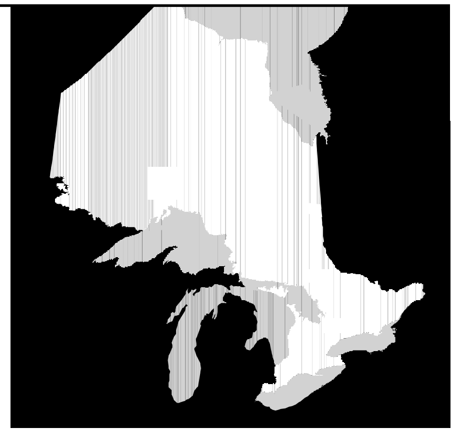
Ontario

**Ministry of Transportation**
**Engineering Standards Branch Report**



# Highway Infrastructure Innovation Funding Program 2005

Using Advanced Road Weather Information Systems (ARWIS) to Control Load Restrictions on Gravel and Surface Treated Highways

## Phase I – Final Report

**ESB-001**

**Technical Report Documentation Page**

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| Publication **Title** | **Using Advanced Road Weather Information Systems (ARWIS) to Control Load Restrictions on Gravel and Surface Treated Highways – Phase I – Final Report** |

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**Abstract**

The economic impacts of the cyclic nature of Canadian weather provides a dilemma for engineers. Pavement damage occurs during the spring thaw period. To mitigate pavement damage, spring load restrictions (SLR) are applied over a certain time frame. Unfortunately, these restrictions impact the transportation industry negatively as the amount of goods that is permitted to be transported is reduced. Therefore, the economic impact of SLR is significant. Conversely, there is possibly an opportunity to employ Winter Weight Premiums (WWP) which enable for heavier loads on the infrastructure.

The intent of this report is to summarize the results of Phase 1, a one year project which involved a literature review of current SLR policies and practices. It also included the installation of two pilot sites in Northwestern and Northeastern Ontario. Under this project, the sensors or thermister strings The primary goal of the instrumentation was to provide real time frost penetration data and relate that to the ARWIS data. The thermister strings were also designed and constructed in a manner that they can be related to current on-going activities and analysis in Quebec and various parts of Northern Canada. A preliminary analysis of data acquired from the Northeast Region study site and surrounding ARWIS data has been performed based on models from Quebec, Manitoba and Minnesota. Initial future steps, including both short- and long-term are described. The immediate future will be focused on data acquisition and ensuring proper functionality of the equipment prior to the spring thaw. Long-term modelling will be performed as data is collected from each site. The ultimate deliverable is to provide the Ministry a means of accurately assessing and applying SLR to the required facilities while mitigating both pavement damage and economic hardships to the transportation industry.

**Key Words** Spring load restrictions, winter weight premiums, thermistors, thaw, freeze, ARWIS

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Using Advanced Road Weather Information Systems (ARWIS) to Control Load Restrictions on Gravel and Surface Treated Highways

## Phase I - Final Report

**May 2006**

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# Executive Summary

The objective of this research is to provide a means to assist personnel in determining the optimum timeframe on imposing seasonal load restrictions in Ontario. To achieve this, an investigation on the current state of the art, the installation of field instrumentation and the state of the current database will lead into recommended future steps to provide a reliable and efficient model that will be completed as the final objective of Phase II.

A literature review summarizes the background and current state of spring load restrictions. From the freeze-thaw phenomenon to available empirical models from other jurisdictions are discussed. Potential alternatives to the spring load restrictions are summarized.

Installing the instrumentation on site presented several challenges, some of which are on-going. The Northeastern site is currently operating properly with no significant issues since the installation of the dial-up modem. Hardware issues in the Northwestern Region are currently being diagnosed by the manufacturer of the dataloggers. A spare unit was installed on-site and is currently operating correctly.

There are both short-term and long-term goals for this project. Both the collection of ARWIS and ground temperature data are to be completed in the short-term. Development of an Ontario based model utilizing this data will be the ultimate objective. This will be done by relating air temperatures with frost depth. Subsequently a model will be developed to assist management in selecting the allowance of winter weight premiums (WWP) and spring load restrictions (SLR). Within these models, a life cycle costing analysis will be performed that relates the construction and maintenance costs with heavy vehicle damage that is influenced by SLR and WWP.

