UNIVERSITY OF ALBERTA

INCORPORATING WEATHER FACTORS INTO CONSTRUCTION MOBILITY SIMULATION

BY

Yinan (Bill) Wang ©

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ABSTRACT

The prediction of construction equipment mobility in winter is important for both cost and time schedule control. Unfortunately, this prediction is subject to the effects of several factors, which leads to an uncertain result. Among these factors, the effects of winter weather impact mobility the greatest. This thesis presents a mathematical algorithm to address the significant weather factor of snow accumulation and its effect upon the speed of the construction hauling equipment using a regression approach. The thesis also discusses other weather factors that impact mobility. A mobility model considering the effect of weather parameters is developed. This mobility model is applied to earthmoving construction simulation in order to analyze the extent to which cold weather affects project duration. The methodology models the occurrence of factors of uncertainty, quantifies their impact upon mobility, and calculates project duration based upon generated weather conditions. This model provides a better tool for scheduling purposes.

Acknowledgement

After one year's research and another year's thesis writing and modification, this thesis is finally accomplished under the supervision of Dr. AbouRizk in this creative and pilot research area. Sincerely thanks to Dr. AbouRizk's kindly support.

This thesis is dedicated to my parents, Qiu and Di, for their encouragement and continuous support throughout my life and study.

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CHAPTER 1: INTRODUCTION

1.1 Overview

An important element of construction management, the improvement of which promises increased management efficiency, is the accurate estimation of project duration and cost. For construction projects involving a large number of activities such as earthwork, mining, and pipeline installation, the mobility of construction equipment is a key factor in determining project duration and cost. Unfortunately, the mobility of construction equipment is difficult to predict because it is highly dependent upon many factors such as weather, road condition, and driver skill. Among these factors, cold weather can have a great impact upon a construction vehicle's mobility as it reduces speed for mechanical or safety reasons. Under severe weather conditions, hauling operations may be terminated, which can significantly delay the progress of a project.

The current approach to calculate the production rate of a construction vehicle takes into account maximum speed, which is dependent upon the total resistance. The maximum speed can be found on the manufacturer's performance chart. This method disregards the effect of various factors influencing a vehicle's speed. In response to the effect of those factors, engineers in the construction industry often estimate the hauling speed of construction vehicles based on their past experience. This rough estimation does not provide accurate information and may result in the failure of a project.

Construction special purpose simulation (SPS) provides an alternative method for the prediction of project cost and duration by simulating different working condition scenarios and processes. The reliability of the model depends upon the accurate prediction of incoming variables feeding the model. The accuracy of the computational model in expressing these variables' impacts on the output will also affect the reliability of the model. This thesis presents an approach to identify significant weather factors and to quantify their effect upon the mobility of construction vehicles. A regression algorithm is developed to quantify the effect of snow accumulation on a construction vehicle's speed. Along with the combination of other influential factors, this approach is applied in an earthmoving simulation model, contributing to the development of the weather-affected mobility model.

1.2 Problem Statement and Objectives

Cold weather is an unavoidable part of life for most Canadians. For example, the first frost in the City of Edmonton normally occurs in late September; the daytime average temperature from November to January ranges from zero degrees to minus 30 degrees Celsius (Statistics Canada). Winter temperatures in far northern Alberta are even lower. Snow is another main factor of cold weather. In Alberta, for instance, between October 2002 and May 2003, the total snow precipitation was recorded to be 225.4cm (Statistics Canada). During this period, the ground is covered with snow for more than 54% of the winter days (Statistics Canada).

Many construction projects are carried out in areas with cold climates. Since large projects tend to have long durations, winter construction is inevitable. Research suggests that cold weather has an adverse effect on construction productivity and efficiency, prolonging project duration and increasing total cost. The mobility of construction equipment, for instance, is highly susceptible to cold weather factors such as snow accumulation, snow precipitation, high wind velocity, and low temperature. Among these factors, snow accumulation and precipitation have the most evident impact on mobility. However, the current simulation model treats the speed as dependant upon the rolling resistance and grade resistance, supposing it is in ideal condition. This assumption disregards the impact of weather on mobility. Even in practical use, a productivity rate is given upon consideration of several effects. This operation neglects the uncertainty of outside factors and may result in an inaccurate estimate for project duration.

The objective of this research is to incorporate the uncertainty of specific weather factors into the calculation of a construction vehicle's speed and to provide a better approach for estimating project duration accurately. To achieve this objective, the following research plan will proceed:

1. Extend the algorithm developed by other research result to calculate the maximum speed of the construction vehicle based on weather factors;
2. Explore the fuzzy method as a potential approach in combination with factors other than snow to complete the mobility model;
3. Incorporate this algorithm into the mobility simulation model to predict construction vehicle speeds and project durations; and
4. Present sensitivity analysis of the algorithm to catch the key factors impacting construction mobility the most and compare simulation results of case study with the estimates of experienced engineers to verify the model.

1.3 Methodology of the Solution

To accomplish the stated objectives, this research was conducted in three phases. In the first phase, a comprehensive literature review and interviews with personnel from the construction industry were undertaken. These had the following purposes: (1) to fully understand the specific domain of the earthmoving process; (2) to explore weather factors that affect the construction process; and (3) to pursue a methodology for quantifying these effects. In the second phase, a mathematical regression algorithm based upon previous research within other domains was adopted and further developed in order to quantify the overall impact. In the third phase, a simulation model was developed using the earthmoving simulation (EMS) template within the *Simphony* simulation environment. This model was used to incorporate the accomplished algorithm into an earthmoving practice. Finally, a comparison of the results with the estimates of construction personnel qualitatively verifies this model. The methodology used in this research is shown in Figure 1-1.

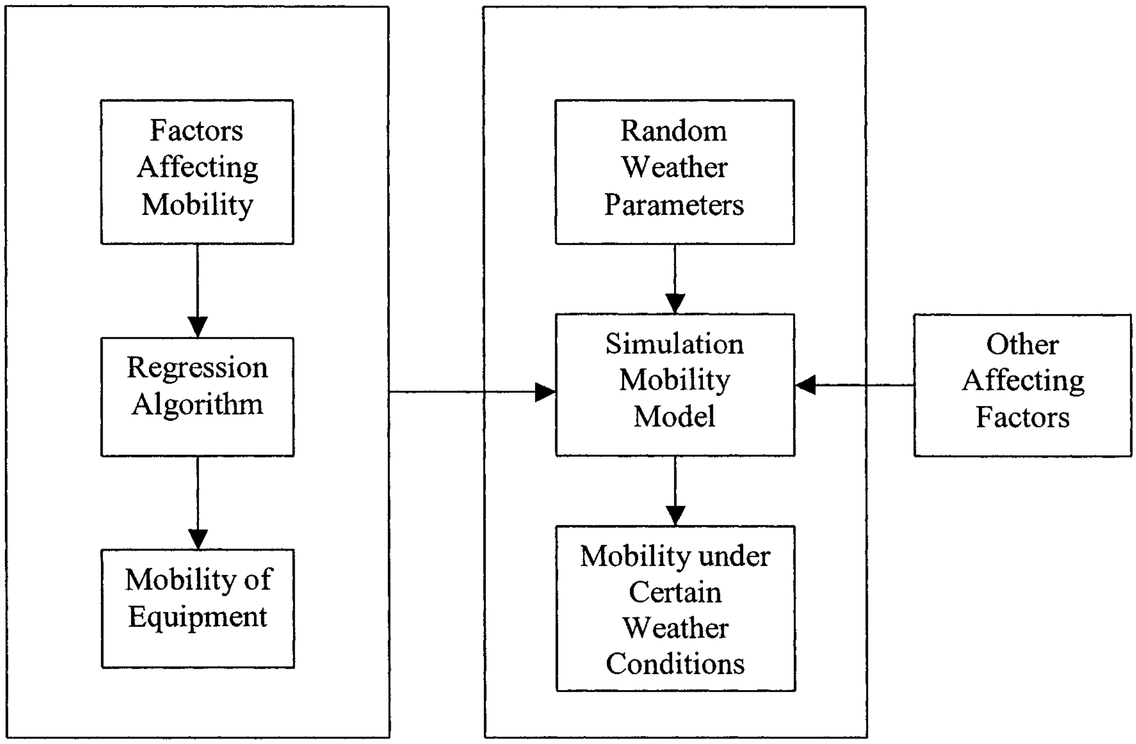


Figure 1-1 Methodology of the Solution

1.4 Thesis Organization

Chapter 2 provides a literature review of relevant research in related areas and discusses the approaches available for implementing the model. Chapter 3 presents a regression algorithm to incorporate the snow accumulation factor into the calculation of the construction vehicle's speed. In Chapter 4, additional weather and other factors affecting mobility are presented. An approach for incorporating these factors into a mobility model is discussed. Chapter 5 introduces a detailed modification and development process of the SPS earthmoving template and the application of simulation within the earthmoving practice to predict the duration of projects. In Chapter 6, a sensitivity analysis is explored for the weather-impacted mobility algorithm and a case study is presented to verify the model. Chapter 7 discusses the conclusions and contribution of this research, the limitations of this model, and possible future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The literature review focuses mainly on the following areas:

1. State-of–the-art research in winter construction and identification of weather factors that affect the mobility of construction vehicles;
2. Methodologies that relate mobility to the weather factors identified; and
3. The application of a simulation approach within the construction field.

2.2 Winter Construction and Weather Factors Affecting Mobility

Many construction projects are carried out in cold weather in Alberta. It is a necessity instead of an alternative due to the long winter duration and severe weather condition. The effects of cold weather are unavoidable for these projects. The negative effect of low temperature and other cold weather factors upon construction activities may result in a reduction of productivity, the extension of project duration, and an increase in operation cost. The National Cooperative Highway Research Program (NCHRP) summarizes the effect of weather elements on workers, equipment, the quality of work performed, and the ease of handling material for highway construction operations in a 1978 survey, the results of which are represented in Table 2-1. It illustrates the degree of impact that weather parameters, especially precipitation, have on different aspects of construction.

	Precipitation			Temperature		Wind		
	Rain	Snow	Sleet	Hot	Cold	0-10 km/h Low	10-30 km/h Med	30+km/h High
Work	S	S	S	L	M-S	L	M	M
Men	S	S	S	L-M	M-S	L	M	S
Equipment	M-S	S	S	L	M	L	L	M
Materials	M	S	S	L	M	L	M	M

S – Severe   M – Moderate   L – Little

Table 2-1 Effects of Weather Elements on Workers, Equipment, Work Quality, and Material Handling (NCHRP 1978)

Cold weather can also be beneficial to mobility in certain aspects. The freezing of typically wet, soft ground in low temperatures, a phenomenon that makes the construction site accessible, is an example of such benefits. Even in Canada, seasonal ice roads are constructed annually to service remote areas inaccessible during other seasons. Case studies identified in this research used paved or packed roads, which did not allow for an analysis of these benefits.

Vehicle mobility is defined as the efficiency with which a vehicle travels from one point to another (Richmond et al. 1995). In this research, the maximum speed that a vehicle can achieve in a given scenario is used to represent its mobility. For certain construction vehicles, the higher their maximum speeds can attain, the greater their mobility will be. Cold weather factors have a strong effect on construction vehicle mobility. Under cold weather conditions, the maximum speed of a vehicle will be greatly impacted by the weather with relation to mechanical or safety factors.

An important resource for defining crucial weather factors having a dramatic impact on the maximum speed of construction vehicles is industry experience collected from knowledgeable practitioners. This approach has been widely used in other research. Moselhi et al. (1995), for example, studied the impact of weather on productivity by distributing questionnaires to several construction personnel. All weather factors that were considered to have an impact on productivity are listed. Productivity factors for different scenarios are given based on available industry knowledge. Temporary work stoppages due to adverse weather conditions are also considered. Findings accumulated from Moselhi's survey are incorporated into a stand-alone decision support system, named *WEATHER*. The module is used to estimate the construction productivity and activity duration while incorporating the effects of weather parameters.

This research employed the following methodology to identify crucial weather factors. Firstly, all potential factors are listed and those that may affect mobility are identified through a literature review. Secondly, construction personnel are contacted and an investigation is carried out to justify and supplement the factors. As a result of this methodology, five key weather factors, which had a major impact on mobility in winter, were identified and studied:

1. Snow accumulation
2. Snow precipitation
3. Average temperature
4. Wind speed

5. Fog

"Snow accumulation" and "snow precipitation" have the most significant impact on mobility. Greater snow accumulation on roads results in a reduced mobility for construction vehicles. Snow on the ground increases road resistance; vehicles must use more output power to conquer it in order to move. When the snow is packed, it makes the road slippery. Under these conditions, drivers must reduce speed for safety reasons. On certain construction sites, various equipments are used to remove the snow; however, this additional procedure also hinders the construction process. Falling snow decreases a driver's visibility. To promote safe operation, vehicles must be operated at lower speeds in these conditions. In extreme situations such as heavy snow weather, the movement of vehicles is temporarily halted altogether.

Low temperature is another factor adverse to mobility; it can decrease the mechanical efficiency of vehicles. Even when the temperature is only marginally low, hauling often has to be halted in order to avoid possible damage to equipment. High wind velocity can also affect the speed of construction vehicles. The wind may decrease the operator's visibility. In certain extreme conditions, the hauling needs to be stopped for safety reasons. This adverse effect also applies to construction sites under the influence of fog.

2.3 Predicting Mobility Based on Weather Factors

Various approaches attempt to quantify the relationship between weather factors and the overall resistance of vehicles. Briefly, these approaches can be divided into two types: 1) traditional, analytical approaches such as the statistical approach or the regression approach, and 2) non-analytical approaches such as the neural network (NN) approach.

Much research in the construction field uses artificial neural networks as an effective methodology for quantifying the relationship of inputs and outputs whenever traditional analytical approaches are not feasible. Unlike analytical approaches, neural networks require no expressly defined model. The behavior of a neural network is defined by the way in which its individual computing elements are connected and by the strength of those connections, called "weights." The weights are automatically adjusted by training the network according to a specified learning rule. This methodology, then, operates in a manner analogous to the learning process of the human brain. Moselhi (1991) presented a NN model that has input factors such as job size, building type, overtime work, and management conditions. This model was able to predict a realistic productivity level for a specific trade as its output. This approach is widely applied in similar research. In Wales's work (1993), the NN approach is used for training the correlation of weights between the weather parameters and the productivity rate.

One reason why the NN model is an applicable approach is that it allows the user to consider numerous input factors that may have an impact on the output. The high number of inputs makes other analysis approaches unachievable. For instance, Portas (1996) made a systematic list of factors influencing wall formwork productivity as NN inputs (this list is shown in Figure 2-1). Another reason for its popularity is that it can provide weights without needing to account for the complicated theoretical relationships between inputs and outputs. With training, a NN model can provide different weight values for input layers, hidden layers, and output layers. The NN model resembles a "black box," providing results without knowing the process's mechanics.

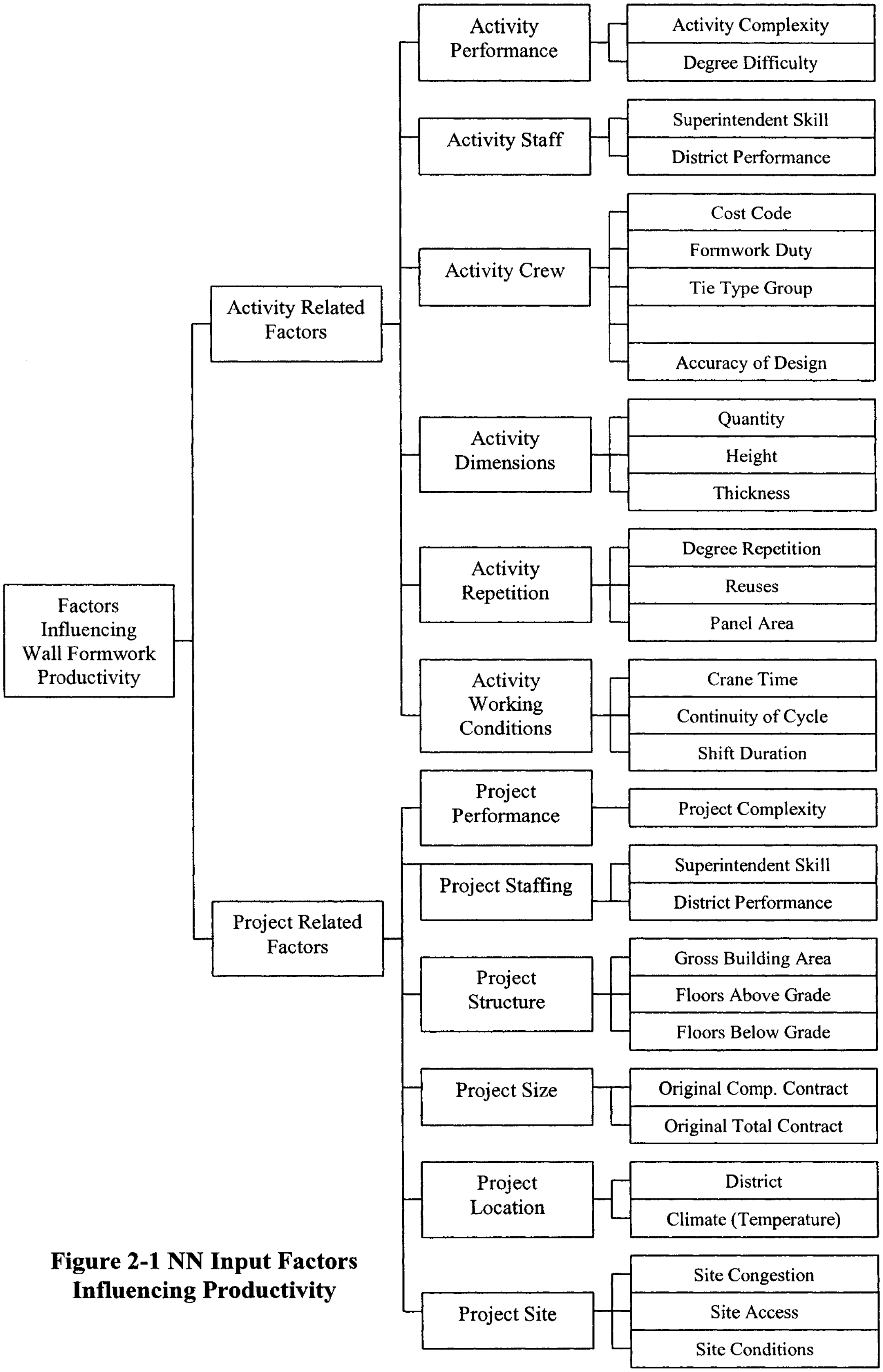


Figure 2-1 NN Input Factors Influencing Productivity

It should be noted, though, that these same reasons limit the utilization of the NN approach. Experience has shown that if the collected information is not enough for training the weight, the result may prove to be unstable when its 'goodness of fit' is tested in comparison to unused data. More importantly, a NN requires a great deal of data to train a system to calculate corresponding weights for computing elements. Under the current conditions, it is impractical to experiment extensively or to collect a large amount of data for this research. A simple but efficient analytical algorithm is needed to present its correlation between weather and mobility. This algorithm needs to meet two requirements: 1) the formula expression must be simple enough to be used in the construction industry and 2) it must be sufficiently accurate at an industrial level of precision.

Many efforts to find an algorithm that could quantify the correlation between weather parameters and mobility have been undertaken. Rada et al. (1989) presented a methodology for analyzing the effects of a site-specific rainfall and evaporation history upon the performance of unpaved roads. In their work, the factors that affect road performance were determined to include the subgrade or natural soil foundation, the layer material properties, traffic, and specific environmental conditions at the site. They introduced two models: a soil moisture prediction model and a damage analysis model. The soil moisture prediction model combines the site-specific weather history with the soil hydraulic properties and soil profile in order to produce a soil moisture content history value as output data. The damage analysis model combines the soil-moisture history value with soil-moisture compaction and soil-moisture strength signatures to develop a predicted soil strength history such as in the California Bearing Ratio (CBR).

The CBR is used together with the traffic mix to estimate the rut-depth failure criterion that will result in road damage. Rada's work focuses on the analysis of these soil damage results.

Albert et al. (2000) contributed a great deal to this area of research. Using FASST (Fast All-Seasons Soil STate) models to build several modules, they were able to represent the relationship among the meteorological conditions, the state of the ground, the cone index (CI), and the overall equipment mobility. Among them, the state of ground includes the snow depth, soil strength, soil temperature, and the state of soil moisture. The cone index is the force per unit basal area required to push a cone penetrometer through a specified increment of soil, which represents the strength property of the soil. This relationship is shown in Figure 2-2. Albert's research focuses specifically on soil conditions in support of mobility. It predicts the state of the ground in all seasons with the most common conditions.

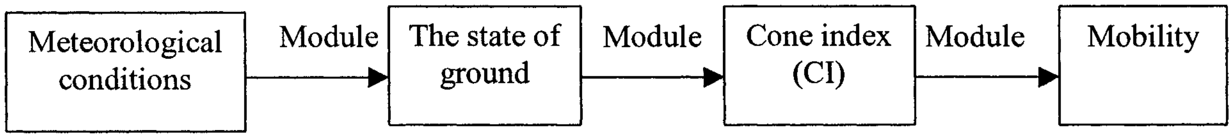


Figure 2-2 Fast All-Seasons Soil State (FASST) Models

Since the mobility of military vehicle is critical for the army, a large amount of research regarding vehicle mobility under cold climates has been conducted for military purposes. Lacombe (2000) made an effort to implement a tire subroutine in the Dynamic Analysis Design System (DADS) model in order to conduct driving simulation on dry, snow-covered, or ice-covered road surfaces. These simulations were based on mechanical analogues of both longitudinal and lateral treads as well as the sidewall deflections of tires. This model only requires a set of easily obtained input parameters that incorporate the mechanical properties of tires operating upon different road conditions.

The United States Cold Regions Research and Engineering Laboratory (CRREL) has been performing long-term research on the mobility of tracked and wheeled vehicles on snow covers for military purposes. Blaisdell et al. (1990) validated a shallow snow mobility model by performing tests under a variety of weather conditions in conjunction with different kinds of military vehicles. They used these test results to determine key weather parameters that affect vehicle mobility and attempted to quantify the relationship between them. Based on the work of CRREL, a nomograph was developed by McFadden and Bennett (1991) to estimate cold environment impact factors for equipment. The nomograph is shown in Figure 2-3.

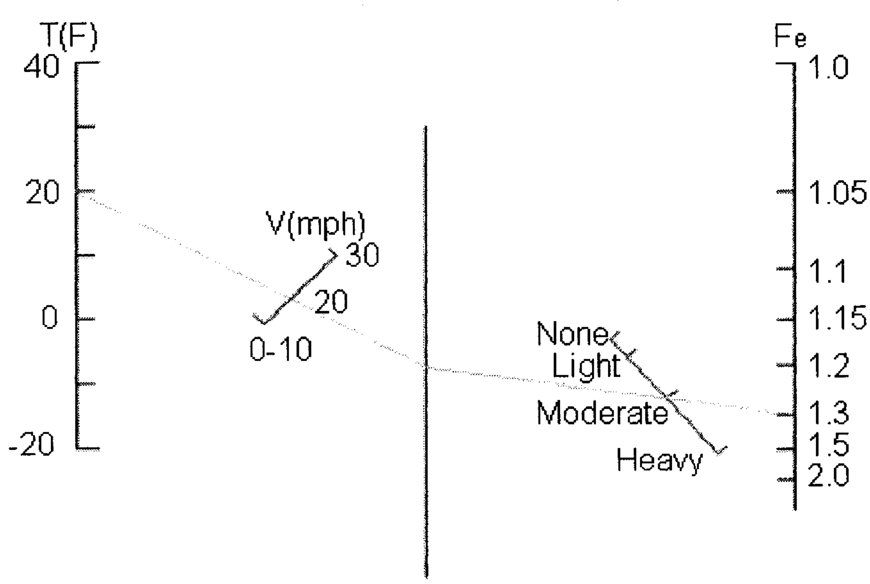


Figure 2-3 Nomograph for Estimating Cold Environment Factors for Equipment (McFadden and Bennett 1991)

From this nomograph, a cold environment factor for equipment (Fe) can be obtained at any air temperature, wind speed, or snowfall condition. The parameters used in nomograph are presented as follows:

T: air temperature (degree Fahrenheit)

V: wind speed (mph)

Ps: Snowfall precipitation, in four grades: none, light, moderate, and heavy

Fe: cold environment factor for equipment task

For example, a temperature of 20^0F (-6.7^0C), a wind velocity of 20-mph (32.2-km/h), and a moderate snowfall precipitation result in a cold environment factor of 1.3. This value means that a task requiring 1 hour to complete under normal conditions would take 1.3 hours in the above conditions. This nomograph is a good application of CRREL research work and provides a rough estimate of weather effects.

Over several years, Richmond et al. (1995) researched and developed the cold region mobility models based on theoretical relationships and empirical expressions in their CRREL Report 95-1. Richmond performed experiments with different vehicles under diverse snow conditions. The test vehicles used included tracked and wheeled vehicles and were in different sizes and weights. The results of this study were comprehensive and generated many variations. As a conclusion, the researchers developed a mathematical algorithm between the character of snow accumulation and the overall resistance of the road by applying a regression approach. Although the algorithm was developed for military purposes, the models can also be used to compare specific vehicles or to determine specific vehicle-terrain interactions.

In this thesis, the regression approach surveyed is extended to the construction domain. An algorithm to incorporate snow accumulation into the calculation of the maximum speed of construction vehicles is presented. The parameters of the algorithm are calculated based on the specifications of the construction vehicles. Other impacting factors can also be extrapolated from this analysis and represented as coefficients to the maximum speed. An important assumption in this model is that the effect of weather factors on mobility can be first considered separately and then subsequently combined together in order to consider the overall effect.

2.4 The Application of Simulation in the Construction Field

Simulation, which has proven to be a useful tool in assisting project management, is widely used in a variety of industrial domains. Simulation can be defined as "the development of a mathematical-logical model of a system and experimental manipulation of the model on a computer" (Pritsker 1985). It provides an inexpensive way to do experimental manipulation with different scenarios, rather than the costly traditional manner of experimentation.

The application of simulation in the construction industry has become acceptable over the past two decades following Halpin's (1977) introduction of the CYLONE methodology. The introduction of the CYLONE process motivated a number of simulation research: for example, Paulson (1978), Chang and Carr (1987), and McCahill and Bernold (1993) (AbouRizk 1998). The repetitive process of a construction project makes it a good subject for a simulation model (AbouRizk 1998). The obstacle that hinders the practical implementation of this approach stems from the unique qualities of a construction project as compared to those found in the manufacturing industry. If the detailed process of a project is fully understood and correctly described, then the simulation model can be built accurately. Simulation has a promising role in the construction area.

Carr (1979) presented a model for uncertainty determination (MUD) to calculate a range estimate (mean and standard deviation) for construction projects. The activity durations in a construction project are not independent of each other. Carr identified the interdependent variables of uncertainty as the productivities of crews and equipment, subsurface site conditions, effectiveness of supervision, dependability of subcontractors, and weather behavior.

Wales (1993) developed a simulation model to perform analysis on how weather parameters affect construction productivity. In Wales's model, the influential weather parameters were generated stochastically based on statistical historical records using the Markov chain approach. The neural network approach was used to train the correlated weights between the weather parameters and the productivity rate, which considered the weather parameters inputs and produced a productivity rate as its output. The daily productivity was produced based on daily weather conditions. The process of the project based upon the weather-affected productivity was continued until the project was finished. In this way, the project duration can be estimated considering the effect of weather parameters.

The application of simulation requires large quantities of programming. It takes much effort for a developer to clarify the detailed process of a specific construction domain, to develop a conceptual model, to execute the model using programming code or universal elements, and then to verify the model by inputting the data, checking for bugs, and analyzing the results. It requires both strong programming ability and background knowledge in the specific construction domain. This high level of competency makes the simulation approach overly academic and has prevented it from practical utilization within the construction industry. General purpose simulation programs are widely used for academic purposes. For instance, Wales achieved the results of his research using SLAMSYSTEM, a simulation network program for general purpose (1993). To conduct his research within the system, Wales put in a large amount of effort to convert the CPM project network into a SLAMSYSTEM network. Furthermore, the output of the SLAMSYSTEM is not graphical and cannot therefore easily be used in the construction industry. A user-friendly simulation tool is needed, which is applicable and accessible within the construction industry rather than solely for academics.

Since 1996, Hajjar and AbouRizk have developed a series of SPS tools for particular construction domains. The first SPS tool, AP2-Earth (1996), is used for the analysis of large earthmoving projects. The second SPS tool, CRUISER (1998), is used for modeling aggregate production plants. A third SPS tool, Construction Site Dewatering (CSD) (1998), provides optimization of construction site dewatering operations. Combining the experiences obtained from the SPS tools, Hajjar and AbouRizk identified key qualities that simulation models should possess and developed a simulation environment accessible by a variety of construction domain simulation tools, namely, *Simphony*. The accomplishment of the *Simphony* platform was a massive advance for practical simulation applications in the construction industry by providing explicit special purpose templates for different construction domains. One of its most important features is that it provides elements with realistic logic instead of generic symbols, making it extremely straight-forward for practitioners use in building a simulation model.

Simphony offers a graphical environment for both tool editors and end-users to develop simulation models. Its open structure allows a developer to create more elements in the package. For end-users, *Simphony* provides a user-friendly environment for creating any construction end-model without a complete knowledge of computer programming. As a simulation tool, *Simphony* provides the following typical functions:

1. Random number generation
2. Tracing
3. Statistical analysis
4. Planning
5. Database access
6. Graphical user interface

Simphony specializes and customizes different construction simulation tools by developing corresponding special purpose templates. At present, seven main SPS templates are commonly used. These are:

1. The Earthmoving template for earthmoving projects;
2. The Crushing template for aggregate production plants;
3. The PERT template for project network scheduling;
4. The Dewatering template for removal of water in construction site;
5. The Range Estimating template for estimating construction costs;
6. The TBM tunneling template for tunneling projects; and
7. The Tower Crane template for operating tower cranes.

Besides these seven templates, there are two additional templates for general purpose simulation: the Common template and the CYCLONE template. Each individual template is a collection of modeling elements for a specific construction domain. Developers can design and modify elements to meet specific modeling requirements. They can also be used to design new templates for a targeted domain. The creation of new elements is implemented through the writing of code directly or by combining common template elements. The weather-affected construction mobility model that this thesis presents is implemented using the Earthmoving template.

2.5 Conclusion

A comprehensive literature review concludes that a mathematical regression approach is utilized to develop the algorithm to calculate the speed of construction vehicle based on the snow accumulation. As explained in Section 2.3, most non-analytical approaches such as neural networks require a large amount of experimental data in order to develop and verify the model, which was not feasible in this research. On the other hand, the research result of CRREL justifies using the regression method in application in this research. The incorporation of this weather-affected mobility algorithm into an earthmoving simulation model is a viable application for predicting project duration more accurately.

CHAPTER 3: SNOW ACCUMULATION-MAXIMUM SPEED ALGORITHM

3.1 Introduction

This chapter presents a mathematical algorithm to correlate snow accumulation and the maximum possible speed of construction vehicles under cold weather conditions. The algorithm is composed of two parts: (1) the snow accumulation-gross traction algorithm presented in Section 3.2; and (2) the gross traction-maximum speed algorithm presented in Section 3.3.

The first part is developed from the regression approach presented by CRREL. They have done many experiments with different type of military vehicles and developed a series of regression formulas based on the experiment results. The approach is applied in this research and relevant formulas are adopted with corresponding value of parameters for specific construction vehicles. The second part develops an algorithm to correlate the gross traction and speed of the construction vehicle based on a rimpull performance chart. The combination of these two algorithms to predict the maximum speed the vehicle can obtain based on certain weather condition is a great contribution of this research.

3.2 Snow Accumulation-Gross Traction Algorithm

3.2.1 Background

Over several years of experimental and theoretical studies, CRREL had developed a regression model to predict the mobility of military vehicles over winter terrain. This mobility algorithm is based on experimental data and mathematical regression. CRREL made a set of snow characterizations for each test. The snow depths ranged from 7.0-cm to 76-cm. A cross-section of the test vehicles that CRREL used to develop the regression algorithm is listed in Table 3-1 (Blaisdell et al. 1990).

	Test Vehicles	Wheels/Tracks
1	CRREL instrumented vehicle (CIV), Based on 1977 Jeep Cherokee	Goodyear Tiempo tires, size P225/75R15
2	M988 High-Mobility Multipurpose Wheeled Vehicle (HMMWV), 4x4	Michelin 37x12.5R16.5LT tires
3	Light Armored Vehicle (LAV) 25, 8x8	Michelin 11.00R16 Tires
4	Light Armored Vehicle (LAV) 25, 8x8	Michelin12.50R20 Tires
5	M997 Heavy Expanded Mobility Tactical Truck (HEMTT), 8x8	Michelin 16.0R20 tires
6	M923 5-ton truck, 6x6	Goodyear 14.00R20xL tires
7	M973 Small Unit Support Vehicle (SUSV), articulated	tracked
8	M113A1 Armored Personnel Carrier (APC)	tracked
9	M2 Bradley Fighting Vehicle System (BFVS)	tracked

Table 3-1 Test Vehicles

Many of these efforts are incorporated into military mobility models, including the Condensed Army Mobility System (CAMMS) (Falls et al. 1989) and the NATO Reference Mobility Model-II (NRMM-II) (Ahlvin and Haley 1992). However, this research can also be used to determine specific vehicle-terrain interactions (Richmond et al. 1995). The normal stresses on tires vary widely from 15-kPa up to 265-kPa. The mathematical regression algorithms are greatly applicable to construction vehicles since the value limits account for the specifications for construction vehicles.

3.2.2 Fundamental Mobility Criteria

An effect mobility model must have two functions: firstly, that given a specific condition, the model must be able to predict whether a vehicle is able to move or not and, secondly, it must be able to predict the speed of the vehicle. According to the CRREL report (Richmond 1995), the basic criteria of a vehicle's mobility can be expressed with traction T and resistance R:

$$T_{net} = T_{gross} - R_{terrain} - R_{internal} \qquad \text{(Equation 3-1)}$$

T_{net}: net traction of the vehicle

T_{gross}: gross traction of the vehicle

$R_{terrain}$: resistance from terrain

$R_{internal}$: resistance from the vehicle

T_{gross} is the maximum total traction force that a specific vehicle is able to generate on a particular terrain. It is a function of factors such as: 1) the tire or track contact pressure, 2) the ability of the running gear to engage with the terrain, 3) the sheer strength of the top layers of the terrain, and 4) the power available to the tire or track. The value of motion resistance is divided into two parts: firstly, that which is produced by external forces referred to as $R_{terrain}$ and, secondly, that which is produced by internal forces referred to as $R_{internal}$. $R_{internal}$ is the resistance caused by friction within the vehicle. Examples of such resistance include tire deformation, track roller resistance, and friction in the driveline component. $R_{internal}$ will remain constant for a specific vehicle on a specific terrain with a specific loading. $R_{terrain}$ is the resistance attributable to the travel surface and is a function of the terrain strength and of the gear characteristics of a vehicle. It is greatly dependent upon the terrain condition.

Equation (3-1) is the mobility criterion in a construction vehicle for "go or no-go". If $T_{net} \geq 0$, that is, if the gross traction is more than or equal to the total motion resistance of the vehicle, according to Newton's law of motion, the vehicle will have enough force to overcome the resistance in the opposite direction of moving trend, then the vehicle is movable. If $T_{net} < 0$, that is, if the gross traction is less than total motion resistance of the vehicle, then the vehicle will not have enough force to overcome the resistance, and the vehicle will be immovable. Equation (3-1) is derived based on the assumption that the vehicle moves on a level surface. If the vehicle is on a sloped surface, resistance or traction from the grade can be added as part of the $R_{terrain}$ or T_{gross} variables, respectively, depending upon whether the grade is negative or positive.

