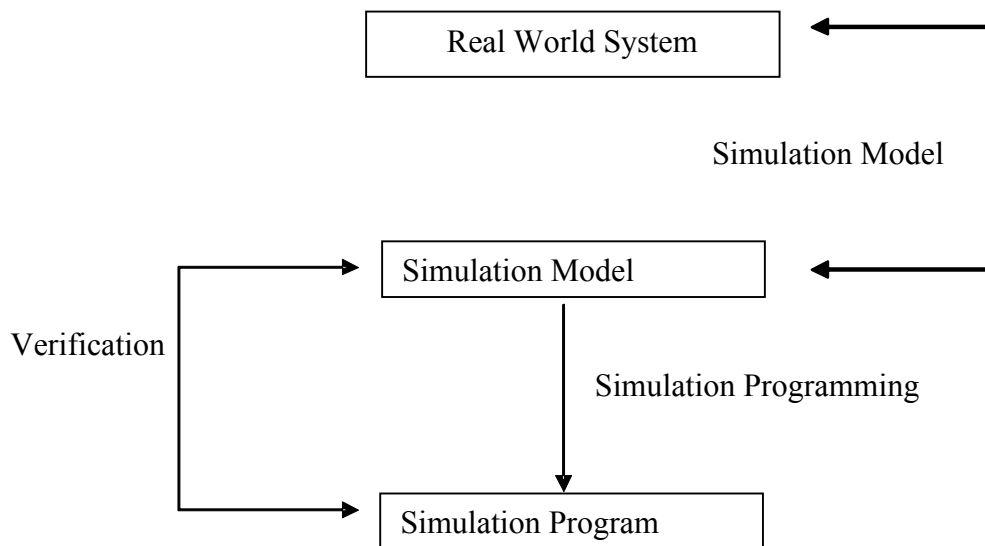
2.1.2.4 Model Translation and Coding

At this stage the conceptual model is translated into a computer-recognizable language or format. The translation can be done using a general purpose language or a simulation package. The simulation package, ProModel®, was selected for this research. ProModel is a discrete-event simulation languated. Appendix A presents program listing.

2.1.2.5 Verification

Verification is simply confirming that the model functions the way it was intended to. It is the process of determining whether the simulation model correctly reflects the conceptual model. In essence, verification is concerned with building the model right [5] [9]. It is the first step towards the development of a sufficiently credible model that produces solutions that are accepted and used by decision makers. It can also been seen as a quality assurance step to increase the chances of developing a successful model. Figure 2.7 depicts the process of verification as interplay between the simulation model and the computerized format of the model.

Figure 2.7. Verification and Validation



Several verification techniques have been discussed by Balci [9], Shannon [4], Maria [10], Banks et al. [5], Kleijnen [11] and Harrell et al. [6]. A summary of the key steps suggested and which were adapted for verification of this model are presented below. They include the following:

- Adopting good programming practices to compile processing logics and programs at each step using the compiler features of the simulation software.
- Evaluating some intermediate simulation results manually.
- Substituting constants for random variables and manually checking results. That is using deterministic data with known results and checking to see if the model produces same results.
- Tracing the processing and executing logic of the computer software used for model translation.
- Verifying that animation imitates the system and behaves correctly.
- Varying input parameters over their acceptable range and checking the output.
- Performing statistical analysis to compare the output with its known expected value.

The model was verified using each of these techniques. Appendix B presents a detailed discussion of the techniques used for this model.

2.1.2.6 Validation

A model that has not been validated may lead to wrong decisions. Validation is therefore an essential and crucial part of model building. While verification has to do with getting the model right, validation has to do with building the right model.

A number of techniques for the validation process have been suggested. They are summarized as follows [6] [10] [11] [12]:

- i. Specify the level of accuracy desired of the model's output variables of interest for the model's intended application.
- ii. Check the validity of the model incrementally as the development process progresses.
- iii. Test the model with real-world data as input and output.
- iv. Perform statistical inference tests and submit the model for examination by other experienced modelers.
- v. Perform a sensitivity analysis to determine how model parameters react to changes in model input variables and whether output agrees with the opinion of the experts.
- vi. Assess end user confidence and address any concerns.
- vii. Develop validation documentation for inclusion in the model documentation.

To ensure that a high degree of realism was built into the model, the end users and experts (Mn/DOT personnel) played a key role in the model development and validation process. This was also to ensure that the model had a high face-validity. The validation process was therefore joint effort between the modeler and the end users. Specific steps included the following:

- i. The model was presented and discussed with the end users as its development progressed.
- ii. Visualizing the animation of the model to verify and validate the operational behavior of the model against the actual system.
- iii. The model was run with some known input conditions and output results of the system and compared to see if the results match.

- iv. Statistical inference tests were conducted on simulated results against the expected or obtained results from historical data.

Results of the validation process are presented and discussed in Chapter 4.

2.1.2.7 Experimental Design and Simulation Runs

After verifying and validating the model, a strategy must be developed to collect and evaluate output data. Some of the issues that are addressed during the experimental design include the following:

- i. Determining performance measures against which output will be compared.
- ii. Identifying input variables that are likely to influence performance measures?
- iii. Determining the length of a run.
- iv. Determining initial conditions for the simulation run.
- v. Determining the number of independent runs.

For this study, the following conditions were established to conduct the simulation runs:

- i. Output will be evaluated against performance targets set in Mn/DOT's winter maintenance guidelines, and past performance reports. The target used in this study is time to achieve bare lane.
- ii. The influence of input variables will not be part of this study.
- iii. The length of a run is equal to the storm duration plus the time to achieve bare pavement.
- iv. Initial conditions assume that all plows and drivers are available at the start of the storm
- v. Five independent runs are sufficient for a reasonable level of accuracy, which is discussed in Appendix C.

2.1.2.8 Output Analysis

Output Analysis included the following:

- i. Calculating numerical estimates of the confidence interval for the performance measures desired over a number of replications

- ii. Establishing that individual output or observations are statistically independent and independently distributed
- iii. Conducting hypothesis tests on the performance measures of interest

A detailed discussion of this output analysis is discussed in Chapter 4.

2.1.2.9 Documentation and Presentation

Program documentation is necessary to understand how the program operates and the underlying assumptions. This allows for easy re-use of the model by the modeler. It also makes it easier for another modeler to easily modify the model for a different purpose. Program documentation has been carried out essentially through outlining the model development steps and explicitly explaining any assumptions that have been made in the process. Details of specific programming logic can be found in Appendix A.

2.1.2.10 Implementation

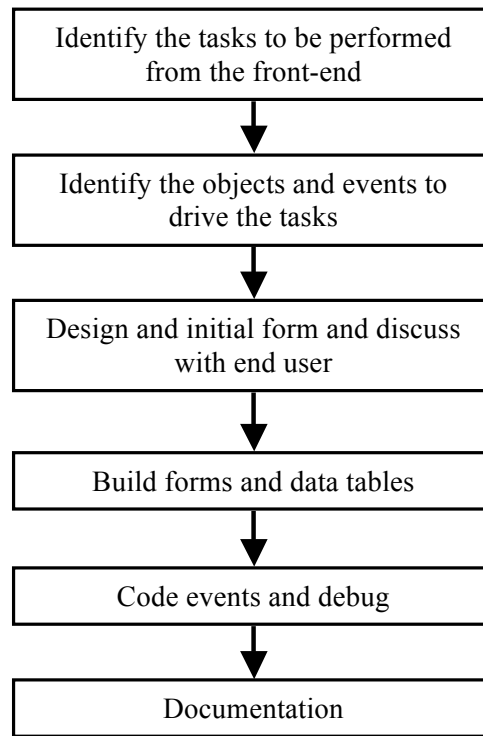
This simulation model is not at the implementation stage yet. Further enhancements to bring it to that stage are in Chapter 4.

2.1.3 VBA User Interface

The user interface also known as the front-end was developed in MS Excel. Excel was selected because it is the most common spreadsheet in ordinary use on personal computers (PCs) and Macs and comes as part of Microsoft Office. It was envisioned that the end users of the DSS will require minimal training and will not be required to purchase any additional software apart from the ProModel simulation software.

The steps leading to the VBA interface follow those outlined in Figure 2.8.

Figure 2.8. Steps for Developing the User Interface



The first step was to identify the tasks to be performed from the front-end. To ensure that the design met their needs, the area supervisors were involved in the task identification process. The underlying problems that the application was to address were discussed. The scope of the interface was also discussed. This was followed by the conceptual design phase. Under this phase, the objects and events that were to perform the different tasks desired by the user were identified. This step led to the development of task-object-events (TOE) charts for the interface. TOE charts outline each task and assign an object to the task in the user interface. Objects include check boxes, option buttons, and text boxes that are placed on the user form. TOE charts for the user interface are attached as Appendix D.

The next step was the design of an initial user form. Figures 2.9 and 2.10 show the main interface screens that have been developed to drive the simulation model.

Figure 2.9. Primary Interface “Splash” Screen

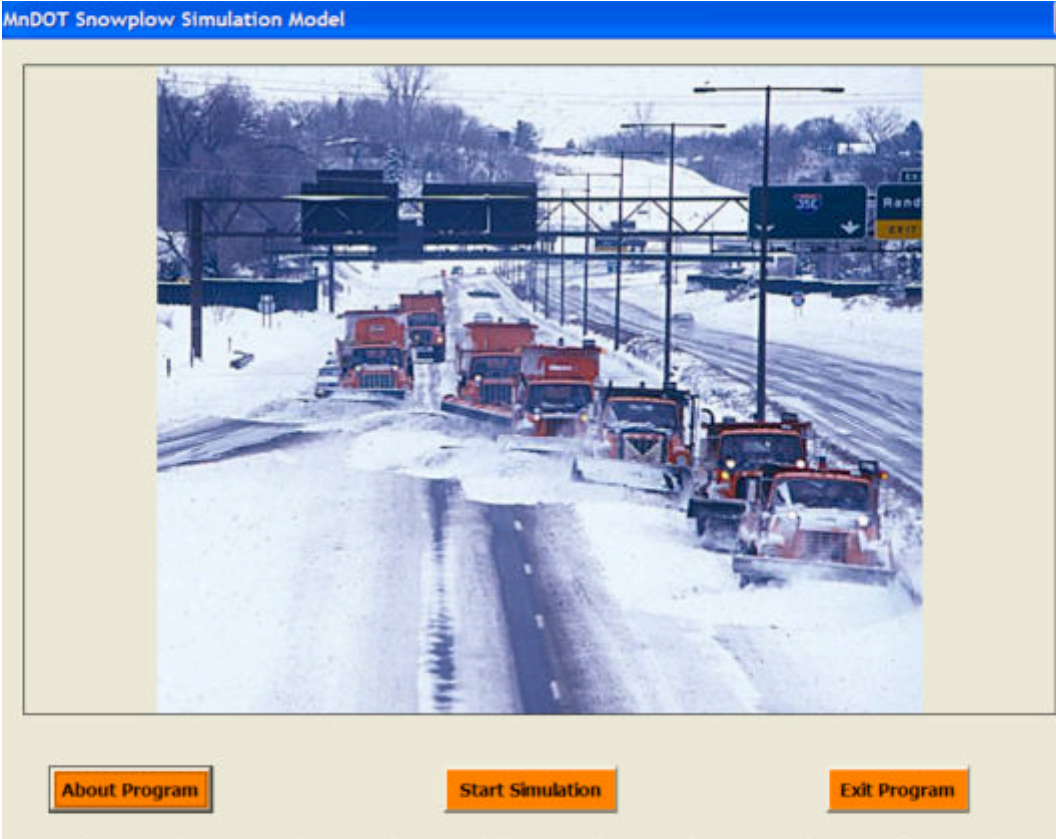
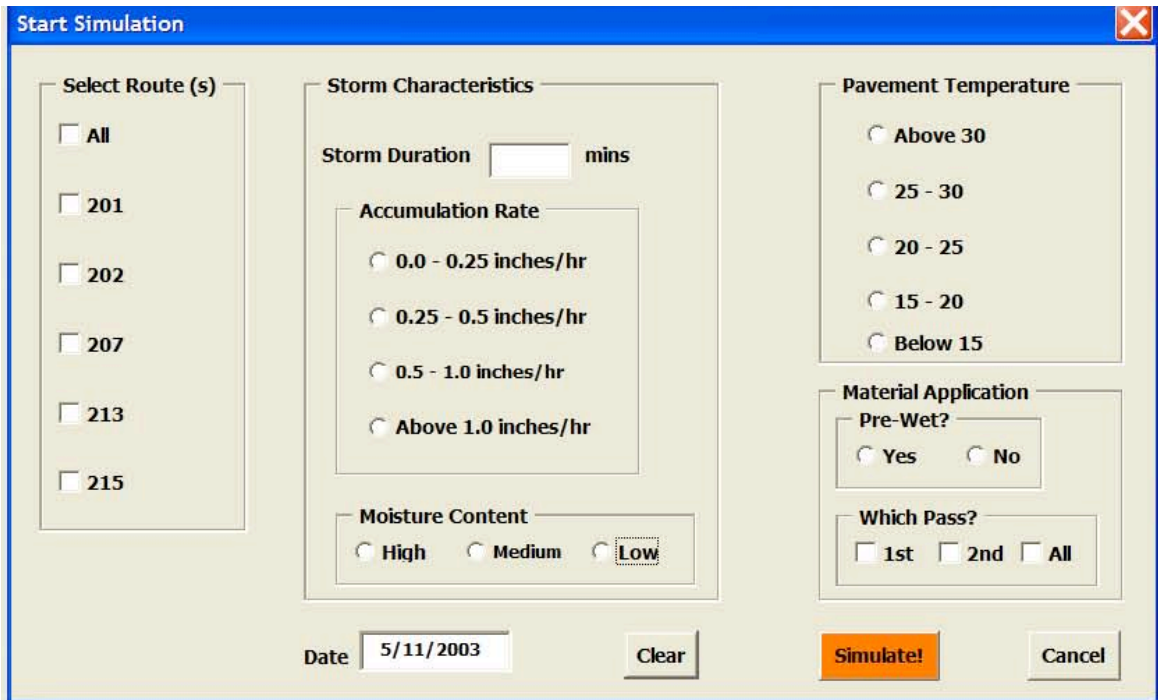


Figure 2.10. User Interface Screen



The model design and data flow are discussed in more detail in Appendix E.

The results from the simulation model are discussed in Chapter 4, and the next chapter discusses the concepts of predictive maintenance.

Chapter 3

Preventive and Predictive Maintenance

3.1 Literature Review: Fleet Predictive Maintenance

Fleet maintenance is one key factor in improving the effectiveness and efficiency of fleet operations, thereby contributing to the overall well-being of the organization. Research shows that vehicle maintenance has become a major cost factor, with costs rising at an average rate of 9% to 11% per year [13]. Sooner or later, every electrical or mechanical device will break down. Maximizing the time between failures, while minimizing the consequences of failures, is the function of maintenance [14].

There are three major types of maintenance: reactive maintenance, preventive maintenance, and predictive maintenance.

Reactive maintenance occurs when the system is kept in service until it breaks down and then be repaired as soon as possible. Under this type of maintenance, the maintenance expenses are high and the downtime is the longest [15].

Preventive maintenance is maintenance that is performed at regularly scheduled intervals. For instance, the operators inspect the vehicle conditions after every 1,000 miles of service. Maintenance is undertaken as soon as the malfunctions are detected in these scheduled inspections. The maintenance expenses are relatively high while downtime is reduced. Preventive maintenance could decrease breakdown, but only when scheduled maintenance finds the problems [16]. Otherwise, the practice of preventive maintenance will be a waste of time.