It is also proposed that further instrumentation be installed at both study sites. Ambient air temperature, moisture, precipitation and solar radiation sensors are examples of possible candidates. The goal of these sensors is to provide on-site validation of the interpolated or extrapolated values from ARWIS stations. In addition, the capability of the data loggers to capture these parameters with each data burst will provide researchers valuable data as well as produce highly accurate models to assist in predicting spring thaw.

# Introduction

Application of spring or seasonal load restrictions (SLR) to certain parts of the highway network can lead to lost productivity and economy. Once these SLR are in place, the payload of certain heavy vehicles is limited. These restrictions are currently determined through certain date thresholds in Ontario. Conversely the application of winter weight premiums (WWP) can provide increased capacity. The Ministry of Transportation of Ontario (MTO) provides information and details on those highways that have SLR through their Schedule 2 (King's Highways) and Schedule 3 (Local Roads Board) listings. There is a need, both economic and structural, to accurately determine the specific thresholds to optimize the movement of goods.

The purpose of this report is to provide a summary of the goals of this research, a description of the state-of-the-art, describing key theoretical information pertaining to SLR and its effects, a description of the study sites and field instrumentation installed, issues encountered and method of resolution pertaining to the study sites, preliminary freezing and thawing models are developed, and recommendations are provided for the successful completion of Phase II of this project.

The two study sites are located in Northern Ontario. In Northeastern Region, the site is located on Highway 569, 3 kilometres east of Highway 11. In Northwestern Region, the study site is located on Highway 527, just north of Highway 811. Both sites have seasonal load restrictions enforced, both have a high number of heavy vehicles traversing the facility, and both are surface treated roads.

# Literature Review

## BACKGROUND

The cyclic nature of climates over a year provides challenges to transportation agencies. It is this variation in climate that will influence pavement performance. A high amount of moisture within the pavement structure will lead to a weakening of the structure. As the temperature drops in the pavement structure, the moisture that is present will condense and form ice lenses. Melting of such lenses within the pavement structure and subgrade will reduce the carrying capacity and result in permanent deformation.

The majority of severe damage occurs at the on-set of spring caused by the heavy loading on the pavement structure. In many jurisdictions, restrictions are placed to reduce the upper load limit in order to mitigate this damage. This is known as a spring load restrictions (SLR). Although the majority of arterials and freeways do not have these SLR applied, many secondary and tertiary roads have seasonal restrictions due to the design and types of vehicular traffic using such roads. Enforcing such restrictions provides economic hardships to the transportation industries, including forestry and mining.

On the contrary, during the winter months, the strength of the pavement structure increases as a result of frost development and provides the ability to carry an increased load without significant damage. This is known as a winter weight premium (WWP) whereby an increased upper limit is temporarily allowed during the winter months when the pavement structure exceeds the initial design strength. Therefore, it is beneficial, not only to the industries but also to the transportation agency, to ensure SLR and WWP are enforced over the proper time frame. The following report focuses on utilizing instrumentation to assist in developing a correlation between air temperature and frost depth. Ultimately this relationship will assist policy makers on when to enforce and lift these WWP and SLR.

The mechanistic empirical pavement design guide (MEPDG) will be used in the analysis. As the MEPDG has been used to determine long term pavement effects based on climatic, subgrade and pavement structure properties, this application can assist in understanding the effects of spring thaw and winter weight premiums on the predicted deterioration of a facility. Subgrade strength is represented by the stiffness parameter or California Bearing Ratio (CBR) value.

## PURPOSE OF LITERATURE REVIEW

A literature review was conducted to provide justification of the proposed methodology. In addition, understanding the dynamics of pavement materials and climatic influence, economic impacts to the highway agency, private companies and the public will be realized. Firstly, the construction of the pavement structure will influence the durability and the upper weight limit allowed on a particular road system. The upper weight limit is a function of freeze-thaw effects. This will result in both positive and negative impacts to industry through winter weight premiums permitted and spring load restrictions enforced. The road agency must ensure pavement damage is mitigated. Understanding these interactions will provide a basis for developing an optimal solution for all concerned.

## PAVEMENT STRUCTURE

Developing a proper pavement structure is essential to provide a long lasting, smooth riding surface. There are several common categories of pavement including flexible, rigid and composite. Each type will have advantages and limitations depending on its application. Differences are found in the surface layer, while most of the structural layer generally remains constant between pavement types. The purpose of the layers is to provide adequate structural capacity and drainage to the pavement structure. Figure 1 illustrates the general layering of flexible pavement.