3.2.3 Gross Traction

Different formulas for calculating gross traction are developed according to various snow conditions. Before gross traction can be calculated, snow must be categorized according to its depth and the substrate status of the snow. Snow can either be on a firm substrate or on a soft substrate. On a firm substrate, the terrain underlying the snow has a high enough rating cone index (RCI) value (RCI>100) to fully support the vehicle of interest without any sinkage. Under such conditions, the mobility is assumed to be unaffected by the substrate; the calculation of traction and resistance is, therefore, straightforward. In this model, we assume that the construction vehicle's travel on compact unpaved or paved roads falls within the firm substrate category. The region of disturbed snow under a vehicle's running gear is referred to as the pressure bulb. The snow cover is "shallow" if the pressure bulb extends to the ground or pavement under the snow cover. If the pressure bulb does not extend to the ground, then the snow cover is "deep". Additionally, when sinkage is greater than two-thirds of the wheel radius and is greater than the ground clearance available for wheel vehicles, the cover is also classified as "deep" snow. Disturbed snow and undisturbed snow have different characteristics.

For shallow, undisturbed snow on top of a firm substrate, considering the slippery surface of the snow, the gross traction for one driven wheel is given as (Blaisdell et al. 1990):

$$T_{gross} = 0.851 N^{0.823} A \qquad \text{(Equation 3-2)}$$

N: the normal stress (kpa) on driving element

A: element contact area (m^2)

Equation (3-2) gives the upper limit of the gross traction. While it is the maximum traction one driven wheel can provide, it is not necessary for the vehicle to output such traction all the time. Each vehicle has its maximum output of power, determined by traction and speed. Traction and speed are reciprocal: the more traction a vehicle provides, the less speed it can have. According to Newton's First Law of Motion, to keep the vehicle at a constant maximum speed, the output of the traction must be equal to its total resistance, which is just large enough to overcome the motion resistance encountered by the vehicle. The vehicle then arrives at its maximum speed. Generally, the maximum speed that a vehicle can obtain is determined by the sum of $R_{internal}$ and $R_{terrain}$, which the vehicle needs to overcome.

For deep, undisturbed snow on top of a firm substrate, the traction is different from shallow snow. There are few published results for accurate prediction algorithm. However, we can assume that the difference is only to a small degree, since the majority of the traction is generated in a full pressure pump. The traction in deep snow can be expressed approximately using Equation 3-2, which was developed from shallow snow.

3.2.4 Motion Resistance

Motion resistance is composed of two parts: resistance from a vehicle's internal operations ($R_{internal}$) and resistance from terrain ($R_{terrain}$). $R_{internal}$ is caused by friction within a vehicle such as tire deformation or due to internal driveline components. It is generally not impacted by outside factors. Ahlvin and Haley (1992) presented the empirical value of internal resistance coefficients. This research is duplicated in Table 3-2.

Wheeled	Tracked	Surface
0.015	0.0375	Superhighways and primary roads and ice
0.025	0.045	Secondary roads
0.0175	0.0525	Trails and cross country (Pfg* > 4.0)
0.015	0.0525	Trails and cross country (Pfg < 4.0)

*Pfg = $w/(nbr)$, in psi, where, w is the weight on an axle, n is the number of wheels on an axle, b is the wheel width and r is the wheel radius.

Table 3-2 Internal Motion Resistance Coefficients

Terrain resistance involves a high level of uncertainty and is affected by environmental factors including overall road and equipment conditions. It is also greatly influenced by cold weather factors. Through a theoretical analysis, the $R_{terrain}$ on snowy roads is found to depend on factors such as snow depth, snow density, snow grain crystal structure, liquid water content, and other variables impacting the mechanical characteristics of snow cover. For practical purposes, the parameters are simplified into snow depth and density.

The motion resistance from the terrain in undisturbed snow is given by Richmond et al. (1995) as:

$$Rterrain = 68.083(\rho_0 ba)^{0.9135} \qquad \text{(Equation 3-3)}$$

ρ_0: density of snow immediately in front of the vehicle's running gear (Mg/m^3)

a: length of the tire contact with snow (m)

b: maximum width of tire (m).

The correlation between a, b, and r is shown in Figure 3-1.

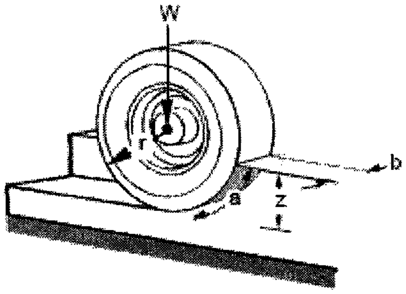


Figure 3-1 Tire Parameters (Richmond et al. 1995)

Among them, parameter a is a function of the tire radius r and the vehicle's sinkage z, given by Richmond et al. as:

$a = r \times \arccos[(r - z)/r]$ (Equation 3-4)

r: tire radius (m)

z: vehicle's sinkage (m).

As Richmond et al. presented, the value of a vehicle's sinkage can be calculated using the data of the initial snow depth and of the initial and theoretical final densities:

$z = h(1 - \rho_0 / \rho_f)$ (Equation 3-5)

h: initial snow depth (cm)

ρ_0, ρ_f: initial and theoretical final densities (Mg/m^3), respectively.

As for ρ_f, it is a function of the applied load. In temperate regions with seasonal snow, the values of ρ_f are estimated as following:

$\rho_f = 0.50 Mg/m^3 \quad P\max \leq 210 KPa$

$\rho_f = 0.60 Mg/m^3 \quad P\max > 350 KPa$

$\rho_f = 0.65 Mg/m^3 \quad P\max > 700 KPa$

Where *Pmax*: maximum applied load

P_0, the initial density of the snow, is a parameter of the weather factors. According to the CRREL Special Report 95-23 (Horrigan and Bates 1995), ρ_0 is a function of air temperature and wind speed, both of which are measurable weather factors. The empirical mathematical expression between them is as follows:

$\rho_0 = 0.152 - 0.0031T + 0.019W$ (Equation 3-6)

ρ_0: average seasonal snow-cover density (g/cm^3)

T: average seasonal air temperature (°C)

W: average wind speed (m/s)

Equation (3-6) is derived from measurements obtained in Alaska, the northern United States, and Canada. It is assumed to be limited to these cold areas.

$R_{terrain}$ can be determined through a vehicle's specifications and weather factors h, T, and W. The algorithm describes the mechanical properties of undisturbed snow on substrate ground. In this way, we can develop an empirical algorithm to calculate the value of motion resistance. A mathematical relation between snow accumulation and total resistance is established.

For deep snow, Richmond et al. (1995) give a coefficient to correct the value of the motion resistance applied to the shallow snow in Equation 3-3. The values of the coefficient are shown in Table 3-3.

Snow-cover Density	Thickness of Snow	Coefficient Value
$\rho_0 < 0.15$ Mg/m3	$z > r$	1.5
	$z >$ ground clearance	2.25
$\rho_0 \geq 0.15$ Mg/m3	$r >$ sinkage $> 0.67r$	1.5
	$z > r$	2.5
	$z >$ ground clearance	3.75

ρ_0: average seasonal snow-cover density
z: vehicle's sinkage
r: tire radius

Table 3-3 Coefficients for Traction from Terrain in Deep Snow (Richmond et al. 1995)

However, the algorithm discussed takes place is on undisturbed snow, which has been driven over less than four times. The snow is considered disturbed if it has been driven over more than four times, as its mechanical properties will be different from those of undisturbed snow. The CRREL assumes that after the snow is disturbed and packed, the resistance to the vehicle caused by snow is in decreasing degrees until it reaches zero. In actuality, the situation will be far more complicated. During packing, new snow may fall and accumulate. The whole process involves continuous interactions.

3.3 Gross Traction-Maximum Speed Algorithm

In the previous section, the correlation between the total resistance to the vehicle and the gross traction was considered as a "go or not-go" criterion. When the gross traction is equal to the total resistance, the vehicle can attain its maximum speed. The second part of the mobility algorithm, namely, "speed made good," results from the calculation of the maximum speed given the total resistance.

3.3.1 Background

Performance charts are published by equipment manufacturers for each model of the construction vehicle. These charts offer specifications for each individual machine and provide helpful performance information about the machine's operation under different conditions. Rimpull performance charts present the correlation between the maximum speed of the machine and the traction required under certain gross weights. Examples of such charts can be found in the Caterpillar Performance Handbook, Version 32 (2001). Under a certain gross weight and given the total required traction (the power to overcome the total resistance), the truck's maximum speed can be measured from the chart.

While rimpull performance charts do perform well overall, they are not convenient to use for research purposes for the following reasons:

1. The chart is not easily applicable for programming computer applications;

2. There are a variety of possible measurement errors depending on the accuracy of the users;

3. The chart is not in a universal form; that is, different machine models have different charts; and

4. Measurement from a chart is a time-consuming process.

3.3.2 Detailed Mathematical Algorithm

As a solution to the constraints identified above, Hicks (1993) developed a mathematical expression to present the function between the maximum speed and the rimpull as an alternative to using the charts. The basic algorithm is presented as:

$$RP_{avail} = F = (V / K_0)^{1/n} \qquad \text{(Equation 3-7)}$$

RP_{avail}: the available rimpull at speed V

F: the total resistance the construction vehicle needs to overcome

V: the speed of the construction vehicle

K_0 and n: the parameters based on different charts

Equation (3-7) provides a power function between V and RP_{avail}. This function allows the rimpull to be determined given a speed, V. On the other hand, the speed V can also be a function of the available rimpull. When the rimpull is used to overcome the total resistance, the vehicle is able to attain its maximum speed.

To present speed V as a function of gross traction F, Equation (3-7) can be transformed into:

$$V / K_0 = F^n$$

Log both sides of the equation:

$$\log_{10} V - \log_{10} K_0 = n \log_{10} F$$

Then:

$$\log_{10} V = n \log_{10} F + \log_{10} K_0$$

Their relationship can be expressed in linear form as:

$$y = kx + b$$

in which:

$$y = \log_{10} V$$

$$k = n$$

$$x = \log_{10} F$$

$$b = \log_{10} K_0$$

After the equation is transformed, the speed V can be presented as a function of gross traction F:

$$V = 10^{n \log_{10} F + \log_{10} K_0} \quad \text{(Equation 3-8)}$$

After the parameters K_0 and n are identified, the mathematical expression between V and F can be calculated. This calculation will obtain the maximum possible speeds at any gross traction level.

3.3.3 Calculation of K_0 and n

Depending on the chart, the parameters K_0 and n in Equation (3-8) have different values. Their values can be estimated using a linear regression approach. To identify the relevant parameters K_0 and n, a group of typical points are selected to fit a regression curve.

Taking the Caterpillar truck model 769D as an example, twelve sample points are selected from the rimpull performance chart, as shown in Figure 3-2.

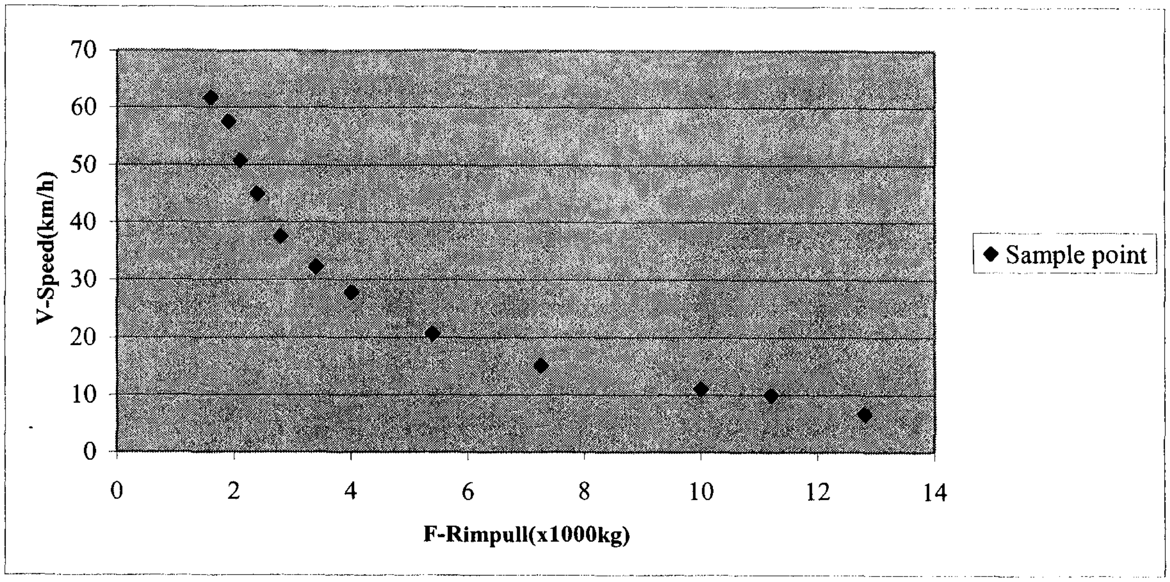


Figure 3-2 Sample points for Model 769D

The regression fit is obtained using the linear regression function in MS Excel as shown in Figure 3-3.

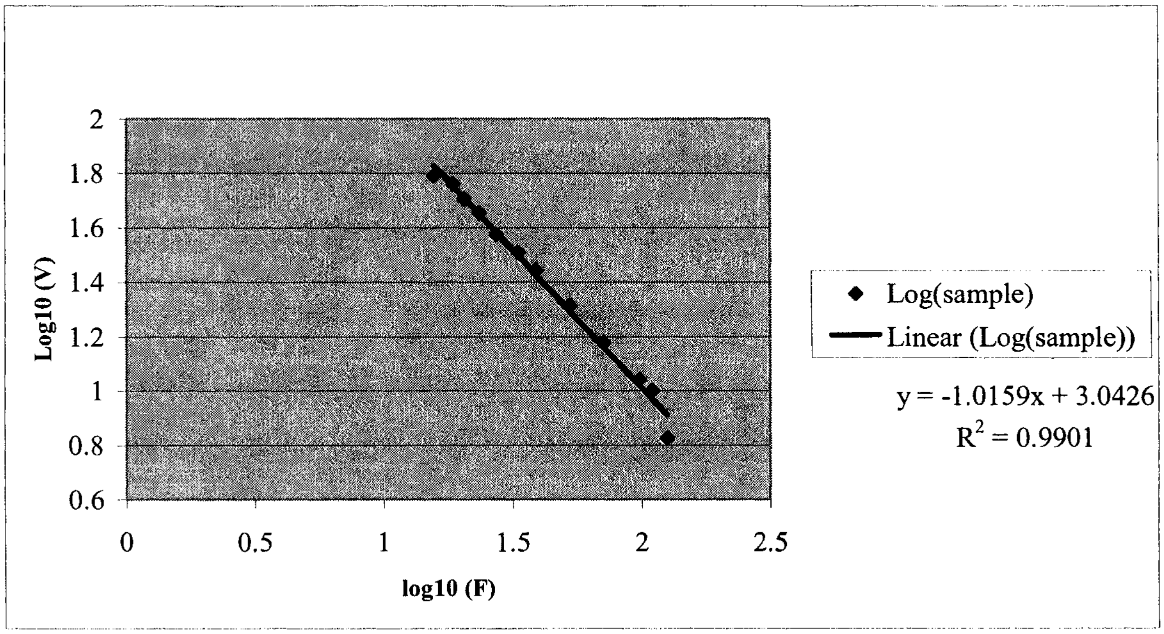


Figure 3-3 Linear Regression Solution for Model 769D

The calculation equation for the Caterpillar truck model 769D is:

$$V = 10^{-1.0159\log_{10} F + 3.0426}$$

The value of 0.9901 for R^2 shows that the linear regression result conforms to sample values. The deviation between the estimated V and the actual V, as shown in Table 3-3, proved that the regression expression is accurate to within 5% in terms of its operational speed. This linear regression approach can be applied to the rimpull performance charts of different construction equipment models as shown in Table 3-4.

Speed (km/h)	Rimpull (x1000kg)	Rimpull (KN)	Log10 (speed)	Log10 (Rimpull)	Log10(speed) (estimated)	Speed(km/h) (estimated)	Deviation
6.7	12.8	125.44	0.82607	2.098436	0.911357883	8.2	21.70%
10	11.2	109.76	1	2.040444	0.970237107	9.3	-6.62%
11	10	98	1.04139	1.991226	1.020208165	10.5	-4.76%
15.1	7.26	71.148	1.17898	1.852163	1.161399214	14.5	-3.97%
20.6	5.4	52.92	1.31387	1.72362	1.291908781	19.6	-4.93%
27.7	4	39.2	1.44248	1.593286	1.424236656	26.6	-4.11%
32.2	3.4	33.32	1.50786	1.522705	1.495897621	31.3	-2.72%
37.5	2.8	27.44	1.57403	1.438384	1.581508616	38.2	1.74%
45	2.4	23.52	1.65321	1.371437	1.649479692	44.6	-0.86%
50.7	2.1	20.58	1.70501	1.313445	1.708358915	51.1	0.77%
57.5	1.9	18.62	1.75967	1.26998	1.752489634	56.6	-1.64%
61.7	1.6	15.68	1.79029	1.195346	1.828265147	67.3	9.14%

Table 3-4 Rimpull parameters calculation of Caterpillar Truck Model 769D

3.4 Average Speed Factors

The speed that the algorithm provides is only a theoretical maximum speed, which depends upon terrain and vehicle characteristics. It is unreasonable to use this speed directly to give an estimation of hauling time in the simulation model. It does not factor in either a vehicle's acceleration or deceleration over the section of road. To make the simulation more reasonable, an average speed should be used rather than a maximum speed. A simple method for accomplishing this, which can be used to account for such acceleration and deceleration scenarios, is to multiply the maximum speed by an average speed factor based on Table 3-5 (Nunnally 1998). In Chapter 5 of this thesis, a nonlinear empirical algorithm is developed to incorporate this table into the simulation mobility model.

Length of Hauling Section	Staring from 0 or Coming to a Stop	Increasing Maximum Speed from Previous Section	Decreasing Maximum Speed from Previous Section
46	0.42	0.72	1.6
61	0.51	0.76	1.51
92	0.57	0.8	1.39
122	0.63	0.82	1.33
153	0.65	0.84	1.29
214	0.7	0.86	1.24
305	0.74	0.89	1.19
610	0.86	0.93	1.12
915	0.9	0.95	1.08
1220	0.93	0.96	1.05
1525	0.95	0.97	1.04

Table 3-5 Average speed factors

3.5 Conclusion

CRREL presented the snow accumulation-total resistance algorithm as only a criterion for vehicle's mobility judgment (go/no-go); that is, if the total resistance is less than or equal to the gross traction, then the vehicle can move. Otherwise, the vehicle cannot move. In this thesis, the algorithm was further developed and extended for more utilization. It is combined with a rimpull performance function to predict the maximum speed of the vehicle (speed made good) based on the specified weather condition, which is one of main contributions of this research.

The snow accumulation-maximum speed correlation is established through total resistance using a mathematical regression approach. The average speed factor is also introduced to replace the maximum speed value with the average speed in the mobility calculation. This modification completes the mobility model and makes the estimation of hauling and return duration within the simulation model more reasonable and accurate.

CHAPTER 4: OTHER FACTORS IMPACTING CONSTRUCTION EQUIPMENT MOBILITY

4.1 Introduction

This chapter presents factors that impact mobility other than snow accumulation. It also explores an approach to incorporate these factors into the mobility model. First, an investigation is presented on weather and other factors that affect the mobility of construction equipments. Second, fuzzy set theory is introduced as a potential method to combine the effect of these factors.

4.2 Other Factors Impacting Construction Equipment Mobility

Snow accumulation on the ground is a significant factor impacting the mobility of construction equipment. In Chapter 3, this factor was expressed as a mathematical algorithm using mechanical analysis and empirical regression. Likewise, many other factors may affect mobility. In actual construction projects, making a complete list of these factors is difficult and, indeed, often impossible since some effects are too obscure and minor to be noticed. Compiling a list of key factors that significantly affect mobility and incorporating these factors into mobility prediction is critical for developing an accurate simulation model.

There are four indicators of cold weather: climatic data, freeze-up and spring thaw dates, the freezing index, and the wind chill (CCRB-Calgary Institute 1994). These indicators provide a complete detailed description of weather conditions for cold weather construction. This research focuses on cold climatic factors such as temperature and snow precipitation. Through a literature review and theoretical analysis of all weather factors, the following cold weather properties have been identified and enumerated:

1. Average temperature
2. Total precipitation
3. Snow precipitation
4. Snow on the ground (snow accumulation)
5. Average wind speed
6. Wind chill temperature
7. Fog
8. Solar radiation

There are also others factors that have a significant impact on the mobility of construction equipment, including road conditions, equipment conditions, and operator skill.

Until now, none of the previous research has presented a comprehensive mathematical algorithm for combining the overall effect of environmental factors into the prediction of the construction equipment's mobility. To develop such a mathematical model, much experimentation and collection of historical data are needed. The use of empirical coefficients, resulting from the experiences of practitioners, can enable this task without amassing the data typically required. To collect the opinions of experienced engineers regarding the way in which construction equipment mobility is affected by cold weather, the North American Construction Group (NACG), one of the largest construction companies in Canada specializing in large civil projects, including earthwork, pipeline, and mining, was contacted. The company has many projects underway involving hauling and delivery processes in Fort McMurray, Alberta. Engineers and project managers have plenty of experience in determining equipment mobility in cold weather.

A questionnaire was completed by one of the project engineers. His answers were sent to other project managers and engineers for review and discussed. Finally, a summary of their opinions on the impact of construction equipment mobility was compiled and shown in the following tables:

Average temperature	Boundary (°C)	<-40	-40 to -20	-20 to -5	above -5
	Degree of Effect	S	M	L	L-S
	Description	Work stops if possible, due to increased risk of mechanical failures	Some additional mechanical issues	Frost allows access to soft areas, not too cold for most equipment	L: Frost no longer growing S: mobility is reduced in soft areas

S-Severe M-Moderate L-Light (same as below)

Table 4-1 Property: Average Air Temperature

Snow accumulation	Boundary (cm)	0-15	15-50	50+	Remarks
	Degree of Effect	L	M	S	Comments refer to accumulations of fresh snow
	Description	Slight reduction due to reduced traction	Plowing needed, light vehicle	Rare, but requires plowing and severely reduces light vehicle	

Table 4-2 Property: Snow Accumulation

	Boundary (cm)	Flurries	Average	Blizzard	Remarks
Snow precipitation	Degree of Effect	L	M	S	
	Description	No major impact, visibilty not appreciably affected	Visibility reduced, speeds reduced to match	In extreme cases mobility equipment needs to be parked	

Table 4-3 Property: Snow Precipitation

	Boundary (km/hour)	0-50	50-100	100+	Remarks
Wind speed	Degree of Effect	L	M	S	
	Description	No appreciable affect	Mild impact on heavy equipment	Noticeable impact on mobile equipment	

Table 4-4 Property: Wind Speed

	Boundary	Light (visibility below 1000 m)	Moderate (visibility 50-200 m)	Heavy (visibility below 50 m)	Remarks
Fog	Degree of Effect	L	M	S	
	Description	Little effect	Mobile equipment forced to slow to conditions	Shut down until visibility improves	

Table 4-5 Property: Fog

Engineers from NACG also provided their opinions of the impact of other factors upon mobility. They are recorded in Tables 4-6 to 4-8.

Driver Skill	Boundary	Novice	Average	High	Remarks
	Degree of Effect	S	M	S	
	Description	Reduces productivity 10-50%	+/- 10%	+10-20%	

Table 4-6 Property: Driver Skill

Equipment condition	Boundary	Poor	Average - Good	Good	Remarks
	Degree of Effect	M	L	L	
	Description	Productivity reduced 5-25%	N/A	+ 5-10% productivity	

Table 4-7 Property: Equipment Condition

Running surface	Boundary	Narrow/rough or soft	Average	Good condition and width	Remarks
	Degree of Effect	S	L	M	
	Description	Productivity reduced 10-50%	N/A	+10-30%	

Table 4-8 Property: Running Surface

These tables consider factors, which have an impact on mobility other than snow accumulation, by presenting the empirical values of mobility impact in different scenarios. Unfortunately, the scenarios are primarily qualitative descriptions rather than quantitative expressions.

4.3 Incorporating Qualitative Factors Using Fuzzy Set Concepts

The expert opinion regarding these factors that impact mobility is useful and reliable. However, it is hard to incorporate these rules into a mobility analysis model since they are primarily linguistic rather than numeric. On the other hand, although construction personnel give boundary values for certain impacting factors, the boundaries of these input factors remain, nevertheless, vague and approximate. For instance, given the average temperature in Table 4-1, the boundary value between the definition of "extreme cold" and "cold" can be disputed. Even if the threshold value is widely accepted as -40 degrees Celsius, this does not mean that a –39.9 degrees Celsius temperature will belong outright within the "cold" category or that a –40.1 degrees Celsius temperature will belong to the "extreme cold" category. Meanwhile, the degrees of the effect of average temperature are categorized as "severe," "moderate," and "light," which, semantically, are also vague and uncertain.

4.3.1 Introduction to Fuzzy Set Theory

Semantic vagueness is natural to language. Fuzzy set theory is an appropriate approach for dealing with this uncertainty. It is characterized by membership functions, which represent the degree to which a definition belongs to the set. Fuzzy set theory is different from conventional crisp set theory, which has a sharp boundary and in which the membership function is a Boolean: 1 or 0. Fuzzy set theory allows the object to have a partial membership function in a set for any value between 0 and 1. In general, any subset $A(x)$ can be expressed with x and its membership functions, $\mu(x)$, as follows:

$$A(x) = [x / \mu_A(x)] \qquad \text{(Equation 4-1)}$$

The fuzzy sets transfer the numerical input into a linguistic description using a membership function during the "fuzzification" process. The value of output linguistic variables can be fuzzily inferred using "IF-THEN" rules. The antecedent "IF" comes from the input linguistic variables, while the consequent "THEN" presents the output linguistic variable. The output can be transferred into a numeric value during the "defuzzification" process. There has been a long tradition of thorough and detailed research into fuzzy set theory (Klir et al. 1997).

4.3.2. Application of Fuzzy Set Theory

The application of fuzzy set theory in this model is composed of three steps:

1. Transfer Numeric Values into Fuzzy Sets

According to fuzzy set rules, the values of variables such as "Average Temperature," "Snow Accumulation," and "Snow Precipitation," can be represented using membership functions, respectively, as follows:

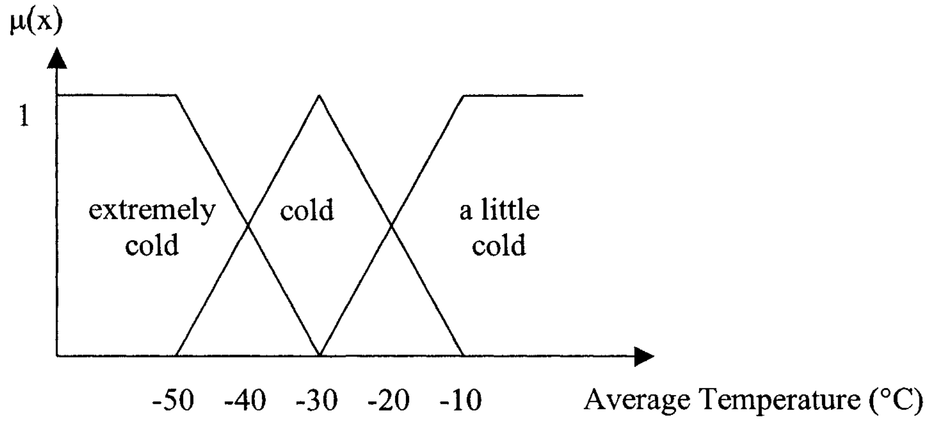


Figure 4-1 Membership Function of Average Temperature

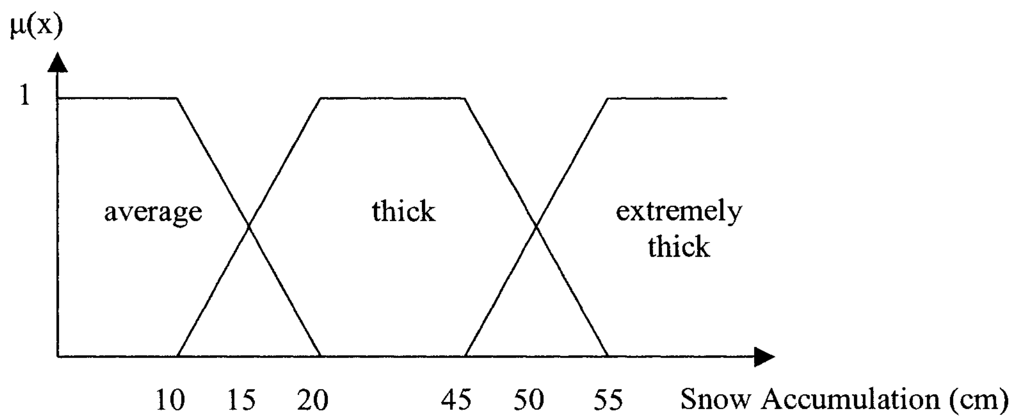


Figure 4-2 Membership Function of Snow Accumulation

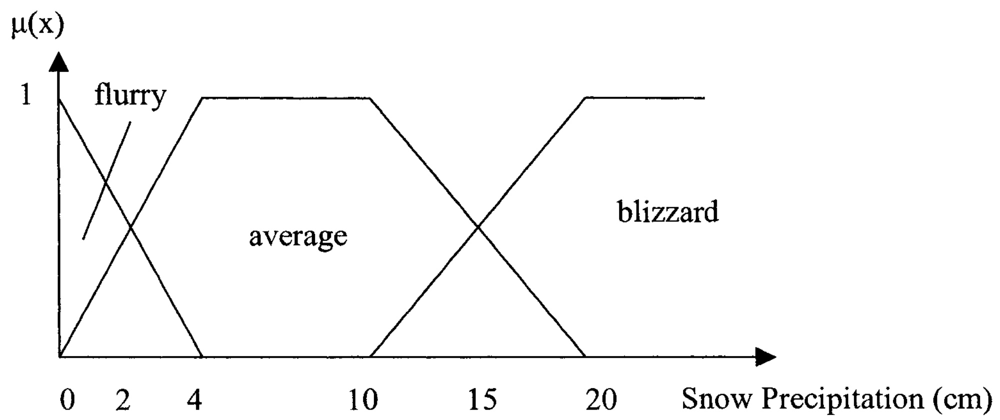


Figure 4-3 Membership Function of Snow Precipitation

2. Fuzzy Rule Inference

In the case of using the fuzzy logic to determine the average temperature, the "IF-THEN" judgment has the following rules:

(1) IF the average temperature=extreme cold, THEN the degree of effect=severe

(2) IF the average temperature=cold, THEN the degree of effect=moderate

(3) IF the average temperature=a little cold, THEN the degree of effect=light

Other input variables, such as snow accumulation and snow precipitation, can also be represented in the same way.

Fuzzy rules for snow accumulation:

(1) IF the snow accumulation=extreme thick, THEN the degree of effect=severe

(2) IF the snow accumulation=thick, THEN the degree of effect=moderate

(3) IF the average temperature=average, THEN the degree of effect=light

Fuzzy rules for snow precipitation:

(1) IF the snow precipitation=blizzard, THEN the degree of effect=severe

(2) IF the snow precipitation=average, THEN the degree of effect=moderate

(3) IF the snow precipitation=flurry, THEN the degree of effect=light

3. Translating the Fuzzy Output into a Numerical Result

The output of fuzzy rules qualifies the overall impact made by factors acting upon this model. The translation of the linguistic output into a numerical value is a necessary process for the overall practicality of the model. The membership function approach is also available for this process. Given the driving skills listed in Table 4-6, for example, a novice decreases productivity between 10% and 50 %. A driver of average skill will either decrease productivity 10% or increase it 10%. Highly skilled driving increases productivity between 10% and 20%. A demonstration of this membership function is represented in Figure 4-4.

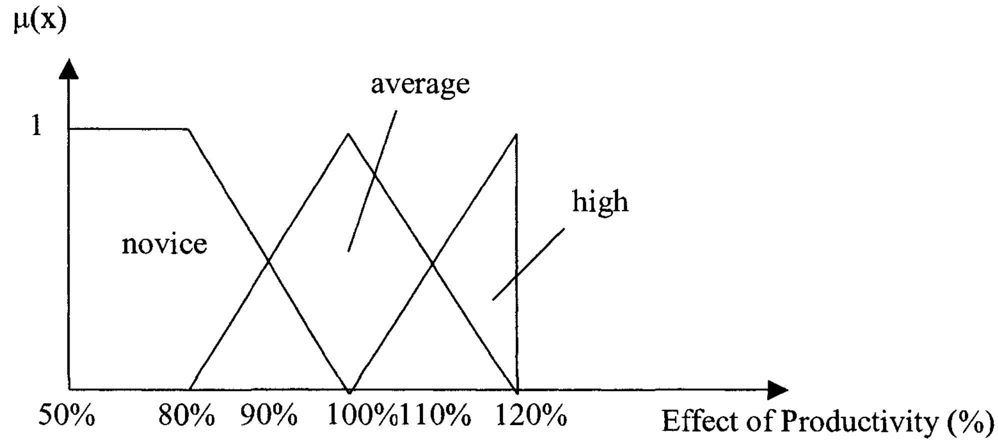


Figure 4-4 Membership Function for Effects of Driving Skill

In this research, unfortunately, construction personnel can only give vague terms, such as "severe," "moderate," and "slight" to describe the effect of most impacting factors. To put this linguistic output into practical use, membership sets and rules must be further developed in cooperation with construction engineers. A hypothetical membership set for the extent of an effect from an average temperature factor is represented in Figure 4-5.

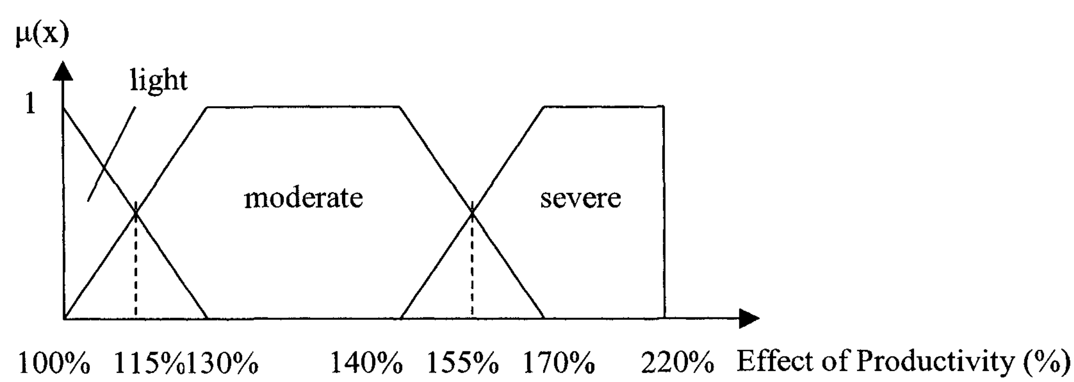
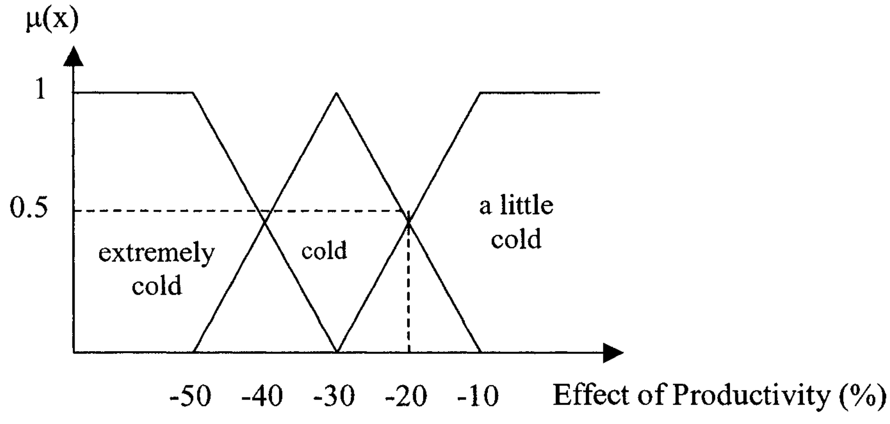


Figure 4-5 Membership Function for Effect of Average Temperature

The average temperature of -20 °C, for instance, as referred to in Figure 4-3, is included in two fuzzy sets shown in Figure 4-6.