A predictive maintenance program can forecast system shutdown and maintain the system before it happens. The literature on predictive maintenance focuses on machine tools, not on vehicles. A common preventive maintenance procedure for machine tools is vibration analysis. It is implemented to detect any malfunction indicated by the abnormal vibration and therefore predict the potential failure of the part. Maintenance action can be carried out in time to prevent the vehicle breakdown, avoiding unexpected downtime and reducing maintenance cost [16]. This method emphasizes maintaining electrical or mechanical systems only when it is needed rather than at routine intervals. Predictive maintenance is performed when there are indications that either a component or the system is likely to fail within a short time [17]. However, there is some argument which states that predictive maintenance is not always the better way of maintaining the system or equipment than preventive maintenance (inspection at intervals) [18].

Regardless of the type of maintenance program selected, all equipment is subject to failure at some point in its life. Several researchers have shown that the lifetimes of vehicle parts follow a Weibull distribution [19] [17]. The Weibull distribution is a continuous distribution that was publicized by Waloddi Weibull in 1951. Although initially met with skepticism, it has become widely used, especially in the reliability field. The Weibull distribution's popularity resulted from its flexibility and its ability to be used with small sample sizes. In addition to being the most useful density function for reliability calculations, analysis of the Weibull distribution provides the information needed for troubleshooting and classifying failure types.

The Weibull cumulative distribution function (CDF) and the corresponding probability density function (PDF) are as follows:

$$F_w(t|\bar{\theta}) = 1 - e^{-(t/\eta)^m} \quad \text{for } t \geq 0$$

and

$$f_w(t|\bar{\theta}) = \frac{m}{\eta} \left(\frac{t}{\eta}\right)^{m-1} e^{-(t/\eta)^m} \quad \text{for } t \geq 0$$

where $\bar{\theta} = (\eta, m)$, η the scale parameter and m is the shape parameter.

Because of its flexibility, there are few observed failure rates that can not be accurately modeled by the Weibull distribution. Some specific cases are

1. the time to failure for electronic components,
2. the time to fail for items that wear out, such as automobile tires, and
3. systems that fail when the weakest component in the system fails/

In addition, the analysis of failure data is an important facet in the development of maintenance strategy for the vehicle. Only by properly understanding the mechanism of failure, through the modeling of failure data, can a proper maintenance plan be developed. This is normally done by means of probabilistic analysis of the failure data. From this, conclusions can be reached regarding the effectiveness and efficiency of predictive maintenance. The optimal frequency of maintenance can also be established by using well developed models. These optimal outputs include profit, cost and availability. A variety of statistical models are mentioned in the literature. These include the Markov model [20] [21] [18], the non-homogeneous Poisson process (NHPP) model [23], the homogeneous Poisson process model (HPP) [18], and the proportional hazards model (PHM). Among these models, Markov model is the most frequently used one.

Markov models are some of the most powerful tools available to engineers and scientists for analyzing complex systems. It contains a sequence of random values whose probabilities at a time interval depends upon the value of the number at the previous time. The controlling factor in a Markov Chain model is the transition probability, which is a conditional probability for the system to go to a particular new state, given its current state. This analysis yields results for both the time dependent evolution of the system and the steady state of the system [18] [20] [21] [22].

Regardless of the type of statistical distribution used to model a system, they all have one commonality: data requirements. Data is obtained through monitoring of the condition of the vehicles. The most frequently used monitoring technologies for vehicles are fuel consumption and oil analysis. Those most frequently used for machine tools are vibration analysis and thermography, although it is feasible that they could be applied to vehicle monitoring.

When fuel consumption begins to rise, it indicates that the vehicle needs attention. Underlying problems may be present and the vehicle should be inspected. This is the only indicator used by the Pennsylvania Department of Transportation, who has had a predictive maintenance system in place for over 5 years.

The oil analysis has two major uses—to determine the condition of a lubricant and to examine the wear particles contained in the lubricant to determine the wear rate of the components in the system. When used to determine the relative condition of the equipment being lubricated, it is often referred to as “wear-particle analysis” [24]. For example, a technician suspects that the lubricant in a gear case contains water perhaps from being left open during an equipment wash down an oil sample could be drawn and checked for water. The decision could then be made to change the lubricant or not, based on the results of the test. This ensures that the correct maintenance is conducted not too much and not too little [25].

Vibration is the motion of machine components caused by dynamic forces, measured by transducers, vibration meters, and vibration analyzers, and so on. The vibrations are analyzed by spectrum analysis, parameter trends, and waveform and phase analysis. The types of faults which can be detected via vibration analysis include misalignment, looseness, bearing defects and wear, unbalance, internal component rubbing, and structural resonant conditions. Therefore, vibration analysis is used primarily with rotating equipment [24]. The advantages of vibration analysis for predictive maintenance lie in its adaptability to a variety of machines, the ability to indicate overall machine condition, problem severity, and specific faults.

Thermography serves primarily to find electrical components that are hotter than normal. Such a condition usually indicates wear or looseness. Thus, thermography allows technicians to perform maintenance on only the electrical components that need attention without requiring that all components get the same level of attention [25]. For example, the correct torque is essential on electrical components to ensure that no heat is generated from a loose connection. Before thermography, it was necessary for each connection in a control panel to be checked manually for correct torque. Using thermography only the connections that are hot receive attention. This reduces the staff necessary to perform preventive maintenance on the connections.

3.2 Process Map of Current Maintenance Process

Mn/DOT does not perform predictive maintenance. Before this type of program can be successfully implemented, it is first necessary to map out the existing process and understand how a predictive maintenance program can be incorporated into the existing process, and to identify changes in the current process. Therefore, a process map was developed which depicts the current maintenance and repair process.

The process map was developed by interviewing the Shop Supervisor of Mn/DOT District 1. The snow plow vehicle maintenance which Mn/DOT is now doing includes scheduled maintenance (preventive maintenance) and unscheduled maintenance (during downtime). This process is shown in Figure 3.1.

The scheduled maintenance consists of Preventive Maintenance Lubrication inspection (PML), Preventive Maintenance Oil Analysis (PMA), Commercial Vehicle Inspection (CVI), and Preventive Maintenance Inspection (PMI). The PML is undertaken every 1,000 miles. The PMA is undertaken every 6 months or every 10,000 miles. And the CVI and PMI are both implemented yearly. If any problems are detected during the inspection, the Unit Service Request forms will be filled out and given to the Shop Supervisor. Afterwards, the Unit Service Request forms are given to the mechanics. Then, the mechanics log on M4 System, and work orders are generated. After that, the repair is conducted. As soon as the repair is done, the mechanics log off the M4 System.

The unscheduled maintenance occurs when a vehicles breaks down during the service time. In this case, the vehicle operator reports the problems to the Shop Supervisor at once. If the problem is minor, the shop supervisor sends a mechanic out to the field to fix the problem. When the mechanic returns, he logs onto the M4 system, generates a work order, enters the time to complete the job, and then logs off the M4 system. If the problem is major, the vehicle operator is asked to take the vehicle back to the shop. The mechanics logs onto the M4 System, and if new parts are required to complete the repair, the new parts are ordered after the work order is generated. Once order is placed, the mechanic logs off the system. As soon as the new parts are received, the mechanic logs onto the M4 system again, completes the repair, and then logs off. If no new parts needed to conduct the repair, the mechanic generates the work order, repairs the vehicle, and logs off.

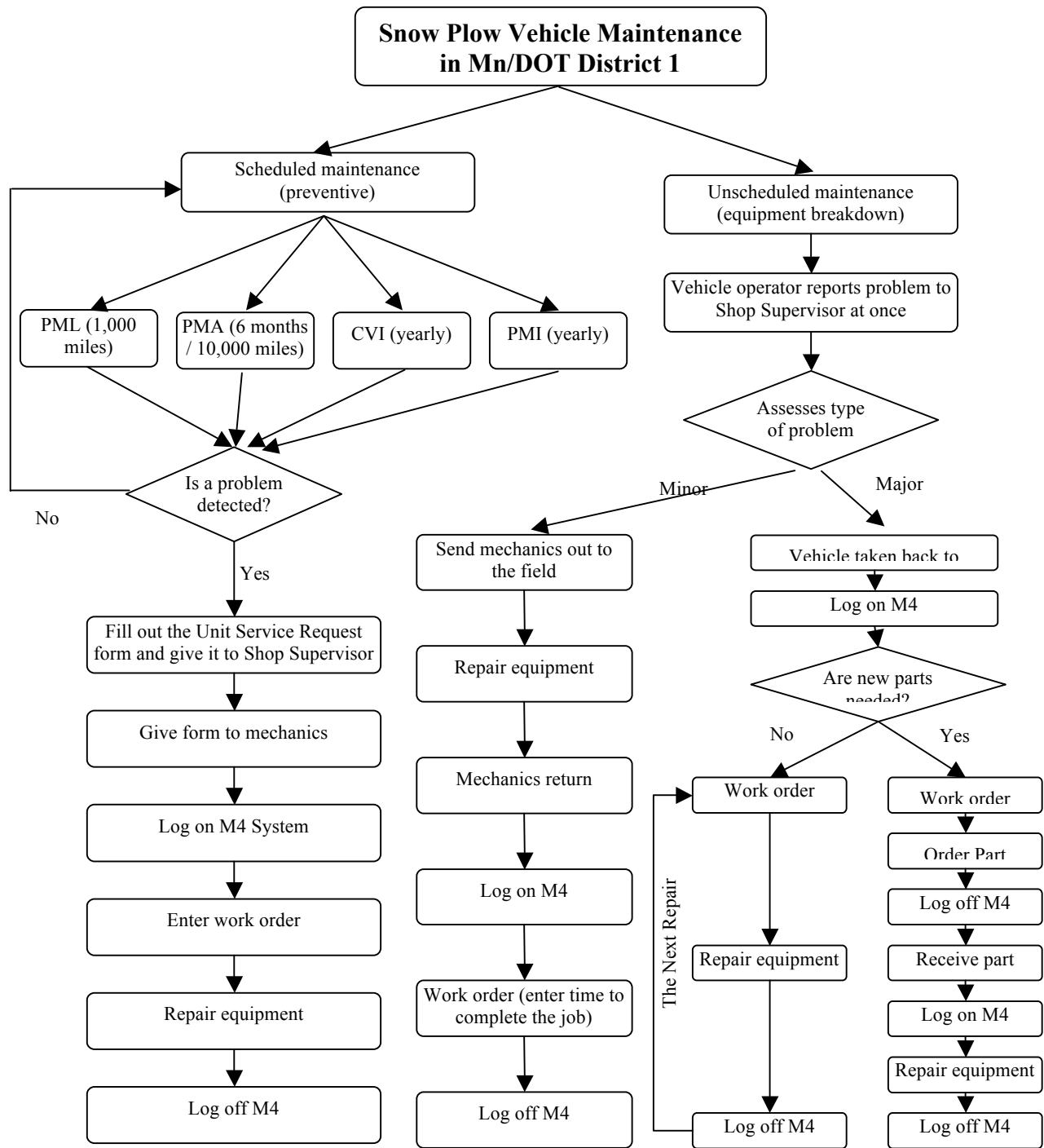


Figure 3.1. Preventive Maintenance and Repair Process

Moving from a preventive to a predictive maintenance system requires some understanding of the type of information that is collected, how it is used, and how it fits into the overall fleet management strategy. The next section discusses the findings from a nationwide survey on fleet management that are directly related to vehicle maintenance.

3.4 Vehicle Maintenance Information

According to a nationwide survey in which 35 out of 48 states responded, preventive and predictive vehicle maintenance information is not a “high level” fleet management measure (Wyrick, Storhaug, 2003). The most common measures are related to cost control whereas maintenance and repair services rank near the bottom. This may explain, in part, the sparse attention paid to predictive vehicle maintenance, as compared to machine tools, in the existing literature.

According to the study conducted by Wyrick and Storhaug, one of the least commonly used measures was miles between unscheduled repairs by type of repair, a measure which is necessary in order to apply statistical concepts to predictive maintenance. This study also showed that between 30% and 40% of the respondents tracked the following data:

- the average hours per repair task
- the average hours per repair
- downtime percentage
- average cost per preventive maintenance service
- unscheduled repairs per vehicle maintained

These types of measures would assist in not only applying statistical concepts to help with establishing a predictive maintenance program, but also to help illustrate the potential benefits of implementing such a program. Further, these measures fall within a category of measures for fleet management which do not receive very much attention.

Nevertheless, several departments of transportation and a few private contractors were contacted directly to discuss predictive maintenance programs. The most notable responses are from Pennsylvania and Michigan. Pennsylvania has had a predictive maintenance program in place for well over 5 years, and it includes 230,000 pieces of equipment. It is important to note that it has taken 5 years of data gathering in order to reap the full benefits of the program, according to Mr. Rugh who was our contact. Until sufficient data is collected on a piece of equipment, it is difficult to predict with much accuracy over time when a problem will occur. Success does not happen overnight. Note also that Michigan has a predictive maintenance program for snowplows only. This has made a tremendous difference in the level of service that is provided, particularly in northern Michigan. Mr. Lester, the contact for Michigan, noted that they rarely experienced snowplow breakdowns to the extent that they had before the program, and he also related one anecdote. The predictive maintenance program had saved them several thousands of dollars by detecting a potential engine failure before it occurred. The following table summarizes these findings.

Table 3.1. Summary of Contacts and Information

Organization/ Company	Contact Person	Date	Information Provided
Arkansas State Highway And DOT	Doug Nielsen	12/12/02	<ul style="list-style-type: none"> No predictive maintenance program
Oregon Department Of Transportation	Joe Jayne	01/29/03	<ul style="list-style-type: none"> No predictive maintenance program
Pennsylvania DOT	Ray Rugh	12/15/02- 12/19/02	<ul style="list-style-type: none"> Predictive maintenance for over 23,000 pieces of equipment. They don't do oil analysis because it is too expensive. The data they collect includes estimated time to repair, daily usage, & monthly usage. Predictive maintenance program gives a broad look at the entire fleet and the fleet manager can look at cost vs. usage
State Of Alaska, DOT & PF, State Equipt Fleet	Gene Darling	12/12/02	<ul style="list-style-type: none"> No predictive maintenance program
Delaware Department Of Transportation	Glenn B. Pusey	01/28/03	<ul style="list-style-type: none"> No predictive maintenance program
Michigan DOT/ Southwest Region	Mark Lester	12/12/02- 12/17/02	<ul style="list-style-type: none"> Predictive maintenance only on snow plows because they're the only reactive vehicles in the fleet. They check crankcase oil every oil change. They do annual DOT inspection every 800

hours or every year.

- The fleet manager polls the mechanics at a team meeting and checks the computer program to determine where the breakdowns are occurring.
- They record all electronic work orders.
- Lights were a continual problem due to corrosion and seals (maintenance practice problem). When switched tail lights to LED, the light problems were over.
- They use “hours” when recording breakdown and repair information. The best way is on fuel burned. New trucks can record fuel consumption.
- They reduced breakdowns during snow storms.
- The software they use is Mainstar by Bender Engineering., and the price is about \$40,000.