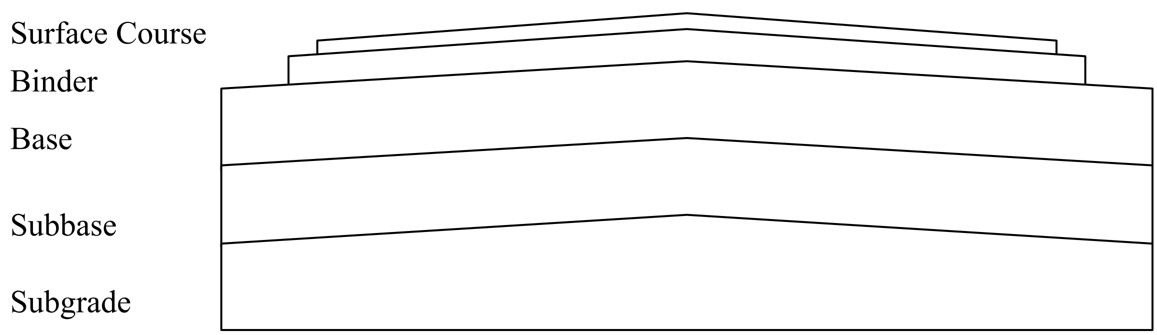


Figure 1. General structure of flexible pavement.

Subgrade consists of the native soil in the area. This can range from organic matter to bedrock. The remaining pavement structure rests on top of the subgrade. Therefore geotechnical investigation to determine stability, carrying capacity and magnitude of settlement must be completed at the engineering stage of highway construction. Removal of undesired material such as clays, is often performed to ensure adequate long term performance [TAC 1997, Craig 1997].

Supporting the pavement are the base and subbase layers. The material employed in these layers are typically granular aggregate material. Examples include dense graded granular base or subbase, treated granular base or subbase and permeable open graded drainage layer [TAC 1997]. The style and material employed in the base or subbase layers will depend on the application and requirements of the design. Treated bases provide increased strength given a reduced amount of granular material being used. Open graded drainage layers can be employed in areas of high precipitation to facilitate rapid standing water removal from the pavement surface.

The asphalt layers can vary in terms of composition depending on application. The purpose of these flexible layers is to resist shear as a result of vehicle loading. Performance of the asphalt can be quantified by identifying and recording low temperature cracking, permanent deformation (rutting, shoving, etc.), fatigue cracking, moisture sensitivity and stripping, and aging of asphalt or aggregate system [TAC 1997].

Rigid or concrete pavements are typically found in high traffic areas and in areas where heavy vehicles are near stationary resulting in a strong likelihood of rutting for asphalt pavements. Load transfer of rigid pavements is opposite to that of flexible. As there is a high modulus of elasticity, any point load exerted on the rigid pavement surface is distributed over the entire area below of the slab.

Within Canada, two thirds of the highway network is comprised of gravel, low-volume roads essential to specific industries requiring remote access to natural resources such as forestry and mining [Tighe 2004]. As vehicles using these facilities are typically heavy commercial trucks, the need exists to attempt to mitigate damage. Therefore focus is primarily on flexible pavements with thin overlays.

## BACKGROUND

Paved roads represent the largest in-place asset value of transport infrastructure in most countries. Preventing accelerated depreciation of this asset while simultaneously providing a desired level of service to the road users, presents a major challenge to pavement engineers. One of the largest challenges in Canada is to design a pavement structure that resists such damage caused by seasonal effects. Over the past several decades theoretical and experimental research has been carried out to examine details of frost heaving. There is however still limited information available on thaw weakening and how that impacts overall pavement performance. Other additional issues include pavement safety during the period of spring weakening. In order to properly predict when thaw weakening occurs, it is important that the pavement network is properly managed.