Definition	Membership Value
a little cold	0.5
cold	0.5

Figure 4-6 Membership Value for Average Temperature of -20 °C

According to the fuzzy set theory rules, the subset can be logically inferred as:

(1) IF the average temperature=a little cold, THEN the degree of effect=light

(2) IF the average temperature=cold, THEN the degree of effect=moderate

The fuzzy inference results for the average temperature are represented in Table 4-9.

Degree of Effect	Membership Value
light	0.5
moderate	0.5

Table 4-9 Membership Value for Effects of Average Temperature -20 °C

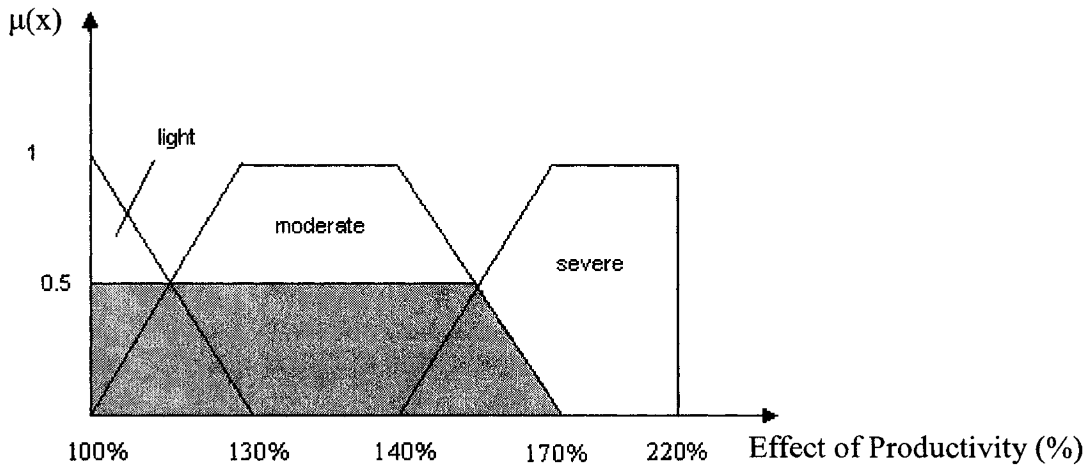


Figure 4-7 Fuzzy Value for Effect of Average Temperature of -20 °C

Using the centroid method, the weight value for the "light" fuzzy set is 110%; the weight value for the "moderate" set is 135%. According to Zadeh (1975), the estimated mean value of the effect's coefficient, $\bar{e}$, and the standard deviation of the effect's coefficient, δ_e, can be obtained as:

$$\bar{e} = 110\% \times 0.5 + 135\% \times 0.5 = 1.225$$

$$\delta_e^{\ 2} = 110\%^2 \times 0.5 + 135\%^2 \times 0.5 - 122.5\%^2 = 0.0156$$

$$\delta_e = 0.125$$

There remains a problem in merely combining the outputs from different factors. The final purpose of the operation is to obtain a numerical coefficient based on the information available. The total effect will not simply be an accumulation of these outputs. The average value, *Average* ($\bar{e}_n$) or max value, *Max* ($\bar{e}_n$) of the outputs is a way to estimate the overall coefficient, depending on different situations.

An alternative solution is to return to the expert system. Instead of setting an "IF-THEN" rule for each input variable, the expert system can be preconditioned with several related inputs using Boolean operators, such as AND and OR, to apply a combination effect to the variables. For example, instead of a single precondition, a fuzzy set rule can be established, such as, [IF average temperature= cold AND snow accumulation= thick AND snow precipitation= average, THEN the degree of effect= moderate]. According to fuzzy logic theory, the AND conjunction uses a minimum operator while the OR conjunction uses a maximum operator. Furthermore, it may be necessary to combine factors from different areas using operators such as MAX-MIN or MAX-PRO of fuzzy logic methodology. Consultation with construction personnel is necessary to set the combination rules for the model.

4.4 Conclusion

This chapter discussed the effect of weather factors other than snow accumulation upon mobility. An investigation of the experience of construction personnel is a reliable resource for developing an expert system in determining the impacts of cold weather factors on construction equipment mobility. This investigation can provide supplemental information for accomplishing a comprehensive and accurate simulation model.

This chapter explores the implementation of fuzzy set theory as an operational approach to incorporate environmental factors into construction equipment mobility. The fuzzy logic approach, as an expert system, is highly dependent on the accuracy and reliability of expert opinion. In order to accomplish the mobility model using a fuzzy logic method, further investigation and cooperation with construction personnel are required. However, due to the limitations of this research, the methodology of fuzzy theory is only presented as a guide for future research. The completed integration of this fuzzy logic approach into mobility simulation with a regression algorithm is not completed in this research.

CHAPTER 5: MODIFICATION OF SPS EARTHMOVING TEMPLATE

5.1 Introduction

Earthmoving construction simulation is a viable area for the application of the mobility algorithm represented in the previous chapter. In the current SPS earthmoving template, the speed of the truck is constant regardless of the weather or other factors, which is not accurately reflective of the true in real situation. This chapter puts the mobility algorithm to practical use by modifying the present earthmoving template developed in the *Simphony* modeling environment. The modification of this SPS template has two goals: (1) to incorporate the weather-affected mobility algorithm into an earthmoving model for practical use and (2) to add increased functionality to the earthmoving simulation template, widening its application in project duration estimation.

5.2 Description of The Earthmoving Construction Process

Earthmoving is a construction activity in which large quantities of materials, including earth, sand, stone, gravel, soil, and minerals, are moved from one location to another. In Alberta, mining is an example of a construction project that undertakes earthmoving extensively. In order to develop a model for earthmoving that would reflect the real situation of a specific project, it is necessary to acquire complete knowledge of that construction process. Based on that knowledge, the required modeling elements are created and the behaviors of modeling elements are defined. These elements can be used to develop a model for any specific project.

It is important to know that while similar work may have been performed previously, no two projects can have identical work conditions. This fact makes the creation of universal elements necessary. Although every repetition of an activity is qualitatively different, certain general themes may be drawn out from an analysis of the processes. A standard earthmoving operation, for example, is composed of three steps:

1. Preparation and loading at the loading site

Generally, the material to be moved is in its natural condition. The material must therefore first be prepared. Preparation consists of the process of breaking up and collecting this material so that it can be easily loaded for hauling. Dozers are commonly used for preparation. In preparation, a number of dozers work between the collection area and the loading piles to prepare the ready-moved earth. The loose earth is then loaded into the incoming trucks using excavators. Excavators consist of shovels, loaders, or backhoes. The preparation step requires dozers, excavators, and trucks to stand in line for loading. The preparation and loading production rate are usually determined based on equipment handbooks. Certain factors, however, such as the number of dozers and excavators in service, the availability of trucks, and the accessibility of the loading site, limit the overall production. Basically, these factors are categorized into two groups: variation due to resource and variation due to site layout. These variable factors incur uncertainty in estimating the duration of preparation and loading.

2. Hauling earth from loading site to dumping site

This step involves a number of trucks that travel along the hauling road back and forth moving earth from the loading site to the dumping site. The main resource in this process is the truck. The production rate of the truck is determined by the cycle time and the load capacity of truck. The cycle time is composed of four components: 1) loading time, 2) hauling time, 3) dumping time, and 4) return time. Among them, hauling time and return time always occupy the largest portion in the total duration of a project. The hauling process should take place at the highest safe speed. It is a function of the truck's gross weight, as well as both the rolling and grade resistances. Hauling speed can be determined using the truck manufacturer's performance chart. In practical terms, the hauling time is calculated by dividing the hauling distance length by the truck's highest safe speed. This time, however, cannot reflect the real situation. The hauling time is the most uncertain variable since the hauling process is affected most acutely by factors such as weather conditions, road conditions, and the working condition of the truck.

3. Dumping and spreading at the dumping site

The third step involves the trucks dumping their payload and dozers subsequently spreading the dumped earth from the dump pile across a particular area. In this step, the availability of dumping sites and dozers are the factors that limit the production rate.

5.3 Introduction of Earthmoving Simulation (EMS) Template

The earthmoving template is a SPS tool for the *Simphony* environment. It provides a graphical, user-friendly interface to a user who has experience in earthmoving construction but lacks simulation knowledge. A practitioner can build a simulation model for a given project based on the existing model element library. For developers who want to customize a modeling element or to create a new element, the template offers an easy-to-handle and powerful platform for modifications.

Based on the earthmoving construction process, the following elements are created in the *Simphony* EMS by Hajjar (1997) for the development of general scenarios:

1. Source Element: defines the location containing all the elements for the preparation and loading processes. Its child elements include the dozers, the excavators, the preparation element, and the pile element;
2. Placement Element: defines the location containing all the elements for dumping and spreading. Its child elements include the dozer, the spreading element, the dumping element, and the pile element;
3. Dozer Element: defines all preparation and spreading equipment;
4. Excavator Element: defines all loading equipment;
5. Road Element: defines single-line, one-way road segments along which trucks travel. A hauling road is made of several road elements with different grades, rolling resistances, and distances;
6. Intersections Element: defines the intersections, across which truck fleets travel and may stop at for traffic reasons or external traffic operations;
7. Truck Element: defines hauling equipment traveling from loading site to dumping site for earth delivery. The element defines the necessary characteristics of the truck such as its model, capacity, and dumping duration;
8. Preparation Element: an element that represents the process of preparing earth;
9. Spreading Element: an element that represents the process of spreading earth; and
10. Pile Element: defines the earth pile for loading or spreading.

There are other elements for assisting in the creation of the proposed model, including traffic split, external traffic, incoming trucks, and outgoing trucks (refer to *Earthmoving*

Simulation Template User's Guide [2000]). Depending on the requirements, each element has four types of attributes: (1) creation and connection, (2) input parameter, (3) output and statistics, and (4) child elements. All of these elements are the necessary units for creating the earthmoving model.

To create an earthmoving model, several steps must be followed:

1. Create a certain number of source and placement elements according to the given project.
2. Under the above parent elements, define and modify the child elements based on the specific construction operation.
3. Create a truck fleet using defined truck elements and connect them with the source element as an incoming resource for the system.
4. Connect the source and placement elements with the road elements according to their logical process.
5. Give and modify parameters for all elements of the model.
6. Define the simulation parameters.

The purpose of the EMS model using the unmodified template is to identify the bottleneck in the system in order to make better resource allocations or to redesign the construction process; however, the initial model does not provide the necessary information for the project's duration.

5.4 Modification of the EMS Template

As mentioned in the previous section, the simulation model built using the unmodified EMS template has limitations in calculating project duration. Although it provides the truck cycle time as an output statistic, it cannot directly estimate project duration. The accurate estimation of project duration nevertheless provides important information, which interests project managers. The modified template has the ability to estimate the modeled project duration.

During the simulation run, each road element requires a period of duration in which to perform its job. This period represents the hauling time for that given road segment. In calculating the hauling duration, the algorithm of the present road element works in the following way: the truck element has an input attribute for speed parameters. Based on these parameters, the speed of the truck is calculated as a function of the total resistance. The total resistance in the present model is a combination of the grade resistance and the rolling resistance, which are included in the road element as input parameters. The hauling duration is then made equal to the hauling distance divided by the speed. This calculation has certain defects:

1. It does not consider the effect of weather and other factors. In this calculation, there is no difference in speed under differing conditions. The previous chapter of this thesis has explained the impact of weather factors on the speed of trucks.
2. The speed used in duration calculation is the maximum speed that a truck can get based on the rimpull chart. In practice, however, depending on different road conditions, the truck needs to accelerate when it starts or changes speed due to a move from a high resistance road to a low resistance road. The truck may also need to decelerate when it stops or changes speed when transferring from a low resistance road to a high resistance road. It is more reasonable to use an average speed instead of a maximum speed to calculate the hauling duration.

To correct these deficiencies, a modification of the present Earthmoving Template is necessary. This modification includes 1) the development of a new element to calculate project duration, 2) the use of an average speed instead of a maximum speed in the element definition, and 3) the incorporation of weather parameters and other impacting factors into the model. To implement these changes, some modifications are made to the truck element and road elements. Two new elements are also created in response to this requirement. The adding and modification of the earthmoving template elements are shown in Figure 5-1.

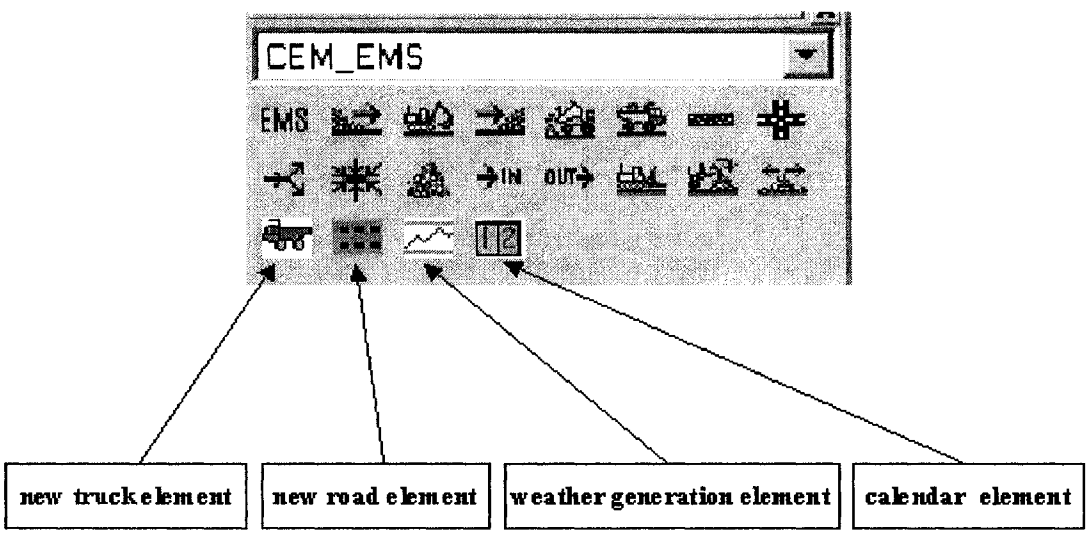


Figure 5-1 Adding and Modification of Earthmoving Template Elements

5.4.1 Modification of the Truck Element

In the present template, the truck element has eight available speed parameters:

1. MeanL
2. StDevL
3. ScaleFactorL

4. YfactorL

5. MeanE

6. StDevE

7. ScaleFactorE

8. YfactorE

These eight parameters calculate the empirical travel speed of the truck. The first four parameters, with the suffix “L”, represent the truck in a *loaded* condition (haul); the last four parameters, with the suffix “E”, represent the truck in an *empty* condition (travel back).

The empirical formula for calculating the maximum speed of the truck is presented as:

$$Speed_{\max} = ScaleFactor \times e^{\left(-(Total\ \text{Re}sis\tan ce - Mean)^{\wedge}2/\text{StDev}\right) + Yfactor} \quad \text{(Equation 5-1)}$$

Different truck models have different values for these parameters. Table 5-1 shows the parameters of the different truck models in this earthmoving template database.

Truck Type ID	Model	Description	Mean L	Stdev L	Scale Factor L	YFactorL	Mean E	Stdev E	Scale Factor E	YFactor E
38	Caterpillar	769C	-0.806	67.464	56.541	25.373	-0.806	67.464	43.789	25.373
39	Caterpillar	771C	-8.499	304.648	36.298	5.212	-3.512	173.904	19.239	22.999
40	Caterpillar	773B	-1.343	43.206	33.352	22.420	0.722	41.831	37.740	31.379
41	Caterpillar	775B	-1.781	55.362	30.149	14.402	-2.066	132.572	27.975	20.138
42	Caterpillar	777C	-1.504	51.215	52.402	7.455	-2.096	102.998	47.747	19.872
43	Caterpillar	785	-1.584	61.149	45.875	5.527	-1.920	149.280	42.655	17.099
44	Caterpillar	789	-0.647	75.042	41.678	2.849	-0.046	109.487	44.085	16.605
45	Caterpillar	793	-0.275	68.168	45.084	1.461	-0.216	140.545	40.491	15.548
47	Caterpillar	D25D	-1.409	54.528	44.667	6.441	1.648	105.226	31.818	14.144
48	Caterpillar	D30D	0.097	33.213	42.877	4.931	1.339	103.779	44.422	8.373
49	Caterpillar	D250D	-0.014	48.091	37.456	5.128	2.547	86.344	38.669	9.939
50	Caterpillar	D300D	0.605	31.852	45.272	5.399	1.890	92.608	46.077	9.471
51	Caterpillar	D350D(Std. Axle)	0.114	32.600	42.325	3.917	1.282	113.835	41.525	6.732
52	Caterpillar	D350D(Ide. Axle)	0.550	35.376	47.367	4.148	1.656	108.448	45.841	7.138
53	Caterpillar	D400D	0.246	58.810	39.501	3.609	2.201	78.769	46.140	10.688
54	Komatsu	HD205-3	-0.265	35.115	34.888	17.796	-2.653	157.809	34.924	20.503
55	Komatsu	HD325-6	-1.178	38.730	52.441	22.392	-1.524	114.217	47.660	29.718
58	Komatsu	HD465-5	0.371	25.146	49.193	19.841	1.461	83.774	44.616	23.905
60	Komatsu	HD785-3	-2.629	41.635	52.742	22.600	-1.651	87.620	36.522	34.034
61	Komatsu	HD1200-1	-1.023	30.913	31.216	20.572	-1.438	68.926	28.626	32.393
62	Komatsu	HD1200-1D	-0.786	26.490	33.128	20.749	-1.680	79.125	30.293	30.461
63	Komatsu	HD1200M-1	-1.488	29.495	47.302	17.279	-1.427	109.296	42.929	22.320
64	Komatsu	HD1600M-1	-1.844	33.790	50.163	17.852	-1.810	110.412	42.684	26.343

Table 5-1 Speed Parameters in *Simphony* Database

In the modified truck element, those eight speed parameters, which calculate the speed of truck without the impact of weather, are eliminated. Instead, new parameters are given. They are:

1. *TruckW*: Net weight of Truck
2. *TruckL*: Payload of Truck

3. *Rtire*: Tire radius

4. *Wtire*: Tire width

5. *k*: Regression factor-k

6. *b*: Regression factor-b

7. *Pf*: Density of packed snow

These parameters have different values for each truck model. Like the previous speed parameters, this data can be stored in the truck's database file within the earthmoving template. According to algorithm developed in Chapter 3, the parameters of the example model 769D are shown in Table 5-2. The combination of these new parameters into earthmoving simulation template can be found in the programming code of the Truck element in Appendix B.

Truck Model	*TruckW*	*TruckL*	*Rtire*	*Wtire*	*k*	*b*	*Pf*
Caterpillar model 769D	302	398	0.912	0.495	-1.0153	3.0419	0.6

Table 5-2 Speed Parameters of Caterpillar Model 769D

5.4.2 Modification of the Road Element

The present road element lists the maximum speed of the truck as a function of the total resistance given by the empirical formula presented in Equation 3-8. The total resistance comes from a combination of the grade resistance and the rolling resistance. These two parameters are input by the user as fixed values for each road segment.

In the modified road element, the grade resistance keeps its original input value; however, the rolling resistance parameter in the road element is no longer in use. It is divided into resistance from internal factors and resistance from terrain, as Chapter 3 describes.

The internal resistance for each truck model is fixed once it is fully loaded or empty. The resistance from the terrain is calculated using Equations 3-3 to 3-6. The three input weather factors--snow accumulation, average temperature, and wind speed--are obtained from the weather element definition. The weather element will be presented in the following section.

The maximum speed a truck can attain on a road is described in Chapter 3 as:

$$V = 10^{n \log_{10} F + \log_{10} K_0} \qquad \text{(Equation 5-2)}$$

However, it is unreasonable to use the maximum speed to calculate the hauling duration. Instead, an average speed factor is used to calculate the average speed by multiplying the maximum speed value. In the road element, the average speed factor is incorporated into the model using Table 3-4, as presented in Chapter 3.

It is inconvenient to put a table into a simulation program. Transforming the table into a mathematical regression formula is a better way to incorporate the factor into the template.

According to the data in Table 3-3, there are three different scenarios for determining the status of a truck's speed: 1) start from zero or if the truck comes to a stop, 2) increasing the maximum speed from the previous section, and 3) decreasing the maximum speed from the previous section.

The data shows that the shorter the distance, the more it affects the speed. Data charts show that there is no linear relationship between the average speed factor and the length of the road. In this research, the trendline function in MS Excel is used to get a nonlinear empirical expression.

1.Truck starts from zero speed or comes to a stop:

This scenario has the most obvious negative effect on the average speed factor, since a truck needs time to change speed between zero and its maximum. A chart of the average speed factor vs. the distance is shown in Figure 5-2. Meanwhile, a logarithmatic trendline is presented.

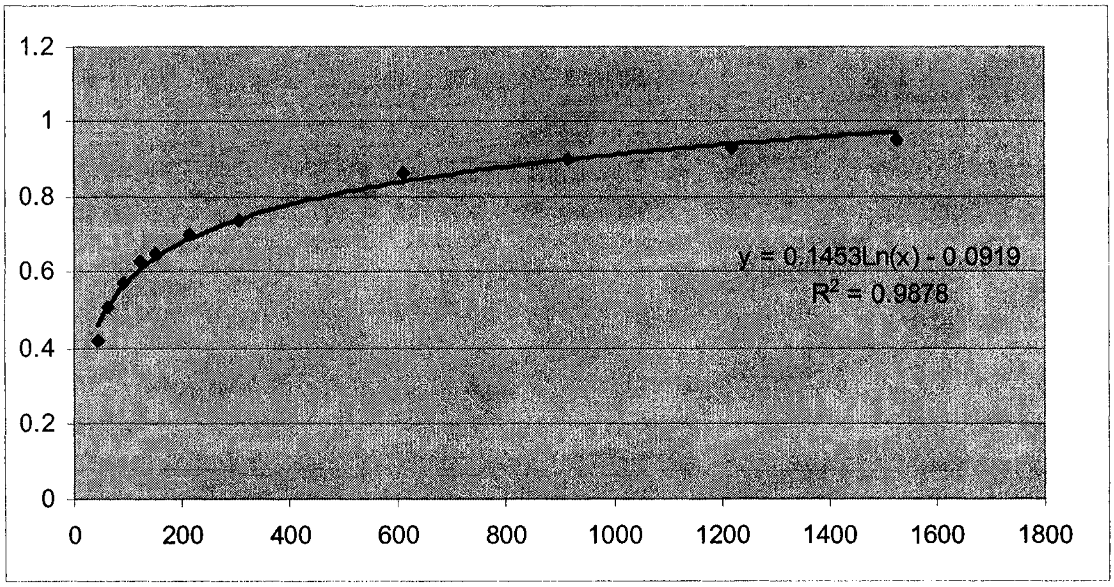


Figure 5-2 Average Speed Factors vs. Distance (Start/Stop Scenario)

The correlation coefficient, R^2= 0.9878, indicates that the tendency to follow the log algorithm line is very strong. Thus this formula is sufficiently accurate to represent their relationship.

When y=1, x=1835

The final algorithm for the “start/stop” scenario is:

$Y = 0.1453 \times \ln(x) - 0.0919$ when $0 < x < 1835$

$Y = 1$ when $x \geq 1835$

2. Truck accelerates to its maximum speed from the previous section

This scenario has less negative effect upon the average speed factor, since the truck requires less effort to change speed than to accelerate from zero speed. The chart of the average speed factor vs. distance in this scenario is shown in Figure 5-3, as is the logarithmatic trendline.

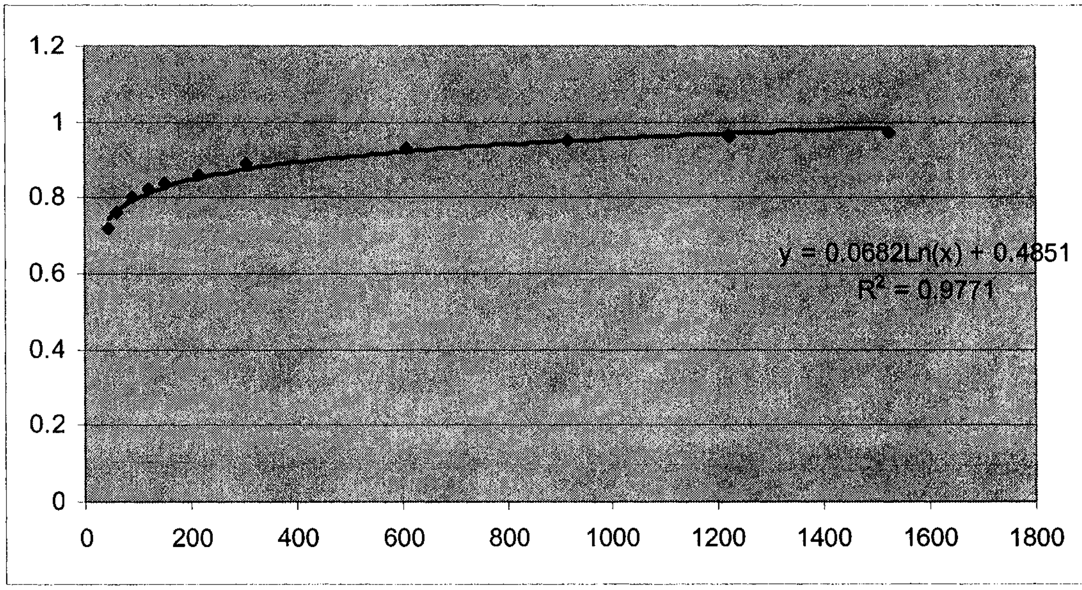


Figure 5-3 Average Speed Factors vs. Distance (Increasing Speed Scenario)

The correlation coefficient, R^2= 0.9771, shows the high accuracy of the trendline.

When y=1, x= 1900

The final algorithm for the "increase in maximum speed" scenario is:

$Y = 0.0682 \times \ln(x) + 0.4851$ when $0 < x < 1900$

$Y = 1$ when $x \geq 1900$

3. Truck decelerates from its maximum speed from previous section

In this scenario, the distance has a positive effect upon the average speed factor. As the previous maximum speed is faster than the present one, the average speed in this section is also faster than the maximum speed since it takes time for it to decrease to the present maximum speed. As a result, the average speed factor is greater than one (1).

The chart of the average speed factor vs. distance is shown in Figure 5-4. The power regression trendline is presented instead of the logarithmatic trendline, as it is more accurate in describing the trend of the data in this scenario.

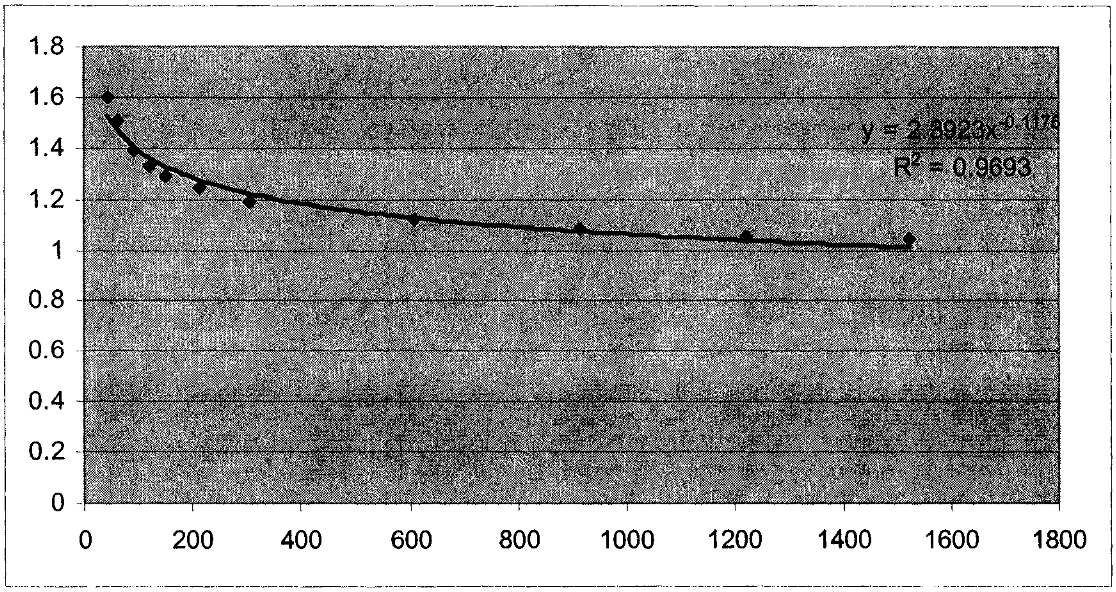


Figure 5-4 Average Speed Factors vs. Distance (Decreasing Speed Scenario)

The correlation coefficient, R^2= 0.9693, indicates the accuracy of the trendline.

When y=1, x= 1456

The final algorithm for the "increases in maximum speed" scenario is:

$Y = 2.3923 \times x^{-0.1175}$ when $0 < x < 1456$

$Y = 1$ when $x \geq 1456$

5.4.3 Addition of the Weather Element

According to Equation 3-6, the calculation of the total resistance needs three key weather factors: the average temperature, the amount of snow accumulation on the ground, and the wind speed. To identify the effects of these uncertainty factors on the earthmoving process, it is necessary to develop precise stochastic models that can capture the arrival processes of these uncertain factors.

Ahuja and Nandakumar (1985) presented a simulation model called PRODUF. This model focuses on the expected variations in activity durations caused by the dynamic project environment. This environment is characterized by factors such as learning curve, weather, and space congestion. The uncertainty of the activity duration estimate due to weather is dependent upon the time of year in which the activity is performed. By simulating weather for each project day and calculating the expected workday loss due to weather for activities planned on that day, this uncertainty can be reduced. This approach is more fully extended in Wales's research (1994), which incorporates weather factors in project simulation. His work is based on the assumption that the weather variables of interest have stochastic characteristics depending on the time of year. For instance, precipitations in January and in July are different from a stochastic perspective.

The weather generation scheme that Wales adopts comes from Richardson's research results (1981). Richardson presented an approach for generating four weather variables: daily precipitation, maximum temperature, minimum temperature, and solar radiation. Daily precipitation is generated independently using the first-order Markov chain-exponential model. With this model, the probability of rain on a given day is conditioned upon the wet or dry status of the previous day. The precipitation amount, given the occurrence of a wet day, follows an exponential distribution. The other three variables are dependant on the wet or dry status of the day as determined by the precipitation model. They are generated using a multivariate model with the means and standard deviations of the variables conditioned in a wet/dry state. In Wales's model, a two-parameter gamma distribution, rather than an exponential distribution, is used to predict the precipitation amount. Unfortunately, Richardson's model is limited to these four weather variables. It cannot extend to other variables such as snow accumulation. Using analysis, the snow accumulation variables are highly correlated in consecutive days and to other weather variables such as snow precipitation, temperature, and solar radiation. There has been no model for generating snow accumulation using the stochastic method until now.

It can never be overly emphasized that an accurate simulation result depends upon a precisely developed model capable of reflecting the real details of the project process. The development of a reliable weather generation system that can represent the characteristics of the given working condition is one of the key properties of a successful model. Further research is necessary for the generation of snow accumulation and average temperature. In this research, before a more advanced and sophisticated weather generation model is developed, an independent, monthly-based distribution model is used to generate snow accumulation and the average temperature. Historical data for this model comes from Environment Canada (http://climate.weatheroffice.ec.gc.ca). The historical data of the weather in Fort McMurray is an example of this practical generation. Daily snow accumulation and average temperature from 1974 to 2003 are shown in Appendix A.

These data are input into the *BestFit* (Version 2.0) program for distribution fitting. *BestFit* is a distribution-fitting program. It can work for both continuous and discreet distributions. The program has the following features: 1) it provides twenty-six available distribution functions, 2) the distribution parameters are selected using the maximum-likelihood approach, 3) it fits optimization using the Levenberg-Marquardt method, and 4) it allows inputs of up to 30,000 data points. The twenty-six built-in functions are shown in Table 5-3.

Functions:		
1.Beta	10.Hypergeometric	19.Pearson Type V
2.Binomial	11.Inverse Gaussian	20.Pearson Type VI
3.Chi-Square	12.Logistic	21.Poisson
3.Chi-Square	13.Log-Logistic	22.Rayleigh
5.Erlang	14.Lognormal	23.Student's t
6.Exponential	15.Lognormal2	24.Triangular
7.Extreme Value	16.Negative Binomial	25.Uniform
8.Gamma	17.Normal	26.Weibull
9.Geometric	18.Pareto	

Table 5-3 Distribution Functions in *BestFit* (Version 2.0)

These distribution functions provide ample options for the given data to fit. The data in this research is fitted as a continuous distribution since both the temperature and snow accumulation can be continuous values. The details of the fitting process are presented as follows:

1. Snow Accumulation

According to the data, snow accumulation in Fort McMurray generally happens from October to May. In May, there are a few days in recorded history that have had snow accumulation. However, this is so rare that the data can, for the most part, be ignored. Snow accumulation is zero for the rest of the year. In those months that have snow, thirty years worth of daily data from each month are collected together as a whole for distribution fitting. There are two kinds of inputs necessary for stochastic analysis: the frequency of occurrence of snow accumulation and the amount of snow. The percentage of days that have snow accumulation is calculated for each month. All of the numbers (greater than zero) are put into *Bestfit* for fitting. An appropriate distribution is selected for each month. In this case, the Beta distribution is selected since it conforms to the historical records. The month-based statistics of snow accumulation in Fort McMurray are shown in Table 5-4.

Month	**January**	**February**	**March**	**April**	**October**	**November**	**December**
Percentage of days with snow	100	100	97.5	37.6	15.4	84.1	100
Distribution	Beta (2.35,4.27,2.98,68.02)	Beta (1.68,2.39,2.98,67.01)	Beta (1.28,2.12,0.98,66.02)	Beta (0.53,1.34,0.98,52.02)	Beta (0.43,1.40,0.93,18.07)	Beta (0.84,2.52,0.97,37.03)	Beta (2.07,3.13,0.98,45.02)

Table 5-4 Month-Based Statistics of Snow Accumulation in Fort McMurray

2. Average Temperature

In each individual month, the accumulated daily data of average temperatures, stretching back thirty years, are divided into two parts: temperatures lower than zero degrees Celsius and temperatures higher than or equal to zero degrees Celsius. These data sets are collected separately and also put into *Bestfit* for fitting. An appropriate distribution is selected for each scenario. In this case, the Beta distribution is selected for both scenarios. The month-based statistics of the average temperature in Fort McMurray are shown in Table 5-5.