Indiana Department Of Transportation	Bob Timm	12/12/02	• No predictive maintenance program
Saskatchewan Highways And Transportation	Allan J Churko	02/28/03	• No predictive maintenance program
Manitoba Transportation And Gov. Services	Blair Dryden	12/20/02	• No predictive maintenance program
Kansas Department Of	Mark	12/13/02	• No predictive

Transportation	Karolevitz		maintenance program
Ohio Department Of Transportation	Tim Wald	12/16/02	<ul style="list-style-type: none"> • They do predictive maintenance for the vehicles in their fleet. No additional detail provided.
Montana DOT	Jim Richman	02/04/03	<ul style="list-style-type: none"> • No predictive maintenance program
Washington DOT	David Farnsworth	12/18/02	<ul style="list-style-type: none"> • They do preventive maintenance • They use M4 system, the same as Mn/DOT
Utah Department of Transportation	Steve McCarthy	02/06/03	<ul style="list-style-type: none"> • No predictive maintenance program
Colorado Department of Transportation	Robert Haines	02/04/03	<ul style="list-style-type: none"> • No predictive maintenance program
South Dakota Department of Transportation	Darrell Cassidy	02/06/03	<ul style="list-style-type: none"> • No predictive maintenance program
Integrated Maintenance & Operations Services Inc.(Ontario's contractor)	Geoffrey Leach	01/28/02- 02/06/03	<ul style="list-style-type: none"> • They do predictive maintenance for their clients. • They are in the leading role in the field
University Of Minnesota	Bill Roberts	12/13/02	<ul style="list-style-type: none"> • No predictive maintenance program
City Of St. Cloud	Chuck Koetter	12/13/02	<ul style="list-style-type: none"> • No predictive maintenance program
City Of Minnetonka	Bruce Guggemos	12/17/02	<ul style="list-style-type: none"> • No predictive maintenance program
United States Postal Service	Jackie Estes	12/13/02	<ul style="list-style-type: none"> • No predictive maintenance program

The next section focuses on the type of information that is gathered by the Pennsylvania Department of Transportation.

3.4 Essential Information For Predictive Maintenance

After contacting several organizations, it was apparent that the Pennsylvania Department of Transportation had experienced the greatest success in implementing a predictive maintenance program. The table below shows the guidelines used by Penn/DOT for each type of equipment, not just snowplows.

Table 3.2. Pennsylvania DOT Predictive Maintenance Guidelines

<u>Category</u>	<u>PM Inspection Interval</u>
<i>Trucks</i>	
All Dump Trucks 11,001 and Over	90 Days/Fuel Consumption
All Other Trucks and Crew Cabs	Fuel Consumption
<i>Winter Control Equipment</i>	
Snow Blower	After every storm
<i>Road Surface Equipment</i>	
Asphalt Heaters	6 months
Asphalt Kettles (Motorized)	6 months
Compressors	6 months
Pavers – Self-Propelled	Fuel Consumption
Roller	Fuel Consumption
Roller - Walk Behind	6 months
Stone Chippers - Self-Propelled	Fuel Consumption
Tack Coat Machine	6 months
Widener – Attachment	6 months
Widener – Self-Propelled	Fuel Consumption
<i>Vegetation Control Equipment</i>	
Small Tractor Mower (Cub Cadet, etc...)	6 months
Tractor Mower	Fuel Consumption
Wood Chipper	Fuel Consumption
<i>Earth Moving Equipment</i>	
Excavator	Fuel Consumption
Grader	Fuel Consumption
Loader	Fuel Consumption
Tractor - Backhoe	Fuel Consumption
Tractor - Maintainer	Fuel Consumption
<i>Traffic Service Equipment</i>	
Cleaner - Pipe Flusher	6 months
Cleaner - Water Blaster	6 months
Light Board - Arrow	6 months

Light Board - Message	6 months
Light - Flood	6 months
Paint Machine - Truck Mounted	Fuel Consumption
Paint Machine - Walk Behind	
Street Sweeper - Self-Propelled	Fuel Consumption
<i>Personnel Vehicles (11,000 GVW or Less, Gasoline or Diesel)</i>	
Sedan	7,000 Miles
Station Wagon	7,000 Miles
Utility Vehicles (Jeep, Blazer, etc.)	7,000 Miles
Van	7,000 Miles
Pickup Truck	7,000 Miles
<i>Other Controlled Equipment</i>	
Concrete Saw	6 months
Forklift	6 months
Trailer - Except Lowboy	6 months
Trailer – Lowboy	With Tractor
Welding Machines (<i>gas or diesel powered</i>)	6 months

As the table above indicates, Penn/DOT practices both preventive and predictive maintenance. Preventive maintenance occurs on a routine basis, indicated by vehicle mileage or calendar time. Predictive maintenance is indicated by the fuel consumption levels. Note that this table does not include the federally mandated inspection of snowplows that occurs before they leave to plow roads, which is another form of preventive maintenance.

Any predictive maintenance program must be in place for several years in order to obtain data that can be used to assist in predicting vehicle failures. The benefits are not realized overnight. Predictive maintenance programs will reflect the features of the software selected to manage the maintenance system; however any predictive maintenance system should contain some essential elements, discussed in the next section.

3.5 Conceptual Model

The conceptual model shown in Figure 3.2 lists the type of data that should be included in a predictive (and preventive) maintenance system. Note that oil analysis is not included as one of the elements because Penn/DOT did not find it to be as useful as fuel consumption; however the type of data to track would be up to the discretion of the user.

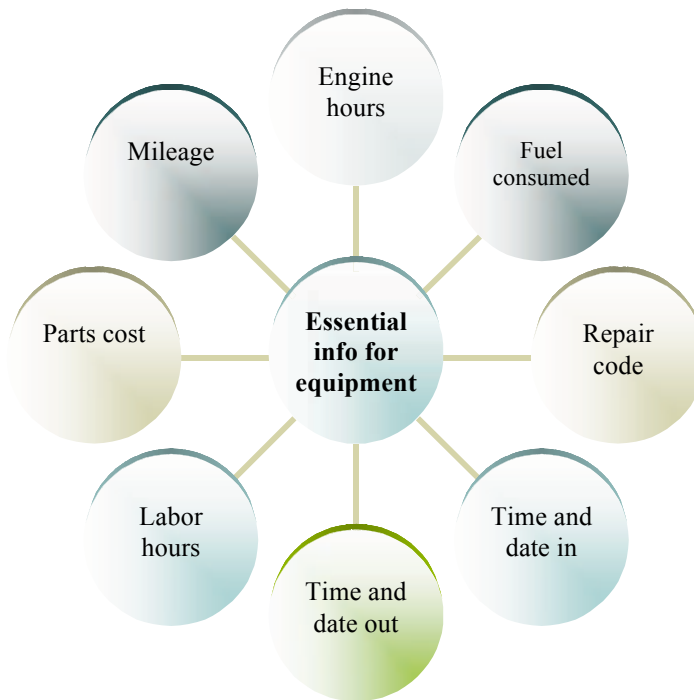


Figure 3.2 Essential Information for Preventive and Predictive Maintenance

Both data collection mechanisms and report generation should receive careful attention. It is very easy to collect too much information and to generate too many reports. Therefore, care must be taken in determining which information to collect and what types of reports are most useful. For example, consider the maintenance record for one snowplow, shown in Figure 3. Note that the most frequently occurring type of repair is “Lighting”, followed by “Miscellaneous”. Although “Lighting” should be probably be broken down into further detail (e.g. rust, seals, wiring) in order to be a more effective measure for predictive maintenance, “Miscellaneous” is certainly a useless category for effective predictive maintenance. Although it may be necessary in any maintenance system, it should no be the second most frequently occurring repair. Mn/DOT needs to carefully select the most appropriate categories and train the mechanics in proper reporting.

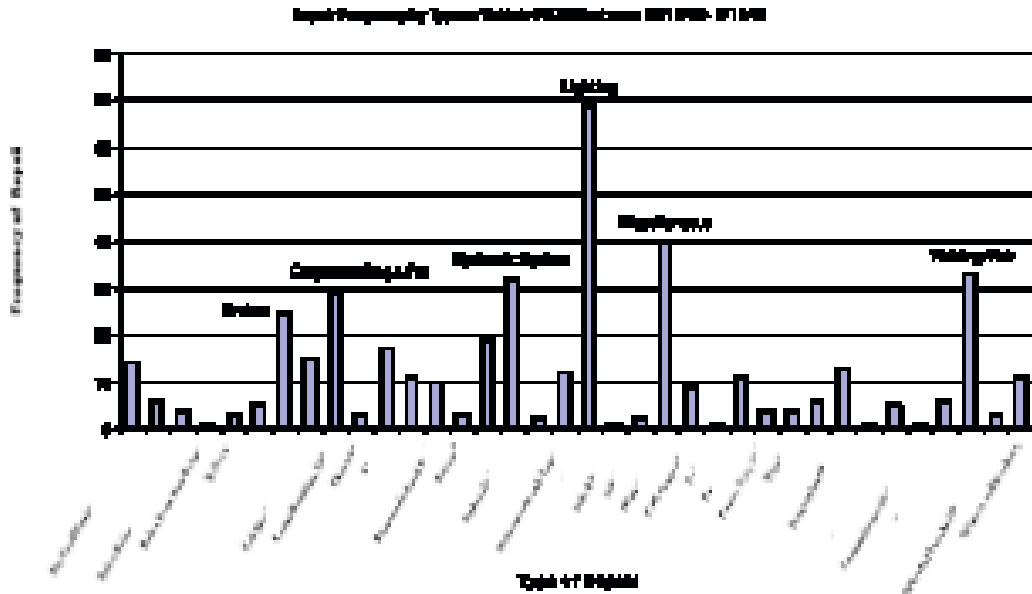


Figure 3.3. Repair Frequency by Category for a Snowplow

Not only can selecting the type of data to be tracked be challenging, but also the type of reports that need to be generated in order to identify problems before they occur. Penn/DOT has had success in tracking fuel consumption as an indicator of potential problems. Reports should alert when the usage of the equipment reaches at least one of requirements for preventive or predictive maintenance in terms of mileage, engine hours, and calendar interval. Eventually, a maintenance system should assist with repair vs. replace analysis, and life cycle analysis.

Chapter 4: Summary of Findings, Conclusion and Recommendations

4.1 Summary of Findings

4.1.1 Snowplow Simulation

The criterion for a valid simulation model was the time to reach bare lane. Therefore, the results from the simulation model were compared to the bare lane reports generated by Mn/DOT, and the appropriate hypothesis tests conducted to determine whether or not the model performance matched the actual system performance. Unfortunately, they did not. Statistical tests were run for three different routes: Route 201, 213, and 215. The bare lane reports listed anywhere between 15 and 20 events for each route, and included the storm duration and the time to bare lane for each event. The weather and road conditions - accumulation rate, moisture content, and surface temperature - were collected from the RWIS data for each event and used as input into the simulation model.

Tables 4.1 through 4.3 show the statistical results for each route.

Table 4.1. Route 201 results

Event	Start Date	Storm Duration (hrs)	Recovery Hours	Actual Recovery Minutes	Simulated Time to Bare Lane (min)		t-statistic	$t_{\alpha/2, 4}$	Conclusion of Hypothesis Testing
					Average	Standard Deviation			
1	10/18/02	4.0	0.0	0.0	541.22	10.34	117.04	2.78	Reject Ho
2	10/19/02	2.0	5.5	330.0	324.73	6.20	-1.90	2.78	Accept Ho
3	10/21/02	4.0	3.0	180.0	432.97	6.10	92.73	2.78	Reject Ho
4	10/25/02	4.0	0.0	0.0	432.97	6.10	158.71	2.78	Reject Ho
5	10/28/02	4.5	0.0	0.0	432.97	8.27	117.07	2.78	Reject Ho
6	11/02/02	4.5	21.5	1290.0	432.97	8.27	-231.73	2.78	Reject Ho
7	11/13/02	8.5	18.0	1080.0	444.22	7.95	-178.82	2.78	Reject Ho
8	11/19/02	1.5	4.5	270.0	324.73	6.20	19.74	2.78	Reject Ho
9	11/20/02	4.0	0.5	30.0	432.97	6.10	147.72	2.78	Reject Ho
10	11/22/02	7.0	10.0	600.0	333.16	5.96	-100.11	2.78	Reject Ho
11	11/24/02	20.5	2.0	120.0	330.24	9.88	47.58	2.78	Reject Ho
12	11/29/02	4.0	5.0	300.0	324.73	6.20	8.92	2.78	Reject Ho
13	12/01/02	9.0	1.0	60.0	444.22	7.95	108.07	2.78	Reject Ho
14	12/05/02	1.3	1.8	108.0	432.97	8.27	87.87	2.78	Reject Ho
15	12/16/02	15.0	12.0	720.0	330.70	9.14	-95.24	2.78	Reject Ho

Figure 4.2. Route 213 Results

Event	Start Date	Storm Duration (hrs)	Recovery Hours	Actual Recovery Minutes	Simulated Time to Bare Lane (min)		test statistic	$t_{\alpha/2, 4}$	Conclusion of Hypothesis Testing
					Average	Standard Deviation			
1	10/21/01	4.0	1.0	60.0	184.69	3.30	84.49	2.78	Reject Ho
2	11/25/01	17.0	0.5	30.0	232.35	8.37	54.06	2.78	Reject Ho
3	11/26/01	59.0	11.0	660.0	181.94	4.85	-220.41	2.78	Reject Ho
4	12/01/01	11.0	1.0	60.0	181.89	5.17	52.72	2.78	Reject Ho
5	12/05/01	22.0	8.0	480.0	186.31	4.87	-134.85	2.78	Reject Ho
6	12/22/01	50.0	4.0	240.0	136.66	3.65	-63.31	2.78	Reject Ho
7	12/25/01	60.0	2.0	120.0	185.94	5.87	25.12	2.78	Reject Ho
8	01/05/02	3.5	1.0	60.0	137.83	4.45	39.11	2.78	Reject Ho
9	01/06/02	3.0	27.0	1620.0	184.69	3.30	-972.56	2.78	Reject Ho
10	01/10/02	9.0	1.0	60.0	184.57	6.62	42.08	2.78	Reject Ho
11	01/14/02	20.0	0.0	0.0	181.55	2.92	139.03	2.78	Reject Ho
12	01/21/02	6.5	11.5	690.0	137.49	3.80	-325.12	2.78	Reject Ho
13	01/24/02	4.5	1.5	90.0	183.50	4.90	42.67	2.78	Reject Ho
14	01/25/02	4.5	5.0	300.0	183.50	4.90	-73.14	2.78	Reject Ho
15	01/27/02	16.0	12.0	720.0	139.73	3.65	-357.51	2.78	Reject Ho
16	01/28/02	8.0	12.0	720.0	136.42	3.88	-308.50	2.78	Reject Ho
17	01/30/02	2.5	8.0	480.0	184.69	3.30	-232.85	2.78	Reject Ho
18	02/11/02	12.0	5.0	300.0	136.36	3.03	-118.28	2.78	Reject Ho
19	02/25/02	16.0	8.0	480.0	139.73	3.65	-209.20	2.78	Reject Ho
20	02/28/02	2.5	8.5	510.0	138.52	2.48	-459.84	2.78	Reject Ho

Table 4.3. Route 215 results

Event	Start Date	Storm Duration (hrs)	Recovery Hours	Recovery Minutes	Simulated Time to Bare Lane (min)		test-statistic	$t_{\alpha/2, 4}$	Conclusion of Hypothesis Testing
					Average	Standard Deviation			
1	10/21/01	4.0	1.0	60.0	287.61	5.14	99.02	2.78	Reject Ho
2	10/25/01	30.0	3.0	180.0	347.67	15.92	23.55	2.78	Reject Ho
3	11/24/01	86.5	37.0	2220.0	283.93	7.64	-566.65	2.78	Reject Ho
4	11/30/01	21.5	1.5	90.0	284.06	8.77	49.48	2.78	Reject Ho
5	12/05/01	22.0	10.0	600.0	278.13	12.73	-56.54	2.78	Reject Ho
6	12/22/01	50.0	4.0	240.0	217.11	7.62	-6.72	2.78	Reject Ho
7	01/05/02	3.0	1.5	90.0	280.33	5.36	79.40	2.78	Reject Ho
8	01/06/02	3.0	33.0	1980.0	215.71	3.86	-1022.04	2.78	Reject Ho
9	01/10/02	9.0	1.0	60.0	283.73	7.91	63.25	2.78	Reject Ho
10	01/14/02	20.0	0.0	0.0	281.33	8.65	72.73	2.78	Reject Ho
11	01/21/02	6.5	0.0	0.0	287.61	5.14	125.12	2.78	Reject Ho
12	01/24/02	4.5	1.5	90.0	215.71	3.86	72.82	2.78	Reject Ho
13	01/25/02	4.0	6.5	390.0	287.61	5.14	-44.54	2.78	Reject Ho
14	01/27/02	16.0	61.5	3690.0	283.25	8.06	-945.13	2.78	Reject Ho
15	02/09/02	3.0	8.0	480.0	280.33	5.36	-83.30	2.78	Reject Ho
16	02/19/02	9.0	0.0	0.0	214.11	5.92	80.87	2.78	Reject Ho
17	02/25/02	15.5	8.0	480.0	211.82	5.84	-102.68	2.78	Reject Ho
18	02/28/02	3.0	8.0	480.0	280.33	5.36	-83.30	2.78	Reject Ho

These results were disappointing, and indicate one of two possibilities. The information that was used for determining plow speeds was incorrect. Recall that this information was based on expert opinion, as no other data was available or easily collected. If this data is incorrect, then the simulation model will not accurately depict the operations of the actual system. The other possibility is that the bare lane reports are inaccurate, another possibility due to the method used to collect the data. Each plow driver records the time that was required for him or her to achieve bare lane. This, too, is a subjective measure based not only on a time estimate, but also on the perception of bare lane.

Taken together, the subjective nature of the data and the collection mechanism could all account for the inaccuracy of the model. These findings indicate the crucial role of accurate data. Without reasonably accurate data, it will be difficult to create a useful management tool. Nevertheless, we will continue to work not only with Mn/DOT but also other organizations who are working on similar tasks to try to improve our approach and our results.

4.1.2 Predictive Maintenance

The predictive maintenance portion of this project was an exploratory project. It appears that part of the reason that predictive maintenance programs do not commonly appear as part of the fleet management programs is due to the focus on cost measures as performance metrics for vehicle fleets. Certainly, maintenance is a critical component of costs, but the level of detail that is used in predictive maintenance programs does not seem to filter to the top as an important measure of fleet performance. Additionally, predictive maintenance programs require several years of implementation before benefits can be realized, as demonstrated by Penn/DOT's experience.

4.2 Conclusion and Recommendations

The simulation model is not yet valid, although the model structure, logic, and design are operating as desired and reflect the operational rules used by the supervisors. Until accurate data is collected, validation will continue to present problems. Nevertheless, it is expected that the data collected from the snowplows equipped with the AVL systems during the upcoming winter will address this issue. The performance metric, time to reach bare lane, has been clearly identified as the single most important measurement for determining system performance and is the primary metric that is used for model validation. All other performance metrics, such as labor cost and material usage, can be tied to the time to reach bare pavement.

It is therefore recommended that data be collected from the snowplows using systems such as AVL or GIS systems. In addition to location information, data should also be collected to determine the rate and quantity of material application. In the future, systems which identify the configuration of the snowplow (e.g. wings up or down, underbelly plow up or down) should be implemented. Gathering this data using real time systems will reduce reporting errors, thereby improving any models

that are used to depict snowplowing operations. It is also recommended that a site visit be made to Ohio, who has recently implemented software developed by Cascade International, for managing snowplow operations. Additionally, it is also recommended that the researchers for this project work closely with other organizations conducting similar work, which include two private consulting firms and the Army's Cold Weather Research Labs.

It is further recommended that the existing model be expanded to include capabilities desired by the user, such as adjusting route lengths, route assignments, and reloading points.

Although MnDOT does an excellent job of preventive maintenance for snowplows, another study [26] indicated that little preventive maintenance was conducted for other vehicles. Before predictive maintenance programs can be successfully implemented, preventive maintenance programs must first be in place.

The exploration of predictive maintenance systems demonstrated that these types of systems require not only software and hardware to track data, but also organizational structures to support them. Predictive maintenance systems require input from the shop level as well as higher management, particularly the fleet manager. The benefits of such a system may take several years to realize as data is being collected in order to be able to predict when a problem may arise.

It is recommended that MnDOT, through a fleet management program, categorize equipment to identify which equipment should have preventive maintenance programs. Next, it is important to determine if the organization is ready to implement a predictive maintenance program and, if so, to identify the vehicles to use for a pilot program. It is also recommended that DOTs who have successfully implemented such programs be contacted to arrange a site visit, and to contact software vendors to identify potential software that will serve not only the needs of the fleet manager, but also the decentralized shops where the maintenance is performed.

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Appendix A Program Listing

* Formatted Listing of Model:
*

Time Units: Minutes
Distance Units: Feet

* Locations
*

Name	Cap	Units	Stats	Rules	Cost
MnDOT_Garage	5	1	Time Series	Oldest, ,	
PlowStart201	1	1	Time Series	Oldest, ,	
PlowEnd201	1	1	Time Series	Oldest, ,	
ActiveStorm	1	1	Time Series	Oldest, ,	
PlowStart202	1	1	Time Series	Oldest, ,	
PlowEnd202	1	1	Time Series	Oldest, ,	
PlowStart207	1	1	Time Series	Oldest, ,	
PlowEnd207	1	1	Time Series	Oldest, ,	
PlowStart213	1	1	Time Series	Oldest, ,	
PlowEnd213	1	1	Time Series	Oldest, ,	
PlowStart215	1	1	Time Series	Oldest, ,	
PlowEnd215	1	1	Time Series	Oldest, ,	

* Entities
*

Name	Speed (fpm)	Stats	Cost
Storm	150	Time Series	
Plow	150	Time Series	

* Path Networks
*

Name Dist/Time	Type Speed Factor	T/S	From	To	BI
PlowingNetwork201 RouteLength201 1	Passing	Speed & Distance	N1	N2	Bi
PlowingNetwork202 RouteLength202 1	Passing	Speed & Distance	N1	N2	Bi
PlowingNetwork207 RouteLength207 1	Passing	Speed & Distance	N1	N2	Bi
PlowingNetwork213 RouteLength213 1	Passing	Speed & Distance	N1	N2	Bi
PlowingNetwork215 RouteLength215 1	Passing	Speed & Distance	N1	N2	Bi

*
* Interfaces
*

Net	Node	Location
PlowingNetwork201	N1	PlowStart201
	N2	PlowEnd201
PlowingNetwork202	N2	PlowEnd202
	N1	PlowStart202
PlowingNetwork207	N1	PlowStart207
	N2	PlowEnd207
PlowingNetwork213	N2	PlowEnd213
	N1	PlowStart213
PlowingNetwork215	N2	PlowEnd215
	N1	PlowStart215

*
* Processing
*

Process			Routing		
Entity Rule	Location	Operation	Blk Move	Output Logic	Destination

```

Storm      ActiveStorm  StormStartTime=Clock()

#TimeBeforePlow=(CriticalDepth/AccumulationRate)*60
StormPlowTime=StormDuration
StormEndTime =StormStartTime+StormDuration
#Wait TimeBeforePlow
Send 1 Plow to PlowStart201
Send 1 Plow to PlowStart202
Send 1 Plow to PlowStart207

```

```

Send 1 Plow to PlowStart213
Send 1 Plow to PlowStart215
Wait StormDuration
1 Storm EXIT
FIRST 1
Plow MnDOT_Garage #ROUTE RouteNumber
1 Plow PlowStart201
SEND 1
Plow PlowStart202
SEND
Plow PlowStart207
SEND
Plow PlowStart213
SEND
Plow PlowStart215
SEND
Plow PlowStart201 #Check status of storm
IF StormEndTime<=Clock() and
TimeToPassesBe4StormEnds201 <= 0 THEN
TimeToPassesBe4StormEnds201 = Clock()
Else
TimeToPassesBe4StormEnds201 =
TimeToPassesBe4StormEnds201 + 0
IF StormEndTime<=Clock() THEN
BEGIN
StartBareLaneTime201=Clock()

PlowTime201=(RouteLength201/(T(PlowSpeed201Min,PlowSpeed201Mode,PlowSpeed201Max)*1.5))*60
INC PassesToBareLane201
END
ELSE
BEGIN

PlowTime201=(RouteLength201/T(PlowSpeed201Min,PlowSpeed201Mode,PlowSpeed201Max))*60
INC PassesUntilStormEnds201
END
1 Plow PlowEnd201
IF PassesToBareLane201<=ReqPassesToBareLane, 1 MOVE FOR PlowTime201
Plow MnDOT_Garage
IF PassesToBareLane201>ReqPassesToBareLane
PlowTime201=(RouteLength201/(T(PlowSpeed201Min,PlowSpeed201Mode,PlowSpeed201Max)*2.0))*60
Move for PlowTime201
TimeToBareLane201=StartBareLaneTime201-TimeToPassesBe4StormEnds201
TimeBareLane[1]=TimeToBareLane201
PassesToBareLane201=PassesToBareLane201-1
MaterialApplied201=(PassesUntilStormEnds201+PassesToBareLane201)*RouteLength201*ApplicationRate
MatApplied[1]=MaterialApplied201

```



```

MaterialCost201=MaterialCostPerLaneMile*(PassesUntilStormEnds201+Passes
ToBareLane201)*RouteLength201

MatCost[1]=MaterialCost201

LaborCost201=LaborCostPerLaneMile*((PassesUntilStormEnds201+PassesToBar
eLane201)*RouteLength201)

LabCost[1]=LaborCost201
  Plow      PlowEnd201  #Check status of storm
              IF StormEndTime<=Clock() and
TimeToPassesBe4StormEnds201 <= 0 THEN
              TimeToPassesBe4StormEnds201 = Clock()
              Else
TimeToPassesBe4StormEnds201 + 0
              TimeToPassesBe4StormEnds201 =
              IF StormEndTime<=Clock() THEN
              BEGIN
              StartBareLaneTime201=Clock()

              PlowTime201=(RouteLength201/(T(PlowSpeed201Min,PlowSpeed201Mode,P
lowSpeed201Max)*1.5))*60
              INC PassesToBareLane201
              END
              ELSE
              BEGIN

              PlowTime201=(RouteLength201/T(PlowSpeed201Min,PlowSpeed201Mode,Pl
owSpeed201Max))*60
              INC PassesUntilStormEnds201
              END
              1      Plow      PlowStart201
IF PassesToBareLane201<=ReqPassesToBareLane, 1  MOVE FOR PlowTime201
              Plow      MnDOT_Garage
IF PassesToBareLane201>ReqPassesToBareLane
PlowTime201=(RouteLength201/(T(PlowSpeed201Min,PlowSpeed201Mode,PlowSpe
ed201Max)*2.0))*60

Move for PlowTime201

TimeToBareLane201=StartBareLaneTime201-TimeToPassesBe4StormEnds201

TimeBareLane[1]=TimeToBareLane201

PassesToBareLane201=PassesToBareLane201-1

MaterialApplied201=(PassesUntilStormEnds201+PassesToBareLane201)*RouteL
ength201*ApplicationRate

MatApplied[1]=MaterialApplied201

MaterialCost201=MaterialCostPerLaneMile*(PassesUntilStormEnds201+Passes
ToBareLane201)*RouteLength201

MatCost[1]=MaterialCost201

```

```

LaborCost201=LaborCostPerLaneMile*((PassesUntilStormEnds201+PassesToBareLane201)*RouteLength201)

LabCost[1]=LaborCost201
  Plow      PlowStart202 #Check status of storm
              IF StormEndTime<=Clock() and
TimeToPassesBe4StormEnds202 <= 0 THEN
              TimeToPassesBe4StormEnds202 = Clock()
              Else
              TimeToPassesBe4StormEnds202 =
TimeToPassesBe4StormEnds202 + 0
              IF StormEndTime<=Clock() THEN
              BEGIN
              StartBareLaneTime202=Clock()

              PlowTime202=(RouteLength202/(T(PlowSpeed202Min,PlowSpeed202Mode,PlowSpeed202Max)*1.5))*60
              INC PassesToBareLane202
              END
              ELSE
              BEGIN

              PlowTime202=(RouteLength202/T(PlowSpeed202Min,PlowSpeed202Mode,PlowSpeed202Max))*60
              INC PassesUntilStormEnds202
              END
              1 Plow      PlowEnd202
IF PassesToBareLane202<=ReqPassesToBareLane, 1 MOVE FOR PlowTime202

              Plow      MnDOT_Garage
IF PassesToBareLane202>ReqPassesToBareLane
PlowTime202=(RouteLength202/(T(PlowSpeed202Min,PlowSpeed202Mode,PlowSpeed202Max)*2.0))*60

Move for PlowTime202

TimeToBareLane202=StartBareLaneTime202-TimeToPassesBe4StormEnds202

TimeBareLane[2]=TimeToBareLane202

PassesToBareLane202=PassesToBareLane202-1

MaterialApplied202=(PassesUntilStormEnds202+PassesToBareLane202)*RouteLength202*ApplicationRate

MatApplied[2]=MaterialApplied202

MaterialCost202=MaterialCostPerLaneMile*(PassesUntilStormEnds202+PassesToBareLane202)*RouteLength202

MatCost[2]=MaterialCost202

LaborCost202=LaborCostPerLaneMile*((PassesUntilStormEnds202+PassesToBareLane202)*RouteLength202)

LabCost[2]=LaborCost202
  Plow      PlowEnd202 #Check status of storm

```

```

                IF StormEndTime<=Clock() and
TimeToPassesBe4StormEnds202 <= 0 THEN
                TimeToPassesBe4StormEnds202 = Clock()
                Else
                TimeToPassesBe4StormEnds202 =
TimeToPassesBe4StormEnds202 + 0
                IF StormEndTime<=Clock() THEN
                BEGIN
                StartBareLaneTime202=Clock()
                PlowTime202=(RouteLength202/(T(PlowSpeed202Min,PlowSpeed202Mode,Pl
lowSpeed202Max)*1.5))*60
                INC PassesToBareLane202
                END
                ELSE
                BEGIN
                PlowTime202=(RouteLength202/(T(PlowSpeed202Min,PlowSpeed202Mode,Pl
owSpeed202Max))*60
                INC PassesUntilStormEnds202
                END
                1 Plow PlowStart202
IF PassesToBareLane202<=ReqPassesToBareLane, 1 MOVE FOR PlowTime202
                Plow MnDOT_Garage
IF PassesToBareLane202>ReqPassesToBareLane
PlowTime202=(RouteLength202/(T(PlowSpeed202Min,PlowSpeed202Mode,PlowSpe
ed202Max)*2.0))*60
Move for PlowTime202
TimeToBareLane202=StartBareLaneTime202-TimeToPassesBe4StormEnds202
TimeBareLane[2]=TimeToBareLane202
PassesToBareLane202=PassesToBareLane202-1
MaterialApplied202=(PassesUntilStormEnds202+PassesToBareLane202)*RouteL
ength202*ApplicationRate
MatApplied[2]=MaterialApplied202
MaterialCost202=MaterialCostPerLaneMile*(PassesUntilStormEnds202+Passes
ToBareLane202)*RouteLength202
MatCost[2]=MaterialCost202
LaborCost202=LaborCostPerLaneMile*((PassesUntilStormEnds202+PassesToBar
eLane202)*RouteLength202)
LabCost[2]=LaborCost202
Plow PlowStart207 #Check status of storm
                IF StormEndTime<=Clock() and
TimeToPassesBe4StormEnds207 <= 0 THEN
                TimeToPassesBe4StormEnds207 = Clock()
                Else
                TimeToPassesBe4StormEnds207 =
TimeToPassesBe4StormEnds207 + 0
                IF StormEndTime<=Clock() THEN