Month	**January**	**February**	**March**	**April**	**October**	**November**	**December**
Percentage of days with Temperature <0	97.6%	93.2%	74.9%	24.1%	28.7%	87.3%	97.8%
Distribution	Beta (1.81,1.60,-39.01,-0.39)	Beta (1.75,1.27,-34.70,-0.10)	Beta (2.68,1.19,-33.50,0.26)	Beta (1.99,0.74,-20.03,-0.07)	Beta (2.44,0.61,-19.80,-0.10)	Beta (3.57,1.41,-35.84,0.64)	Beta (2.19,1.46,-39.92,-0.18)
Percentage of days with Temperature ≥0	2.4%	6.8%	25.1%	75.9%	71.3%	12.7%	2.2%
Distribution	Beta (0.43,0.81,0,8.30)	Beta (0.62,1.45,0,9.10)	Beta (1.14,2.99,0,10.40)	Beta (1.55,3.66,0,20.40)	Beta (1.26,3.00,0,18.30)	Beta (0.76,2.56,0,9.80)	Beta (0.41,0.88,0,6.50)

Table 5-5 Month-Based Statistics of Average Temperature in Fort McMurray

3. Wind speed

No daily average wind speed is available in the historical record. Instead, a monthly average wind speed based on records collected only from 1959 to 1990 was obtained from Environment Canada. It is shown in Table 5-6. In considering the motion resistance affected by snow accumulation, the significance of resistance from the terrain did not prove to be as "sensitive" to the wind speed as it was to the other two weather variables. In this model, a constant value of wind speed for each month is used in calculating resistance.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Speed(km/h)	13	13	13	15	16	14	11	11	13	13	12	13

Table 5-6 Monthly Average Wind Speed in Fort McMurray (1959-1990)

This weather element can randomly generate weather variables based on the stochastic characteristics of a given month. In this model, the three necessary weather variables, snow accumulation, average temperature, and wind speed are generated. The procedure of determining the weather element in each simulation run is as follows:

1. Get present date information from the calendar element and identify the present month.
2. Generate two uniform random numbers, RND(A) and RND(B), between [0,1]. If random number RND(A) is less than or equal to the occurrence of snow accumulation, the system produces a snow accumulation amount greater than zero. Its value is generated according to the distribution function corresponding to the month; otherwise, the amount is zero. If random number RND(B) is less than or equal to the occurrence of a temperature lower than zero, the system generates a random temperature lower than zero; otherwise, the system generates a random temperature higher than zero. Either value is produced according to the distribution function, which corresponds to the specific month.
3. The element sends these three weather parameters, snow accumulation, average temperature, and monthly average wind speed, to other elements as global variables.
4. The element waits for the next incoming date from the calendar element before proceeding.

The approach in this thesis is to generate random weather variables according to the historical record. This approach can also be extended to generate any other variables impacting construction equipment mobility.

5.4.4 Addition of Calendar Element

The previous section mentions the development of the weather element. The generation of daily weather variables should be based around a date in a given month. This operation requires the development of the calendar element. Meanwhile, a time-counting system should be developed in order to estimate project duration. A calendar element is thus necessary to satisfy both requirements. There are three functions that the calendar element should provide:

1. Automatically count the time when the simulation model runs and report the duration of the project once the process is over;
2. Provide the present time for the weather element; and
3. Consider the duration of each work shift per day and off-work on the weekend.

During the design period, the calendar element uses both a project start date and the number of working hours per day as inputs. It provides the mean and deviation of the project duration as statistical outputs. In this system, the element only regards Saturday and Sunday as holidays. The procedure of developing the calendar element is depicted in Figure 5-5.

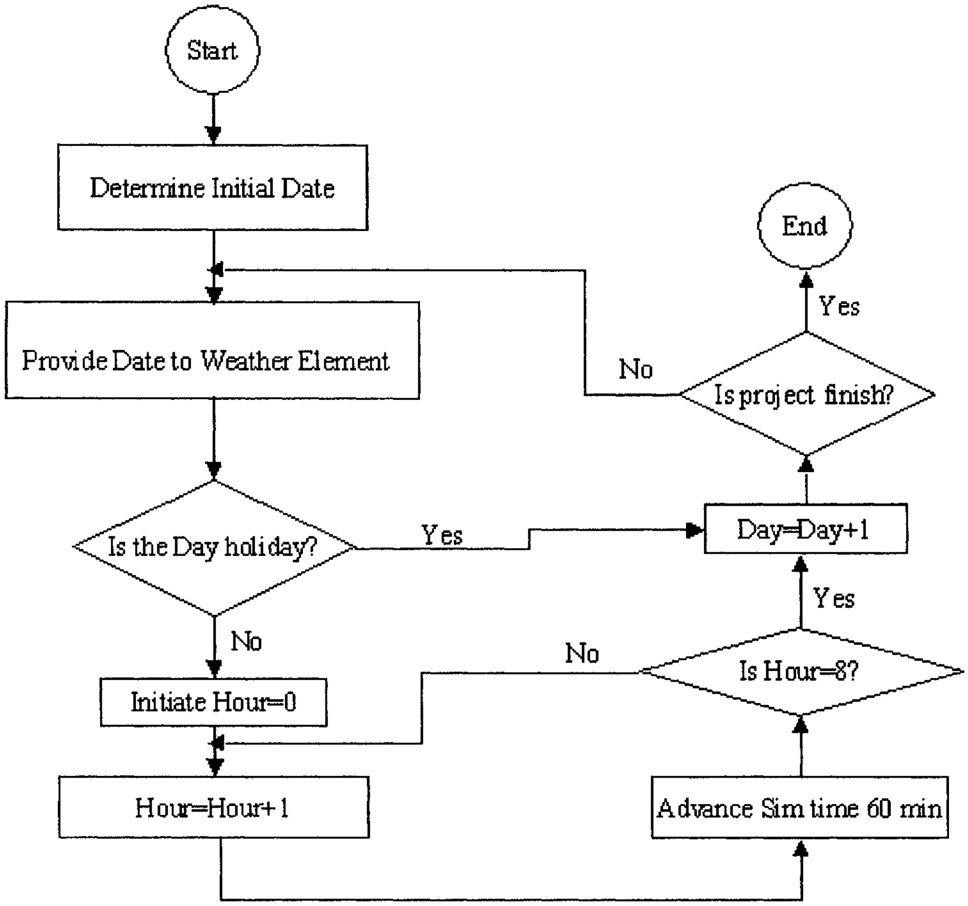


Figure 5-5 Flowchart of Calendar Element

Finally, according to the logical relationship of the flowchart, the calendar element is developed using a composite of common template elements in *Simphony*. It is a stand-alone element, so it can be inserted into other template models as a calendar element in order to measure project durations. The composition of the calendar element is shown in Figure 5-6.

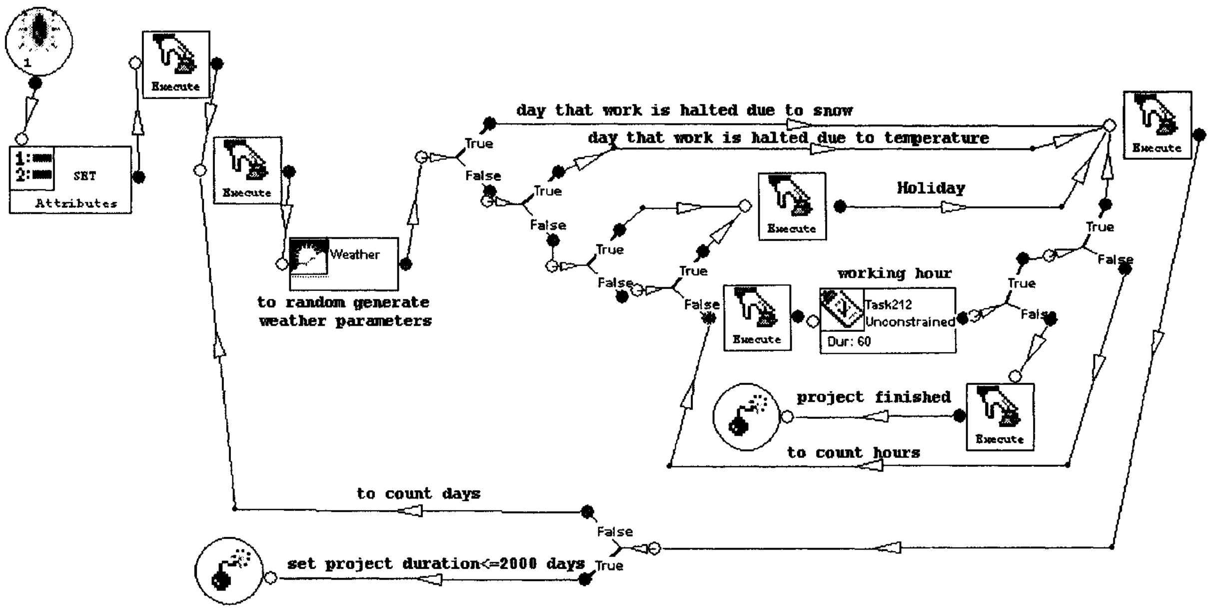


Figure 5-6 Composition of Calendar Element

5.5 Conclusion

This chapter introduces the application of a snow accumulation-mobility algorithm for use in an earthmoving simulation model. Additions to and modifications of the SPS earthmoving template are presented in the form of a simulation tool. The capabilities of the modified SPS earthmoving template are listed as:

1. Performing sensitivity analysis of mobility within cold weather parameters;
2. Estimating earthmoving project durations based on a given start date; and
3. Optimizing resources allocation in response to weather factors by identifying the bottleneck in the simulation results.

Using distribution values developed from historical data, each simulation run represents the completion of the simulated project layout under one scenario of a predictable site condition. The model provides a reliable approach to risk and sensitivity analyses of real projects based on the uncertainty of the construction site condition.

CHAPTER 6: SENSITIVITY ANALYSIS AND CASE STUDY

6.1 Introduction

In applying the weather-affected mobility algorithm, sensitivity analysis proves to be a reliable approach for analyzing how cold weather affects the mobility of construction vehicles. It is a useful tool for scheduling projects during the winter construction season. This chapter describes the sensitivity analysis of a Caterpillar truck's speed based on weather parameters relating to snow accumulation. As an application, an earthmoving project is presented to verify the modified SPS earthmoving template qualitatively.

6.2 Sensitivity Analysis of the Maximum Speed to Weather Parameters

Fiacco (1983) defined sensitivity analysis as the impact of local perturbations upon a solution. It provides several benefits from the view of construction management. Firstly, it indicates those input variables, which are sensitive to construction productivity and, therefore, helps us to identify the data items that require the most effort to obtain with any accuracy. Secondly, it shows how vulnerable the results are to inaccuracy due to the input data and will therefore inform us of the degree of risk that the estimations of project productivity and duration may have. Finally, sensitivity analysis results also provide us with knowledge on the reliability of the algorithm and help us to identify the most critical parameters in the network.

The sensitivity of the maximum speed for weather parameters related to snow accumulation is analyzed for a specific truck model. Using the Caterpillar truck model 769D as an example, the result of analyzing the sensitivity of the truck to snow depth and to the average temperature at its the maximum speed and with uncertain extraneous variables are presented in Figures 6-1 to 6-4.

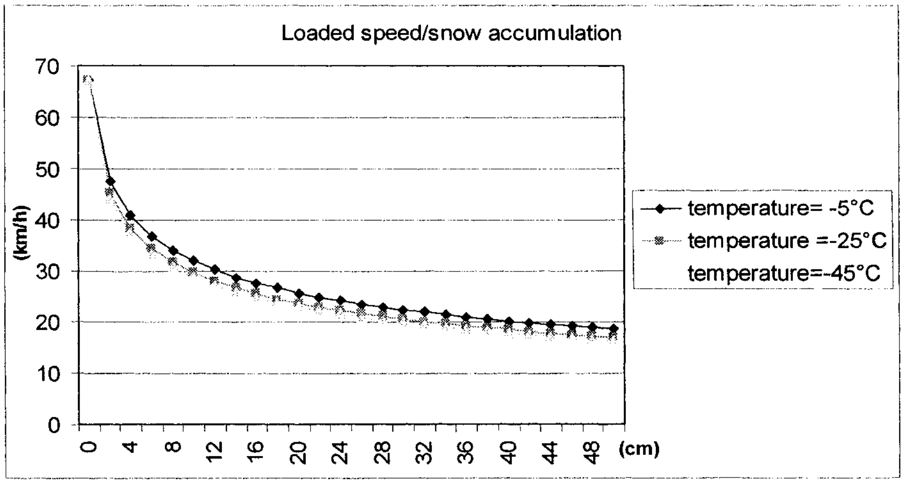


Figure 6-1 Loaded Speed vs. Snow Accumulation (Caterpillar 769D)

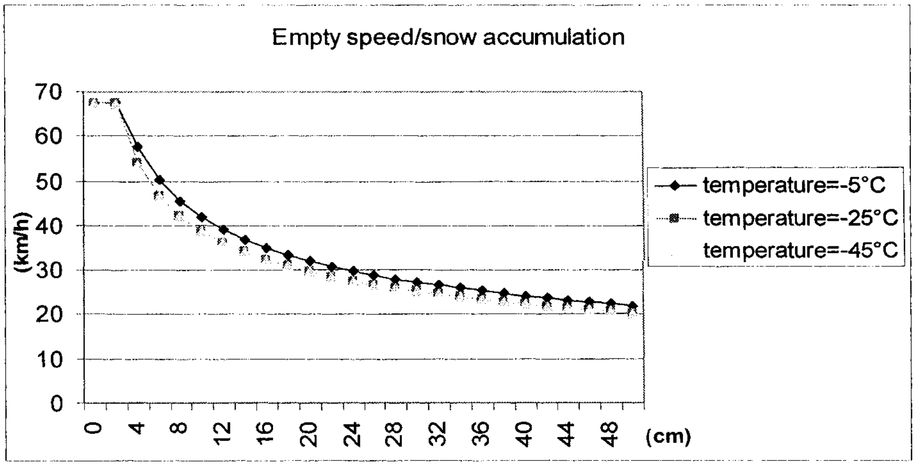


Figure 6-2 Empty Speed vs. Snow Accumulation (Caterpillar 769D)

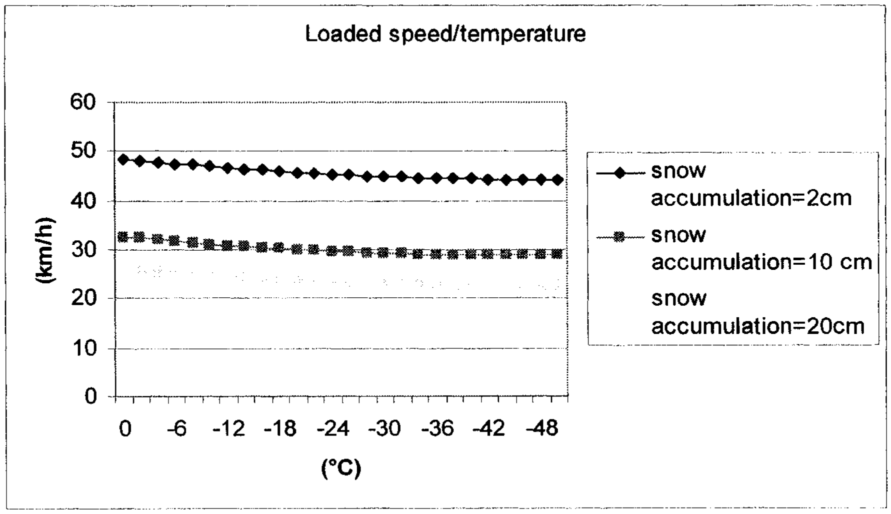


Figure 6-3 Loaded Speed vs. Temperature (Caterpillar 769D)

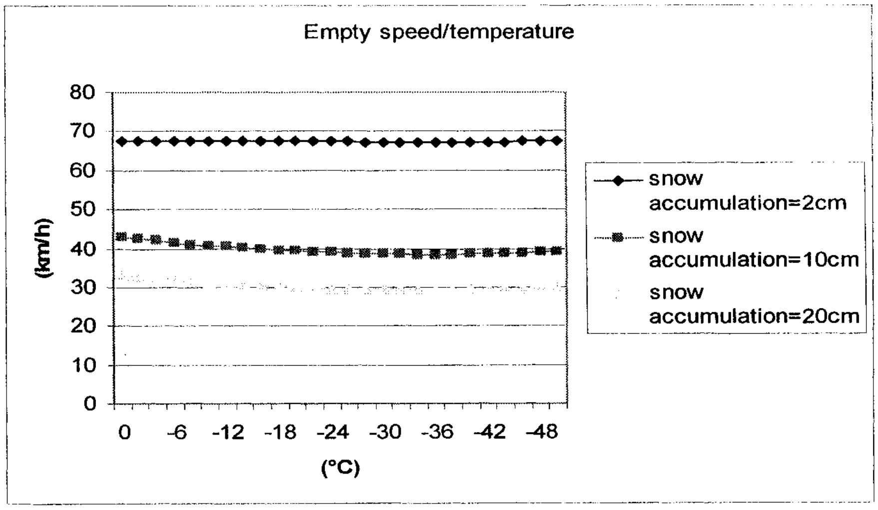


Figure 6-4 Empty Speed vs. Temperature (Caterpillar 769D)

The above figures show that, for those weather parameters related to snow accumulation, the maximum speed is highly sensitive to the thickness of the snow accumulation. As for the average temperature, its effect upon maximum speed is not as obvious.

6.3 Case Study of an Earthmoving Project

In this section, the earthmoving project from the *Simphony* sample projects is simulated to verify the model. The working condition in this case study is the same as the sample earthmoving project, except that the specific weather factors, snow accumulation, average temperature, and wind speed, are considered instead and incorporated into the model. To simplify the model and avoid any interference with the allocation of resources, the Caterpillar model 769D truck is the only kind selected for the hauling task. It is assumed that the total amount of hauled earth is 40,000 m^3, which takes approximately ten days to move. To demonstrate the impact of snow accumulation on project duration, eight different scenarios are selected for comparison. The project starts on the first day of the month in each scenario and continues throughout the year. A typical layout of an earthmoving project is shown in Figure 6-5.

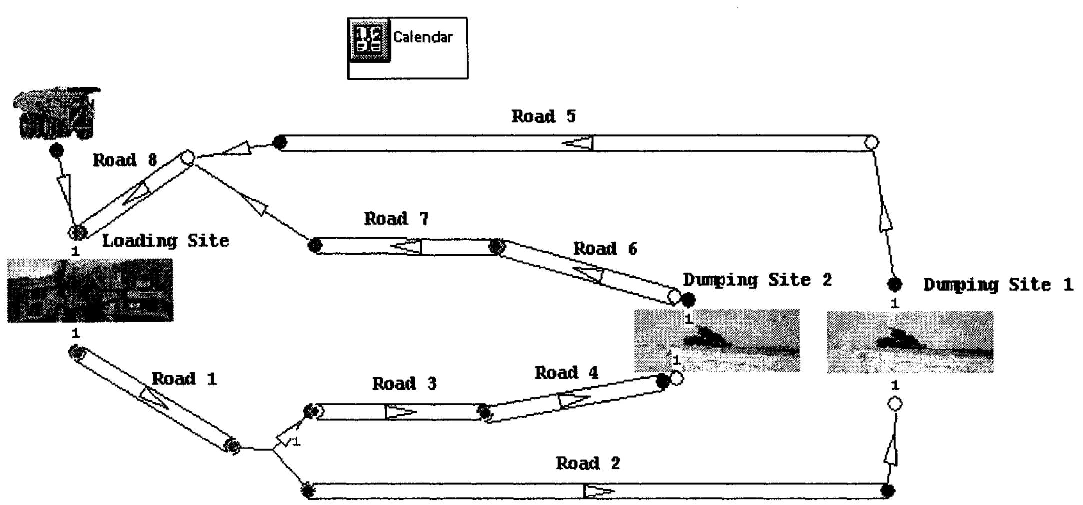


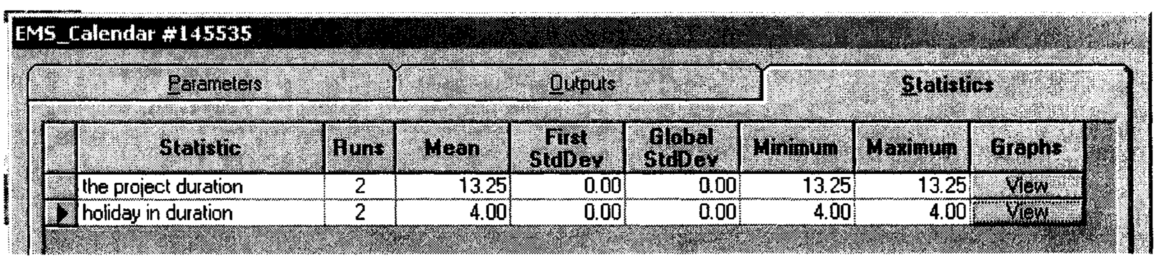
Figure 6-5 Layout of an Earthmoving Project

The parameters of the road sections are shown in Table 6-1.

Road section	Road 1	Road 2	Road 3	Road 4	Road 5	Road 6	Road 7	Road 8
Distance (m)	500	3800	1400	500	3800	500	1400	500
Grade resistance (%)	6	0	0	6	0	-6	0	-6

Table 6-1 Parameters of Road Section

As the model runs the simulation for each scenario, the estimation results of duration prove to be varied. Figure 6-6 gives the statistics results of the project duration starting on May 1st.

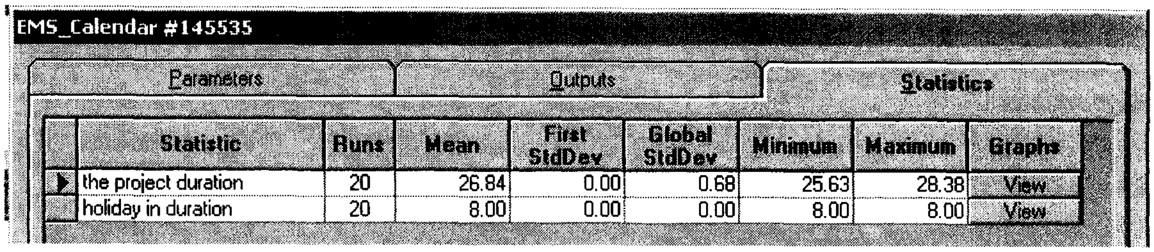

EMS_Calendar #145535

Parameters | Outputs | Statistics

Statistic	Runs	Mean	First StdDev	Global StdDev	Minimum	Maximum	Graphs
the project duration	2	13.25	0.00	0.00	13.25	13.25	View
holiday in duration	2	4.00	0.00	0.00	4.00	4.00	View

Figure 6-6 Statistics of Duration
(Project starting on May 1st)

Figures 6-7 to 6-9 show the statistics of the duration of the project beginning on January 1st. For this scenario, the snow accumulation has a severe impact on the truck mobility, which dramatically prolongs the project duration.



EMS_Calendar #145535

Parameters | Outputs | Statistics

Statistic	Runs	Mean	First StdDev	Global StdDev	Minimum	Maximum	Graphs
the project duration	20	26.84	0.00	0.68	25.63	28.38	View
holiday in duration	20	8.00	0.00	0.00	8.00	8.00	View

Figure 6-7 Statistics of Duration
(Project starting on January 1st)

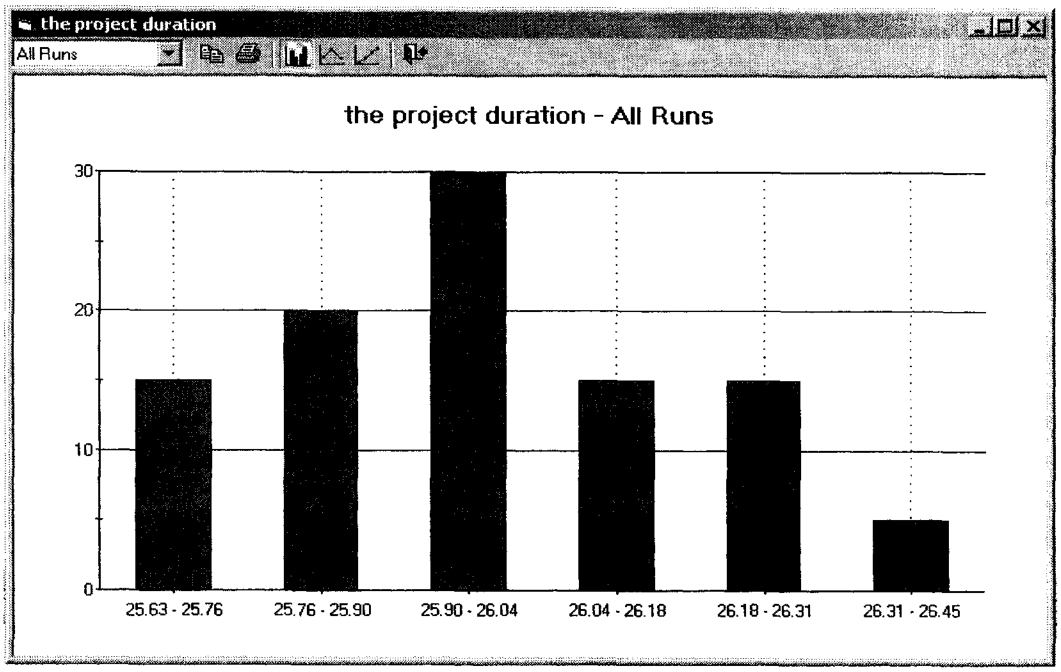


Figure 6-8 Histogram of Duration
(Project starting on January 1st)

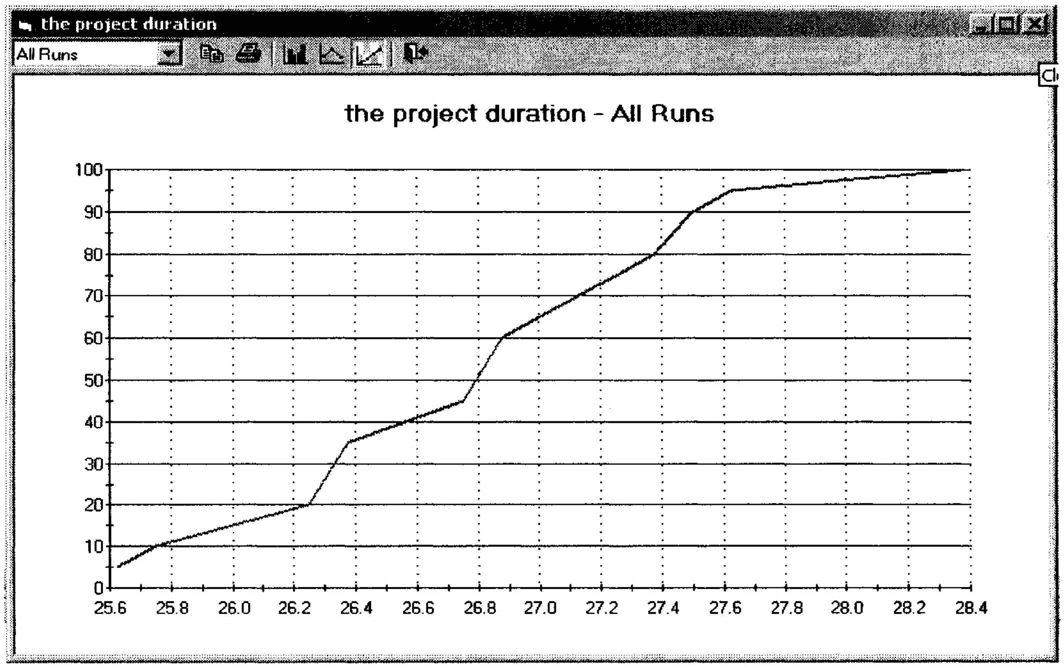


Figure 6-9 Cumulative Density Function (CDF) of Duration (Project starting on January 1st)

Table 6-2 shows all eight scenarios with different start dates for the same project. The comparison of results in this model shows that, for the same project, it takes more time in winter than under normal conditions to implement the operation. For instance, if the project starts on January 1st, it will take 9.35 more working days than if the project starts on May 1st, which is an extra 101% of the normal duration. The test results conform to the empirical estimations of experienced project managers from the North American Construction Group (NACG). They estimated that a delay of 5-100% of the duration is a reasonable range to predict due to adverse cold weather.

Project Start Date	Jan 1	Feb1	Mar1	Apr1	May1~Sep1	Oct1	Nov1	Dec1
Project Duration	26.84	26.8	23.73	14.98	13.25	13.63	16.48	22.33
Holidays in Duration	8	7.4	6	4	4	4	4	6
Work Days	18.6	19.4	17.73	10.98	9.25	9.63	12.48	16.33

Table 6-2 Project Duration in Different Scenarios

The model in this case study has been simplified; it assumes that the snow accumulation will keep its characteristics even after vehicles pass over several times. In reality, the snow packing will be disturbed and change its mechanical properties. New snow may also accumulate during the construction process, which makes it a complicated interactive system. To model the system accurately, a further study of the snow accumulation analysis mechanism is necessary. Furthermore, the allocation of resources is always a primary concern in planning a construction schedule. Since hauling takes more time, scheduling engineers may add more trucks to the project in order to keep the other processes busy instead of idling. The allocation of resources is another issue beyond the scope of this research.

6.4 Conclusion

The modified EMS template incorporates snow accumulation into the construction mobility simulation model. It measures the degree to which the speeds of construction vehicles are sensitive to snow-related weather factors. For construction practitioners, it provides a useful tool for estimating the project duration more accurately before construction proceeds based solely on historical weather information. During construction, the tool can also help to update the project schedule based on the current weather condition. The simulation model can be run in different scenarios with different start dates. An appropriate start time can then be selected based on this information. The case study in this thesis is a pilot exploration. In its present phase, it only provides a qualitative verification of the template. To verify the accuracy of the model, further work in cooperation with construction personnel should proceed. The methodology presented by this thesis provides a useful approach for incorporating uncertainty variables into the simulation of mobility in construction. It can easily be extended to include variables other than weather.

CHAPTER 7: CONCLUSIONS AND FUTURE EXPANSION

7.1 Research Summary

In term of accomplishing its research goals, this research did identify the key weather factors affecting the mobility of construction equipment in winter and develop a regression algorithm to incorporate weather factors related to snow accumulation into the calculation of a construction vehicle's speed. Although it explores fuzzy set theory as a potential approach to combine other factors besides snow into mobility analysis, the operational application of the fuzzy set approach as a supplement of the algorithm in mobility simulation is not accomplished.

The central thrust of this research is to determine causes of uncertainty. By generating uncertainty parameters accurately using simulation and then quantifying their correlation to the output, which is the project duration in this case, the causes of uncertainty can be identified.

The research accomplishes this work by means of three phases:

The first phase focuses on the identification of weather parameters that affect the speed of the vehicles and the development of a weather-affected mobility algorithm. A literature review, a survey, and purposeful discussions with experienced project managers from the construction industry were undertaken prior to the search for the key weather parameters. Finally, a mathematical regression algorithm was developed to correlate the weather inputs with the maximum speeds of the vehicles. Other weather parameters are also considered for incorporation into the model.

The second phase focuses on the application of the mobility algorithm to the EMS model. The algorithm is implemented in the EMS special purpose template developed using the *Simphony* platform. The template is modified to incorporate weather-affected mobility theory into the final calculation of the truck's speed. Certain new elements are also developed to estimate the completion time of the simulated project.

In the third phase, a demonstrative sample of the earthmoving project is developed to verify the model. A comparison of the results of the simulation with those of the actual project shows that this algorithm can offer a reasonable prediction for the earthmoving project.

7.2 Assumption in the Mobility Model

This mobility model only considers the stable conditions of "snow on the ground" or of "no snow on the ground." The seasonal freezing and thawing effects are beyond the scope of this research. To develop the mobility model, several assumptions have been made:

1. The effects of different factors on mobility can be considered separately and subsequently combined together as a total effect. The snow-affected vehicle's speed is calculated using a regression algorithm as a basic value. Also, a two-level judgment is used to combine certain factors, such as the average temperature and total snow accumulation. Other affecting factors, including driver skill and road condition, are also considered using the coefficient.
2. The hauling road has been packed and is strong enough to support the weight pressure of snow and vehicles. This is an important assumption for the regression algorithm to calculate the resistance to the vehicle under the condition of undisturbed snow on a

firm substrate. According to CRREL's research results, Equations 3-2 and 3-3 are suitable for undisturbed snow on strong substrate. For snow on a firm substrate, sinkage only occurs in the snow and not in the substrate. The calculation of traction and resistance is straightforward. Shoop (1993) proved that terrain with a rating cone index (RCI) higher than 100 is strong enough to resist sinkage. The roads on which this research focuses have been packed and have an RCI greater than 100.

3. After the vehicle has passed four times, the snow reaches its critical density of 0.55Mg/m3. *Rterrain* becomes zero for all vehicles. The snow is then presumably totally packed and will cause no more sinkage. Although *Rterrain* still exists due to the difference between the snow's surface and the normal surface of the road, it is assumed that vehicles experience no resistance from the snow terrain from a mechanical point of view.
4. This model is suitable for remote areas where a maintenance system is not available. For certain projects, the construction site has a high maintenance system to keep roads in a clean and clear condition. Although maintenance operations may hinder the hauling process, the mobility of the vehicle will not be affected by snow from a mechanical perspective. In this case, the effect of snow accumulation can be ignored.

7.3 **Research Contributions**

As a pilot research project examining winter construction mobility simulation, this work has contributed to the wider field of research in the following ways:

1. The research incorporates uncertainty of weather parameters into a construction mobility model in order to provide a more accurate project duration estimate.

Furthermore, this approach for defining and generating uncertainty can also be extended to factors other than weather, as a stand-alone element in the *Simphony* modeling environment.

2. As a practical application of the weather-affecting mobility algorithm, it modifies and improves the EMS template for earthmoving project. Its application can be extended to other templates.
3. The creation of a calendar element is designed for the EMS in this case. However, the calendar element can be separated from the earthmoving model system and used in other SPS templates for different construction domains. It is an important conceptual component for estimating duration and other key outputs for mega projects composed of multiple construction domains.

The first contribution benefits from the regression algorithm developed in military mobility research based on a theoretical analysis, data collected through experimentation, and mathematical regression. The development of the weather-affecting mobility model for earthmoving simulation is a good extension of the algorithm. By comparing different start dates, the user can determine the results of the most appropriate project schedule. The model also provides a sensitivity analysis of weather parameters affecting the project duration in different scenarios. This result can provide powerful evidence for project delay claims.

The accurate estimation of project duration is one of the key factors contributing to a successful construction project. The incorporation of weather factors offers a more accurate analysis of risk by considering uncertain input parameters. A closer examination of the affecting factors can help to articulate risk more precisely and to reduce it to an acceptable low level.

7.4 Future Work

To transform this mobility theory into a useable practice, much future work must still be undertaken. Firstly, although the snow accumulation-mobility algorithm comes from the CRREL mobility model and is verified by the opinion of experienced project managers in the construction industry, the verification of model accuracy in the construction field must depend primarily on data collected from a real project. In the future, greater cooperation with the construction industry is necessary for the development and verification of the model.

Secondly, the modified model in this research only considers the impact of weather parameters. An actual project, however, is affected by several environmental factors in combination. For instance, a driver's visibility is affected by weather conditions such as falling snow and fog in addition to the road and traffic conditions. A comprehensive consideration of these factors requires a precise understanding of the project procedures as well as a complete analysis of the system. The extension of this research to include other factors is another task necessary for the application of the model.

Thirdly, there is more work to be done in developing the EMS simulation template. One of the goals of this development work will focus on researching a better weather generation model. Unlike the approach that Wales (1993) adopted in his research, the weather generation model that this paper presents is based on a general statistical approach. It considers only the seasonal quality of weather, ignoring the time-series quality of weather. To improve the accuracy of the model, a more sophisticated weather generation model is required. Another goal for the future is the practical application of the modified EMS template to the construction industry. Its application will be the most efficient and direct way to verify the model.

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Appendix A: Historical Weather Data of Fort McMurray

Table A-1 Snow Accumulation (cm)

January	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	38	8	13	13	25	27	4	26	27	24	12	19	19	19	24
2	43	5	13	13	24	27	4	26	26	24	12	19	30	19	25
3	43	5	13	14	24	27	5	25	26	25	4	17	31	19	24
4	43	5	13	16	24	27	7	25	26	27	3	13	31	23	24
5	43	5	13	16	24	27	12	24	26	27	3	13	32	24	24
6	41	13	13	16	24	27	14	25	25	28	4	11	31	24	23
7	43	15	13	16	26	27	14	30	25	27	4	11	30	24	23
8	43	15	13	16	26	27	13	32	25	25	4	11	30	23	23
9	41	15	13	17	26	28	13	31	25	27	4	11	32	23	23
10	41	15	13	17	26	28	13	31	25	28	3	11	32	22	22
11	41	15	13	17	26	28	13	30	27	28	3	11	30	21	22
12	41	15	13	17	26	28	13	29	28	32	7	11	20	16	22
13	41	15	15	17	30	28	17	29	28	32	8	10	20	16	22
14	41	18	15	17	31	28	16	27	32	33	7	10	19	16	23
15	41	18	15	17	31	28	16	26	32	33	7	10	16	16	28
16	48	18	15	17	31	27	14	26	29	33	5	13	16	17	27
17	48	18	15	16	31	27	14	25	29	32	5	19	16	17	26
18	48	23	13	16	31	27	14	25	30	31	5	22	16	24	26
19	46	23	13	16	30	26	14	25	30	31	5	22	17	24	27
20	46	30	10	16	30	25	14	25	29	30	5	22	22	27	26
21	46	36	10	16	29	25	12	24	29	30	5	22	23	28	29
22	46	33	10	16	28	25	12	23	29	33	7	21	25	27	30
23	46	33	10	16	29	25	12	23	29	32	9	20	25	27	29
24	46	33	15	16	29	30	6	23	29	32	10	20	25	26	30
25	46	36	18	16	29	32	7	23	29	31	12	20	25	26	30
26	46	36	18	17	29	32	7	25	30	31	14	20	25	27	33
27	48	36	18	17	29	32	7	26	31	32	15	20	25	27	33
28	48	36	15	17	29	32	7	26	32	32	16	20	26	28	44
29	48	36	18	17	29	31	7	26	33	33	15	21	29	32	51
30	48	33	18	17	28	30	7	26	33	33	14	21	29	31	57
31	48	33	15	18	28	31	7	27	33	32	13	21	29	31	57

January	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	31	32	25	22	17	26	12	36	31	15	M	M	M	M	M
2	31	37	25	22	17	27	14	36	32	14	M	M	M	M	M
3	32	37	25	22	20	27	14	51	34	11	M	M	M	M	M
4	32	37	25	20	22	27	14	51	35	11	M	M	M	M	M
5	32	36	24	20	22	27	14	51	35	15	M	M	M	M	M
6	32	38	24	20	23	28	14	51	35	15	M	M	M	M	M
7	32	38	24	23	23	28	14	54	35	15	M	M	M	M	M
8	32	38	24	23	22	28	15	54	33	15	M	M	M	M	M
9	32	38	24	23	22	31	15	54	34	14	M	M	M	M	M
10	32	37	24	23	22	31	15	50	34	14	M	M	M	M	M
11	32	36	24	23	22	31	16	55	34	14	M	M	M	M	M
12	32	36	24	23	21	31	19	62	34	14	M	M	M	M	M
13	30	35	24	24	21	32	24	68	34	14	M	M	M	M	M
14	30	35	24	24	21	32	24	68	34	15	M	M	M	M	M
15	30	34	22	23	21	32	24	68	27	14	M	M	M	M	M
16	33	34	22	27	22	33	23	60	26	17	M	M	M	M	M
17	34	34	22	27	22	32	22	58	26	16	M	M	M	M	M
18	34	34	23	27	22	32	22	57	25	15	M	M	M	M	M
19	46	34	27	27	22	31	22	56	27	16	M	M	M	M	M
20	46	34	27	26	22	34	22	55	27	15	M	M	M	M	M
21	45	34	27	26	25	33	22	55	32	15	M	M	M	M	M
22	46	34	22	32	27	33	21	55	33	16	28	M	M	M	M
23	46	36	22	32	27	34	20	55	38	16	33	M	M	M	M
24	46	37	22	38	27	34	19	55	36	16	32	M	M	M	M
25	45	37	26	38	27	38	19	55	36	16	32	M	M	M	M
26	42	45	28	38	33	38	19	55	35	15	31	M	M	M	M
27	34	46	33	37	33	37	19	55	36	15	31	M	M	M	M
28	30	46	30	36	34	35	18	55	35	15	31	M	M	M	M
29	18	46	29	36	34	36	17	55	35	15	34	M	M	M	M
30	22	45	28	35	28	37	17	55	36	15	30	M	M	M	M
31	22	45	28	33	12	37	14	55	41	15	33	M	M	M	M

Table A-1 Snow Accumulation (continued)

February	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	48	33	13	20	28	31	7	28	33	32	8	21	29	30	57
2	48	33	18	20	28	30	6	27	33	41	8	21	29	31	55
3	48	33	30	20	28	30	6	27	33	41	7	20	29	31	54
4	48	33	30	17	28	30	9	26	33	40	7	23	24	30	54
5	48	30	30	17	28	31	9	25	33	38	7	23	24	29	53
6	51	30	30	17	26	32	8	26	38	36	7	23	24	28	53
7	51	30	30	15	26	32	8	25	38	35	7	23	24	20	52
8	51	30	30	13	26	33	7	24	38	35	6	23	24	20	51
9	58	28	20	13	26	33	8	24	37	37	6	24	24	20	50
10	58	28	20	12	26	37	8	24	36	37	18	24	24	20	50
11	56	30	20	12	26	37	8	24	36	35	19	24	24	19	51
12	56	30	20	13	26	38	8	24	36	34	19	31	24	25	48
13	58	30	20	14	26	40	8	24	36	32	18	31	25	30	48
14	58	33	20	16	25	44	8	24	35	32	18	31	27	30	48
15	58	33	20	15	21	44	8	21	35	31	18	31	27	30	50
16	56	33	25	14	21	42	8	16	34	31	15	33	27	30	50
17	56	30	25	16	20	40	8	16	33	30	14	33	27	29	49
18	56	28	28	16	20	40	8	16	33	34	13	33	27	29	46
19	53	28	33	15	20	40	8	16	33	37	10	35	27	29	46
20	53	25	36	13	19	40	9	18	32	38	8	35	27	30	49
21	53	25	38	13	19	40	9	18	33	35	6	33	27	29	41
22	51	25	38	13	18	40	9	17	33	34	5	31	27	29	39
23	53	25	30	13	24	40	9	16	33	34	5	32	27	30	39
24	53	25	30	13	27	40	9	16	33	33	4	32	28	34	39
25	53	20	25	13	25	39	9	16	33	31	3	31	28	33	39
26	53	20	25	13	25	43	8	16	33	30	3	31	24	33	38
27	51	18	25	12	25	45	8	17	37	30	3	29	22	31	35
28	51	18	25	12	24	43	8	17	39	30	3	24	16	32	33
29			25				8				3				33

February	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	22	45	29	32	12	38	14	55	39	15	37				
2	22	44	27	31	12	38	15	55	40	14	M				
3	22	44	18	31	12	37	15	55	39	14	M				
4	22	43	13	31		36	16	53	39	14	40				
5	22	43	12	30	12	36	16	53	37	14	40				
6	21	42	11	29	12	36	16	53	39	14	38				
7	21	45	10	29	12	34	16	49	38	14	39				
8	21	45	10	29	12	34	15	47	39	15	38				
9	21	45	10	31	12	34	20	49	38	15	38				
10	21	45	10	31	12	34	20	54	38	15	37				
11	21	45	10	31	12	34	20	54	37	15	42				
12	21	45	10	31	12	34	19	54	36	14	41				
13	21	45	12	32		34	19	53	39	15	40				
14	21	45	12	36	13	34	19	58	40	15	41				
15	21	44	12	37		34	19	58	40	15	41				
16	21	44	12	37	12	38	18	57	42	14	39				
17	21	44	12	39	12	38	18	57	46	14	40				
18	21	44	12	39	14	44	18	60	45	14	45				
19	21	44	12	39		55	20	67	49	13	44				
20	20	43	12	39	14	53	23	67	47	14	43				
21	20	45	13	40		53	23	67	52	14	43				
22	20	46	12	41	12	53	18	67	51	14	40				
23	20	48	14	42		53	18	66	50	15	39				
24	20	48	18	40	11	55	18	62	39	16	42				
25	22	49	20	39	11	53	23	60	38	16	41				
26	22	49	19	35	10	52	28	60	38	16	41				
27	27	48	19	23	9	52	28	60	42	16	41				
28	27	45	23	23	7	52	28	60	49	16	41				17
29				14				60							

March	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	56	18	25	12	24	45	8	16	39	30	4	18	13	33	36
2	56	18	25	12	24	45	13	16	39	30	4	19	10	33	36
3	56	18	25	15	24	45	13	18	39	30	3	19	7	34	35
4	56	23	25	15	24	43	13	18	37	34	3	18	7	37	35
5	56	23	23	14	24	42	12	18	37	34	3	18	6	37	35
6	56	25	23	10	23	42	12	22	35	34	4	17	6	37	35
7	56	25	23	6	23	45	12	24	35	33	10	18	7	37	34
8	53	23	28	6	23	45	12	24	35	35	10	18	8	36	33
9	53	23	28	5	24	44	16	24	36	34	10	15	9	36	30
10	53	23	25	4	23	42	16	20	36	33	10	14	8	36	29
11	53	23	25	4	24	41	17	17	35	29	10	13	8	35	29
12	53	23	25	3	24	41	27	15	35	24	10	13	7	35	28
13	51	23	23	5	23	46	27	14	35	24	9	12	6	34	27
14	56	20	23	24	23	46	26	11	37	24	9	12	5	33	26
15	58	20	23	24	23	45	27	7	36	29	9	11	4	40	27
16	58	20	23	24	23	43	27	4	35	29	8	9	4	43	28
17	56	20	20	19	23	40	27	2	34	29	7	8	4	43	28
18	56	20	18	22	22	38	27	2	35	27	7	5	6	42	29
19	56	20	18	22	22	36	23	2	35	27	5	3	6	39	34
20	56	20	18	22	20	34	20	2	35	27	3	3	7	42	39
21	56	23	18	22	17	32	19	2	35	29	2	4	6	48	39
22	56	23	18	22	17	32	20	2	32	34	2	3	5	46	39
23	56	23	18	22	17	32	23	2	31	34	2	2	7	46	34
24	56	23	18	25	17	32	23	T	32	30	1	1	9	45	30
25	56	23	18	27	19	41	20	T	32	30	1	1	9	43	28
26	53	23	18	26	19	40	19	T	32	29	T	T	8	38	28
27	53	23	15	23	18	40	16	0	30	29	0	T	6	38	28
28	53	23	15	23	17	42	10	0	35	27	0	T	3	38	28
29	53	23	13	23	15	41	8	0	33	28	0	T	1	38	28
30	51	25	13	22	12	41	6	T	52	27	0	T	T	36	28
31	48	28	10	20	13	40	5	0	54	25	0	T	T	25	28
March	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
1	27	41	24	10	5	52	27	66	48	16	40				
2	27	41	24	10	5	40	27	63	48	16	40				
3	27	40	24	10	5	30	26	63	47	16	40				
4	27	40	24	9	5	25	26	63	46	16	40				
5	27	39	24	8	4	23	26	63	45	16	39				
6	27	39	25	8	4	23	26	63	46	16	39				
7	29	38	24	12		23	26	63	45	16	39				
8	35	37	24	12	3	23	26	63	44	15	39				
9	34	39	24	12	3	23	26	58	46	16	39				
10	34	40	24	11	4	24	28	60	45	15	39				
11	39	39	25	10		25	31	55	46	15	39				
12	41	39	25	10	4	23	29	50	45	15	39				
13	42	39	25	9	3	20	23	48	45	14	38				
14	41	37	24	9	3	10	23	49	45	14	38				
15	42	35	23	8	4	8	18	48	44	14	38				
16	42	34	23	8	4	8	17	52	45	15	38				
17	41	34	23	8		8	24	51	44	16	39				
18	39	33	22	8	4	7	24	48	43	14	39				
19	39	31	18	8	4	5	24	48	46	15	36				
20	39	33	10	8	4	25	22	51	45	13	35				
21	38	36	10	8	3	25	16	53	40	13	33				
22	37	32	10	6	2	20	8	53	38	13	32				
23	35	30	4	6	T	18	8	53	36	12	28				
24	33	29	11	6	T	17	8	50	36	13	22				
25	34	29	11	6	0	15	10	49	36	10	17				
26	38	29	11	5	0	13	10	49	28	6	8				
27	38	27	11	4	0	12	10	49	27	0	1				
28	49	26	11	9	0	9	9	49	28	0	2				
29	49	19	11	9	T	8	9	49	28	0	2				
30	44	11	10	8	0	6	9	49	25	0	2				
31	35	9	9	8	0	5	10	49	23	0	2				5

Table A-1 Snow Accumulation (continued)

April	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	46	28	10	18	12	39	3	0	52	24	0	T	0	28	27
2	46	28	8	16	12	39	2	0	50	19	0	0	0	27	22
3	51	25	3	16	12	39	1	T	49	12	0	0	0	24	19
4	51	25	3	15	11	39	T	0	48	9	0	0	0	19	19
5	51	25	T	15	5	39	T	0	47	T	0	0	0	15	20
6	48	25	T	11	4	38	T	0	46	T	0	0	0	5	20
7	48	23	0	9	4	39	0	1	45	0	1	0	0	T	18
8	48	23	0	4	2	36	0	T	44	3	1	0	0	T	36
9	48	23	0	2	1	29	0	0	40	10	0	0	0	T	34
10	43	20	0	0	1	27	0	T	41	9	0	0	0	0	21
11	33	10	0	0	T	25	0	1	39	6	0	0	0	0	18
12	23	5	0	0	9	31	0	17	39	6	0	0	0	8	10
13	18	T	0	0	7	31	0	9	33	5	0	0	0	T	5
14	8	3	0	0	8	33	0	6	32	2	0	0	0	0	3
15	T	T	0	0	8	32	0	4	26	0	0	T	0	0	2
16	T	0	0	0	6	30	0	1	33	0	0	0	0	0	0
17	T	0	0	9	T	25	0	3	23	0	0	0	0	0	0
18	0	0	0	0	T	23	0	1	17	0	0	0	8	0	0
19	0	0	0	0	T	17	0	T	15	0	0	0	0	0	0
20	0	0	0	0	0	17	0	0	9	0	0	0	2	0	0
21	0	0	0	0	0	16	0	0	6	0	0	23	0	0	0
22	0	0	0	0	0	16	0	0	0	0	0	27	0	0	0
23	0	0	0	0	0	14	0	0	0	0	0	23	1	0	0
24	0	0	0	0	0	12	0	0	0	0	0	10	0	0	0
25	0	0	0	0	0	12	0	0	0	0	0	4	0	0	0
26	0	0	0	0	0	9	0	0	0	0	0	1	0	0	0
27	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	1	0	0	0	0	0	0	7	0	0
30	0	0	0	T	0	T	0	0	0	0	0	0	7	0	0
April	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
1	29	9	9	8	T	3	11		23	0				M	5
2	26	7	8	7	0	3	12		22	0				M	4
3	24	2	5	4	0	2	12		19	0				M	4
4	25	1	2	3	0	2	12		19	0				M	3
5	24	1	2	2	0	2	14		22	0				M	3
6	22	T	2	2	4	2	15		19	0				M	3
7	20	T	2	3	12	0	15		19	0				M	3
8	18	2	2	5	11	0	13		18	0				M	2
9	18	3	T	4	11	0	12		17	0				M	T
10	18	2	T	11	7	0	10		18	0				M	0
11	15	T	T	10	2	0	8		17	0				M	0
12	12	T	T	7	T	0	3		16	0				M	0
13	5	T	T	4	0	0	3		12	0				M	0
14	1	T	T	T	0	T	1		12	0				M	0
15	1	T	T	T	0	0	1		11	0				M	0
16	1	T	T	T	0	0	1		5	0				M	0
17	T	T	0	T		0	T		2	0				M	0
18	T	T	0	T	0	0	0		0	0				M	0
19	T	T	0	T	0	0	0		0	0				M	0
20	0	T	0	T		0	0		0	0				M	0
21	0	0	0	0		0	0		0	0				M	0
22	0	0	0	0	0	0	0		0	0				M	0
23	0	0	0	0	2	0	0		0	0				M	0
24	0	0	0	0	0	1	0		0	0				M	0
25	0	0	0	0		T	0		0	0				M	0
26	0	13	0	0		0	0		0	0				M	0
27	0	12	0	0	0	0	0		0	0				M	T
28	0	12	0	0	0	0	0		0	0				M	0
29	0	10	0	0	0	0	0		0	0				M	0
30	0	4	0	0	0	0	0		0	0				0	0

Table A-1 Snow Accumulation (continued)

May	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	0	0	0	0	0	1	0	0	0	0	0	0	5	0	0
2	T	0	0	0	0	T	0	0	0	0	0	0	0	0	2
3	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
4	0	0	0	0	0	T	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	2	T	0	0	0	0	0
6	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0
7	0	0	0	0	0	T	0	0	7	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	T	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	T	0	0	0	1	0	0	0	T	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	T	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
1	0	T	0	0	0	0	0	M	0	0			M	M	0
2	0	0	0	0	0	0	0	M	0	0			M	M	0
3	0	0	0	0	0	0	0	M	0	0			M	M	1
4	0	0	0	0	0	0	0	M	0	0			M	M	5
5	0	0	0	0	0	0	0	M	0	0			M	M	2
6	0	0	0	0		0	0	M	0	0			M	M	T
7	0	0	0	0		0	0	M	0	0			M	M	0
8	0	0	0	0	0	0	0	M	0	0			M	M	0
9	0	0	0	0	0	0	0	M	0	0			M	M	0
10	0	1	0	0	0	0	0	M	0	0			M	M	0
11	0	0	0	0		0	0	M	0	0			M	M	0
12	0	0	0	0	0	0	0	M	0	0			M	M	0
13	0	0	0	0		0	0	M	0	0			M	M	0
14	0	0	0	0	0	0	0	M	0	0			M	M	0
15	0	0	0	0	0	0	0	M	0	0			M	M	0
16	0	0	0	0	0	0	0	M	0	0			M	M	0
17	0	0	0	0	0	0	0	M	0	0			M	M	0
18	0	0	0	0	0	0	0	M	0	0			M	M	10E
19	0	0	0	0		0	0	M	0	0			M	M	5E
20	T	0	0	0		0	0	M	0	0			M	M	T
21	0	0	0	0	0	0	0	M	0	0			M	M	0
22	T	0	0	0	0	0	0	M	0	0			M	M	0
23	0	0	0	0	0	0	0	M	0	0			M	M	0
24	0	0	0	0	0	0	0	M	0	0			M	M	0
25	0	0	0	0	0	0	0	M	0	0			M	M	0
26	0	0	0	0	0	0	0	M	0	0			M	M	0
27	0	0	0	0		0	0	M	0	0			M	M	0
28	0	0	0	0		0	0	M	0	0			M	M	0
29	0	0	0	0		0	0	M	0	0			M	M	0
30	0	0	0	0		0	0	M	0	0			M	M	0
31	0	0	0	0		0	0	0E	0	0			0	0	0

Table A-1 Snow Accumulation (continued)

October	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	T	0	0
3	0	0	T	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	3	0	0	0	0	0	0	0	0	1	2	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	T	0
9	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0
10	0	0	0	2	0	0	0	0	0	6	0	0	0	T	0
11	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
13	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
14	0	0	T	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	T	0	0	0	0	0	0	0	0	0	0	T	0
16	0	0	T	0	0	0	0	0	0	T	0	0	0	0	0
17	0	0	0	0	0	0	0	0	T	T	6	3	0	0	0
18	0	0	0	0	0	0	0	0	1	0	3	0	0	0	0
19	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
20	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
21	0	0	0	0	0	0	0	2	T	0	0	0	0	0	T
22	0	0	T	0	0	0	0	2	0	0	0	0	0	0	1
23	0	T	T	0	0	0	0	5	0	0	0	0	0	0	7
24	0	T	T	0	0	0	0	7	0	0	2	0	0	0	7
25	0	0	0	0	0	0	0	6	0	0	2	0	0	0	7
26	0	T	0	0	0	0	0	14	0	0	7	15	0	0	12
27	0	T	0	0	T	0	0	14	0	0	6	14	0	0	0
28	0	3	0	0	0	0	0	10	0	0	6	12	T	0	18
29	0	T	0	0	2	0	0	7	0	0	6	14	T	0	17
30	T	T	0	0	2	0	0	5	0	0	5	12	2	0	17
31	0	T	0	0	2	0	0	4	0	0	5	13	3	0	15
October	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
1	0	0	0	0	0	0	0			0	0			M	M
2	0	0	0	0	0	0	0			0	0			M	M
3	0	1	0	0	0	0	0			0	0			M	M
4	0	0	0	0	0	0	0			0	0			M	M
5	0	0	0	0	0	0	0			0	0			M	M
6	0	0	0	0	T	0	0			0	0			M	M
7	0	0	0	0	T	0	0			0	0			M	M
8	0	0	0	0	0	0	0			0	0			M	M
9	0	0	0	0	0	0	0			0	0			M	M
10	0	0	0	0	0	0	0			0	0			M	M
11	0	1	0	0	0	0	0			T	0			M	M
12	0	0	0	0	0	0	0			0	0			M	M
13	0	8	0	0	0	0	0			0	0			M	M
14	0	2	4	0	0	0	0			0	0			M	M
15	T	3	2	3		0	0			0	0			M	M
16	0	0	0	2	0	0	0			0	0			M	M
17	0	2	0	2	0	0	0			0	0			M	M
18	0	4	0	2	0	0	T			0	0			M	M
19	0	2	0	4	0	0	0			0	0			M	M
20	0	3	0	4	0	0	0			0	0			M	M
21	0	3	T	0	0	0	0			0	0			M	M
22	0	4	T	T	0	0	0			0	0			M	M
23	0	8	0	T	0	0	0			0	0			M	M
24	0	8	1	T	0	0	0			0	0			M	M
25	0	6	3	0	0	0	T			0	0			M	M
26	0	3	4	0	0	0	0			0	0			M	M
27	0	3	4	0	0	0	1			0	0			M	M
28	1	3	4	0	T	0	3			0	0			M	M
29	T	2	4	0	T	0	4			0	0			M	M
30	T	1	4	0	1	1	4			0	0			M	M
31	2	1	4	0	0	T	4			0	0			5E	1E

Table A-1 Snow Accumulation (continued)

November	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	0	T	0	0	0	0	0	T	0	0	5	12	3	0	14
2	0	T	T	T	0	T	0	0	T	0	5	12	3	0	15
3	0	T	0	4	0	M	0	0	T	0	5	11	3	0	15
4	0	0	0	4	0	3	0	0	0	0	6	11	T	0	15
5	0	0	0	3	1	3	0	0	2	0	6	14	0	0	14
6	0	T	0	7	1	3	0	0	T	0	6	14	1	0	12
7	0	0	0	6	0	3	1	T	T	T	8	14	7	0	12
8	0	3	0	6	0	11	5	0	2	0	9	14	7	0	22
9	0	3	0	6	T	11	5	0	3	1	9	14	7	0	24
10	0	3	0	6	3	13	3	0	3	1	8	12	7	0	23
11	0	3	0	6	1	14	4	0	7	1	8	12	7	0	22
12	0	3	0	6	1	11	3	0	7	6	8	12	7	0	21
13	0	3	0	2	1	8	2	0	5	4	13	12	7	0	22
14	0	T	0	1	1	6	2	0	5	3	21	12	8	3	23
15	0	T	0	1	2	4	2	0	5	3	21	10	8	6	25
16	0	T	0	T	12	2	2	T	5	3	21	9	8	6	23
17	0	T	0	T	17	T	2	1	5	3	21	9	8	6	23
18	0	T	T	7	14	T	2	2	8	3	25	9	8	6	26
19	3	3	T	8	10	T	3	3	6	4	25	9	8	8	27
20	3	3	T	5	9	T	2	2	13	6	27	9	9	8	28
21	10	3	T	5	8	T	2	2	15	8	25	9	11	6	27
22	15	3	T	5	9	T	1	3	14	6	23	9	11	5	23
23	15	3	T	5	10	T	1	4	14	6	18	9	11	5	24
24	13	5	T	5	10	T	1	4	13	6	17	10	18	5	29
25	13	8	T	4	10	T	2	4	13	5	15	10	25	5	29
26	10	10	T	4	12	T	2	4	13	5	15	10	25	4	29
27	10	10	T	7	13	T	2	4	13	5	15	10	32	4	29
28	10	15	T	7	21	T	2	5	10	5	15	12	32	2	30
29	8	15	T	8	20	T	2	4	13	9	15	15	30	2	30
30	8	13	3	11	20	T	3	8	14	9	16	17	28	2	29
November	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
1	3	1	4	0	0	T	5	12	0					M	
2	5	1	4	2	0	3	6	12	0					M	
3	6	3	4	4	1	3	6	12	0					M	
4	6	4	4	4	7	3	4	12	0					M	
5	6	7	4	4	9	2	4	12	0					M	
6	6	6	4	4	7	2	4	12	0					M	
7	9	5	4	3		2	6	12	0					M	
8	11	4	7	4	8	2	6	12	0					M	
9	19	5	13	4	8	2	6	12	0					M	
10	30	5	13	6	9	2	7	12	0					M	
11	27	4	14	7	9	2	7	12	0					M	
12	22	8	10	7	7	1	8	12	0					M	
13	25	7	4	6	9	1	9	12	0					M	
14	28	8	11	7	9	1	9	14	0					M	
15	26	8	11	12	6	1	9	14	0					M	
16	29	8	9	12	6	1	12	14	0					M	
17	30	8	6	12	6	1	12	15	1					M	
18	28	7	14	12	6	2	11	16	2					M	
19	25	11	16	11	7	3	11	16	2					M	
20	25	11	17	11	10	2	12	17	2					M	
21	25	15	17	12		2	12	19	2					M	
22	25	17	18	12	10	2	13	20	3					M	
23	24	17	18	15	10	2	13	21	3					M	
24	26	16	18	15	10	2	13	21	2					M	
25	27	16	18	14	10	2	13	22	2					M	
26	28	15	17	14	10	2	13	22	4					M	
27	28	16	16	13		3	13	22	4					M	
28	28	17	15	13	8	3	13	23	7					M	
29	23	19	17	12	8	3	13	26	9					M	
30	22	37	17	12	8	3	20	25	9					3E	

Table A-1 Snow Accumulation

December	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	8	13	3	10	20	T	3	8	14	9	16	17	25	2	26
2	8	10	3	12	19	T	3	8	15	9	17	17	25	2	20
3	13	10	3	12	18	T	3	7	15	8	17	17	25	2	23
4	13	15	3	16	19	T	5	6	16	10	18	17	25	4	22
5	15	18	3	17	19	1	7	6	15	11	18	17	25	6	20
6	15	18	3	16	18	5	10	8	15	12	17	16	26	12	17
7	15	18	3	16	18	11	10	12	16	13	12	16	29	9	18
8	15	15	3	16	18	10	10	12	15	13	9	16	29	11	18
9	13	20	5	15	18	12	10	10	16	13	9	16	29	11	18
10	8	23	5	15	22	12	8	11	16	13	9	16	30	11	18
11	8	23	5	17	22	12	12	16	16	13	9	21	30	11	19
12	8	23	5	17	21	13	18	16	16	13	9	21	30	12	21
13	8	23	8	17	21	13	17	16	15	15	10	19	29	15	21
14	8	25	8	16	20	14	16	16	16	15	10	19	28	15	22
15	8	28	8	16	20	15	17	15	16	15	12	19	28	15	22
16	8	28	8	15	20	14	16	15	15	14	12	20	26	15	22
17	5	25	8	16	21	13	15	14	19	14	12	20	26	15	22
18	5	23	8	20	21	17	14	14	19	13	12	21	24	15	24
19	5	20	8	21	21	17	14	14	19	13	12	24	24	20	30
20	5	20	8	21	22	11	14	14	22	13	16	26	24	20	34
21	5	18	8	20	26	8	14	20	22	13	20	25	24	20	33
22	5	18	8	20	28	8	14	27	22	13	20	23	23	26	33
23	8	18	8	22	28	8	13	29	23	14	20	20	23	27	32
24	8	18	13	23	30	8	13	28	25	14	19	20	23	25	32
25	8	18	13	23	30	7	13	27	25	12	19	19	23	25	32
26	8	15	13	23	30	7	15	28	26	12	19	18	21	21	32
27	8	15	13	23	30	6	22	29	28	14	20	19	20	19	31
28	8	13	13	23	31	5	24	29	28	14	20	19	20	19	31
29	8	13	13	27	31	5	28	28	29	13	20	19	20	19	31
30	8	13	13	27	29	5	27	28	29	13	19	19	19	26	31
31	8	13	13	25	27	4	26	27	26	13	19	19	19	24	31
December	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	22	35	17	11	8	8	24	25				0	M	M	M
2	22	33	19	11	8	8	25	25				T	M	M	M
3	22	32	19	12	8	8	26	25				T	M	M	M
4	21	23	19	11	9	8	26	25				T	M	M	M
5	20	22	22	9	9	8	27	29				1	M	M	M
6	20	21	27	9	9	8	27	28				1	M	M	M
7	23	19	28		9	8	27	28				1	M	M	M
8	23	14	29		9	8	27	27				0.2	M	M	M
9	26	10	30		9	8	27	28				0	M	M	M
10	25	10	29	10	9	8	24	29				0.2	M	M	M
11	25	10	29	10	8	10	24	29				0	M	M	M
12	30	13	29	10	8	10	24	29				0	M	M	M
13	33	12	32	10	8	10	30	29				0	M	M	M
14	33	12	32	10	8	10	33	29				T	M	M	M
15	44	12	31	10	10	10	33	29				0.2	M	M	M
16	45	17	30		11	10	35	29				T	M	M	M
17	44	17	28		11	11	36	29				1.8	M	M	M
18	44	19	28	11	12	11	36	32				1	M	M	M
19	43	19	28	11		11	36	31				2	M	M	M
20	43	19	28	11	18	11	36	31				0	M	M	M
21	43	18	28		20	9	36	31				0.8	M	M	M
22	43	18	26	12	21	9	35	31				0	M	M	M
23	36	19	26	12	25	9	34	31				0	M	M	M
24	35	21	26	18	26	8	34	32				0.2	M	M	M
25	35	22	23	18		8	34	30				0.2	M	M	M
26	35	22	23		30	8	34	32				3	M	M	M
27	34	25	23	17	30	8	33	31				0.4	M	M	M
28	34	26	22	17		8	32	31				1	M	M	M
29	33	26	22		26	10	32	31				0	M	M	M
30	33	25	22	17		12	32	32				0	M	M	M
31	33	25	22	17	26	12	36	32				T	9	10	25

M=Missing E = Estimated Empty = Not Available T = Tracing

Table A-2 Average Temperature (°C)