```

```

BEGIN
    StartBareLaneTime207=Clock()

    PlowTime207=(RouteLength207/(T(PlowSpeed207Min,PlowSpeed207Mode,PlowSpeed207Max)*1.5))*60
        INC PassesToBareLane207
    END
    ELSE
    BEGIN

        PlowTime207=(RouteLength207/T(PlowSpeed207Min,PlowSpeed207Mode,PlowSpeed207Max))*60
            INC PassesUntilStormEnds207
        END
        1 Plow PlowEnd207
    IF PassesToBareLane207<=ReqPassesToBareLane, 1 MOVE FOR PlowTime207

        Plow MndOT_Garage
    IF PassesToBareLane207>ReqPassesToBareLane
    PlowTime207=(RouteLength207/(T(PlowSpeed207Min,PlowSpeed207Mode,PlowSpeed207Max)*2.0))*60

    Move for PlowTime207

    TimeToBareLane207=StartBareLaneTime207-TimeToPassesBe4StormEnds207

    TimeBareLane[3]=TimeToBareLane207

    PassesToBareLane207=PassesToBareLane207-1

    MaterialApplied207=(PassesUntilStormEnds207+PassesToBareLane207)*RouteLength207*ApplicationRate

    MatApplied[3]=MaterialApplied207

    MaterialCost207=MaterialCostPerLaneMile*(PassesUntilStormEnds207+PassesToBareLane207)*RouteLength207

    MatCost[3]=MaterialCost207

    LaborCost207=LaborCostPerLaneMile*((PassesUntilStormEnds207+PassesToBareLane207)*RouteLength207)

    LabCost[3]=LaborCost207
    Plow PlowEnd207 #Check status of storm
        IF StormEndTime<=Clock() and
    TimeToPassesBe4StormEnds207 <= 0 THEN
        TimeToPassesBe4StormEnds207 = Clock()
    Else
        TimeToPassesBe4StormEnds207 =
    TimeToPassesBe4StormEnds207 + 0
        IF StormEndTime<=Clock() THEN
        BEGIN
            StartBareLaneTime207=Clock()

            PlowTime207=(RouteLength207/(T(PlowSpeed207Min,PlowSpeed207Mode,PlowSpeed207Max)*1.5))*60

```

```

        INC PassesToBareLane207
    END
    ELSE
    BEGIN

        PlowTime207=(RouteLength207/T(PlowSpeed207Min,PlowSpeed207Mode,PlowSpeed207Max))*60
            INC PassesUntilStormEnds207
        END
        IF PassesToBareLane207<=ReqPassesToBareLane, 1 MOVE FOR PlowTime207
            Plow MndOT_Garage
        IF PassesToBareLane207>ReqPassesToBareLane
            PlowTime207=(RouteLength207/(T(PlowSpeed207Min,PlowSpeed207Mode,PlowSpeed207Max)*2.0))*60

        Move for PlowTime207

        TimeToBareLane207=StartBareLaneTime207-TimeToPassesBe4StormEnds207

        TimeBareLane[3]=TimeToBareLane207

        PassesToBareLane207=PassesToBareLane207-1

        MaterialApplied207=(PassesUntilStormEnds207+PassesToBareLane207)*RouteLength207*ApplicationRate

        MatApplied[3]=MaterialApplied207

        MaterialCost207=MaterialCostPerLaneMile*(PassesUntilStormEnds207+PassesToBareLane207)*RouteLength207

        MatCost[3]=MaterialCost207
        LaborCost207=LaborCostPerLaneMile*((PassesUntilStormEnds207+PassesToBareLane207)*RouteLength207)
        LabCost[3]=LaborCost207
        Plow PlowStart213 #Check status of storm
            IF StormEndTime<=Clock() and
                TimeToPassesBe4StormEnds213 <= 0 THEN
                    TimeToPassesBe4StormEnds213 = Clock()
                Else
                    TimeToPassesBe4StormEnds213 =
                TimeToPassesBe4StormEnds213 + 0
            IF StormEndTime<=Clock() THEN
                BEGIN
                    StartBareLaneTime213=Clock()

                    PlowTime213=(RouteLength213/(T(PlowSpeed213Min,PlowSpeed213Mode,PlowSpeed213Max)*1.5))*60
                        INC PassesToBareLane213
                    END
                ELSE
                BEGIN

                    PlowTime213=(RouteLength213/T(PlowSpeed213Min,PlowSpeed213Mode,PlowSpeed213Max))*60
                        INC PassesUntilStormEnds213

```

```

                                END                                1    Plow    PlowEnd213
IF PassesToBareLane213<=ReqPassesToBareLane, 1 MOVE FOR PlowTime213
                                Plow    MnDOT_Garage
IF PassesToBareLane213>ReqPassesToBareLane
PlowTime213=(RouteLength213/(T(PlowSpeed213Min,PlowSpeed213Mode,PlowSpe
ed213Max)*2.0))*60

Move for PlowTime213

TimeToBareLane213=StartBareLaneTime213-TimeToPassesBe4StormEnds213

TimeBareLane[4]=TimeToBareLane213

PassesToBareLane213=PassesToBareLane213-1

MaterialApplied213=(PassesUntilStormEnds213+PassesToBareLane213)*RouteL
ength213*ApplicationRate

MatApplied[4]=MaterialApplied213
MaterialCost213=MaterialCostPerLaneMile*(PassesUntilStormEnds213+Passes
ToBareLane213)*RouteLength213

MatCost[4]=MaterialCost213
LaborCost213=LaborCostPerLaneMile*((PassesUntilStormEnds213+PassesToBar
eLane213)*RouteLength213)

LabCost[4]=LaborCost213
    Plow    PlowEnd213    #Check status of storm
                                IF StormEndTime<=Clock() and
TimeToPassesBe4StormEnds213 <= 0 THEN
                                TimeToPassesBe4StormEnds213 = Clock()
                                Else
                                TimeToPassesBe4StormEnds213 =
TimeToPassesBe4StormEnds213 + 0
                                IF StormEndTime<=Clock() THEN
                                BEGIN
                                StartBareLaneTime213=Clock()

                                PlowTime213=(RouteLength213/(T(PlowSpeed213Min,PlowSpeed213Mode,P
lowSpeed213Max)*1.5))*60
                                INC PassesToBareLane213
                                END
                                ELSE
                                BEGIN

                                PlowTime213=(RouteLength213/T(PlowSpeed213Min,PlowSpeed213Mode,Pl
owSpeed213Max))*60
                                INC PassesUntilStormEnds213
                                END                                1    Plow    PlowStart213
IF PassesToBareLane213<=ReqPassesToBareLane, 1 MOVE for PlowTime213
                                Plow    MnDOT_Garage
IF PassesToBareLane213>ReqPassesToBareLane
PlowTime213=(RouteLength213/(T(PlowSpeed213Min,PlowSpeed213Mode,PlowSpe
ed213Max)*2.0))*60

```

```

Move for PlowTime213

TimeToBareLane213=StartBareLaneTime213-TimeToPassesBe4StormEnds213

TimeBareLane[4]=TimeToBareLane213

PassesToBareLane213=PassesToBareLane213-1

MaterialApplied213=(PassesUntilStormEnds213+PassesToBareLane213)*RouteLength213*ApplicationRate

MatApplied[4]=MaterialApplied213
MaterialCost213=MaterialCostPerLaneMile*(PassesUntilStormEnds213+PassesToBareLane213)*RouteLength213
MatCost[4]=MaterialCost213

LaborCost213=LaborCostPerLaneMile*((PassesUntilStormEnds213+PassesToBareLane213)*RouteLength213)

LabCost[4]=LaborCost213
  Plow      PlowStart215 #Check status of storm
              IF StormEndTime<=Clock() and
TimeToPassesBe4StormEnds215 <= 0 THEN
              TimeToPassesBe4StormEnds215 = Clock()
              Else
              TimeToPassesBe4StormEnds215 =
TimeToPassesBe4StormEnds215 + 0
              IF StormEndTime<=Clock() THEN
              BEGIN
              StartBareLaneTime215=Clock()

              PlowTime215=(RouteLength215/(T(PlowSpeed215Min,PlowSpeed215Mode,PlowSpeed215Max)*1.5))*60
              INC PassesToBareLane215
              END
              ELSE
              BEGIN

              PlowTime215=(RouteLength215/(T(PlowSpeed215Min,PlowSpeed215Mode,PlowSpeed215Max))*60
              INC PassesUntilStormEnds215
              END
              1      Plow      PlowEnd215
IF PassesToBareLane215<=ReqPassesToBareLane, 1 MOVE FOR PlowTime215

              Plow      MnDOT_Garage
IF PassesToBareLane215>ReqPassesToBareLane
PlowTime213=(RouteLength213/(T(PlowSpeed213Min,PlowSpeed213Mode,PlowSpeed213Max)*2.0))*60

Move for PlowTime213

TimeToBareLane215=StartBareLaneTime215-TimeToPassesBe4StormEnds215

TimeBareLane[5]=TimeToBareLane215

PassesToBareLane215=PassesToBareLane215-1

```

```

MaterialApplied215=(PassesUntilStormEnds215+PassesToBareLane215)*RouteL
ength215*ApplicationRate
MatApplied[5]=MaterialApplied215
MaterialCost215=MaterialCostPerLaneMile*(PassesUntilStormEnds215+Passes
ToBareLane215)*RouteLength215

MatCost[5]=MaterialCost215

LaborCost215=LaborCostPerLaneMile*((PassesUntilStormEnds215+PassesToBar
eLane215)*RouteLength215)

LabCost[5]=LaborCost215
  Plow      PlowEnd215      #Check status of storm
                                IF StormEndTime<=Clock() and
TimeToPassesBe4StormEnds215 <= 0 THEN
                                TimeToPassesBe4StormEnds215 = Clock()
                                Else
                                TimeToPassesBe4StormEnds215 =
TimeToPassesBe4StormEnds215 + 0
                                IF StormEndTime<=Clock() THEN
                                BEGIN
                                StartBareLaneTime215=Clock()

                                PlowTime215=(RouteLength215/(T(PlowSpeed215Min,PlowSpeed215Mode,P
lowSpeed215Max)*1.5))*60
                                INC PassesToBareLane215
                                END
                                ELSE
                                BEGIN

                                PlowTime215=(RouteLength215/T(PlowSpeed215Min,PlowSpeed215Mode,Pl
owSpeed215Max))*60
                                INC PassesUntilStormEnds215
                                END
                                1      Plow      PlowStart215
IF PassesToBareLane215<=ReqPassesToBareLane, 1 MOVE FOR PlowTime215

                                Plow      MnDOT_Garage
IF PassesToBareLane215>ReqPassesToBareLane
TimeToBareLane215=StartBareLaneTime215-TimeToPassesBe4StormEnds215

TimeBareLane[5]=TimeToBareLane215

PassesToBareLane215=PassesToBareLane215-1

MaterialApplied215=(PassesUntilStormEnds215+PassesToBareLane215)*RouteL
ength215*ApplicationRate

MatApplied[5]=MaterialApplied215
MaterialCost215=MaterialCostPerLaneMile*(PassesUntilStormEnds215+Passes
ToBareLane215)*RouteLength215
MatCost[5]=MaterialCost215

LaborCost215=LaborCostPerLaneMile*((PassesUntilStormEnds215+PassesToBar
eLane215)*RouteLength215)

LabCost[5]=LaborCost215

```



```

*****
*****
*
*                               Arrivals
*
*****
*****
Entity      Location      Qty each  First Time Occurrences Frequency
Logic
-----
Storm       ActiveStorm  1         0         1         0
Plow        MnDOT_Garage  5         0         1         0

```

```

*****
*****
*
*                               Attributes
*
*****
*****
ID          Type          Classification
-----
DonePlowing Integer      Entity

```

```

*****
*****
*
*                               Variables (global)
*
*****
*****
ID          Type          Initial value  Stats
-----
StormStartTime      Real          0              Time Series
TimeBeforePlow      Real          0              Time Series
StormEndTime        Real          0              Time Series
PlowTime201         Real          0              Time Series
PlowTime202         Real          0              Time Series
PlowTime207         Real          0              Time Series
PlowTime213         Real          0              Time Series
PlowTime215         Real          0              Time Series
StormPlowTime       Real          0              Time Series
TimeToPassesBe4StormEnds201 Integer      0              Time Series
TimeToPassesBe4StormEnds202 Integer      0              Time Series
TimeToPassesBe4StormEnds207 Integer      0              Time Series
TimeToPassesBe4StormEnds213 Integer      0              Time Series
TimeToPassesBe4StormEnds215 Integer      0              Time Series
PassesToBareLane201 Integer      0              Time Series
PassesToBareLane202 Integer      0              Time Series
PassesToBareLane207 Integer      0              Time Series
PassesToBareLane213 Integer      0              Time Series
PassesToBareLane215 Integer      0              Time Series
StartBareLaneTime201 Real          0              Time Series
StartBareLaneTime202 Real          0              Time Series
StartBareLaneTime207 Real          0              Time Series

```

StartBareLaneTime213	Real	0	Time Series
StartBareLaneTime215	Real	0	Time Series
PassesUntilStormEnds201	Real	0	Time Series
PassesUntilStormEnds202	Real	0	Time Series
PassesUntilStormEnds207	Real	0	Time Series
PassesUntilStormEnds213	Real	0	Time Series
PassesUntilStormEnds215	Real	0	Time Series
TimeToBareLane201	Real	0	Time Series
TimeToBareLane202	Real	0	Time Series
TimeToBareLane207	Real	0	Time Series
TimeToBareLane213	Real	0	Time Series
TimeToBareLane215	Real	0	Time Series
MaterialApplied201	Real	0	Time Series
MaterialApplied202	Real	0	Time Series
MaterialApplied207	Real	0	Time Series
MaterialApplied213	Real	0	Time Series
MaterialApplied215	Real	0	Time Series
MaterialCost201	Real	0	Time Series
MaterialCost202	Real	0	Time Series
MaterialCost207	Real	0	Time Series
MaterialCost213	Real	0	Time Series
MaterialCost215	Real	0	Time Series
LaborCost201	Real	0	Time Series
LaborCost202	Real	0	Time Series
LaborCost207	Real	0	Time Series
LaborCost213	Real	0	Time Series
LaborCost215	Real	0	Time Series

 *
 *
 *

Arrays

ID	Dimensions	Type
TimeBareLane	5	Integer
MatApplied	5	Integer
MatCost	5	Integer
LabCost	5	Integer

 *
 *
 *

Macros

ID	Text
RouteLength201	81.92
RouteLength202	51.54
RouteLength207	26.42
RouteLength213	34.06
RouteLength215	53.04
PlowSpeed201Min	1

PlowSpeed201Mode	2
PlowSpeed201Max	8
PlowSpeed202Min	4
PlowSpeed202Mode	5
PlowSpeed202Max	6
PlowSpeed207Min	7
PlowSpeed207Mode	8
PlowSpeed207Max	9
PlowSpeed213Min	10
PlowSpeed213Mode	11
PlowSpeed213Max	12
PlowSpeed215Min	13
PlowSpeed215Mode	14
PlowSpeed215Max	15
StormDuration	300
ApplicationRate	510
CriticalDepth	1
AccumulationRate	1.5
ReqPassesToBareLane	2
MaterialCostPerLaneMile	1.98
LaborCostPerLaneMile	0.98

```

*****
*****
*
*
*
*****
*****

```

External Files

ID	Type	File Name
Prompt	-----	-----
(null)		C:\Models&Interface\All_Routes.xls

Appendix B Model Verification

Hand Simulation

A hand simulation was performed using deterministic values for a one-time storm arrival with duration of 5 hours. For storm characteristics, it was assumed as having an accumulation rate of above 1.0 inch per hour and high moisture content. From Table 3.6 above, the plow will have a speed of 8 miles per hour. Assuming also a pavement temperature of between 15 and 20 degree Fahrenheit, the material application rate will be between 600 to 800 pounds per two lanes. An average application rate of 700 pounds is used. When the storm ends, plows are required to make two passes to achieve bare lane or bare pavement. Results of the hand simulation performed on Route 201 are discussed and presented below. Table 3.8 summarizes the scenario for the hand simulation and calculation.

Table B.1: Scenario for Hand Simulation

Route Number	201
Route Length	81.92 lane miles
Storm Duration	5 hours
Snow Accumulation Rate	Above 1.0 inches per hour
Moisture Content	High
Plow Speed	8 miles per hour
Pavement Temperature	15 – 20 °F
Material Application Rate	700 lbs per lane mile

Consider the following:

S_{ar}	snow accumulation rate
T_{p201}	time it takes the snowplow to move from the beginning of route 201 to the end or vice versa when the storm is active.
\tilde{T}_{p201}	time it takes the snowplow to move from the beginning of route 201 to the end or vice versa when the storm ends.

$T_{pbse201}$	time for passes before storm ends
T_{tbl201}	time to plow to bare lane after the storm has ended
M	amount of material applied during the passes to bare lane
M_{ar}	material application rate
N_{ptse}	number of passes to on route until storm ends
N_{ptbl}	number of passes to bare lane

For this hand simulation example;

$$\begin{aligned}
 T_{p201} &= \frac{\text{Lane - miles}}{\text{PlowSpeed}} & (3.7) \\
 &= \frac{81.92\text{miles}}{8\text{miles / hr}} \\
 &= 10.24\text{hr} \quad \text{or} \quad 614.40 \text{ min}
 \end{aligned}$$

Since the storm duration is shorter than the time it takes to plow from beginning of route 201 to the end, the storm will end before the plow has made one pass.

$$\begin{aligned}
 N_{ptse} &= 1 \\
 T_{pbse201} &= 614.40 \text{ min}
 \end{aligned}$$

The plow speed during the passes to bare lane or bare pavement is increased by a factor of 1.5. As mentioned earlier, plows make an average of two (2) passes to bare lane after the storm. Similarly, from equation (3.7), time to bare lane after the storm is therefore given as:

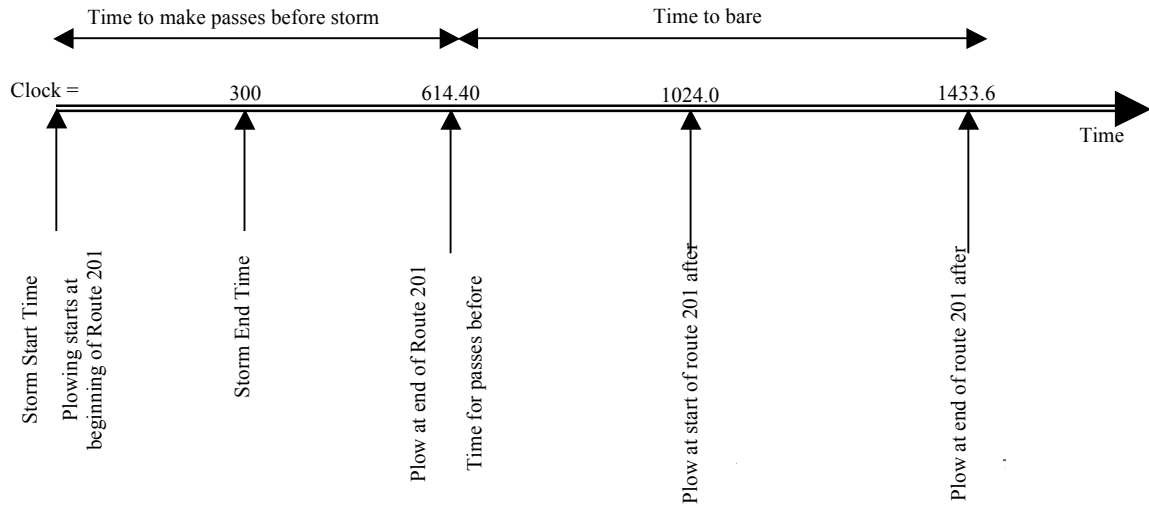
$$\begin{aligned}
 \tilde{T}_{p201} &= \frac{81.92\text{miles}}{8\text{miles / hr} \times 1.5} \\
 &= 6.83\text{hr} \quad \text{or} \quad 409.60 \text{ min}
 \end{aligned}$$

Plow makes 2 passes to bare lane therefore, T_{tp201} is 819.20 minutes, and N_{ptbl} is 2.

$$\begin{aligned}
 M &= (N_{ptbl} + N_{ptse}) \times M_{ar} \times RouteLength & (3.8) \\
 &= (3) \times 700 \times 81.92 = 172,032 \text{ lbs}
 \end{aligned}$$

The hand calculations above are illustrated on the time-advance chart in Figure 3.10.

Figure B.1: Time-advance chart for a storm event on route 201



Trace Listing

The Trace feature of ProModel lists events step by step as they happen during a simulation. A complete output for a storm arrival and exit event as used for the hand simulation scenario is presented below. During simulation, the trace prompt can be followed to verify that the model is doing what it was intended to do. The trace feature was used in conjunction with visualization of the flow of entities to ensure that activities in the system were taking place as programmed. This provided an insight into how activities were processed and how the summary statistics were being collected.

Trace Model: C:\DOCUME~1\MIE\MYDOCU~1\SIMULA~1\Models\MODEL_~1.MOD

00:00.000 Trace Start

00:00.000 1 Storm scheduled to arrive at ActiveStorm.

00:00.000 Storm arrives at ActiveStorm.

00:00.000 For Storm at ActiveStorm:

00:00.000 Storm enters ActiveStorm.

00:00.000 Real: StormStartTime = 0.000000 (old value = 0.000000)

00:00.000 Real: StormPlowTime = 300.000000 (old value = 0.000000)

00:00.000 Real: StormEndTime = 300.000000 (old value = 0.000000)

00:00.000 Send 1 Plow to PlowStart201.
 00:00.000 Send 1 Plow to PlowStart202.
 00:00.000 Send 1 Plow to PlowStart207.
 00:00.000 Send 1 Plow to PlowStart213.
 00:00.000 Send 1 Plow to PlowStart215.
 00:00.000 Wait 5 Hr 0.000 Min.
 00:00.000 5 Plow scheduled to arrive at MnDOT_Garage.
 00:00.000 Plow arrives at MnDOT_Garage.
 00:00.000 For Plow at MnDOT_Garage:
 00:00.000 Plow enters MnDOT_Garage.
 00:00.000 Select route from route block #1; output quantity is 1.
 00:00.000 For Plow at MnDOT_Garage:

 00:00.000 Being requested to send to PlowStart201.
 00:00.000 The main entity is routed out as Plow.
 00:00.000 Output is named as Plow.
 00:00.000 Start move to PlowStart201.
 00:00.000 Plow arrives at PlowStart201.
 00:00.000 For Plow at PlowStart201:
 00:00.000 Plow enters PlowStart201.
 00:00.000 Real: TimeToPassesBe4StormEnds = 0.000000 (old value = 0.000000)
 00:00.000 Real: PlowTime201 = 614.400000 (old value = 0.000000)
 00:00.000 Int: PassesUntilStormEnds = 1 (old value = 0)
 00:00.000 Select route from route block #1; output quantity is 1.
 00:00.000 For Plow at PlowStart201:
 00:00.000 PlowEnd201 is selected for routing.
 00:00.000 The main entity is routed out as Plow.
 00:00.000 Output is named as Plow.
 00:00.000 Start move to PlowEnd201.
 00:00.000 For Plow at PlowStart201:
 00:00.000 Process completed.
 00:00.000 Release the captured capacity.
 00:00.000 For Plow at MnDOT_Garage:
 00:00.000 Process completed.
 00:00.000 Release the captured capacity.
 00:00.000 Plow arrives at MnDOT_Garage.
 00:00.000 For Plow at MnDOT_Garage:
 00:00.000 Plow enters MnDOT_Garage.
 00:00.000 Select route from route block #1; output quantity is 1.
 00:00.000 For Plow at MnDOT_Garage:
 00:00.000 No matching request for routing.
 00:00.000 Plow arrives at MnDOT_Garage.
 00:00.000 For Plow at MnDOT_Garage:
 00:00.000 Plow enters MnDOT_Garage.
 00:00.000 Select route from route block #1; output quantity is 1.
 00:00.000 For Plow at MnDOT_Garage:
 00:00.000 No matching request for routing.
 00:00.000 Plow arrives at MnDOT_Garage.
 00:00.000 For Plow at MnDOT_Garage:
 00:00.000 Plow enters MnDOT_Garage.
 00:00.000 Select route from route block #1; output quantity is 1.

00:00.000 For Plow at MnDOT_Garage:
 00:00.000 No matching request for routing.
 00:00.000 Plow arrives at MnDOT_Garage.
 00:00.000 For Plow at MnDOT_Garage:
 00:00.000 Plow enters MnDOT_Garage.
 00:00.000 Select route from route block #1; output quantity is 1.
 00:00.000 For Plow at MnDOT_Garage:
 00:00.000 No matching request for routing.
 05:00.000 For Storm at ActiveStorm:
 05:00.000 Select route from route block #1; output quantity is 1.
 05:00.000 For Storm at ActiveStorm:
 05:00.000 The main entity is routed out as Storm.
 05:00.000 Output is named as Storm.
 05:00.000 Exits the system.
 05:00.000 For Storm at ActiveStorm:
 05:00.000 Process completed.
 05:00.000 Release the captured capacity.
 10:14.400 Plow arrives at PlowEnd201.
 10:14.400 For Plow at PlowEnd201:
 10:14.400 Plow enters PlowEnd201.
 10:14.400 Real: TimeToPassesBe4StormEnds = 614.400000 (old value = 0.000000)
 10:14.400 Real: StartBareLaneTime = 614.400000 (old value = 0.000000)
 10:14.400 Real: PlowTime201 = 409.600000 (old value = 614.400000)
 10:14.400 Int: PassesToBareLane = 1 (old value = 0)
 10:14.400 Select route from route block #1; output quantity is 1.
 10:14.400 For Plow at PlowEnd201:
 10:14.400 PlowStart201 is selected for routing.
 10:14.400 The main entity is routed out as Plow.
 10:14.400 Output is named as Plow.
 10:14.400 Start move to PlowStart201.
 10:14.400 For Plow at PlowEnd201:
 10:14.400 Process completed.

 10:14.400 Release the captured capacity.
 17:04.000 Plow arrives at PlowStart201.
 17:04.000 For Plow at PlowStart201:
 17:04.000 Plow enters PlowStart201.
 17:04.000 Real: TimeToPassesBe4StormEnds = 614.400000 (old value = 614.400000)
 17:04.000 Real: StartBareLaneTime = 1024.000000 (old value = 614.400000)
 17:04.000 Real: PlowTime201 = 409.600000 (old value = 409.600000)
 17:04.000 Int: PassesToBareLane = 2 (old value = 1)
 17:04.000 Select route from route block #1; output quantity is 1.
 17:04.000 For Plow at PlowStart201:
 17:04.000 PlowEnd201 is selected for routing.
 17:04.000 The main entity is routed out as Plow.
 17:04.000 Output is named as Plow.
 17:04.000 Start move to PlowEnd201.
 17:04.000 For Plow at PlowStart201:
 17:04.000 Process completed.
 17:04.000 Release the captured capacity.
 23:53.600 Plow arrives at PlowEnd201.

23:53.600 For Plow at PlowEnd201:
23:53.600 Plow enters PlowEnd201.
23:53.600 Real: TimeToPassesBe4StormEnds = 614.400000 (old value = 614.400000)
23:53.600 Real: StartBareLaneTime = 1433.600000 (old value = 1024.000000)
23:53.600 Real: PlowTime201 = 409.600000 (old value = 409.600000)
23:53.600 Int: PassesToBareLane = 3 (old value = 2)
23:53.600 Select route from route block #1; output quantity is 1.
23:53.600 For Plow at PlowEnd201:
23:53.600 MnDOT_Garage is selected for routing.
23:53.600 The main entity is routed out as Plow.
23:53.600 Output is named as Plow.
23:53.600 Real: PlowTime201 = 307.200000 (old value = 409.600000)
23:53.600 Start move to MnDOT_Garage.
23:53.600 For Plow at PlowEnd201:
23:53.600 Process completed.
23:53.600 Release the captured capacity.
29:00.800 Plow arrives at MnDOT_Garage.
29:00.800 Real: TimeToBareLane = 819.200000 (old value = 0.000000)
29:00.800 Int: PassesToBareLane = 2 (old value = 3)
29:00.800 Real: MaterialApplied = 172032.000000 (old value = 0.000000)
29:00.800 Real: MaterialCost = 486.604800 (old value = 0.000000)
29:00.800 Real: LaborCost = 240.844800 (old value = 0.000000)
29:00.800 For Plow at MnDOT_Garage:
29:00.800 Plow enters MnDOT_Garage.
29:00.800 Select route from route block #1; output quantity is 1.
29:00.800 For Plow at MnDOT_Garage:
29:00.800 No matching request for routing.
29:00.800 Generate reports.

29:00.800 Simulation Terminated

Verification Statistics

Known output statistics at specific locations were again collected to verify that the processing logic was as programmed. Deterministic input values were used with a foreknowledge of output statistics. The scenario used in the hand simulation was simulated to verify if the same output results should be obtained. Table B.2 shows the output for this step. The key output statistics that were compared with the hand simulation results are highlighted, and a summary is presented in Table B.3.

Table B.2 . Variables for Verification Statistics: Hand Simulation Scenario
Normal Run

Name	Total Changes	Minimum Value	Maximum Value	Current Value
LaborCost*	1	240.8	240.8	240.8
MaterialApplied*	1	172032.0	172032.0	172032.0
MaterialCost*	1	486.60	486.60	486.60
PassesToBareLane*	4	1	3	2
PassesUntilStormEnds*	1	1	1	1
PlowTime201*	5	307.2	614.4	307.2
PlowTime202*	0	0	0	0
PlowTime207*	0	0	0	0
PlowTime213*	0	0	0	0
PlowTime215*	0	0	0	0
StartBareLaneTime*	3	614.4	1433.6	1433.6
StormEndTime*	1	300	300	300
StormPlowTime*	1	300	300	300
StormStartTime*	1	0	0	0
TimeBeforePlow*	0	0	0	0
TimeToBareLane*	1	819.2	819.2	819.2
TimeToPassesBe4StormEnds*	4	0	614.4	614.4

Table B.3: Summary Verification Statistics for Hand Simulation Scenario

Variable Name	Value
PlowTime201	614.4 minutes
StormEndTime	300 minutes
PassesUntilStormEnds	1
TimeToPassesBe4StormEnds	614.40
PassesToBareLane201	2

TimeToBareLane201	819.20 minutes
MaterialApplied201	172032 lbs

The known output statistics were equal to what was obtained in the hand simulation. This confirmed that the model was doing what it was supposed to do.