January	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	-13.4	0.3	-16.4	-18	-10.9	-25.1	-16.7	-20.9	-38.2	-16.3	-11.8	-22.8	-22.5	-13.5	-16.4
2	-12	-6.1	-25	-21.1	-15.8	-18.8	-12.2	-16.9	-36.3	-15	-2.7	-7.3	-19.4	-15.2	-17.9
3	-11.7	-5.6	-26.1	-18.8	-14.9	-26.3	-14.6	-14.2	-30.7	-8.4	-4.2	2.8	-17.3	-13.1	-29.4
4	-16.7	-13.9	-27	-19.6	-24.6	-24.1	-17.9	-6.5	-33.8	-10.2	-3.2	-1.8	-13.3	-10.8	-34.8
5	-17.8	-13.9	-36.1	-18.9	-29.5	-15.2	-22.4	-12.4	-35.5	-16.3	-5.3	0.3	-20.7	-9.9	-28.8
6	-21.4	-18.7	-35.6	-13.1	-24	-16.4	-27.5	-16.7	-34.7	-19.7	-9.9	-2.3	-18.9	-8.9	-19.4
7	-20.6	-30.9	-31.4	-21.4	-28.8	-13.9	-31.8	-12.2	-33.3	-10.7	-19.5	-13	-7.6	-5.8	-18.8
8	-28.1	-27.5	-30	-23.7	-32.1	-11.2	-28.7	-19.2	-28.9	-3.7	-22.7	-15.2	-3.5	-8.7	-20.7
9	-31.7	-28.3	-20.9	-28.9	-22.7	-19.4	-27.3	-20.6	-29.5	-16.4	-28.5	-15.1	-3.6	-4	-22.9
10	-31.4	-32.5	-18.6	-29.7	-16	-23.8	-31.6	-12.7	-27.9	-28	-26.9	-17.9	-1.3	5.6	-26.7
11	-28.4	-29.2	-17.8	-29.8	-19	-25.9	-34.9	-6.6	-23.7	-26.5	-18.9	-13.5	-2.3	3.9	-29.5
12	-30.6	-24.8	-22.3	-33.6	-17.4	-28.7	-25.1	-3.6	-26.9	-20.5	-19.8	-1.2	-6.7	-0.8	-30.3
13	-29.5	-21.7	-26.2	-32.3	-20.7	-27	-23.5	-3.1	-25	-19.9	-29.1	-7.9	-2.8	-12.2	-22.7
14	-35	-27.2	-25.9	-28.6	-16.6	-27.3	-21.4	-7.8	-25.3	-19.4	-18.2	-10.4	-0.9	-17.9	-15.2
15	-28.9	-30.9	-23.4	-24.8	-23.1	-27.9	-15.3	-8.3	-29.8	-15.2	-13.1	-11.7	-2.6	-14.9	-10.9
16	-26.7	-22.5	-10.6	-23.5	-25.1	-26.6	-8	-9.6	-30.6	-23.8	-23.5	-16.8	-7.4	-9.2	-17.3
17	-24.2	-22	-0.6	-11.4	-28.2	-20.5	-8.5	-9.4	-27.6	-16.9	-25	-20.5	-6.1	-12	-15.4
18	-17.5	-22.2	-4.8	-1.7	-29.4	-8	-8.5	-6.6	-33.6	-15.6	-23	-31.1	-4.9	-9.8	-12.3
19	-8.9	-10.3	-2.2	-5.9	-22	-3.4	-11.6	-7.5	-37.6	-12.8	-26.9	-35.5	-8.1	-6.3	-13.2
20	-15	-9.5	-2.8	-10.5	-16.5	-9.3	-7.5	1.1	-36.7	-12.8	-20.3	-28.3	-17.3	-4.5	-5.6
21	-25.3	-15	-9.2	-4.9	-13.3	-17.6	-7.1	-3.1	-38.3	-14.3	-23	-16.7	-20.6	-11.3	-6.7
22	-27.8	-12.2	-4.8	-1.4	-10.4	-19.7	-13.6	-6	-36.5	-19.6	-18.3	-7.2	-22.8	-11.3	-7.5
23	-30.3	-12.2	-9.8	-3.3	-15.1	-16.3	-0.8	0	-29.4	-27.7	-8.7	-5.2	-16.4	-12.2	-9.2
24	-22.5	-15.6	-19.5	-7.1	-23.3	-19	-8.3	-1	-25.1	-32.3	-22.3	-9.8	-11.8	-11.9	-21.9
25	-23.6	-18.9	-24.5	-8.9	-25.6	-23.8	-23.4	-5.5	-25.9	-32.2	-23.4	-4.5	-19.2	-9.6	-12.7
26	-24.2	-17.5	-20.3	-19.1	-25.1	-22.8	-24.5	-11.1	-22.6	-25.8	-25.3	-11.9	-12	-10.3	-8.9
27	-32.8	-15	-6.2	-30.9	-26	-11.7	-25.8	-9.5	-29.6	-17.6	-7	-10	-10.2	-9.9	-17.7
28	-31.7	-20.3	-13.4	-31.9	-24.3	-19.5	-26.3	-9.9	-32.7	-13.1	-6.3	-19.6	-17.4	-7.6	-22.6
29	-33.9	-21.7	-6.7	-26.3	-25.2	-13.5	-25.7	-13.1	-36.6	-10.4	-11.5	-32.7	-21.2	-8.5	-25.1
30	-31.4	-21.1	-3.1	-19	-20.8	-19.4	-23.6	-9.2	-28.5	-4.6	-3.6	-28.6	-16.4	-11.7	-29.2
31	-28.6	-31.2	3.4	-11.5	-27	-26.3	-21.3	-10.7	-26.1	-12.7	1.1	-30.7	-9.5	-12.8	-32.9
January	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
1	-24.9	-12.6	-26.3	-9.7	-26.7	-31.1	-11.4	-10.6	-21.3	-25.5	-25.1	-30.6	-5.4	-22.5	-6.3
2	-15.2	-21.8	-21.4	-4.1	-17.8	-25.4	-17.3	-12.3	-22.8	-29.1	-29.5	-26.6	-4.3	-19.7	-9
3	-15.6	-27	-16.2	-3.8	-17	-29.3	-22.7	-21	-19.8	-33.5	-28.2	-27.6	-2.1	-10.8	-9.6
4	-9.6	-29.3	-20.6	-12.3	-26.7	-34.7	-20.9	-32.6	-24.6	-34	-19.8	-26	-4.2	-8.6	-6.8
5	-18	-24.5	-32.2	-19.3	-22.5	-29.3	-15.5	-32.6	-24	-28.9	-25	-21	-9.4	-11.3	0.2
6	-26.2	-13.9	-31.7	-15.7	-20.4	-28.1	-15.5	-22.2	-13.7	-32.1	-28.2	-22.8	-13.6	-5.9	6.3
7	-30.3	-15.5	-31.6	-12.6	-24.8	-28.1	-16.1	-11.8	-16.7	-35	-30.6	-14.9	-12.8	3	8
8	-31.8	-7.7	-37.4	-11.7	-30.1	-31.4	-21.1	-7.9	-23.1	-33.4	-32.6	-10.1	-10.5	3.3	-1.7
9	-32.9	-5	-30.9	-5.3	-22.6	-31.8	-22.6	-8.4	-33.5	-34.8	-27.3	-13.8	-4.4	-1.7	-17.4
10	-24.8	-9.7	-27.7	-0.4	-19.6	-36.2	-17.1	-13.2	-35.2	-33.2	-28.7	-26.4	-5.2	0.3	-25.6
11	-15.5	-17.5	-25.2	-7.8	-22.2	-31.5	-15.2	-16.9	-30.7	-29.4	-31	-23.2	-9.7	-1.4	-23.8
12	-7.4	-17.7	-14.7	-15.2	-23.6	-32.9	-11.8	-23.2	-17.3	-31.3	-24.9	-24.6	-12.3	-4.7	-27.8
13	-6.6	-13.9	-10.1	-19.8	-25.3	-33.9	-9.4	-30.1	-15.6	-34.5	-11.2	-28.5	-14.4	-3	-26.4
14	-22.5	-12.9	-6.3	-27.7	-18.5	-31.3	-8.2	-28.2	-10.8	-29.2	-1.7	-30.7	-15.9	-10.2	-24.6
15	-17.5	-7.9	-8.2	-12.2	-11.6	-30.2	-8.5	-29.9	-26	-18.6	-0.6	-29.2	-16.1	-11.9	-20
16	-16.8	-15.6	-11.5	-20.6	-17	-32.7	-10.2	-31.6	-27.9	-16	-6.9	-26	-2.9	-17.9	-12.4
17	-13	-14	-13.1	-23.6	-18.1	-31.3	-14.6	-36.9	-18.3	-17.2	-14	-27.9	-4.6	-24.8	-9.2
18	-19.2	-13	-4.6	-17.8	-12.1	-30.3	-16.4	-39	-6.9	-17.5	-13.7	-30.3	-10	-15.4	-17
19	-21.1	-18.1	-19.6	-7.1	-13.6	-26.8	-13.1	-38.2	-9	-18.9	-15.5	-31.4	-5.3	-24	-18.6
20	-8.4	-6.8	-19.3	-3	-9.1	-15.6	-13.5	-31	-15.3	13.8E	-16.5	-21.7	-0.5	-26.8	-22.6
21	-8.9	-8.4	-5.4	-10.8	-12.4	-17.9	-14.7	-24	-16.2	-10	-19.8	-18.9	-2.5	-30.2	-23.1
22	-19.8	-13.3	-10.1	-18.6	-14.9	-13.9	-13.5	-24.9	-19	-15.5	-21.5	-17.8	-6.3	-32.8	-28.1
23	-21.1	-11	-21.7	-23.6	-23.1	-16.3	-11	-29	-26.5	-21.7	-27.1	-13.3	-11.9	-30.8	-26.1
24	-14.9	-12.4	-13.3	-21.5	-18.7	-16.2	-10.6	-25.6	-32.7	-17.4	-18.9	-11.5	-6.2	-31.5	28.2E
25	-7.7	-17.1	-11.1	-27.1	-18.7	-11.8	-13.4	-25.9	-27.6	-11.3	-11.1	-11.9	-8.3	-30.8	-29.8
26	6.6	-27.8	-9.1	-16.2	-21.6	-10.1	-18	-29.4	-31.3	-12.3	-18.7	-14.3	-9	-29.5	-19.6
27	3.2	-30.2	-13.4	-7.6	-23.1	-9.5	-12.3	-33.2	-30.8	-5.8	-16.2	-8.4	-10.1	-34.3	-21.9
28	-1.7	-30.6	-20.5	-12	-21.9	-5.5	-11.8	-32	-26.7	-10.5	-10.2	-2.6	-0.5	-30.8	-29.2
29	-10.2	-33.8	-22.5	-6.9	-6.2	-11.5	-5	-30	-13.6	-9	-15.2	0.1	-5.8	-31.6	-17.7
30	-28	-36.8	-26.2	-4.7	8.3	-8	0.3	-28.6	-10.5	-3.5	-15.7	-3.3	-12.4	-30.7	-12.8
31	-31.8	-31.4	-21.7	2.5	2.6	-10.1	-3.4	-36.6	-9.6	-9.1	-12.2	-5.8	-22.7	-19.5	-14.9

Table A-2 Average Temperature (continued)

February	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	-32.8	-31.7	-2.5	-12.6	-22.7	-24.8	-13.2	-15.5	-28.6	-20.6	-7.5	-32.6	-8.4	-14	-32.6
2	-28.6	-31.1	-11.4	-7.7	-26.1	-31.1	-9.2	-13.4	-25.9	-23.8	-1.6	-32	-6.6	-11.9	-30.5
3	-18.9	-31.7	-21.1	-4.6	-30.7	-32.2	-4.3	-8.4	-23.6	-28.9	-10.1	-28	-1.6	-14.3	-29.8
4	-22	-27.2	-18.1	-16	-25.6	-27.5	-4.5	-3.6	-26.6	-28.5	-22.9	-19.7	-5.4	-5.7	-30.2
5	-17	-17.5	-15	-9.3	-12.9	-27.8	-4.4	-10.2	-20.2	-27.8	-6.6	-28.3	-10	1.1	-26.5
6	-17.2	-16.4	-7.3	-6.1	-9.8	-30.4	-7.6	-16.8	-12.1	-18.1	-10.1	-28.1	-12.2	2.8	-21.4
7	-11.4	-23.9	0	1.3	-10.9	-25.3	-3.1	-25.8	-19.7	-17.1	-4.5	-30.6	-19.8	-0.5	-25.4
8	-11.4	-27.3	0.6	1.9	-12.8	-32.6	1.2	-22.1	-23	-13.2	-3.9	-30.1	-23.4	-0.1	-28
9	-16.4	-26.2	-17.5	-2.2	-12.4	-28.5	-8.1	-27.1	-17.6	-11.9	-13.7	-26.6	-20	-5.6	-34
10	-8.9	-29.5	-24.5	1.6	-14.6	-30.4	-13.7	-26.8	-13.4	-14.1	-16.3	-27.7	-20.6	0.2	-25
11	-20.3	-32	-20	-0.8	-17.6	-27.9	-16.3	-29.3	-23.5	-9.9	-15.8	-27.5	-12.5	-6.6	-11.8
12	-26.1	-34.5	-20.3	-3.1	-15.1	-29.7	-17.5	-27.4	-24.9	-4.9	-5.5	-20.5	-15.7	-14.2	-13.4
13	-25.6	-23.9	-20.3	-5.5	-13.4	-28.6	-19.9	-19.6	-22	-2.9	-6.6	-26.4	-19.4	-17.1	-19.8
14	-15.6	-25.3	-20	-3.5	-12.3	-33.1	-15.2	-3.3	-19.7	0.1	-7.8	-22.6	-16.8	-12.5	-13.4
15	-9.2	-17	-10.8	2.3	-14.9	-32.8	-16.2	6.2	-20.3	-10.5	-6.1	-7.4	-27.5	-9.8	-7.9
16	-1.1	-7.2	-13.6	-1.3	-13.9	-22.9	-15.9	-5.2	-9.3	-23.5	-6.2	-20	-31.2	-5	-4.6
17	-4.7	-11.1	-15.8	-3.3	-10.9	-23.1	-13.7	-8.3	-5.7	-18.6	-4	-25.7	-29.2	-5.6	-4.6
18	-13.4	-0.6	-16.7	-2.9	-6.2	-17.9	-15.4	-0.8	-4.9	-14.8	-2.6	-17.9	-31.7	-4.9	-7.1
19	-10.3	0.9	-18.9	-3.2	-0.8	-19.1	-19.8	-4.6	-1.3	-11.3	1.5	-6.2	-30.5	-5.8	-14.5
20	-12	-3.6	-21.7	1.9	0.2	-22.7	-20.9	-4.9	-1.9	-6.8	3.8	-19.6	-21	0.4	-1.6
21	-7.8	-7.5	-13.9	-2.1	1.6	-22.4	-13.7	-6.4	-14.2	-5.2	2.7	-14.7	-18.4	-5.3	-2.4
22	-6.4	-7.5	-0.3	1.5	-3.2	-27.7	-12	-3.7	-20.5	-6.1	-3.1	-21.1	-19.3	-10.4	-14.3
23	-8.6	5	-6.9	-2.6	-4	-27.8	-14	-3.1	-24.7	-2.7	-3.6	-16.2	-17.5	-8.5	-19
24	-11.2	0.8	-7.5	-3.8	-16.4	-25.5	-15.4	-7.3	-25.5	1.6	-2.6	-16.9	-7.7	-10.8	-12.9
25	-12.8	-4.4	-17.8	-3.4	-19.9	-19.2	-4.9	-5.9	-26.1	-3	-6.3	-18.2	3	-12.4	0.8
26	-15.6	-8.6	-22	-6.3	-14.9	-18.6	-11.5	-7.4	-24	-11.6	-10.8	-8.2	-0.1	-11	4.2
27	-19.2	-9.2	-24.5	-2.2	-15.7	-26.5	-8.3	-5.5	-15.8	-14.6	-11.4	0.1	3.7	-9.9	2.9
28	-15.8	-13.1	-25.6	-0.7	-15.5	-19.2	-14.3	-0.3	-17.3	-11.8	-4.8	2.1	4.6	-10	0.6
29			-20.3				-12.9				-5.1				-3.5

February	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	-32.6	-32.2	-1.8	-5.1	3.4	-15.3	-4.9	-34.7	-5.4	-7.4	-13.5	-11.5	-8.6	-12.9	-15.6
2	-31.3	-24	7.8	-13.5	3	-20.1	-11.9	-31.1	-7.1	-6.8	-21.9	-7.5	-4.6	-12.3	-18
3	-22.9	-18.1	1.7	-9.3	-9.2	-18.2	-12.3	-25.6	-3.7	-5.9	-24.7	-9.1	-1.5	-8.5	-18.4
4	-14.4	-19.4	-0.6	-4		-15.1	-2.4	-23.8	-5.8	-6.8	-22.6	-9.7	-2.9	-14.4	-14
5	-7.9	-18.6	1.8	-3.2	-15.4	-25.7	-3.6	-14	-5.6	-5.7	-18.7	-12.9	-9.4E	-15.1	11.8E
6	-6.8	-15.6	4.8	-15.6	-4.9	-33.4	-10.4	-4.9	-6.8	-7.7	-11.9	-11.8	20.4E	-12.8	-6.7E
7	-17.7	-12.8	1.2	-17.4	-7.1	-27.5	-4.7	-1.3	-3.7	-10.9	-14.7	-5.3	-25.4	-15.8	-10.9
8	-17.1	-18.3	-5.5	-12.5	-8.4	-28.9	-2.2	-3.1	-3.4	-14.9	-9.7	-11.5	-27.4	-17.2	-23
9	-8.5	-27.9	-16	-22.4	-18.4	-27.5	-12.9	-4.6	-9.7	-7	-11.2	-25	-22.5	-19.1	-17.5
10	-4.4	-20.5	-11	-29.8	-17.5	-26.3	-21.4	-6.4	-11.6	-5	-13.3	-21.4	17.9E	-7.7	-13.5
11	-2.4	-21.5	-13.5	-23.8	-13.6	-29.4	-22.5	-6.3	-21.1	-5	-19.2	-21.1	-21.7	-9.6	-22.2
12	-6.2	-29.6	-11.9	-19	-14.7	-18	-18.6	0.3	-15.1	-1.8	-7	-23.6	18.8E	-6.2	-16.1
13	-17.3	-25.2	-20.9	-14.8		-19.7	-16	-5.7	-15.2	-1.5	-10.6	-14.4	19.4E	-0.4	-17
14	-28.2	-26.9	-19.8	-15.8	-20.2	-25.7	-19	-16	-17.9	-1	-7	-14.8	13.0E	-2.7	-18.3
15	-29.4	-32.7	-11.5	-8		-17.5	-23.6	-19.1	-17.9	-3.1	-5.8	-26.5	17.6E	0.5	-13.9
16	-24.6	-30.8	-11.8	-14	-23	-21.9	-24	-9	-14.4	-1.6	-8.9	-22.5	-15.4	0.3	-18.1
17	-20.7	-25.7	-11.4	-9.9	-15.1	-20.6	-22.9	-10.4	-17.3	-3.2	-6.9	-16.3	-13.1	-3.7	-23.5
18	-12.5	-15.4	-9.9	-14	-10.5	-17.9	-20.6	-11.1	-18.7	-4.3	-7.6	-13	19.9E	-14.4	-17.2
19	-12.6	-7.5	-15.3	-18.2		-22.5	-14.6	-15.6	-11.9	-6.5	-8.1	-8.8	-21.1	-3.2	-25.2
20	-11.9	-9.4	-20.6	-22.2	-20.2	-28	-8.8	-6.6	-15.8	-3.2	-5.6	-2.7	-21.9	1.8	-31.5
21	-10.2	-19.7	-21.7	-22.6		-32.6	0.4	-5.4	-18.9	-2	-3.6	-4.9	-17.5	-2.5	-30.5
22	-6.6	-16	-15.8	-15.7	-22.8	-27.7	-6.5	-9	-19.4	-2.9	-2.8	-1.2	11.7E	-10	-26.8
23	-3.5	-21	-13.9	-11.4		-21.9	-12.9	-17.9	-8.3	-6.9	-3.5	1.1	16.2E	-18.8	-25.2
24	-9.5	-20.9	-13.9	-1.9	-10.5	-24.9	-12.3	-25.1	3.2	-7.6	-0.8	2.5	-27.2	-22.6	-23
25	-18	-4.5	-4.2	5	-6.1	-25.5	-15.4	-26.7	-4.7	-8.1	-4.8	-0.5	-30.2	-15.8	-17
26	-15.9	-15.1	-6.4	7.3	-2.1	-23.3	-21.6	-22.7	-9.6	-4.7	-4.5	-2.8	-23.6	-11.1	13.1E
27	-13.8	-6.2	-7.8	8.6	5.2	-22.3	-21.9	-20.4	-5.7	-8.4	-4.4	-1.4	-8.8	-18.6	-12.9
28	-23.6	3.2	-21.5	4.9	8.2	-9.4	-22.3	-13.4	-10.8	-8.9	-5.8	-4	6.5	-24.5	-19.8
29				9.1				-8.3				-5.2			

March	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	-10.6	-9.2	-28.1	0.5	-13.9	-19	-10.7	-5.2	-22.6	-6.5	-3.3	-12	6.6	-16.8	-9.3
2	-16.4	-6.4	-25	-1.5	-21	-19	-19.6	-1.4	-21.3	-10.3	1.8	-16.9	3.8	-17	-9.8
3	-15.3	-5.9	-22.5	-3.6	-19.6	-3.1	-24.7	-5.5	-15.8	-4.9	-3.8	-10.6	-6.5	-17.2	-6.1
4	-10	-6.1	-19.7	0.1	-17.7	-10.4	-15.9	-0.1	-15.8	-12.3	-8.8	-12.5	-2.7	-13.9	-1.3
5	-17.2	-6.7	-9.8	3.9	-17.9	-14.8	-13.4	-2.1	-15.8	-12.5	-6.9	-13.2	-8.6	-17.6	-2.5
6	-24.5	-16.4	-8.4	3.8	-8.7	-15.6	-14.9	-4.6	-22.1	-6.9	-11.9	-15	-18.7	-13.2	0.1
7	-23.9	-22.2	-11.2	1.9	-8.6	-10.8	-9.6	-5.4	-20.9	-7.7	-17.3	-6.9	-11.7	-20.6	0.2
8	-20.9	-20.3	-11.2	0.7	-3.3	-19.3	-10.9	-8	-20.1	-10.1	-15	-0.8	-12.4	-19.5	3
9	-18.9	-17.8	-11.1	1.8	-0.9	-15.6	-22.7	0.5	-10.7	-5.1	-11	-0.1	-3.3	-9	1.8
10	-8.7	-12.8	-15.6	0.6	-3.8	-2.6	-19.1	4.7	-13.5	4.2	-17.1	-2.6	-8.9	-16	-2.6
11	-6.4	-15.3	-11.2	-0.7	-9.6	-11.1	-10.5	5.1	-3.7	6.1	-17.6	0.4	-1	-16.2	-3.6
12	-8.7	-6.7	-5	4.9	-15.9	-11.3	-11.9	2.5	-11.3	-1.2	-17.1	1.3	-4.1	-11.7	-1.9
13	-13.4	-4.5	-10.8	-3.4	-11.2	-19	-15	4.1	-7.1	-3.1	-24	1.3	0.5	-5.3	-3
14	-18.6	-3.3	-12.2	-11.6	-9.9	-13.2	-13.9	5.6	-7.8	-2.6	-23.8	0.1	1.3	-4.5	-1.5
15	-22.2	-5.9	-10.6	-12.7	-12.7	-2.6	-10.4	4	-10.4	-7.1	-20.6	1	-0.8	-4.9	-1.8
16	-11.2	-5.8	-4.8	-8.9	-9.2	-1.7	-10.3	5.7	-16.5	-13.1	-8.1	4.4	0.5	-5.4	-5.4
17	-13.9	-9.5	3.1	-5.6	2.1	-0.3	-4.5	1.1	-13.3	-11	-7.2	6.9	-3.3	-2.9	-8.3
18	-13.4	-12.2	-4.8	-10.4	-2.6	0.6	-2.6	-5.1	-9.8	-12.2	-0.3	2.7	-9.5	1.7	-9.2
19	-10.3	-7.5	-12.8	-13.1	-0.9	3.5	-2.3	-12	-5.6	-10.1	2.5	1	-6.5	-2.2	-12.2
20	-16.4	-3.6	-16.4	-13.7	1.9	3.7	-3.9	-18.9	-2.4	-8.2	3.1	1.7	-3.1	-3.6	-9.8
21	-20.3	-2	-6.4	-19.6	-2.9	-2.7	-6.5	-15.4	-2.4	-6.6	3.3	-1.6	-0.8	-3.5	-4.7
22	-24.8	-4.7	-11.2	-19.8	-9.3	-3.9	-5.8	-10.8	-0.2	-10.7	1.7	1.2	-7	-4.3	-4.1

Table A-2 Average Temperature (continued)

April	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	-2.5	-16.7	-0.6	-7.3	-1	-12.9	3.7	2.9	-15.8	4.7	5.5	7.7	-5.3	1.7	5
2	-9.7	-12.8	2.8	-12.6	-1.1	-14	3.2	3.1	-16.3	4.8	5.8	4.7	-4.3	5.9	4.3
3	-9.4	-10	5.3	-3.5	-2.6	-11.8	9.6	3.7	-17	5	5.2	0.5	4.7	3.9	3
4	-8.3	-10	5.3	-1.1	2.6	-20	3.8	2.5	-12.8	5.5	7.7	0.2	7.7	3.9	-4
5	-5	-8.4	6.7	3.9	-4.1	-19.3	-0.6	4.8	-12.1	5.9	6.6	0.5	7.4	6	-4.2
6	-4.2	-6.1	11.4	4.3	-9.7	-8.3	-2.8	-0.3	-5.3	6.5	-0.1	-1	6.9	9.9	-1.5
7	3.7	-2	11.1	7.5	2.4	-2.4	4.5	-3.2	-8.5	6	-1.7	-2.8	5.6	4.6	-3.6
8	5.3	-0.3	10.6	11.6	5.7	5.2	6.7	-2.9	-1	-7.8	5.8	8	12.6	4.1	-5
9	2.2	4.4	4.7	6.3	5.4	2.7	4.3	-0.6	-4.2	-11.9	7	5.8	2.6	-1.8	-1.5
10	7.2	4.2	4.5	6.3	2.5	1.5	5.1	-2.7	-1.1	-9.9	6.7	4.7	-7.9	-1.7	6.5
11	7	7.2	13.3	7.6	-0.3	-1.3	7.8	-8.3	-0.1	-7.6	4.8	-1.6	-8.2	-1.9	5.7
12	6.4	7	14.8	7.4	-2.5	-3.8	7.7	-14.7	-1.8	-2	4.6	8.6	-9.5	1.5	3.2
13	3.3	5.3	9.2	12	-7.4	-3.8	10.3	-14.9	4.1	1.9	6	12	-8.3	6.3	2.9
14	5.9	0	5.9	7.5	-5.5	-3	6.2	-6.9	2.6	3.6	10.4	6.5	-3	9.2	9.9
15	7	0.6	5.6	5.7	-4.2	-0.8	12	-0.9	-3.7	0.2	17.1	-2	3.6	7.8	10.7
16	5	2.8	2.3	6.2	3.4	-0.3	11.7	-6.6	-0.5	5.7	15.2	-0.8	5.8	6.8	0.7
17	5.3	3.1	0.9	5.7	3.7	2.4	12.9	-2.5	5.2	9.2	9.1	6	3.9	7	1.5
18	7	5	5.6	4	2.1	2.2	12.8	-0.8	2.9	12	6.4	8.2	2.7	4.7	3.9
19	6.2	6.1	3.9	4	4.7	-2	15	5.7	3.7	7.6	10.4	5.3	1.7	6.1	1.9
20	5.3	4.7	5	3.3	5.3	-0.9	12.2	11.1	4.5	13.8	12.5	2.4	4.4	6.2	0.2
21	6.1	2.3	8.3	3.1	4.5	-2.3	7.9	8.1	9.9	12.6	15.2	-3.7	7.2	9.4	3.1
22	8.6	3.1	6.4	5.8	4.3	0.4	11.2	9.5	7.3	13.1	11.5	-3.7	3.8	3.4	4.5
23	10.3	9.2	7.5	10.1	4.1	3.2	15.1	11.8	5.4	9.8	8	0.2	2.8	5.7	3.6
24	9.2	10	10.3	14.7	6.6	1.4	14.8	6.4	4.1	5.4	4.3	1.7	3.4	6.5	3.7
25	13.1	9.7	8.6	16.5	7.9	4.1	16.4	7	4	2.5	3.2	4.7	5.4	7.1	4.3
26	5.9	14.5	8.9	13.8	15.1	5.3	17.8	5.6	7.5	-1.1	2.7	7	10.5	9	7.8
27	4.5	6.7	10	6.5	12.1	1.3	19.8	5.3	10.1	2.5	4.1	6.5	9.5	13.3	13.5
28	8.9	2.5	11.4	12.5	12.5	3.7	20.4	7.4	12.6	1.4	3.3	6	3.7	11.9	14.8
29	2.8	4.5	9.5	9.4	9.8	3.5	20	8.2	8.6	6.1	3.3	5.3	-1.3	12	12.6
30	-1.1	4.2	8.6	2.6	8.9	2.6	12	8.9	8.4	3.3	5.8	5.9	-1.3	15.5	8.2
April	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	1.7	3.3	7.6	4.8	6.2	-1.3	1.6	-15.1	-4.1	3.8	2	3.6	1.7	-15.2	-8.9
2	1.7	7.4	4.5	10	7.2	3.1	-10.8	-9.5	-2.4	4	5.1	0.3	0.4	-12.9	-7
3	-4	1.3	4	7.7	5.5	-3.8	-18.4	-4.8	-2.4	4.3	5.2	1.2	1.1	-9.7	-6.5
4	-3.7	-1.2	6.4	4.5	3.5	-6.8	-12.3	-1.7	-8.2	4	0.4	0.7	1.4	-11	-6.9
5	-0.7	1.9	5.7	1.5	0.1	-6.6	-5.3	7.4	-13.2	2.9	-3	-9.5	2.9	-11.3	-5.5
6	2.4	3.5	4.9	-0.7	-2.2	-2.8	-3	9.1	-17	4.9	1.2	-6.6	1.1	-5.2	-1.1
7	-3.5	-1	4.2	-3.4	-2.7	0.6	-6.5	3.8	-15.5	7	4.2	-6.7	1	-7	1.4
8	-2.9	-6.2	5.9	-8.3	-1.6	1.7	-3.3	4.2	-8.4	10.4	4.8	-7.3	3.6	-10.8	7
9	-2.8	-8.5	4.6	-12.6	0.6	2.2	1.8	1.4	-7.7	6.8	-0.8	-5.1	3.4	-8.4	6.7
10	1.3	-5.2	4	-15.7	1.9	7.9	8	-1.1	-2.6	4.4	0.4	-6.2	0.5	1	4.1
11	6.4	0.6	5.1	-13.7	3.4	11.1	5.3	-3.8	0.6	2.5	3	-4.7	-1	3.7	3.5
12	6.2	-1.9	8.7	-2.6	4.1	7.7	2.5	0.8	1	0.4	9.3	-6.7	1.2	4.7	9.1
13	3.1	-1.1	10.4	6.5	4	4.3	2.8	1.1	-1	0.6	5.7	-12.4	3.6	2.8	1.4
14	3.9	0.1	8.5	7.4	6.1	2.3	1.8	1.6	-3.8	1.7	3.1	-11.2	1.1	0.8	1.3
15	-4.5	-2.9	1.8	9.1	7.8	5.1	1.6	3.3	5.1	4.5	1.6	-6.9	-1.9	-2.8	4.8
16	-11.1	0.7	1.4	11.9	7	9.1	1.4	6.4	10.5	6	1.5	2.2	0.8	-6.2	4.8
17	-4.2	7.7	5.5	7.3		9.8	4.8	3.1	8.1	4.7	6.3	0.7	5.8	-1.2	6.8
18	-0.6	9.9	7.9	-3.3	1.6	2.7	6.2	-0.2	5.6	5.1	5.5	4.6	5.8	-3	6.7
19	3	7.6	12.1	-2.2	4.2	4.1	4.7	5.5	4.4	9.7	9.9	7.3	0.9	2	7.4
20	7	12	9.3	5.8		8.4	7.5	4.3	5.6	7.4	6	7.1	-4.7	6.9	9.1
21	3.6	11.3	5.7	10		10.2	7	-0.2	9.2	8.1	6.4	9.5	-0.9	7	14.5
22	1.9	12.1	8.5	6.7	9.1	12.8	6.1	2.3	6.1	9.6	7.1	16.2	3.3	1.6	13.8
23	0.6	7.3	7.4	5.4	2	2.1	3.9	4.8	4.9	8.9	14.6	9.4	4	-7.7	9.5
24	2.1	3.9	6	6.3	-0.8	-2.7	8.8	3	6.5	11.1	11.5	7.4	8.3	-6.3	9.8
25	1.7	0.2	4.7	7.6		1.3	5.5	1.4	6.4	5	17	6.5	7.8	-4.7	5.6
26	4.4	-4.4	5.4	14.9		1.2	5	3.3	8.3	11.7	6.7	4.9	7.5	-1.4	3.9
27	7.7	-3.8	4.7	15	7.2	1.5	3	6.8	9.5	11.2	2.7	6.8	15	0.9	5.9
28	10.9	-0.5	5.7	9.1	9	2.2	3.8	7.8	2	8.9	2.4	13.2	14.4	5.1	2.2
29	11.9	1.6	4.7	6.5	7.9	7.3	6.1	8.1	2.7	12.7	4.6	13.1	11.9	2.8	5.6
30	13.6	1.9	2.3	4.9	11.3	11.1	5.9	7.4	2.3	8.9	0.8	8.9	8.5	-1.9	7.8

Table A-2 Average Temperature (continued)

May	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	0.8	3.7	5	7.8	7	0.4	15.4	11.5	10	0.8	7.7	7.9	1.4	15.5	6
2	-2.8	3.6	7.5	14.8	10.4	-0.2	21.3	5.8	12	-1	9.5	13.2	6.1	15.2	-0.4
3	-1.7	5.6	12.3	15.7	9.3	-0.6	11.3	6.8	11	-1.9	11.1	14.6	4.8	13.6	-0.1
4	2	6.2	6.7	14	8.4	-0.3	9.2	7.9	3.5	4.2	7.9	9.4	7.7	14.2	2.6
5	11.1	9.8	4.5	12.1	7.8	2	6.6	9.9	-2.9	2.3	3.7	4.2	5.4	11.1	8
6	12.2	12.2	9.2	9.5	8.3	2.5	5.2	10.5	-4.2	5.2	1.7	8.1	6.2	12.8	12.6
7	11.4	11.7	12.8	14.7	7.4	2.9	9.5	9.4	-2	11.5	3.5	12.6	11	18.3	11.3
8	7.5	14.2	10	18.1	9.9	6.1	13.7	3.2	2.7	7.6	4.6	10.4	12.3	13	13.8
9	7.2	14.5	9.5	14.3	7.1	7.3	11.4	5.3	6.3	5.3	3.4	10.2	9.6	5.4	8
10	7.8	15.6	15.6	18.5	2.4	8.5	10	9.7	-0.4	4.5	4.3	10.8	3.1	5.4	3.9
11	7.3	14.8	13.9	20	1.9	9.7	10	12.9	10.2	8.7	2.7	11	8.6	8.5	7.6
12	7.8	15.6	11.1	14.2	4.4	8.3	9.8	16.2	11	8.4	5.3	11.4	7.9	13.1	8.3
13	8.1	10.3	11.4	11.5	10.9	9.5	12.1	13.4	9	3.2	9.8	11.5	10.3	6	14.8
14	8.4	9.2	10	10.4	14.5	9.1	12.5	6.8	11.1	1.7	15.2	14.8	6.6	9.4	13.8
15	8.1	4.8	8.6	7.7	12.2	8.4	13	5.1	15.2	6.5	11.7	12.3	4.4	8.6	8.5
16	5	6.7	13.6	4.2	10.6	10.4	16.1	9.9	14.3	8.3	9.1	15.1	6.7	7	11.5
17	4.5	8.4	12.8	3.3	11.4	8.8	16.5	14.9	14.3	7.1	6.8	18	9.2	11.6	14.5
18	6.1	7.8	7.8	5.6	13	6.9	17.4	17.6	11.4	6.1	8.6	11.7	13.6	6.8	11.3
19	9.2	6.9	7.8	9.7	14.7	9.2	14.7	16.8	10.3	9.4	10.9	13.4	17.4	1.1	10
20	11.1	7.8	12.5	11.9	17.6	10.1	14	18.7	11.9	6.4	6.7	16.5	20.3	3.2	11.2
21	11.7	11.2	10.3	13.5	18.4	10.7	14.4	14.9	15.9	9.6	8.2	18.6	13.9	8.7	12
22	12	13.4	14.5	13.7	12	11.7	12.6	15.2	17	0.1	4.9	17.5	12	8.8	13.7
23	11.7	11.1	18.1	13.9	7.2	17.5	12.6	16.3	14.7	2	5.5	10	12.5	10.5	15.2
24	11.4	7.8	18.4	16.1	8.4	18.7	8.6	19.2	14.5	8.5	7.4	11.4	14.4	11.2	13.3
25	14.5	3.9	14.2	15.8	5.7	15.7	7.8	19.3	14.7	15.8	8.8	6.7	19.7	13.8	13.4
26	15.9	7	13.9	11.7	3.7	17.5	7.5	19.7	10.7	13.2	8.4	8.3	24.2	14.8	14.8
27	8.9	5.6	15.6	12.4	10.4	13.9	5.9	18.6	7.7	11.6	9.7	11.8	21.7	17.1	13.4
28	3.1	8.6	14.2	11.8	15.9	6.4	8.1	15.4	9.3	13.6	13.6	7.4	19.4	15	18.2
29	3.4	12.8	10.3	13.9	11.5	3.6	7.6	13.5	11.3	15.9	17.8	5.8	20.5	14.6	16.1
30	7.2	15.3	12	14.2	13.8	9.1	4.7	11.6	15.3	16.5	12.8	8.3	15.3	15.5	13.3
31	9.5	11.7	17	13.1	11.2	11.3	7.4	14.4	14	13.1	10.1	7.8	13.2	13.9	9.6
May	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
1	9.5	2.3	2.7	6.2	10.4	11.8	6.9	7	4.3	12.1	7.7	10.5	7.1E	0.5	10.3
2	7	5.2	5.5	8	11	9.7	3.5	5	6	15.6	4.9	10.4	8.3E	0.6	-0.1
3	8.5	8.9	7.4	9.5	6.5	5.3	3	3.8	7.9	13.5	8.4	10.4	13.1	-7	-2.6
4	3	12.4	8.3	17.2	9	6.6	4.1	4.5	9.6	10.1	5.3	9.1	14.3	-6.9	-0.4
5	10.3	14.1	8	16.8	15.5	9.4	8.2	1.3	7.8	5.3	5.8	3.8	13.2	-0.9	1.7
6	14.9	8.8	9.8	12.8		16	11.9	-1.4	11.1	7.5	6.4	4.1	3.5	-2	1.4
7	15.9	4.9	11.1	7.3		12.8	10.1	-4.1	8.1	14.3	7.7	5.3	5.2	-0.9	6
8	16.4	4.1	12.2	9.3	9.6	8.8	11.9	-4.6	10.1	12.8	4.8	4.9	9.5	2.2	3.3
9	19.3	9.6	9.9	8.2	11.1	11.2	15.9	-1.2	13.6	12.7	7.4	7.9	7.1	3.5	4.7
10	20.1	3.7	14.9	7.3	11.4	12.2	12.3	1.6	9.4	9.3	5.6	6.4	6.6E	7.3	6.9
11	13.5	4.5	18.7	4.1		11.7	9.8	4.6	8.6	7.6	7.7	5.3	8.2	5.8	11.3
12	8.9	4.8	17.9	5.1	18.3	11.9	8.7	6.8	12.2	7.5	6.7	5.7	10.9	10.9	16.5
13	11.2	7.1	15.1	8.2		11.4	9.1	5	6.3	8	8	4.8	13.8	14.7	15.1
14	12.5	8.1	8.7	6.9	7.1	8.9	10.1	2.1	7.3	10.4	6.3	1.1	10.6	9.9	16.4
15	15.8	7.4	7.9	4.8	6.8	11.3	11.3	4.9	13.6	12	6.5	5.6	8.5	5.2	10.8
16	14.4	8	13.2	9.3	7.2	8	14	9.3	10.3	10.1	3.4	3.9	9.1	10.9	6.8
17	12.8	7	17.2	9.7	9.4	8.5	14.6	12.3	7.2	10.8	4.3	5.9	9.3	12.8	0.2
18	9.5	6.5	19.6	11.6	11	8.1	5.5	12.6	5.1	12.6	6.4	9.7	7.1	14	0.8
19	4.7	3.4	19.9	3.2		7.7	7	13	6.7	15.2	6.9	11.7	7.2	11.7	5.9
20	3.2	9	20.8	3		10.3	4.6	9	6.5	14.9	7.5	10.6	4.6	10.9	9.2
21	2.5	11.2	11.8	4.2	9.9	6.3	6.5	8.7	4.7	17	11.9	9.6	5.2	6.9	10.3
22	2.4	15.7	7.9	5.8	7.2	7.1	8	9.2	5.2	18.5	13.9	11.9	8.9	2.8	11.9
23	5.1	18.1	5.4	7.6	8.9	13.6	10.3	9.3	7.8	19.9	12.9	9.3	16.6	1.7	14.1
24	7.2	18.2	6.6	11.3	4.7	15	5.9	10	11.7	18.9	18.6	10	16.7	8.4	19.5
25	6.9	20.6	10.2	13.6	3.9	17.9	6.1	15	11.5	20.6	19.5	8.7	16.5	7.4	22.9
26	7.4	19.3	10.3	15.4	8	19.7	10.1	12.8	9.6	16.4	12.4	9	14.9	11.1	15.8
27	4.3	19.8	11.3	16.5		15.1	16.9	12.2	9.5	14.5	11.6	9.1	14.5	12.2	14.7
28	7.2	19.6	12.5	13.1		12.1	23.1	15.2	14.7	7.2	11.5	11	18.8	13	14.3
29	10.8	20.7	16.5	10.1		12.5	21.1	13.7	14.2	9.7	8.6	7.9	17.5	16.6	12
30	9.4	23.7	16.2	13		13.7	19	16.4	13.8	8.2	9.1	8.2	8.3	13.5	13.6
31	14.3	19.7	14.1	17.2		13.1	15.9	14.7	16.1	4.9	13.8	8.8	6.9	9.6	15

Table A-2 Average Temperature (continued)

October	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	0.6	12.5	7.5	9	7.2	9	7.7	9.7	12.9	7.6	9.5	10.8	-0.3	6.3	6.4
2	8.6	11.1	4.5	6	5.8	8.3	9	7.8	7	5.1	9.6	6.7	-2.1	16.8	2.9
3	2.2	13.4	-1.4	1.1	8.5	7.3	13.4	5.1	4.2	8.6	4	4.8	2.9	16.4	3.7
4	-6.4	10.9	-3.3	1.6	2.9	11.5	13.2	2.9	4	5.6	6.8	2.5	-0.4	10.1	10.9
5	-4.5	7	-4.2	0.6	0.7	2.7	11.2	4.5	7	-0.3	8.8	0.6	6.4	6.7	12.2
6	4.8	3.1	0.6	3.7	8.1	9.4	17.9	7.3	7.8	0.4	6.5	-1.9	5.7	4.1	13.5
7	5.8	0	8.1	4	11.3	2.5	13.8	6.9	7.2	3.3	11.5	-1	-1.9	2	13.5
8	6.7	0	9.7	1.7	11.9	6.9	12.1	7	5.6	4.1	16.3	-0.6	-0.1	-2.5	12.2
9	15	0.6	8.6	-1.3	11.5	5.6	10	5.4	5.3	5.4	13.2	-1.8	7.3	0.6	11.2
10	2.8	1.7	9.5	-1.3	7.2	12.9	7	2.7	9.8	-3.6	12.3	6.5	-0.2	2.9	10.9
11	1.1	3.9	6.9	0.3	3.5	5.6	4.2	2.9	11.9	-1	14.9	6.2	5	8	11.6
12	7.3	3.1	6.1	8.9	6	7.8	4.7	1.7	8.6	5.5	7.4	4	11.6	9.1	12.1
13	2.3	7	4.7	6.6	5.1	13.3	4.2	0.9	14.2	4.7	4.4	0	7	2.6	12.1
14	-2	7.3	-0.6	4.8	6.1	6.6	2.8	3.6	10.3	4.3	4.4	-0.7	7.9	-1.4	10.7
15	5.6	4.2	1.4	10.2	5.6	5.5	4.3	7.8	2.7	0.9	1.4	-1.2	14	0.5	4.5
16	10	7	-0.3	10.3	6.9	3.8	3.4	7.2	2.9	-4.2	-1.6	0.5	13	6.6	3.7
17	7.2	8.1	0.9	7.8	1.1	3.6	6.1	1.6	-2	-2.2	1.4	1.9	6.1	2.6	4.5
18	7.3	4.7	1.9	9.3	14.7	3.4	9.2	2.2	-4.8	4.6	3	4	4.3	-1.2	3.3
19	8.1	3.9	3.6	6.6	15.5	0.7	8.6	-0.3	-3.2	5	2.2	6.3	6.4	-2.2	1
20	6.1	5.3	-3.9	1.3	3.7	M	5.2	-7	1.5	8.1	1.6	3.6	8.8	-1.1	-0.5
21	2	4.7	-5.9	0.6	0.6	1.6	3.5	-5.9	0.1	6.9	2.4	4.8	10.8	1.5	-0.8
22	5	3.6	-7.5	7.3	2.4	-0.9	1.4	-7.3	4	7.1	-1	1.6	10.2	-1.4	-6.5
23	10.3	-1.7	-7.8	7.9	2.2	0.8	1.9	-1.2	7.2	4.6	-3.9	0.2	9.8	-0.8	-6.9
24	5.3	-2.8	-3.4	6.9	1.5	4.5	-0.1	-8.9	5.6	3.3	-8.6	-0.2	7.1	4.1	-3.3
25	6.7	-4.8	-4.5	2.6	3.3	1.3	1.8	-12.7	6.2	5.8	-1	-1.8	5.3	7.5	-3.1
26	4.5	-4.2	5.3	4.6	2.4	4	-2.9	-10.7	4.1	6.5	-8.6	-2	2.4	3	-7.3
27	7	-6.7	14.4	5.3	1.6	5.9	-2.2	-6.6	3.3	1.1	-15	-1	-0.3	3.4	-13.3
28	2	-6.4	7	4.9	1.3	3.7	3.9	-2.3	1.9	2	-16.6	-3.6	-6.8	4.4	-9.5
29	-0.6	-1.4	0.8	4.7	-1.6	2.3	8.6	2.1	-3.2	5.4	-15.2	-0.8	-9.2	2.7	-8.1
30	-0.3	-0.9	-0.9	3.3	-1.8	-1.1	1	-1.2	1.9	5.4	-19.6	-3.9	-7	1.4	-1.2
31	2.5	1.7	0.6	-0.5	9.3	-1	-5.4	4.4	1	2.1	-19.8	-2.6	-6.8	1.7	0.4

October	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	-0.9	5.2	5.7	15	-3.2	3	5.9	-2.5	10.2	12.4	-3.9	3.1	7	3.5	9.4
2	1.5	3.9	3.4	13	8.6	2.7	9.2	5.5	8	11.8	-1.3	-0.9	6.3	6.8	10
3	9.3	0.4	1.1	18.3	6.2	3.2	8.2	6.7	5.8	9.7	0.1	-1	6	4.4	11.9
4	9.3	2.4	2.2	8.3	4.3	11.7	6.2	10	3.3	9.9	-0.2	-2.7	1.7E	0.7	13.6
5	3	-0.1	5.6	5.4	0	13.5	5.4	2.4	1.3	5.7	2.4	-4.1	1.4	-0.3	13.2
6	3.4	0.1	7.8	1.6	-4.1	8.4	5.8	4.1	4.7	6.3	3.4	-0.3	7.4	1.8	13.4
7	6.8	3.2	8.7	5.7	-1.7	8.7	6.5	8.1	-0.7	11.5	6.9	6.9	7.7	3.3	15.2
8	7.4	2.8	6.4	6	2.5	6.2	9.9	9.9	-1.9	3.5	6.5	8.4	7.9	6.4	12.4
9	6.1	9.5	7.9	7	7	7.5	8.1	8.3	-3.7	3.4	5.4	7.1	4.3E	4.4	11
10	6.4	2.8	14.9	9.3	4.5	5.4	7.7	10.2	-0.3	0.4	4	8.1	7.0E	-0.3	8.5
11	3.7	-2	14.9	1.6	2.5	3.9	5.2	9.5	1.6	-1.9	3.1	7.7	6.7E	-2.6	5.8
12	0.8	-1.6	8.3	-1.3	1	3	3.6	2.1	-1.7	-2.3	1.7	5.1E	4	-4.3	1.6
13	2.6	-0.1	1.8	-1.9	2.6	5.4	6	2.3	-2	0.8	6.3	4	4	2.3	3
14	1.6	-2.1	-0.5	-5.6	1.9	5	8.5	6.8	-1.9	0.9	3.7	7.6	2.4	-4.5	-0.5
15	1.1	-4.5	3.6	-7.4		3.9	5.5	3.1	-0.7	1.9	0.6	4.7	1.8	-4	-0.1
16	1.2	-6.5	-2.7	-8.1	1.1	3.1	1.4	1.6	7.3	4	0.5	6.7	2.7	-1.9	-0.9
17	2.9	-1	-7.8	-9.5	1.2	9.8	-1.6	-1.2	1.8	4.6	2.4	5	1.8	-2.5	2.5
18	8.8	1.1	-7.3	-9.6	5.9	5.3	2.1	-1.6	-0.4	4.2	0.8	7.9E	-0.1	-4.3	-0.2
19	7.2	0.7	-5.6	-4.1	5.6	2.4	5	-1.8	-2.8	6	8.1	4.4	-2.7	-5.1	4.4
20	5	-1.8	0.1	-1.9	0.5	3.7	4.9	0.4	-5.5	7.5	10.3	0.5	-5.8	-6.7	4.2
21	4.5	-4.1	-3.5	3.2	4.4	0.9	5.2	1.2	3.4	9.5	3.8	2.6	-8.4	-7.4	9.5
22	1.7	-1.1	-6.7	4.6	7.4	1.7	-1.1	4.4	0.7	8.5	9	5.9	-5.7	-3.9	4.7
23	2.1	-1.7	-6.7	8.2	6.5	2.4	2	-0.9	0.1	4.7	7.3	12.6	-7.6	-3.4	2.8
24	-1.3	1.3	-5.7	8.2	0.2	2.3	-0.6	0.3	-0.7	0.6	7.3	5.6	-8.7	-0.1	-0.3
25	1.6	3.2	-7.5	3.6	-0.8	5.7	0.3	-1.4	-0.9	5	5.2	3	-1.2	-2.8	-0.4
26	1.8	-1.7	-12.3	1	-1.9	7.5	2.2	-5.5	6.7	9	5.6	-4.9	-0.5	-6.3	3.5
27	3.2	-4.9	-16.9	1.7	3.2	5.9	-0.6	-0.1	1.6	3	1.6	4.3	0.8	-8.1	4
28	-2.5	0.5	-13.1	1	-8.2	2.7	-4.2	-5.9	-4.3	6.2	-0.3	2.9	-5	-9.5	-1.3
29	-6	-1.4	-13.3	1.1	-7.5	-2.2	-4.3	-15.8	-5.9	2.5	1	3.4	-2.6	-11.8	-4
30	-4.3	-3.4	-14.6	2	2.4	-5.7	-4.4	-15.9	-2.5	-5.1	5.2	-2	-0.1	-10.6	-9.7
31	-9.2	-3.8	-14.9	1.8	1.4	-7.1	-8.3	-11.2	-0.8	-4.3	-1.3	0.3	-0.5	-6.9	-9.8

Table A-2 Average Temperature (continued)

November	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	2.5	-4.5	2	0.6	8.2	-2.9	0.5	4.1	-4.7	-1.7	-20.4	-3.1	-11.6	1.8	-3.6
2	2.3	-4.2	0.3	-0.6	9.8	-0.9	2.9	2.9	-11.1	0.3	-16.1	-3.8	-9.1	1	-2.2
3	5	-0.6	4.2	-3.8	3.3	-3	2.5	1.4	-9.6	2.3	-13.3	-2.9	-3.5	1.1	-6.6
4	7.2	2.8	7.2	-4.7	0.2	-3.4	2.8	2	-3.2	0.3	-15.3	-4.7	3.1	-6	-2.6
5	3.4	-0.3	-0.6	-3.9	-1.9	-7	4	5.9	-0.6	2.6	-10.4	-7.1	-1.6	-5.5	-3.7
6	3.1	-0.9	-6.7	0.5	1.6	-7.4	0.8	5.9	-7.3	-1.5	-10.1	-11.8	-9.4	-0.9	0.7
7	-1.7	-2.3	2	-1	3.4	-7.8	-3.1	-2.6	-8.2	-2.3	-7.2	-13.5	-15.5	-4.2	-3.6
8	1.7	-1.2	2.5	-6.5	-6.4	-11.3	-5.2	-4.1	-9.9	-5.4	-12	-17.8	-19.5	-3.5	-6.2
9	-1.2	-5.3	-3.4	-8.3	-11.2	-8.9	-2.3	5	-2.9	-6.6	-13.8	-18.7	-20.9	2	-8.1
10	-2.3	-7.3	-5	-9.2	-9.9	-5.9	-1.3	1.6	-5.3	-5.3	-7.6	-17.6	-19.2	3.7	-8.7
11	-7	-5.3	-4.5	-2.9	-6.7	-3.7	-1.4	1.3	-17.7	-3.3	-13.1	-18.3	-19.5	5.7	-7.2
12	-7.3	-4.5	-5	1.6	-6.8	-4.9	-4.1	3.5	-18.7	-0.4	-15.4	-9.8	-20.6	-0.6	-6.5
13	-4.2	1.1	-3.9	3.1	-7.9	-2	-5.3	1.7	-13.7	-2	-18.5	-5.8	-15.1	-2.5	-10.6
14	-3.9	2	-5.3	-1	-7.9	2.3	-2.9	-4	-5.5	-3.6	-19	0.5	-20.9	-0.9	-13.6
15	-1.1	0.8	-3.4	-1.4	-8.7	6.1	-2.6	-6.7	-7	-2.5	-20.1	-0.8	-20.1	-6.5	-8.2
16	3.9	-0.3	2.2	-7.2	-15.2	5.4	-5.2	-5	-16.8	-1.6	-24.4	-12.3	-19.8	-12.2	-12.4
17	-6.7	-5	0.6	-9.3	-23.6	-1.5	-0.1	-4.1	-12.4	-1.6	-15.5	-22.2	-20.8	-14.6	-12.8
18	-10.6	-10	-0.9	-15.5	-27.7	-0.8	-1.8	-3.1	-15.6	-2.3	-13.8	-23.9	-21.5	-9.6	-17
19	-11.7	-12	0	-20.9	-24.7	-4.3	-0.4	-2.8	-21.1	-2.7	-8.8	-21.7	-22	-15.9	-11.8
20	-7.8	-12.5	-6.1	-20.6	-16.1	-1.1	-1.4	-2.6	-22.7	-4	-5.6	-21.2	-17	-6.3	-12.9
21	-8.7	-18.4	-12.2	-21.8	-17.3	0.1	-1.2	-4	-21.4	-5.9	-2	-24	-14	-1.9	-6.2
22	-11.1	-22	-10	-24.1	-10.8	0.4	-10.9	-3.2	-23.4	-6.5	-3	-26.2	-18.6	-11.1	-4.6
23	-16.4	-23.4	-3.9	-25.1	-8	-3.4	-10.6	-6	-26.1	-7.6	2.6	-27.1	-7.5	-10.1	-5.5
24	-10.3	-13.1	-4.8	-20.8	-8.8	-6.8	-9.6	-8.4	-24	-11.9	-3.6	-30.3	-7.1	-5.4	-7.8
25	-3.9	-11.4	-15.3	-16.8	-10.2	-9.2	-4.2	-7.5	-29.5	-13.9	-12.9	-35.1	-14	-5.2	-14.3
26	-10	-14.5	-19.7	-12.9	-16.7	-11.4	-1.3	-9.8	-22.5	-10.4	-16.2	-30.7	-4.8	-5.3	-20.5
27	-13.3	-16.4	-20.9	-15.5	-17.5	-15	-0.7	-9.8	-13.3	-10.9	-17.3	-22.3	-12.5	2.5	-19.2
28	-11.4	-19.2	-18.3	-15	-20.3	-9.5	1	-4.7	-10.3	-10	-9.7	-17.7	-15	1.1	-14.2
29	-7.5	-23.4	-13.9	-9.4	-23.7	-8.6	-11.2	-0.9	-4.4	-10.1	-11.1	-19.7	-7.6	-0.4	-14
30	-7.8	-20.8	-5.6	-12.8	-23.9	-6.5	-23.5	-6.6	-4.9	-12.6	-13.3	-20	-1.7	-1.6	-1.9
November	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
1	-9.7	-4.1	-15.9	1.4	0.2	-3.3	-12.7	-3.5	0.5	-1	0.8	1.5	-1	-7	-14.2
2	-5.9	-5	-14.9	-0.3	-2.9	-5.7	-9.8	0.2	-2.2	0.3	3.8	-2.2	3.1	-6.9	-16.6
3	-4.2	-5.3	-10.6	-1.3	-4.1	-3.6	-5.3	-8.4	1.2	1.3	1.7	-3.1	2.5	-2	-15.6
4	-4.5	-7.4	-12.1	-3	-7.6	1.3	-4.6	-6.3	-0.1	1	-2.7	-2.1	4.9	-0.7	-12.2
5	0.2	-13.3	-15.6	-0.6	-7.2	1	-5.6	-2.2	5.3	0.8	-6.5	-8	-2.1	-7.7	-9.7
6	-2.3	-10.6	-15.9	-0.4	-8.6	-5.9	-10.7	-3.3	1.9	-1.7	-4.6	-9.3	-4.3	-9.5	-13
7	-8.3	0.8	-9.6	-0.7		-4.5	-11.4	-4.5	-2.4	-4.3	-2.6	-7.8	-6.8	-9.6	-7.9
8	-8.9	-3.6	-16.8	-0.7	-10.5	-2.9	-12	-13.8	-6.3	-4.2	-3.5	-8.1	-2	-12.7	-6.9
9	-11.3	-15.6	-16.7	-2.9	-4.8	-4.2	-13.6	-13.9	-7	-3.3	-0.5	-11.5	0.6	-12.8	-3.5
10	-10.4	-18.1	-6.1	-3.5	-3.7	-7	-14.3	-13.6	-5.5	-7.5	1.5	-16.2	-4.9	-15.1	0.3
11	-18	-21.8	-2.2	-1.6	-0.3	-0.8	-15.2	-17.3	-4.1	-14	-3.2	-12.6	-1.6	-14.7	-6
12	-24.4	-12.2	1.9	-7.2	-3.5	0.1	-12	-16.5	-3.4	-10.7	1.3	-5.3	-0.9	-15.7	-7.8
13	-27.2	-6.3	-4.9	-8.5	-6.1	-2.8	-13.9	-12.9	-4.5	-10.5	-2.4	-6.8	0.3	-21.2	3.7
14	-22.8	-4.9	-9.1	-6.5	-4.2	-5.2	-5.9	-9.3	-8.2	-14.9	-0.9	-7.8	-0.2	-20.7	3
15	-23.6	-6.2	-4.7	-5.5	-2	-6.2	-9	-12.8	-9.1	-22	-2.3	-12.6	0.1	-10.3	-3.4
16	-16.6	-1.5	2.5	-2.2	-9.6	-7.4	-4	-15.4	-7.5	-18.5	-2.6	-11.3	3.8	-7.1	-3.1
17	-17.5	0.3	-6.7	-5.4	-8.5	-8	-0.9	-15.5	-10.6	-11.9	-6.5	-2.4	1.7	-2.3	-6.4
18	-6.2	-4.6	-14.4	-5.7	-11.9	-7.7	0.1	-14.9	-8.8	-9.7	-6.7	-4	-3.1	-3.3	-3.5
19	-5.8	-12.6	-13.6	-2.8	-7.4	-4.1	-5.1	-19.2	-9.9	-12.3	-11.3	-9.8	-4	-5.4	-9.2
20	-14.8	-17.9	-10.5	-1.6	-6.8	-12.9	-10.4	-20.9	-16.4	-9.3	-5	-10.4	-8.2	-0.2	-15.4
21	-12.2	-17	-9.2	-3.8		-17.9	-9.2	-18.4	-17.4	-6.2	-3.1	-11.6	-3.9	1	-17.6
22	-18.4	-18.7	-8.9	-8.5	-26.5	-10	-13.7	-17.7	-13.5	-8.8	-7.5	-2.6	-0.9	-0.4	-18.7
23	-15.5	-24.3	-10.4	-13	-19.7	-5.8	-15.8	-16.2	-6.6	-6.3	-10.2	-1.4	-5.5	-12.3	-14.9
24	-13.1	-24.2	-7.3	-9.7	-11.4	-18.8	-21.9	-21.8	0.2	-5.5	-9.2	2.2	-14.1	-11.1	-9.4
25	-18.4	-29.2	-9.6	-6.6	-9.1	-24.9	-22.7	-21.1	0.1	-4	-3	-0.1	-15.6	-11	-13.3
26	-24.5	-27.4	-11	-3.2	-2.8	-18.3	-18.6	-16.7	-5.5	-8.5	-6.8	-1.4	-11.9	-7.9	-12.9
27	-23.6	-22.4	-7.3	-2.1		-16.2	-17.4	-13.9	-8	-7.8	-13	-6.7	-11.3	-1.8	-12
28	-3.7	-12.7	-11.5	-2.8	-10.7	-14.2	-21.3	-10.5	-7.3	-6.4	-9.9	-6.7	12.9E	8	-9
29	-6.2	-13.4	-21.2	-1.3	-3.1	-12.2	-23.8	-15.5	-4.8	-13.3	-8.8	-7.3	-13.3	1.2	-13.1
30	-5.7	-24.7	-23.8	-2	-4.3	-14.3	-20.4	-12.3	0.2	-14.8	-3.8	-7.8	-13.6	-0.8	-14.2

Table A-2 Average Temperature

December	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
1	-5.6	-27.2	-7.5	-17.5	-16.4	-1.3	-26.3	-7.9	-9.6	-15	-12.9	-18.5	-3.9	-6.2	3.5
2	-5.3	-28.9	-2.8	-19.9	-16.7	-2.1	-27.4	-7.2	-10.8	-13.6	-13.1	-21.7	-10.5	-4.1	-3.1
3	-6.1	-24.5	-7.8	-25.1	-6	-4.5	-25.9	-6.3	-8.1	-16.1	-12.4	-23.3	-14.6	-3.4	-7.9
4	-8.9	-25	-18.1	-27.3	-8.1	-7.7	-27.5	-12.4	-10.2	-21.1	-18.2	-18.9	-11	-6.9	1
5	-8.9	-24.2	-24.8	-33.1	-20.4	-1.1	-25.9	-10.2	-16.7	-17.3	-19.8	-9.2	-8.7	-6.8	0.1
6	-19.5	-18.1	-28.1	-39	-22.6	-9.2	-29.2	-6.6	-19.4	-13.7	-3.7	-3.5	-10.8	-7	-8.3
7	-16.4	-20.3	-29.2	-39.9	-23.4	-19.6	-27.5	-12.9	-28.5	-24.9	2.9	-3.4	-6.4	-2.3	-16.1
8	-0.6	-14.2	-25.6	-36.9	-21.5	-17.2	-25.6	-17.2	-18.2	-27.6	-2.5	-8.7	-20.5	-6.7	-21.6
9	-1.1	-22.5	-24.2	-36.5	-11.5	-16.2	-30.8	-14.7	-15.6	-30.6	-1.3	-11.2	-19.7	-11.9	-18
10	-10.6	-31.1	-23.4	-33.9	-4.8	-23.2	-29.3	-10.2	-30.1	-22.2	-17	-11.1	-10.6	-10.5	-12.1
11	-10.3	-33.4	-28.1	-22.4	-12.4	-16.7	-21	-12.4	-19.6	-17.3	-28.2	-15.2	-16.8	-12.3	-2.7
12	-12.8	-28.6	-24.2	-17.3	-11.6	-17.5	-22.8	-13.4	-16	-17.9	-24	-24.9	-14	-11.1	-0.6
13	-11.1	-31.7	-7.3	-18.5	-10.5	-27.2	-20.3	-17.1	-13.7	-23	-23	-24.5	-6.7	-13.6	-9.8
14	-8.1	-27.2	-8.1	-14.1	-0.9	-27.9	-12.7	-23	-12.6	-31.7	-16.5	-16.7	-12.2	-15	-20.2
15	-8.6	-26.7	-2	-12.6	-8.2	-27.6	-5.5	-23.9	-11.9	-30	-27.3	-21.7	-7.5	-16.3	-9.9
16	-7	-32.5	-4.2	-9.6	-14.5	-23.4	-4.8	-17.5	-11.8	-30.1	-31	-20.8	-2.8	-17.1	-7.6
17	-4.5	-20	-8.1	-12.3	-21.7	-18	-19.9	-18.2	-13	-26.9	-28.2	-16.6	-0.9	-16.9	-3.4
18	-13.6	-2.8	-13.9	-18.8	-21	-9.6	-27.1	-11.7	-14.7	-30.4	-14.9	-12	-5	-10.6	-1.8
19	-12.3	-0.6	-16.4	-19.8	-21.1	-2.7	-32.4	-13.2	-13.7	-28.8	-11.5	-10.2	-14.9	-11.7	-7.2
20	-15.9	0.9	-12.2	-13.5	-12	-0.4	-35.2	-10.5	-16	-28.7	-18.2	-2.9	-8.5	-22.7	-13.4
21	-13.7	-9.7	-11.4	-16	-14	-2	-34.1	-11.3	-20.7	-28.7	-28.3	1.5	-0.4	-10.7	-13.9
22	-13.7	-14.8	-15	-17.7	-28	-6.7	-29.4	-10.5	-20.8	-29.9	-30.5	-1.1	-7	-10	-20.2
23	-18.1	-11.7	-8.3	-23.2	-27.3	-13.3	-29.4	-11.5	-15.4	-34.7	-32.8	-11.8	-4.2	-15.4	-21.9
24	-8.3	-9.2	-17.3	-25	-18.3	-7.9	-28.7	-19	-11.2	-22.9	-21.4	-11.4	-7.2	-18.8	-22.9
25	-0.6	0	-23.9	-26.6	-19.5	-12.7	-24.7	-24.9	-8.1	-13.1	-35.2	-1.7	-1.4	-6	-21.5
26	-7.8	-3.4	-22.8	-19.2	-25.2	-3.5	-16.5	-22.1	-15.8	-11	-33.9	-9.6	3.5	-2.3	-24.6
27	-8.3	0.6	-26.2	-12	-30.3	6.5	-21.3	-29.3	-23.7	-14.1	-36.2	-11.7	-1.4	-7.3	-28
28	-11.7	-2.3	-25.6	-13.5	-34.6	-0.3	-23.2	-28.7	-26.9	-19	-38.6	-12	-5.6	-9.7	-29.8
29	-7.3	-7	-25.6	-20.8	-37.4	-2.1	-11.4	-27.9	-22.4	-15.4	-32.7	-8.9	-5.6	-13.2	-23.9
30	-6.4	-9.5	-17.5	-18	-32.9	-9	-4.4	-34.4	-12.8	-21	-29.6	-14.4	-8.9	-20.6	-24.7
31	-7.5	-11.1	-12.8	-18.2	-22.5	-17.6	-9.6	-37.7	-6.5	-15.1	-26.6	-21.9	-15.1	-22.1	-28.5
December	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
1	-8.2	-31.6	-28.8	-5.1	-9.8	-19.2	-17.8	-12.7	-7.3	-15.1	-9.8	-8.5	-12.5	-6.1	-13.7
2	-7.7	-27.3	-29.3	-7.8	-7.3	-26.3	-13.6	-15	-10.7	-8.8	-13.1	-5.9	-15.3	-18.3	-12
3	2.1	-21.8	-33	-14.3	-2.6	-27.8	-12.8	-14.1	-9.9	-11.7	-14	-14.4	-21.3	-20.4	-4.2
4	-5.1	-10.3	-27.1	-6.4	-3.5	-28	-21.2	-11	-11.8	-10	-12	-22.8	-22.9	-10.2	-13.9
5	-18	-20.5	-26.7	-6	-4.5	-18.6	-26.7	-12.4	-12.1	-8.8	-1.9	-12.7	-18.5	-10	-7
6	-21	-9.6	-19.2	-17.1	-14.3	-16.3	-27.7	-14	-10.9	-9.9	-6.9	-7.7	-15.4	-15.2	-11.1
7	-22.7	4.9	-20.5		-15.1	-14.6	-29.1	-9.9	-12.3	-9.2	-9.7	-15.5	-13.6	-17.9	-12.8
8	-20	-4.5	-21.3		-17.9	-19.2	-29.5	-10.7	-12.9	-8.4	-7.8	-23.9	-4.9	-5.1	-17.1
9	-23.4	-13	-11		-17.4	-26.2	-28	-15.2	-8.5	-7.2	-7.7	-33.3	-13.4	-2.5	-22
10	-27.9	-12.4	-8.9	-12.8	-8.5	-27	-32.4	-13.5	-6	-1.4	-9.5	-27.9	-27	-3.8	-24.6
11	-20.9	-15.3	-12.1	-16.1	-1.3	-23.6	-31.5	-13.4	-1.4	-1.6	-10.6	-28.6	-24.8	-5.1E	-23
12	-15.7	-20.1	-17.4	-17.8	-8.8	-21.6	-23.3	-14.4	1.8	-6.8	-16.9	-29.5	-12.3	-6.6	-17.3
13	-15.4	-11.6	-24.7	-11.7	-8.3	-9.1	-19.4	-18.7	0.3	-3.3	-15.9	-33.3	-7.5	-4.9	-15.7
14	-10.7	-6.8	-27.1	-4.4	-5.5	-12.9	-21.4	-15.5	-2.8	-3.4	-25.5	-33.6	-7.4	-5.8	-13.4
15	-11.9	-14	-11.8	-18	-4.9	-15	-22.4	-11.6	-7.7	-12.6	-22.2	-33.1	-14.6	-2.6	-14.4
16	-21.2	-22.8	-9.5		-6.4	-14.3	-17.8	-15.1	-10.5	-13.7	-15.7	-29.2	-15.1	-2.6	-3.6
17	-32.4	-21.2	-17		-7.4	-16.3	-15.4	-21.6	-6.2	-12.9	-12.4	-23.6	10.6E	-1	-2.3
18	-35.6	-32.1	-14.1	-25.5	-6.3	-12.8	-10.6	-19.2	-14.4	-20.7	-18.7	-23.7	-17.5	-3	-5.1
19	-38.9	-32.6	-8.9	-26.2		-8.3	-9.4	-14.1	-16.2	-28.5	-31.4	-23.6	-12.4	-11.2	-5.9
20	-37.4	-35.7	-6.2	-28	-7.1	-3.8	-9.9	-25.5	-11	-31.1	-26	-28	-19	-19.1	-2.4
21	-34.6	-31.3	-1.3		-15.8	0.2	-11.9	-36.3	-9.2	-26.8	-21.5	-18.3	-19	-19.4	-3.5
22	-20.8	-17.9	-8.4	-25.8	-14.8	0.7	-6.8	-36.9	-9.5	-20.3	-9	-28.4	-13.1	-21.1	-8.9
23	-6.9	-18	-2.7	-24	-13	-0.2	-2.7	-31.2	-3.7	-20.9	0.4	-27	-14.8	-19.1	-6
24	-14.7	-26.4	-3.2	-24.7	-12.1	-7.3	-5.7	-28.2	-5.7	-26	3.5	-22.7	-11.9	-11.3	-8.3
25	-15.5	-33.9	-1.1	-33.1		-8.4	-3.9	-22.7	-5.6	-19.1	-2.2	-19.1	-5.8	-14.2	-6.6
26	-5.3	-22.7	-5.8		-22.8	-13.3	-7.7	-23.7	-3.3	-17.9	-5.3	-13.6	-10.2	-9.6	-4.8
27	-11.6	-23.3	-8.5	-34.7	-19.9	-13.6	-5.4	-33.7	-5.5	-26.7	1.1	-10.5	-13.7	-9.9	-13.3
28	-13.5	-35.1	-5.8	-35.6		-16.1	-8.2	-35.5	-10.2	-33.2	6.1	-12.2	-20.2	-12.6	-18.4
29	-2.5	-34.9	-7.1		-11.5	-18.8	-10.2	-34.1	-12.8	-32.7	-1.3	-12.1	-22.3	-12.7	-22.4
30	-7.8	-34.5	-10.6	-36.9		-17.8	-9.4	-30.7	-14.9	-30.5	-14.8	-11.8	-21.6	-13.6	-20
31	-10	-29.2	-11	-31.7	-24.9	-14.2	-8.3	-25.8	-13.9	-31.2	-27.4	-11.9	-19.9	-12.2	-21.7

M=Missing E = Estimated Empty = Not Available T = Tracing

Table A-3 Wind Speed (Canadian Climate Normals 1971-2000, FORT MCMURRAY)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Speed (km/h)	8.4	9.1	9.6	11	11	9.7	9	8.7	9.7	11	9	8.6
Most Frequent Direction	E	E	E	E	E	E	SW	SW	E	E	E	E
Maximum Hourly Speed (km/h)	67	56	54	54	63	48	72	50	51	63	60	52
Direction	SW	W	SW	NW	W	W	W	W	W	W	W	W
Maximum Gust Speed (km/h)	89	94	74	79	80	97	113	80	96	97	97	85
Direction (km/h)	SW	NW	SW	W	W	NW	W	NW	SW	W	W	W