Appendix C

Establishing the Number of Replications

To establish the number of statistically independent replications, the time to bare lane for a storm event will be used as the key decision variable. Five (5) replications will be used to obtain initial estimates of the averages and standard deviations. The following illustrates how the number of independent replications, R can be determined:

Let ε be the error in estimating the average or mean μ using $\bar{\chi}$ such that the limits on μ are $\pm \varepsilon$.

$$P(|\bar{\chi} - \mu| < \varepsilon) \geq 1 - \alpha \quad (3.9)$$

The $100(1 - \alpha)\%$ confidence interval is given as;

$$\bar{\chi} \pm t_{\frac{\alpha}{2}(R-1)} \frac{S_{\chi}}{\sqrt{R}} \quad (3.10)$$

where $S_{\bar{\chi}} = \frac{S_{\chi}}{\sqrt{R}}$ is the standard error.

From the relations (3.9) and (3.10),

$$t_{\frac{\alpha}{2}(R-1)} \frac{S_{\chi}}{\sqrt{R}} \leq \varepsilon \quad (3.11)$$

$$R \geq \left(\frac{t_{\frac{\alpha}{2}(R-1)} S_{\chi}}{\varepsilon} \right)^2 \quad (3.12)$$

Appendix D

Task-Object-Events Charts for User-Interface Design Form

Task	Object (s)	Event
Display the following information: Picture of snowplows plowing highway 35 About Program Command Button Start Simulation Command Button Exit Program Command Button	Image Frame Command Button Command Button Command Button	None None None None
Read about the program	About Program Button	Click
Exit Program	Exit Program Button	Click
Show Start Simulation Form	Start Simulation Button	Click
Display the following when the start simulation button is clicked: Route options to select Storm characteristics of the event Pavement temperature options Type of material to be applied On which passes to apply material Today's date An option to clear screen and restart process Simulation command button How to cancel the simulation process	Select Routes Frame, Route checkboxes Storm Characteristics Frame, Storm Duration Label, Storm Duration Textbox, Storm Duration Units Label, Accumulation Rate Frame, Accumulation Rate Option Button1, Accumulation Rate Option Button2, Accumulation Rate Option Button3, Accumulation Rate Option Button4, Moisture Content Frame, Moisture Content Option High Button, Moisture Content Option Medium Button, Moisture Content Option Low Button Pavement Temperature Frame, Pavement Temperature Option Button1, Pavement Temperature Option Button2, Pavement Temperature Option Button3, Pavement Temperature Option Button4, Pavement Temperature Option Button5 Material Application Frame, Pre-Wet? Frame, Yes Option button, No Option button, Which Pass Frame, 1 st Pass Checkbox, 2 nd Pass Checkbox, All Passes Checkbox Date Label, Date Textbox Clear button Simulate button Cancel button	None, Click None, Click None, Click None, Click None Click Click Click

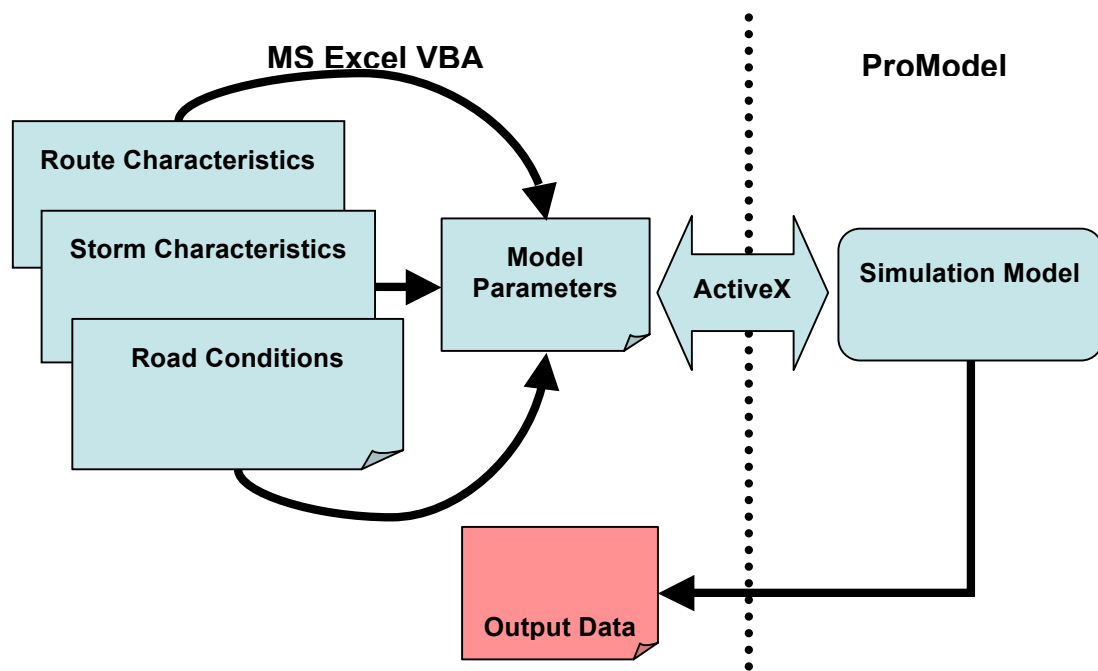
Appendix E

Model Design and Data Flow

Figure E.1, the Data Flow Diagram, maps the interactions between the different components of the DSS.

Data tables for the different parameters that are used in the simulation model exists in MS Excel. The worksheet Route Characteristics (labeled “RouteNumber&Length”) contains the route numbers, route lengths, number of ramps and reloading points presented in Table 3.3. The Storm Characteristics worksheet (also labeled “AccumulationRateMoistureSpeed”) contains plow speeds based on the different combinations of moisture content and snow accumulation rate. The Road Condition worksheet also contains material application rates based on road pavement temperatures. This worksheet is labeled “MaterialApplication.”

Figure E1: Model Design and Data Flow



A user begins by selecting the route options they want to simulate. If they select the “All” check box from the front-end, the routes characteristics for all the five routes are passed to a worksheet called “MacroValues” and designated as “Model Parameters” in Figure 3.13. The user then selects options for the storm characteristics and pavement temperature which passes a speed and material application rate respectively to the Model Parameters worksheet. Material application rate also depends on whether it is “Pre-wet” or not. The user can also decide on which passes to apply chemicals or materials. When the “Simulate” command button is clicked, data from the “MacroValues” worksheet is read by means of ActiveX commands into ProModel for the simulation run. Specific variables of interest can then be exported into a worksheet called “Output.” Exporting output data into MS Excel has not been achieved in this thesis because of some software glitches. However, automatic output data is generated by the ProModel software. A screen capture of the data worksheets

is shown in Figure 3.14. The VBA code supporting all the objects and controls on the interface screen, and interchange of data between the user interface and the ProModel simulation software is presented below.

'General declarations

```
Dim pmObject As CProModel
```

```
    Dim CurrentCell As Object
```

```
Private Sub AllRoutesOptionButton_Click()
```

```
'opens the output file of key variables for the scenario when all routes are simulated
```

```
    Workbooks.Open Filename:= "C:\Models&Interface\All_Routes.xls"
```

```
    OneRouteOptionButton.Enabled = False
```

```
    OneRouteOptionButton.Locked = True
```

```
    OneRouteOptionButton.Value = False
```

```
End Sub
```

```
Private Sub OneRouteOptionButton_Click()
```

```
'opens the output file of key variables for the scenario when only one route is simulated
```

```
    Workbooks.Open Filename:= "C:\Models&Interface\1_Route.xls"
```

```
    AllRoutesOptionButton.Enabled = False
```

```
    AllRoutesOptionButton.Locked = True
```

```
    AllRoutesOptionButton.Value = False
```

```
End Sub
```

```
Private Sub SimulationResultsExitProgramCommandButton_Click()
```

```
'enables user to close the user interface and exit the simulation program
```

```
    Unload ResultsForm
```

```
    Application.Quit
```

```
End Sub
```

```
Private Sub SimulationResultsNewSimulationCommandButton_Click()
```

```
'closes the output file that was opened for viewing and resets for a new simulation
```

```
    Dim CurrentSheet As Object
```

```
    Set CurrentSheet = ActiveWindow
```

```
    ActiveWindow.Close
```

```
    Unload ResultsForm
```

```
    StartSimulationForm.Show
```

```
End Sub
```

```
Private Sub AboutProgramCommandButton_Click()
```

```
'opens about program page to user
```

```
    AboutProgramPageForm.Show
```

```
End Sub
```

```
Private Sub ExitProgramCommandButton_Click()
```

```
'exit user interface and excel
```

```
    Unload SplashScreenForm
```

```
    Application.Quit
```

```
End Sub
```

```
Private Sub StartSimulationCommandButton_Click()
```

```
'closes the splash screen and opens the start simulation page
```

```
    Unload SplashScreenForm
```

```
    StartSimulationForm.Show
```

```
End Sub
```

```
Private Sub WindConditionsOKCommandButton_Click()
Unload Me
End Sub
```

```
Private Sub AccumulationRateOptionButton1_Click()
'assign an average accumulation rate when the range 0.00 - 0.25 inches/hr is selected
If AccumulationRateOptionButton1.Value = True Then
    Worksheets("MacroValues").Range("B9, B36").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("F2").Value
End If
End Sub
```

```
Private Sub AccumulationRateOptionButton2_Click()
'assign an average accumulation rate when the range 0.25 - 0.50 inches/hr is selected
If AccumulationRateOptionButton2.Value = True Then
    Worksheets("MacroValues").Range("B9, B36").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("F3").Value
End If
End Sub
```

```
Private Sub AccumulationRateOptionButton3_Click()
'assign an average accumulation rate when the range 0.50 - 1.00 inches/hr is selected
If AccumulationRateOptionButton3.Value = True Then
    Worksheets("MacroValues").Range("B9, B36").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("F4").Value
End If
End Sub
```

```
Private Sub AccumulationRateOptionButton4_Click()
'assign an average accumulation rate when the range Above 1.0 inches/hr is selected
If AccumulationRateOptionButton4.Value = True Then
    Worksheets("MacroValues").Range("B9, B36").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("F5").Value
End If
End Sub
```

```
Private Sub CancelSimulationCommandButton_Click()
'closes the start simulation form or page
    Unload Me
End Sub
```

```
Private Sub ClearStartSimulationScreenCommandButton_Click()
'clears all previously check options for the user to restart
    Call UserForm_Initialize
    RouteAllSelectionCheckBox.Value = False
    RouteAllSelectionCheckBox.Locked = False
    Route201SelectionCheckBox.Enabled = True
    Route201SelectionCheckBox.Locked = False
    Route201SelectionCheckBox.Value = False
    Route202SelectionCheckBox.Enabled = True
    Route202SelectionCheckBox.Locked = False
    Route202SelectionCheckBox.Value = False
    Route207SelectionCheckBox.Enabled = True
    Route207SelectionCheckBox.Locked = False
    Route207SelectionCheckBox.Value = False
```



```

Route213SelectionCheckBox.Enabled = True
Route213SelectionCheckBox.Locked = False
Route213SelectionCheckBox.Value = False
Route215SelectionCheckBox.Enabled = True
Route215SelectionCheckBox.Locked = False
Route215SelectionCheckBox.Value = False
StormDurationTextBox.Value = ""
AccumulationRateOptionButton1.Value = False
AccumulationRateOptionButton2.Value = False
AccumulationRateOptionButton3.Value = False
AccumulationRateOptionButton4.Value = False
MoistureContentLowOptionButton.Value = False
MoistureContentMediumOptionButton.Value = False
MoistureContentHighOptionButton.Value = False
PavementTempOptionButton1.Value = False
PavementTempOptionButton2.Value = False
PavementTempOptionButton3.Value = False
PavementTempOptionButton4.Value = False
PavementTempOptionButton5.Value = False
MaterialApplicationPreWetYesOptionButton.Value = False
MaterialApplicationTypePreWetNoOptionButton.Value = False
MaterialApplication1stPassCheckBox.Value = False
MaterialApplication2ndPassCheckBox.Value = False
MaterialApplicationAllPassesCheckBox.Value = False
PercentSaltFrame.Enabled = True
HundredPercentSaltOptionButton.Enabled = True
HundredPercentSaltOptionButton.Locked = False
HundredPercentSaltOptionButton.Value = False
FiftyPercentSaltOptionButton.Enabled = True
FiftyPercentSaltOptionButton.Locked = False
FiftyPercentSaltOptionButton.Value = False
End Sub

Private Sub MaterialApplicationTypePreWetNoOptionButton_Click()
'disable the option buttons for the percentage of salt when this option is selected
'this option returns values from the Salt Institute which does not state the percentage salt
  If MaterialApplicationTypePreWetNoOptionButton.Value = True Then
    PercentSaltFrame.Enabled = False
    HundredPercentSaltOptionButton.Enabled = False
    HundredPercentSaltOptionButton.Locked = True
    FiftyPercentSaltOptionButton.Enabled = False
    FiftyPercentSaltOptionButton.Locked = True
  End If
End Sub

Private Sub MoistureContentLowOptionButton_Click()
'show this form if a low moisture content option is selected
  WindConditionsUserForm.Show
End Sub

Private Sub ResultsCommandButton_Click()
  StartSimulationForm.Hide
  ResultsForm.Show
End Sub

```

```
Private Sub Route201SelectionCheckBox_Click()  
'pass route number and length for only route 201 to macro values workwheet when this check  
box is clicked  
    If Route201SelectionCheckBox.Value = True Then  
        Worksheets("MacroValues").Range("B3").Value =  
Worksheets("RouteNumber&Length").Range("B2").Value  
        Worksheets("MacroValues").Range("B2").Value = 1  
    End If  
End Sub
```

```
Private Sub Route202SelectionCheckBox_Click()  
'pass route number and length for only route 202 to macro values worksheet when this check  
box is clicked  
    If Route202SelectionCheckBox.Value = True Then  
        Worksheets("MacroValues").Range("B3").Value =  
Worksheets("RouteNumber&Length").Range("B3").Value  
        Worksheets("MacroValues").Range("B2").Value = 2  
    End If  
End Sub
```

```
Private Sub Route207SelectionCheckBox_Click()  
'pass route number and length for only route 207 to macro values worksheet when this  
checkbox is clicked  
    If Route207SelectionCheckBox.Value = True Then  
        Worksheets("MacroValues").Range("B3").Value =  
Worksheets("RouteNumber&Length").Range("B4").Value  
        Worksheets("MacroValues").Range("B2").Value = 3  
    End If  
End Sub
```

```
Private Sub Route213SelectionCheckBox_Click()  
'pass route number and length for only route 213 to macro values worksheet when this  
checkbox is clicked  
    If Route213SelectionCheckBox.Value = True Then  
        Worksheets("MacroValues").Range("B3").Value =  
Worksheets("RouteNumber&Length").Range("B5").Value  
        Worksheets("MacroValues").Range("B2").Value = 4  
    End If  
End Sub
```

```
Private Sub Route215SelectionCheckBox_Click()  
'pass route number and length for only route 215 to macro values worksheet when this  
checkbox is clicked  
    If Route215SelectionCheckBox.Value = True Then  
        Worksheets("MacroValues").Range("B3").Value =  
Worksheets("RouteNumber&Length").Range("B6").Value  
        Worksheets("MacroValues").Range("B2").Value = 5  
    End If  
End Sub
```

```
Private Sub RouteAllSelectionCheckBox_Click()  
'if all routes are selected, then macrovalues values to pass to macrovalues sheet  
    If RouteAllSelectionCheckBox.Value = True Then  
        Route201SelectionCheckBox.Enabled = False  
        Route201SelectionCheckBox.Locked = False
```

```

Route202SelectionCheckBox.Enabled = False
Route202SelectionCheckBox.Locked = False
Route207SelectionCheckBox.Enabled = False
Route207SelectionCheckBox.Locked = False
Route213SelectionCheckBox.Enabled = False
Route213SelectionCheckBox.Locked = False
Route215SelectionCheckBox.Enabled = False
Route215SelectionCheckBox.Locked = False
Worksheets("MacroValues").Range("B14:B18").Value =
Worksheets("RouteNumber&Length").Range("B2:B6").Value
End If
End Sub

```

```

Private Sub SimulateCommandButton_Click()
' make macro values worksheet active
ActiveWorkbook.Sheets("MacroValues").Activate

```

```

'force user to select a route option before simulating
If RouteAllSelectionCheckBox.Value = False Then
If Route201SelectionCheckBox.Value = False Then
If Route202SelectionCheckBox.Value = False Then
If Route207SelectionCheckBox.Value = False Then
If Route213SelectionCheckBox.Value = False Then
If Route215SelectionCheckBox.Value = False Then
MsgBox ("You Must Select a Route")
End If
End If
End If
End If
End If
End If

```

```

'force user to select accumulation rate
If AccumulationRateOptionButton1.Value = False Then
If AccumulationRateOptionButton2.Value = False Then
If AccumulationRateOptionButton3.Value = False Then
If AccumulationRateOptionButton4.Value = False Then
MsgBox ("Accumulation rate is missing")
End If
End If
End If
End If

```

```

'force user to select moisture content
If MoistureContentLowOptionButton.Value = False Then
If MoistureContentMediumOptionButton.Value = False Then
If MoistureContentHighOptionButton.Value = False Then
MsgBox ("Please, select moisture content")
End If
End If
End If

```

```

'force user to select type of material being applied
If MaterialApplicationPreWetYesOptionButton.Value = False Then
If MaterialApplicationTypePreWetNoOptionButton.Value = False Then
MsgBox ("Is your material Pre-Wet or not?")