Appendix B: Computer Code of Adding and Modified EMS Element

Weather Element:

```
Option Explicit

Public Function EMS_WeatherGenerator_OnCreate(ob As
CFCSim_ModelingElementInstance, x As Single, y As Single) As Boolean
        EMS_WeatherGenerator_OnCreate=True
        ob.OnCreate x,y,True

        ob.AddAttribute "ProjectLocation","Location of the
Project",CFC_Text,CFC_Single,CFC_ReadWrite,1900
        ob("ProjectLocation")="Fort Macmurrey"

        ob.AddAttribute "MonthOfYear","Month of
Year",CFC_Numeric,CFC_Single,CFC_Hidden
        ob("MonthOfYear")=1

        ob.AddAttribute "SnowAccumulation", "Snow
Accumulation(cm)",CFC_Numeric,CFC_Single,CFC_Hidden
        ob.AddAttribute "AverageTemperature", "Average
Temperature",CFC_Numeric,CFC_Single,CFC_Hidden
        ob.AddAttribute "WindSpeed", "Average Wind
Speed(km/h)",CFC_Numeric,CFC_Single,CFC_Hidden

        ob("SnowAccumulation")=0
        ob("AverageTemperature")=0
        ob("WindSpeed")=0

        ob.AddStatistic "SnowAccumulation", "Snow Accumulation(cm)",False,True
        ob.AddStatistic "AverageTemperature", "Average Temperature",False,True
        ob.AddStatistic "WindSpeed", "Average Wind Speed(km/h)",False,True

        ob.AddAttribute
"Description","Description",CFC_Text,CFC_Single,CFC_ReadOnly
        ob("Description")="Weather Generator"

        ob.SetNumCoordinates 2
        ob.CoordinatesX(0)=x
        ob.CoordinatesY(0)=y
        ob.CoordinatesX(1)=x+80
        ob.CoordinatesY(1)=y+40


        ob.AddConnectionPoint "In" , x-5, y+20, CInput, 5
        ob.AddConnectionPoint "Out",x+85,y+20,COutput,5

End Function
Public Sub EMS_WeatherGenerator_OnDragDraw(ob As
CFCSim_ModelingElementInstance)
        ob.OnDraw
End Sub
```

```
Public Sub EMS_WeatherGenerator_OnDraw(ob As
CFCSim_ModelingElementInstance)

   CDC.ChangeFont "Courier New",13,True,False,False,False

         CDC.RenderPicture
"weather.jpg",ob.CoordinatesX(0)+1,ob.CoordinatesY(0)+1,28,28
         CDC.Rectangle
ob.CoordinatesX(0),ob.CoordinatesY(0),ob.CoordinatesX(0)+28,ob.CoordinatesY(0)+28
         CDC.Rectangle
ob.CoordinatesX(0),ob.CoordinatesY(0),ob.CoordinatesX(1),ob.CoordinatesY(1)

         CDC.ChangeFont "Arial",11,True,False,False,False
         CDC.TextOut ob.CoordinatesX(0)+30,ob.CoordinatesY(0)+7, "Weather"

         ob.DrawConnectionPoints

End Sub

Public Sub EMS_WeatherGenerator_OnListBoxInitialize(ob As
CFCSim_ModelingElementInstance, attr As CFCSim_Attribute, lstList As Object)
         'lstList.additem "January"
         'lstList.additem "Feburary"
         'lstList.additem "March"
         'lstList.additem "April"
         'lstList.additem "October"
         'lstList.additem "November"
         'lstList.additem "Else"

End Sub

Public Sub EMS_WeatherGenerator_OnSimulationInitialize(ob As
CFCSim_ModelingElementInstance)

         ob.AddEvent "GivenWeather",True

End Sub
Public Sub EMS_WeatherGenerator_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)

         Gattr.Add("SnowAccumulation",0)
         Gattr.Add("AverageTemperature",0)
         Gattr.Add("WindSpeed",0)

End Sub

Public Sub EMS_WeatherGenerator_OnSimulationProcessEvent(ob As
CFCSim_ModelingElementInstance, MyEvent As String, Entity As CFCSim_Entity)
         Dim A As Single
         Dim B As Single
```

```
ob("MonthOfYear")=ob.CurrentEntity("Currentmonth")

Select Case MyEvent
        Case "GivenWeather"

        A=Sampler.Uniform(0,1)
        B=Sampler.Uniform(0,1)

   ob("SnowAccumulation")=0
        ob("AverageTemperature")=0
        ob("WindSpeed")=0

   If ob("MonthOfYear")=1 Then
        If A<0.000 Then
                ob("SnowAccumulation")=0
                Else
                ob("SnowAccumulation")=Sampler.Beta(2.35,4.27,2.98,68.02)
                End If
                If B<=0.976 Then
                ob("AverageTemperature")=Sampler.Beta(1.81,1.60,-39.01,-0.00)
                Else
                ob("AverageTemperature")=Sampler.Beta(0.43,0.81,0.00,8.30)
                End If
                ob("WindSpeed")=8.4
        End If

   If ob("MonthOfYear")=2 Then
     If A<0.000 Then
                ob("SnowAccumulation")=0
         Else
                ob("SnowAccumulation")=Sampler.Beta(1.68,2.39,2.98,67.01)
         End If
         If B<=0.932 Then
                ob("AverageTemperature")=Sampler.Beta(1.75,1.27,-34.70,-0.00)
         Else
                ob("AverageTemperature")=Sampler.Beta(0.62,1.45,0.00,9.10)
         End If
                ob("WindSpeed")=9.1
        End If

        If ob("MonthOfYear")=3 Then
           If A<=0.025 Then
                ob("SnowAccumulation")=0
           Else
                ob("SnowAccumulation")=Sampler.Beta(1.28,2.12,0.98,66.02)
           End If
           If B<=0.749 Then
                ob("AverageTemperature")=Sampler.Beta(2.68,1.19,-33.50,-0.00)
           Else
                ob("AverageTemperature")=Sampler.Beta(1.14,2.99,0.00,10.40)
           End If
```

```
        ob("WindSpeed")=9.6
    End If

    If ob("MonthOfYear")=4 Then
            If A<=0.624 Then
              ob("SnowAccumulation")=0
        Else
              ob("SnowAccumulation")=Sampler.Beta(0.53,1.34,0.98,52.02)
        End If
        If B<=0.241 Then
              ob("AverageTemperature")=Sampler.Beta(1.99,0.74,-20.03,-
0.00)
        Else
              ob("AverageTemperature")=Sampler.Beta(1.55,3.66,0.00,20.40)
        End If
              ob("WindSpeed")=10.9
    End If

    If ob("MonthOfYear")=10 Then
            If A<=0.846 Then
              ob("SnowAccumulation")=0
        Else
              ob("SnowAccumulation")=Sampler.Beta(0.43,1.40,0.93,18.07)
        End If
        If B<=0.287 Then
              ob("AverageTemperature")=Sampler.Beta(2.44,0.61,-19.80,-
0.00)
        Else
              ob("AverageTemperature")=Sampler.Beta(1.26,3.00,0.00,18.30)
        End If
              ob("WindSpeed")=10.5
    End If

    If ob("MonthOfYear")=11 Then
            If A<=0.159 Then
              ob("SnowAccumulation")=0
        Else
              ob("SnowAccumulation")=Sampler.Beta(0.84,2.52,0.97,37.03)
        End If
        If B<=0.873 Then
              ob("AverageTemperature")=Sampler.Beta(3.57,1.41,-35.84,-
0.00)
        Else
              ob("AverageTemperature")=Sampler.Beta(0.76,2.56,0.00,9.80)
        End If
              ob("WindSpeed")=9
    End If

    If ob("MonthOfYear")=12 Then
        If A<0.000 Then
              ob("SnowAccumulation")=0
```

```
                Else
                      ob("SnowAccumulation")=Sampler.Beta(2.07,3.13,0.98,45.02)
                End If
                If B<=0.978 Then
                      ob("AverageTemperature")=Sampler.Beta(2.19,1.46,-39.92,-
0.00)
                Else
                      ob("AverageTemperature")=Sampler.Beta(0.41,0.88,0.00,6.50)
                End If
                      ob("WindSpeed")=8.6
             End If

        'Entity("SnowAccumulation")=ob("SnowAccumulation")
        'Entity("AverageTemperature")=ob("AverageTemperature")
        'Entity("WindSpeed")=ob("WindSpeed")
        Gattr.SetValue("SnowAccumulation", ob("SnowAccumulation"))
        Gattr.SetValue("AverageTemperature", ob("AverageTemperature"))
        Gattr.SetValue("WindSpeed", ob("WindSpeed"))

        ob.stat("SnowAccumulation").Collect ob("SnowAccumulation")
        ob.stat("AverageTemperature").Collect ob("AverageTemperature")
        ob.stat("WindSpeed").Collect ob("WindSpeed")

        ob.TransferOut Entity

        End Select

End Sub
```

New Road Element:

```
Option Explicit

Public Function EMS_Road_Uncertain_OnCreate(ob As
CFCSim_ModelingElementInstance, x As Single, y As Single) As Boolean
        EMS_Road_Uncertain_OnCreate=True

        ob.SetNumCoordinates 2
        ob.CoordinatesX(0)=x
        ob.CoordinatesY(0)=y
        ob.CoordinatesX(1)=x+50
        ob.CoordinatesY(1)=y+50

        ob.AddAttribute "Length", "Road Length in Meters", CFC_Numeric, CFC_Single,
CFC_ReadWrite,5
        ob.AddAttribute "Grade", "Percent Grade Resistance", CFC_Numeric,
CFC_Single, CFC_ReadWrite,-30,30
```

```
        ob.AddAttribute "Fr", "Road performance factor(including visibility)(<=1)",
CFC_Numeric, CFC_Single, CFC_ReadWrite,0,1

        ob.Attr("Length")=1000
        ob.Attr("Grade")=2
        ob.Attr("Fr")=1

        ob.AddConnectionPoint "c1", ob.CoordinatesX(0),ob.CoordinatesY(0),CInput,5
        ob.AddConnectionPoint "c2", ob.CoordinatesX(1),ob.CoordinatesY(1),COutput,5

        '======================
        ob.AddAttribute "DoAnimation","Do
animation",CFC_Text,CFC_ListBox,CFC_ReadWrite
        ob.AddAttribute "InstNum","",CFC_Numeric,CFC_Single, CFC_Hidden
        ob.AddAttribute "InstAssociation","",CFC_Collection,CFC_Single,CFC_Hidden
        ob("DoAnimation") = ""
        '======================


End Function

Public Sub EMS_Road_Uncertain_OnDragDraw(ob As
CFCSim_ModelingElementInstance)
        ob.OnDraw
End Sub

Public Sub EMS_Road_Uncertain_OnDraw(ob As CFCSim_ModelingElementInstance)
        Dim ratio As Double
  Dim Length As Integer
  Dim xoffset As Integer
  Dim yoffset As Integer
  Dim x As Single
  Dim y As Single

        ob.DrawConnectionPoints

        'CDC.ChangeLineStyle  CFC_SOLID, 3,RGB(0,0,255)


        With CDC
                Length = Sqr((ob.CoordinatesX(1) - ob.CoordinatesX(0)) ^ 2 +
(ob.CoordinatesY(1) - ob.CoordinatesY(0)) ^ 2)
        If Length<5 Then Exit Sub
        ratio = Length / 5
                If ob.Selected Then
                        CDC.ChangeLineStyle CFC_SOLID, 1,RGB(255,0,0)
                End If

           xoffset = (ob.CoordinatesY(1) - ob.CoordinatesY(0)) / ratio
           yoffset = (ob.CoordinatesX(1) - ob.CoordinatesX(0) )/ ratio
```

```
        .MoveTo ob.CoordinatesX(0) - xoffset, ob.CoordinatesY(0)+ yoffset
        .LineTo ob.CoordinatesX(1) - xoffset, ob.CoordinatesY(1) + yoffset

            .MoveTo ob.CoordinatesX(0) + xoffset, ob.CoordinatesY(0) - yoffset
        .LineTo  ob.CoordinatesX(1) + xoffset, ob.CoordinatesY(1) - yoffset

        .ArrowHead ob.CoordinatesX(0)  ,ob.CoordinatesY(0) , ob.CoordinatesX(1)
,ob.CoordinatesY(1) ,10

    End With

End Sub

Public Sub EMS_Road_Uncertain_OnGetBoundingRect(ob As
CFCSim_ModelingElementInstance, mRect As CFCGraphics_Rect, HitTest As Boolean)

    Dim t As Single
        t=5

    If ob.CoordinatesX(0)<ob.CoordinatesX(1) Then
        mRect.Left=ob.CoordinatesX(0)-t
        mRect.Right=ob.CoordinatesX(1)+t
    Else
        mRect.Left=ob.CoordinatesX(1)-t
        mRect.Right=ob.CoordinatesX(0)+t
    End If
    If Abs(ob.CoordinatesX(0)-ob.CoordinatesX(1))<=5 Then
        mRect.Left=ob.CoordinatesX(1)-10
        mRect.Right=ob.CoordinatesX(1)+10
    End If
    If ob.CoordinatesY(0)<ob.CoordinatesY(1) Then
        mRect.top=ob.CoordinatesY(0)-t
        mRect.bottom=ob.CoordinatesY(1)+t
    Else
        mRect.top=ob.CoordinatesY(1)-t
        mRect.bottom=ob.CoordinatesY(0)+t
    End If
    If Abs(ob.CoordinatesY(0)-ob.CoordinatesY(1))<=5 Then
        mRect.top=ob.CoordinatesY(1)-10
        mRect.bottom=ob.CoordinatesY(1)+10
    End If

 End Sub

Public Function EMS_Road_Uncertain_OnHitTest(ob As
CFCSim_ModelingElementInstance, x As Single, y As Single) As Boolean
    ' we need to figure out the distance to the central line
    Dim slope As Double
    Dim Temp1 As Double
    Dim Temp2 As Double
```

```
        Dim mRect As New CFCGraphics_Rect
        Dim InRect As Boolean

        EMS_Road_Uncertain_OnHitTest=False

        ' first check if point is inside the bounding rectangle
        ob.OnGetBoundingRect mRect,True
        If Not (x>mRect.Left And x<mRect.Right And y>mRect.top And y<mRect.bottom)
Then
                Exit Function
        End If

        ' Then check some special cases

        If (Abs((ob.CoordinatesX(1)-ob.CoordinatesX(0)))<0.1) Or
(Abs((ob.CoordinatesY(1)-ob.CoordinatesY(0)))<0.1) Then
                EMS_Road_Uncertain_OnHitTest=True
                Exit Function
        End If

        slope=(ob.CoordinatesY(1)-ob.CoordinatesY(0))/(ob.CoordinatesX(1)-
ob.CoordinatesX(0))

         Temp1 = (x/slope+y-
ob.CoordinatesY(0)+slope*ob.CoordinatesX(0))/(slope+1/slope)
         Temp2 = slope*(Temp1-ob.CoordinatesX(0))+ob.CoordinatesY(0)

        If   ( Sqr( (Temp1-x)^2)+  (Temp2-y)^2) < 20 Then
                EMS_Road_Uncertain_OnHitTest=True
        End If

End Function

Public Sub EMS_Road_Uncertain_OnListBoxInitialize(ob As
CFCSim_ModelingElementInstance, attr As CFCSim_Attribute, lstList As Object)
        lstList.additem "Yes"
        lstList.additem "No"
End Sub

Public Sub EMS_Road_Uncertain_OnMove(ob As CFCSim_ModelingElementInstance,
ByVal x1 As Single, ByVal y1 As Single, ByVal x2 As Single, ByVal y2 As Single)
           With ob
                   If Sqr((.CoordinatesX(0) - x1) ^ 2 + (.CoordinatesY(0) - y1) ^ 2) <= 10
Then
                 .CoordinatesX(0) = .CoordinatesX(0) + (x2 - x1)
                 .CoordinatesY(0) = .CoordinatesY(0) + (y2 - y1)

                     .ConnectionPoints("c1").x = .ConnectionPoints("c1").x + (x2 - x1)
                 .ConnectionPoints("c1").y = .ConnectionPoints("c1").y + (y2 - y1)
```

```
            ElseIf Sqr((.CoordinatesX(1) - x1) ^ 2 + (.CoordinatesY(1) - y1) ^ 2) <= 10
Then
                .CoordinatesX(1) = .CoordinatesX(1) + (x2 - x1)
                .CoordinatesY(1) = .CoordinatesY(1) + (y2 - y1)

                                .ConnectionPoints("c2").x = .ConnectionPoints("c2").x +
(x2 - x1)
                .ConnectionPoints("c2").y = .ConnectionPoints("c2").y + (y2 - y1)

            Else
                .CoordinatesX(0) = .CoordinatesX(0) + (x2 - x1)
                .CoordinatesY(0) = .CoordinatesY(0) + (y2 - y1)
                .CoordinatesX(1) = .CoordinatesX(1) + (x2 - x1)
                .CoordinatesY(1) = .CoordinatesY(1) + (y2 - y1)

                .ConnectionPoints("c1").x = .ConnectionPoints("c1").x + (x2 - x1)
                .ConnectionPoints("c1").y = .ConnectionPoints("c1").y + (y2 - y1)
                .ConnectionPoints("c2").x = .ConnectionPoints("c2").x + (x2 - x1)
                .ConnectionPoints("c2").y = .ConnectionPoints("c2").y + (y2 - y1)
                        End If
        End With

End Sub

Public Function EMS_Road_Uncertain_OnRelationValid(srcCP As
CFCSim_ConnectionPoint, dstCP As CFCSim_ConnectionPoint) As Boolean
        EMS_Road_Uncertain_OnRelationValid=True

        If srcCP.RelationsTo.Count>0 Then
                MessagePrompt "Only one relation is allowed from this connection point "
                EMS_Road_Uncertain_OnRelationValid=False
        End If

End Function

Public Sub EMS_Road_Uncertain_OnSimulationInitialize(ob As
CFCSim_ModelingElementInstance)
        ob.AddEvent "StartTravel",True
        ob.AddEvent "FinishTravel"
End Sub

Public Sub EMS_Road_Uncertain_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)
        If ob.Parent("DoAnimation")="Yes" Then
                ob("DoAnimation")="Yes"
        Else
                        ob("DoAnimation")="No"
        End If
        '===================================
        If ob("DoAnimation") = "Yes" Then
                Dim dds As CFCAnim_Drawing
```

```
                Dim cp As CFCSim_ConnectionPoint
                Dim rel As CFCSim_Relation
                Dim b As Boolean
                Dim i As Integer
                Dim p1 As CFCSim_Point
                Dim p2 As  CFCSim_Point

                Set dds = ob.Parent("Screen").Reference.createDrawing(ob.Id & "Main")
                Call dds.SetFillStyle(DA_FILL_EMPTY)
                Call dds.SetLineColor( "gray")
                Call dds.SetLineWidth(10)
                Call dds.SetLineJoinStyle(0)
                Call dds.addLine(0,0,ob.CoordinatesX(1)-
ob.CoordinatesX(0),ob.CoordinatesY(1)-ob.CoordinatesY(0))
                Call dds.addLine(ob.CoordinatesX(1)-
ob.CoordinatesX(0),ob.CoordinatesY(1)-
ob.CoordinatesY(0),ob.ConnectionPoints("c2").RelationsTo(1).dstConnection.x-
ob.CoordinatesX(0),ob.ConnectionPoints("c2").RelationsTo(1).dstConnection.y-
ob.CoordinatesY(0))
                Call
dds.addLine(0,0,ob.ConnectionPoints("c1").RelationsFrom(1).srcConnection.x-
ob.CoordinatesX(0),ob.ConnectionPoints("c1").RelationsFrom(1).srcConnection.y-
ob.CoordinatesY(0))

                If
ob.ConnectionPoints("c1").ElementsFrom(1).ElementType<>"EMS_Road_Uncertain"
Then
                        Call ob.Parent("Screen").Reference.addPathLine(ob.Id &
"Path",ob.ConnectionPoints("c1").RelationsFrom(1).srcConnection.x,ob.ConnectionPoint
s("c1").RelationsFrom(1).srcConnection.y,ob.ConnectionPoints("c1").x,ob.ConnectionPoi
nts("c1").y)
                End If
                Call ob.Parent("Screen").Reference.addPathLine(ob.Id &
"Path",ob.CoordinatesX(0),ob.CoordinatesY(0),ob.CoordinatesX(1),ob.CoordinatesY(1))
                Call ob.Parent("Screen").Reference.addPathLine(ob.Id &
"Path",ob.ConnectionPoints("c2").x,ob.ConnectionPoints("c2").y,ob.ConnectionPoints("c
2").RelationsTo(1).dstConnection.x,ob.ConnectionPoints("c2").RelationsTo(1).dstConne
ction.y)

                Call ob.Parent("Screen").Reference.Show(ob.Id &
"Main",ob.CoordinatesX(0),ob.CoordinatesY(0),0)

                Dim Direction As String
                If ob.CoordinatesX(0)>ob.CoordinatesX(1) Then
                        Direction="RtoL"
                '       i=1
                Else
                        Direction="LtoR"
                '       i=-1
                End If
```

```
                'Call ob.Parent("Screen").Reference.addPathArc(ob.ID &
"Path",i*90,(i+1)*90,Abs(ob.ConnectionPoints("c2").x-
ob.ConnectionPoints("c2").RelationsTo(1).dstConnection.x),Abs(ob.ConnectionPoints("c
2").y-ob.ConnectionPoints("c2").RelationsTo(1).dstConnection.y))

                Call ob.Parent("Screen").Reference.addBitmap(ob.Id & "TruckEmpty",
GetImage(ob,"Truck"& Direction & "Empty.bmp"))
                Call ob.Parent("Screen").Reference.addBitmap(ob.Id & "TruckLoaded",
GetImage(ob,"Truck"& Direction & "Loaded.bmp"))

                ob("InstNum") = 0
                Call ob("InstAssociation").Collection.Clear
        End If
        '=============================
End Sub

Public Sub EMS_Road_Uncertain_OnSimulationProcessEvent(ob As
CFCSim_ModelingElementInstance, MyEvent As String, Entity As CFCSim_Entity)
        Dim duration As Double
        Dim TotalResistance As Double
        Dim AverageSpeed As Double
        Dim MaximumSpeed As Double

        Dim Rinternal As Double
        Dim Rterrain As Double
        Dim Rgrade As Double
        Dim Z As Double
        Dim Po As Double
        Dim Te As Double
        Dim ArccosTe As Double
        Dim test As Double

        Select Case MyEvent
        Case "StartTravel"

        Tracer.Trace "previous MaximumSpeed is " &  Entity("MaximumSpeed")

                ' calculate Rterrain under weather condition
                Po=0.152-
0.0031*Gattr("AverageTemperature")+0.019*Gattr("WindSpeed")/3.6
                Z=Gattr("SnowAccumulation")*(1-Po/Entity("Pf"))
                Te=(Entity("Rtire")-Z/100)/Entity("Rtire")
                If -Te*Te+1=0 Then
                Te=0.9999
                End If
           ArccosTe=Atn(-Te/Sqr(-Te*Te+1))+2*Atn(1)
                If Gattr("SnowAccumulation")=0 Then
                        Rterrain=0
                Else

        Rterrain=6*68.083*(Po*Entity("Wtire")*(Entity("Rtire")*ArccosTe))^0.9135
```

```
        End If

        'Tracer.Trace "show Rterrain" & Rterrain

        ' calculate loaded MaximumSpeed under weather condition
        If Entity("PayLoad") >0 Then
                Rinternal=(Entity("TruckW")+Entity("TruckL"))*0.0175
                'Tracer.Trace "show the Rinternal" & Rinternal
                Rgrade=(Entity("TruckW")+Entity("TruckL"))*ob("Grade")/100
                TotalResistance=Rinternal+Rterrain+Rgrade

                If TotalResistance<Rinternal Then
                TotalResistance=Rinternal
                End If

                Tracer.Trace "show the TotalResistance=" & TotalResistance

MaximumSpeed=10^(Entity("k")*(Log(TotalResistance)/Log(10))+Entity("b"))

        Else
        ' calculate empty MaximumSpeed under weather condition
                Rinternal=Entity("TruckW")*0.0175
                Rgrade=Entity("TruckW")*ob("Grade")/100
                TotalResistance=Rinternal+Rterrain+Rgrade

                If TotalResistance<Rinternal Then
                TotalResistance=Rinternal
                End If

                Tracer.Trace "show the TotalResistance=" & TotalResistance

MaximumSpeed=10^(Entity("k")*(Log(TotalResistance)/Log(10))+Entity("b"))
        End If

        'set the boundary of the MaximumSpeed
                If MaximumSpeed >67.3 Then
                        MaximumSpeed=67.3
                End If

                If MaximumSpeed <8.2 Then
                        MaximumSpeed=8.2
                End If

        ' calculate AverageSpeed
                If Entity("MaximumSpeed")=0 Then
                        If ob("length")<1835 Then

AverageSpeed=MaximumSpeed*(0.1453*Log(ob("length"))-0.0919)
                        Else
                                AverageSpeed=MaximumSpeed
                        End If
```

```
                        Else
                                If Entity("MaximumSpeed")<MaximumSpeed Then
                                        If ob("length")<1900 Then

        AverageSpeed=MaximumSpeed*(0.0682*Log(ob("length"))+0.4851)
                                        Else
                                                AverageSpeed=MaximumSpeed
                                        End If
                                Else
                                        If ob("length")<1456 Then
                                        AverageSpeed=MaximumSpeed*(-0.1489*
                                        Log(ob("length"))+2.0845)
                                        Else
                                                AverageSpeed=MaximumSpeed
                                        End If
                                End If
                        End If



                        '================
                        If ob("DoAnimation")="Yes" Then
                                Call ob("InstAssociation").Collection.Add(Chr(1) &
ob("InstNum"),CStr(Entity.Id))
                                Call ob.Parent("Screen").Reference.pathObj(ob.Id &
"Path",ob.Id & "TruckLoaded",Chr(1) & ob("InstNum"))
                                Call ob.Parent("Screen").Reference.startPath(ob.Id &
"Path", Chr(1) & ob("InstNum"),SimTime)
                                ob("InstNum") = ob("InstNum") + 1
                        End If
                        '================

                        'provide present MaximumSpeed to the Entity
                                Entity("MaximumSpeed")=MaximumSpeed

                ' calculate duration
                duration = (ob("length")/(AverageSpeed*Entity("Fv")*ob("Fr"))) *  60/1000
                Tracer.Trace "Truck: " & Entity.Id & " will travel with a speed(km/h) of " &
AverageSpeed & " for a duration(m) of " & duration,"Simulation"
                Tracer.Trace "MaximumSpeed is " & MaximumSpeed
                Tracer.Trace "AverageSpeed is " & AverageSpeed
                ob.ScheduleEvent Entity,"FinishTravel",duration

        Case "FinishTravel"

                Tracer.Trace "Truck entity completed travel: " & Entity.Id , "Simulation"
                ob.TransferOut Entity

                '================
                If ob("DoAnimation")="Yes" Then
```

```
                                Call ob.Parent("Screen").Reference.endPath(ob.Id &
"Path",ob("InstAssociation").Collection(CStr(Entity.Id)),SimTime)
                                Call
ob("InstAssociation").Collection.Remove(CStr(Entity.Id))
                End If
                '================

        End Select
End Sub

Public Function EMS_Road_Uncertain_OnValidateParameters(ob As
CFCSim_ModelingElementInstance, Parameters As Object) As Boolean
        EMS_Road_Uncertain_OnValidateParameters=ob.OnValidateParameters(Param
eters,True)

        If EMS_Road_Uncertain_OnValidateParameters=False Then Exit Function

        'If Abs(Parameters("Grade")+Parameters("RR"))>55 Then
                'MessagePrompt "Total Resistance 'RR + Grade resistance' cannot
exceed fifty five"
                'EMS_Road_Uncertain_OnValidateParameters=False
        'End If
End Function
```

New Truck Element:

```
Option Explicit

Public Function EMS_Truck_Uncertain_OnCreate(ob As
CFCSim_ModelingElementInstance, x As Single, y As Single) As Boolean
        EMS_Truck_Uncertain_OnCreate=True

        ob.SetNumCoordinates 2
        ob.CoordinatesX(0)=x
        ob.CoordinatesY(0)=y
        ob.CoordinatesX(1)=x+60
        ob.CoordinatesY(1)=y+38

        '===== Find the path of the current project and consider that the trucks db is
located there as a default
        ob.AddAttribute "FileName", "Data Source", CFC_Text,CFC_Single,
CFC_Hidden
        ob("FileName")= SimphonyPath & "\templates\Trucks.mdb"
        '========

        ob.AddAttribute "Type", "Truck Type", CFC_Text,CFC_ListBox, CFC_ReadWrite
        ob.AddAttribute "Quantity", "Number of Trucks", CFC_Numeric, CFC_Single,
CFC_ReadWrite,1,100
        ob.AddAttribute "Capacity", "Truck Capacity in Cubic Meters", CFC_Numeric,
CFC_Single, CFC_ReadWrite,5,200
```

```
        ob.AddAttribute "DumpingTime", "Truck Dumping Duration", CFC_Distribution,
CFC_Single, CFC_ReadWrite
        ob.AddAttribute "IPriority", "Truck Priority at Intersections", CFC_Numeric,
CFC_Single, CFC_ReadWrite,1
        ob.AddAttribute "LPriority", "Truck Loading Priority ", CFC_Numeric, CFC_Single,
CFC_ReadWrite,1
        ob.AddAttribute "Path", "Path Number to Follow on Branches", CFC_Numeric,
CFC_Single, CFC_ReadWrite,1
        ob.AddAttribute "Fv", "Vehicle performance factor(including operator skill)(<=1)",
CFC_Numeric, CFC_Single, CFC_ReadWrite,0,1

        '**** Truck Parameters *****
        ob.AddAttribute "TruckW", "Netweight of Truck", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        ob.AddAttribute "TruckL", "Payload of Truck", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        ob.AddAttribute "Rtire", "Tire radius", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        ob.AddAttribute "Wtire", "Tire width", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        ob.AddAttribute "k", "Regression factor-k", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        ob.AddAttribute "b", "Regression factor-b", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        ob.AddAttribute "Pf", "Density of packed snow", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        ob.AddAttribute "MaximumSpeed", "Maximum Speed of truck", CFC_Numeric,
CFC_Single, CFC_Hidden,,,".00000000"

        '**** Speed Parameters *****
        'ob.AddAttribute "MeanL", "MeanL", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        'ob.AddAttribute "StDevL", "StDevL", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        'ob.AddAttribute "ScaleFactorL", "ScaleFactorL", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        'ob.AddAttribute "YFactorL", "YFactorL", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"

        'ob.AddAttribute "MeanE", "MeanE", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        'ob.AddAttribute "StDevE", "StDevE", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        'ob.AddAttribute "ScaleFactorE", "ScaleFactorE", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"
        'ob.AddAttribute "YFactorE", "YFactorE", CFC_Numeric, CFC_Single,
CFC_Hidden,,,".00000000"


        ob("Type")="Caterpillar Model 769D"
```

```
ob("Type").LimitList=True

ob("Quantity")=1
ob("Capacity")=45
ob("IPriority")=1
ob("LPriority")=1
ob("Path")=1
ob("Fv")=1

ob("TruckW")=302
ob("TruckL")=398
ob("Rtire")=0.912
ob("Wtire")=0.495
ob("k")=-1.0153
ob("b")=3.0419
ob("Pf")=0.6
ob("MaximumSpeed")=0

'ob("MeanL")=-1.50380179214948
'ob("StDevL")=51.2146624521371
'ob("ScaleFactorL")=52.4015363713796
'ob("YFactorL")=7.45532863433904

'ob("MeanE")=-2.09562038669374
'ob("StDevE")=102.99761324689
'ob("ScaleFactorE")=47.7472478284794
'ob("YFactorE")=19.8717075598002


With ob("DumpingTime").Distribution
        .DistType=CFC_Constant
        .ParameterValue(0)=1
End With

ob.AddConnectionPoint "c1",
ob.CoordinatesX(0)+65,ob.CoordinatesY(0)+17,COutput,5

ob.AddStatistic "CycleTime","Truck Cycle Time",False,True



End Function

Public Sub EMS_Truck_Uncertain_OnDraw(ob As CFCSim_ModelingElementInstance)

        CDC.RenderPicture "Hauling
unit.gif",ob.CoordinatesX(0),ob.CoordinatesY(0),ob.CoordinatesX(1)-
ob.CoordinatesX(0),ob.CoordinatesY(1)-ob.CoordinatesY(0)
        If ob.Selected Then
                CDC.Rectangle ob.CoordinatesX(0)-2,ob.CoordinatesY(0)-
2,ob.CoordinatesX(1)+2,ob.CoordinatesY(1)+2
```

```
        End If
        ob.DrawConnectionPoints
End Sub

Public Sub EMS_Truck_Uncertain_OnListBoxInitialize(ob As
CFCSim_ModelingElementInstance, attr As CFCSim_Attribute, lstList As Object)
        Select Case attr.Name
        Case "Type"
                Dim dbName As String
                Dim dbs As Database
                dbName =ob("FileName")
                Set dbs = DBEngine.Workspaces(0).OpenDatabase(dbName)

                Dim myset As Recordset

                Set myset = dbs.OpenRecordset ("select * From EMS_TruckTypes")
                  myset.MoveFirst
                  While Not myset.EOF
                        lstList.AddItem myset!Description
                        myset.MoveNext
                  Wend
                End Select
End Sub

Public Sub EMS_Truck_Uncertain_OnListBoxSelectItem(ob As
CFCSim_ModelingElementInstance, attr As CFCSim_Attribute, lstList As Object)
        Select Case attr.Name
        Case "Type"
                Dim dbName As String
                Dim SQL As String
                Dim dbs As Database
                dbName =ob("FileName")

                Set dbs = DBEngine.Workspaces(0).OpenDatabase(dbName)

                Dim myset As Recordset

                SQL ="SELECT * FROM EMS_TruckTypes WHERE Description = '" &
lstList.text & "'"
                Set myset = dbs.OpenRecordset (SQL)

                attr.Value=lstList.text
                 myset.MoveFirst
                'ob("MeanL")=myset!MeanL
                'ob("StDevL")=myset!StDevL
                'ob("ScaleFactorL")=myset!ScaleFactorL
                'ob("YFactorL")=myset!YFactorL

                'ob("MeanE")=myset!MeanE
                'ob("StDevE")=myset!StDevE
                'ob("ScaleFactorE")=myset!ScaleFactorE
```

```
                'ob("YFactorE")=myset!YFactorE

                ob("TruckW")=myset!TruckW
                ob("TruckL")=myset!TruckL
                ob("Rtire")=myset!Rtire
                ob("Wtire")=myset!Wtire
                ob("k")=myset!k
                ob("b")=myset!b
                ob("Pf")=myset!Pf

                'MessagePrompt ob!MeanL
        End Select
End Sub

Public Function EMS_Truck_Uncertain_OnRelationValid(srcCP As
CFCSim_ConnectionPoint, dstCP As CFCSim_ConnectionPoint) As Boolean
        EMS_Truck_Uncertain_OnRelationValid=True

        If srcCP.RelationsTo.Count>0 Then
                MessagePrompt "Only one relation is allowed from this connection point "
                EMS_Truck_Uncertain_OnRelationValid=False
        End If
End Function

Public Sub EMS_Truck_Uncertain_OnSimulationInitializeRun(ob As
CFCSim_ModelingElementInstance, RunNum As Integer)
        Dim truck As CFCSim_Entity
        Dim i As Integer

        Dim myset As Recordset

'   Set myset = SimphonyConnection.OpenRecordset("select * From EMS_TruckTypes
where description ='" & ob("Type") & "'", dbOpenSnapshot)

        For i=1 To ob("Quantity")
                Set truck=      ob.AddEntity
                truck("capacity")=ob("capacity")
                Set truck("DumpingTime")=ob("DumpingTime").Distribution
                Set truck("CycleStat")= ob.stat("CycleTime")
                truck("PayLoad")=0
                truck("StartTime") = -1
                truck("LPriority")=ob("LPriority")
                truck("IPriority")=ob("IPriority")
                truck("Path")=ob("Path")
                truck("Fv")=ob("Fv")

                ' set speed parameters
                'truck("MeanL")=ob("MeanL")
                'truck("StDevL")=ob("StDevL")
                'truck("ScaleFactorL")=ob("ScaleFactorL")
                'truck("YFactorL")=ob("YFactorL")
```

```
            'truck("MeanE")=ob("MeanE")
            'truck("StDevE")=ob("StDevE")
            'truck("ScaleFactorE")=ob("ScaleFactorE")
            'truck("YFactorE")=ob("YFactorE")

            truck("TruckW")=ob("TruckW")
            truck("TruckL")=ob("TruckL")
            truck("Rtire")=ob("Rtire")
            truck("Wtire")=ob("Wtire")
            truck("k")=ob("k")
            truck("b")=ob("b")
            truck("Pf")=ob("Pf")
            truck("MaximumSpeed")=ob("MaximumSpeed")

            Tracer.Trace "Truck entity created and transferred: " & truck.Id ,
"Simulation"
      '====
      '     ob.Parent("Screen").Reference.addBitmap(truck.ID &
"Truck",GetImage(ob,"TruckWaiting.bmp"))
      '====
            ob.TransferOut truck
      Next
End Sub
```