```

End If
End If

'force user to select pavement temperature
If PavementTempOptionButton1.Value = False Then
 If PavementTempOptionButton2.Value = False Then
 If PavementTempOptionButton3.Value = False Then
 If PavementTempOptionButton4.Value = False Then
 If PavementTempOptionButton5.Value = False Then
 MsgBox ("No temperature option is selected")
 End If
 End If
 End If
 End If
End If
End If
End If

'checks accumulation rate and moisture content options and passes plowspeeds to
macrovalues worksheet

If RouteAllSelectionCheckBox.Value = True Then
 If AccumulationRateOptionButton1.Value = True Then
 If MoistureContentLowOptionButton.Value = True Then
 Worksheets("MacroValues").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C2")
 Worksheets("MacroValues").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D2")
 Worksheets("MacroValues").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E2")
 ElseIf MoistureContentMediumOptionButton.Value = True Then
 Worksheets("MacroValues").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C6")
 Worksheets("MacroValues").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D6")
 Worksheets("MacroValues").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E6")
 Else
 Worksheets("MacroValues").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C10")
 Worksheets("MacroValues").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D10")
 Worksheets("MacroValues").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E10")
 End If
 ElseIf AccumulationRateOptionButton2.Value = True Then
 If MoistureContentLowOptionButton.Value = True Then
 Worksheets("MacroValues").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C3")
 Worksheets("MacroValues").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D3")
 Worksheets("MacroValues").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E3")
 ElseIf MoistureContentMediumOptionButton.Value = True Then
 Worksheets("MacroValues").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C7")

```

Worksheets("Macro Values").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D7")
Worksheets("Macro Values").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E7")
Else
Worksheets("Macro Values").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C11")
Worksheets("Macro Values").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D11")
Worksheets("Macro Values").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E11")
End If
ElseIf AccumulationRateOptionButton3.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("Macro Values").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C4")
Worksheets("Macro Values").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D4")
Worksheets("Macro Values").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E4")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("Macro Values").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C8")
Worksheets("Macro Values").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D8")
Worksheets("Macro Values").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E8")
Else
Worksheets("Macro Values").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C12")
Worksheets("Macro Values").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D12")
Worksheets("Macro Values").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E12")
End If
ElseIf AccumulationRateOptionButton4.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("Macro Values").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C5")
Worksheets("Macro Values").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D5")
Worksheets("Macro Values").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E5")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("Macro Values").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C9")
Worksheets("Macro Values").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D9")
Worksheets("Macro Values").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E9")
Else
Worksheets("Macro Values").Range("B19,B22,B25,B28,B31").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C13")
Worksheets("Macro Values").Range("B20,B23,B26,B29,B32").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D13")

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Worksheets("MacroValues").Range("B21,B24,B27,B30,B33").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E13")
End If
End If
ElseIf Route201SelectionCheckBox.Value = True Then
If AccumulationRateOptionButton1.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C2")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D2")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E2")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C6")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D6")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E6")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C10")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D10")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E10")
End If
ElseIf AccumulationRateOptionButton2.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C3")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D3")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E3")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C7")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D7")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E7")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C11")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D11")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E11")
End If
ElseIf AccumulationRateOptionButton3.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C4")

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Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D4")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E4")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C8")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D8")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E8")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C12")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D12")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E12")
End If
ElseIf AccumulationRateOptionButton4.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C5")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D5")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E5")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C9")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D9")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E9")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C13")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D13")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E13")
End If
End If
ElseIf Route202SelectionCheckBox.Value = True Then
If AccumulationRateOptionButton1.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C2")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D2")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E2")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C6")

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Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D6")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E6")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C10")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D10")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E10")
End If
ElseIf AccumulationRateOptionButton2.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C3")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D3")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E3")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C7")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D7")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E7")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C11")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D11")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E11")
End If
ElseIf AccumulationRateOptionButton3.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C4")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D4")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E4")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C8")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D8")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E8")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C12")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D12")

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Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E12")
End If
ElseIf AccumulationRateOptionButton4.Value = True Then
    If MoistureContentLowOptionButton.Value = True Then
        Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C5")
        Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D5")
        Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E5")
        ElseIf MoistureContentMediumOptionButton.Value = True Then
            Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C9")
            Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D9")
            Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E9")
        Else
            Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C13")
            Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D13")
            Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E13")
        End If
    End If
ElseIf Route207SelectionCheckBox.Value = True Then
    If AccumulationRateOptionButton1.Value = True Then
        If MoistureContentLowOptionButton.Value = True Then
            Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C2")
            Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D2")
            Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E2")
            ElseIf MoistureContentMediumOptionButton.Value = True Then
                Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C6")
                Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D6")
                Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E6")
            Else
                Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C10")
                Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D10")
                Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E10")
            End If
        End If
    ElseIf AccumulationRateOptionButton2.Value = True Then
        If MoistureContentLowOptionButton.Value = True Then
            Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C3")

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Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D3")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E3")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C7")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D7")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E7")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C11")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D11")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E11")
End If
ElseIf AccumulationRateOptionButton3.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C4")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D4")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E4")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C8")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D8")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E8")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C12")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D12")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E12")
End If
ElseIf AccumulationRateOptionButton4.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C5")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D5")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E5")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C9")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D9")

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Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E9")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C13")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D13")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E13")
End If
End If
ElseIf Route213SelectionCheckBox.Value = True Then
If AccumulationRateOptionButton1.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C2")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D2")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E2")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C6")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D6")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E6")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C10")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D10")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E10")
End If
ElseIf AccumulationRateOptionButton2.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C3")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D3")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E3")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C7")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D7")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E7")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C11")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D11")

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Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E11")
End If
ElseIf AccumulationRateOptionButton3.Value = True Then
    If MoistureContentLowOptionButton.Value = True Then
        Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C4")
        Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D4")
        Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E4")
        ElseIf MoistureContentMediumOptionButton.Value = True Then
            Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C8")
            Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D8")
            Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E8")
        Else
            Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C12")
            Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D12")
            Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E12")
        End If
    ElseIf AccumulationRateOptionButton4.Value = True Then
        If MoistureContentLowOptionButton.Value = True Then
            Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C5")
            Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D5")
            Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E5")
            ElseIf MoistureContentMediumOptionButton.Value = True Then
                Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C9")
                Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D9")
                Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E9")
            Else
                Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C13")
                Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D13")
                Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E13")
            End If
        End If
    ElseIf Route215SelectionCheckBox.Value = True Then
        If AccumulationRateOptionButton1.Value = True Then
            If MoistureContentLowOptionButton.Value = True Then
                Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C2")

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Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D2")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E2")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C6")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D6")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E6")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C10")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D10")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E10")
End If
ElseIf AccumulationRateOptionButton2.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C3")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D3")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E3")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C7")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D7")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E7")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C11")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D11")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E11")
End If
ElseIf AccumulationRateOptionButton3.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C4")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D4")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E4")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C8")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D8")

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Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E8")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C12")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D12")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E12")
End If
ElseIf AccumulationRateOptionButton4.Value = True Then
If MoistureContentLowOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C5")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D5")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E5")
ElseIf MoistureContentMediumOptionButton.Value = True Then
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C9")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D9")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E9")
Else
Worksheets("MacroValues").Range("B4").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("C13")
Worksheets("MacroValues").Range("B5").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("D13")
Worksheets("MacroValues").Range("B6").Value =
Worksheets("AccumulationRateMoistureSpeed").Range("E13")
End If
End If
End If

```

'checks the option button selected for pavement temperature and returns a macro value for material application rate

```

If PavementTempOptionButton1.Value = True Then
If MaterialApplicationPreWetYesOptionButton.Value = True Then
If HundredPercentSaltOptionButton.Value = True Then
Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("C13").Value
ElseIf FiftyPercentSaltOptionButton.Value = True Then
Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("D13").Value
Else
Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("C3").Value
End If
End If
ElseIf PavementTempOptionButton2.Value = True Then
If MaterialApplicationPreWetYesOptionButton.Value = True Then
If HundredPercentSaltOptionButton.Value = True Then

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        Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("C15").Value
        ElseIf FiftyPercentSaltOptionButton.Value = True Then
            Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("D15").Value
        Else
            Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("C4").Value
        End If
    End If
ElseIf PavementTempOptionButton3.Value = True Then
    If MaterialApplicationPreWetYesOptionButton.Value = True Then
        If HundredPercentSaltOptionButton.Value = True Then
            Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("C22").Value
            ElseIf FiftyPercentSaltOptionButton.Value = True Then
                Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("D22").Value
            Else
                Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("C5").Value
            End If
        End If
    ElseIf PavementTempOptionButton4.Value = True Then
        If MaterialApplicationPreWetYesOptionButton.Value = True Then
            If HundredPercentSaltOptionButton.Value = True Then
                Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("C23").Value
            ElseIf FiftyPercentSaltOptionButton.Value = True Then
                Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("D23").Value
            Else
                Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("C6").Value
            End If
        End If
    Else
        If MaterialApplicationPreWetYesOptionButton.Value = True Then
            If HundredPercentSaltOptionButton.Value = True Then
                Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("C24").Value
            ElseIf FiftyPercentSaltOptionButton.Value = True Then
                Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("D24").Value
            Else
                Worksheets("MacroValues").Range("B8,B35").Value =
Worksheets("MaterialApplication").Range("C7").Value
            End If
        End If
    End If

'simulate all routes
If RouteAllSelectionCheckBox.Value = True Then
    Dim pmObject As CProModel
    Set pmObject = CreateObject("ProModel")

```

```

pmObject.LoadModel ("C:\Models&Interface\All_Routes.MOD")
Dim CurrentCell As Object
Range("A14").Select
Set CurrentCell = ActiveCell
Do While Not IsEmpty(CurrentCell)
    pmObject.SetMacro ActiveCell.Value, ActiveCell.Offset(0, 1).Value
    ActiveCell.Offset(1, 0).Select
    Set CurrentCell = ActiveCell
Loop
pmObject.Simulate
Dim Status As Integer
Do
    DoEvents
    Status = pmObject.GetStatus
Loop Until Status = 8
MsgBox ("Simulation Complete")
pmObject.Quit
Set pmObject = Nothing
Set CurrentCell = Nothing
End If
If Route201SelectionCheckBox.Value = True Then
    Set pmObject = CreateObject("ProModel")
    pmObject.LoadModel ("C:\Models&Interface\Model_1_Route.mod")
    Range("A2").Select
    Set CurrentCell = ActiveCell
    Do While Not IsEmpty(CurrentCell)
        pmObject.SetMacro ActiveCell.Value, ActiveCell.Offset(0, 1).Value
        ActiveCell.Offset(1, 0).Select
        Set CurrentCell = ActiveCell
    Loop
    pmObject.Simulate
    Do
        Status = pmObject.GetStatus
    Loop Until Status = 8
    MsgBox ("Simulation Complete")
    pmObject.Quit
    Set pmObject = Nothing
    Set CurrentCell = Nothing
End If
If Route202SelectionCheckBox.Value = True Then
    Set pmObject = CreateObject("ProModel")
    pmObject.LoadModel ("C:\Models&Interface\Model_1_Route.mod")
    Range("A2").Select
    Set CurrentCell = ActiveCell
    Do While Not IsEmpty(CurrentCell)
        pmObject.SetMacro ActiveCell.Value, ActiveCell.Offset(0, 1).Value
        ActiveCell.Offset(1, 0).Select
        Set CurrentCell = ActiveCell
    Loop
    pmObject.Simulate
    Do
        Status = pmObject.GetStatus
    Loop Until Status = 8
    MsgBox ("Simulation Complete")
    pmObject.Quit

```



```

Set pmObject = Nothing
Set CurrentCell = Nothing
End If
If Route207SelectionCheckBox.Value = True Then
Set pmObject = CreateObject("ProModel")
pmObject.LoadModel ("C:\Models&Interface\Model_1_Route.mod")
Range("A2").Select
Set CurrentCell = ActiveCell
Do While Not IsEmpty(CurrentCell)
pmObject.SetMacro ActiveCell.Value, ActiveCell.Offset(0, 1).Value
ActiveCell.Offset(1, 0).Select
Set CurrentCell = ActiveCell
Loop
pmObject.Simulate
Do
Status = pmObject.GetStatus
Loop Until Status = 8
MsgBox ("Simulation Complete")
pmObject.Quit
Set pmObject = Nothing
Set CurrentCell = Nothing
End If
If Route213SelectionCheckBox.Value = True Then
Set pmObject = CreateObject("ProModel")
pmObject.LoadModel ("C:\Models&Interface\Model_1_Route.mod")
Range("A2").Select
Set CurrentCell = ActiveCell
Do While Not IsEmpty(CurrentCell)
pmObject.SetMacro ActiveCell.Value, ActiveCell.Offset(0, 1).Value
ActiveCell.Offset(1, 0).Select
Set CurrentCell = ActiveCell
Loop
pmObject.Simulate
Do
Status = pmObject.GetStatus
Loop Until Status = 8
MsgBox ("Simulation Complete")
pmObject.Quit
Set pmObject = Nothing
Set CurrentCell = Nothing
End If
If Route215SelectionCheckBox.Value = True Then
Set pmObject = CreateObject("ProModel")
pmObject.LoadModel ("C:\Models&Interface\Model_1_Route.mod")
Range("A2").Select
Set CurrentCell = ActiveCell
Do While Not IsEmpty(CurrentCell)
pmObject.SetMacro ActiveCell.Value, ActiveCell.Offset(0, 1).Value
ActiveCell.Offset(1, 0).Select
Set CurrentCell = ActiveCell
Loop
pmObject.Simulate
Do
Status = pmObject.GetStatus
Loop Until Status = 8

```

```
    MsgBox ("Simulation Complete")
    pmObject.Quit
    Set pmObject = Nothing
    Set CurrentCell = Nothing
End If
End Sub
```

```
Private Sub StormDurationTextBox_Change()
'returns a macro value for storm duration
If RouteAllSelectionCheckBox.Value = True Then
    Worksheets("MacroValues").Range("B34").Value = StormDurationTextBox.Value
Else
    Worksheets("MacroValues").Range("B7").Value = StormDurationTextBox.Value
End If
End Sub
```

```
Private Sub UserForm_Initialize()
'This opens the startsimulation form and loads the fields for current date
    CurrentDateTextBox.Value = Date
End Sub
```