A recent analysis of a comprehensive, Canada-wide study on long-term pavement performance has clearly demonstrated that the highest rate of deterioration occurs in wet, low-freeze zones with fine grained subgrades [Tighe 2001]. The term, low-freeze, applies to areas with a high number of freeze-thaw cycles. The reason that increased freeze-thaw cycles result in accelerated deterioration for the foregoing situations is due to frost heaving in the freezing cycle (where the subgrade is saturated) combined with subsequent thaw weakening of the structure. In colder (high freeze) areas, the freezing front progresses rapidly into the subgrade, and stays there until spring thaw weakening (i.e., only one or a very few freeze-thaw cycles). This means that the structure stays strong throughout the winter. The problem with a warmer condition with a larger number of freeze-thaw cycles is usually exacerbated by a freezing front that only penetrates to a limited depth in the subgrade, thereby incurring the uptake of water due to capillary rise, and adding to the frost heave and subsequent thaw weakening [Haas 2004].

Fatigue damage in asphalt pavements weakened by spring thaw can significantly reduce pavement life and serviceability. During the spring thaw, large quantities of water become trapped in pavement layers. Several factors that can contribute to this include: material expansion from drawn up groundwater (via capillary forces) and pavement thaw from surface down to subgrade occurs and saturated conditions do not allow for drainage of the layers [Tighe 2000]. Normally an asphalt pavement structure will behave in such a manner that the load is transferred through the structure as shown in Figure 2. However when the pavement structure is partially thawed and saturated, the vertical stress on the saturated layer is transformed into strain as the stress cannot be transferred down into the subsequent layers. In this state, the pavement structure will be subject to load related deformations. The worst case occurs when the thaw enters into the subgrade as the pavement structure experiences a very severe loss of strength. When heavy loads are repeatedly applied to the pavement in the weakened condition, extensive fatigue damage can occur [Gough 1985]. Thus, measures that can adequately predict weakened state can provide cost savings and reduce damage to pavement life. In short if heavy truck loading is minimized or eliminated during this period, it will mitigate fatigue damage associated with thaw weakening.

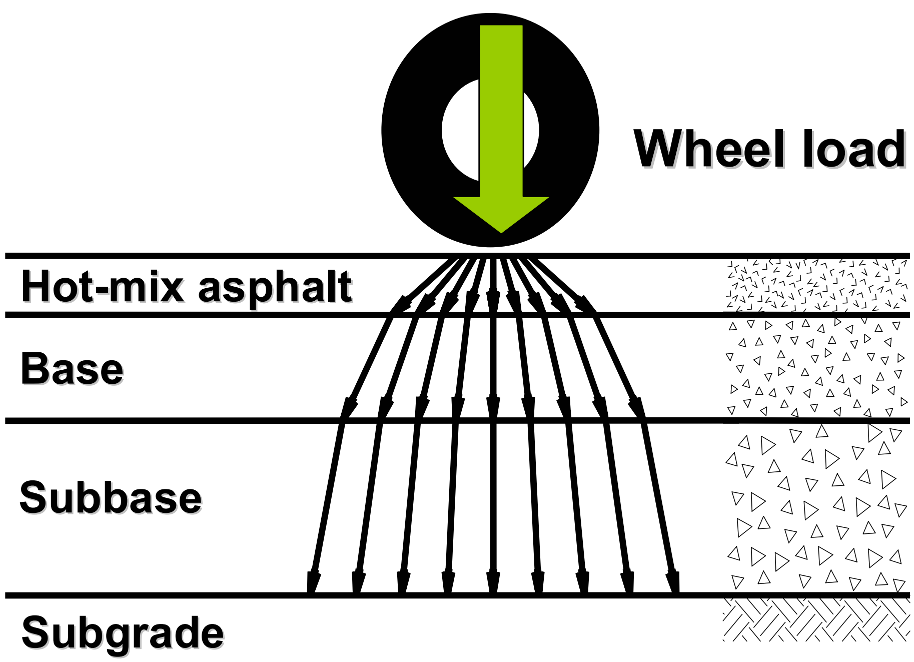


Figure 2: Flexible Structure

## Role of Load Associated (Traffic) Data

Another critical aspect in monitoring pavements is to properly estimate the number of loads and respective weight of each load. Pavement service life depends to a large degree on the traffic levels to which it is subjected [TAC 1997]. The pavement damage resulting from each load is dependent on truck axle distribution, tire load and pressure, axle weight and the stiffness and thickness of each pavement layer. The most accurate method of determining the number of Equivalent Single Axle Loads (ESALs) carried by the pavement structure is to measure axle loads using equipment such as weigh in motion (WIM) devices. Several generalized relationships have been developed for various provinces in Canada and can be found in [TAC 1997]. It is critical that traffic data be collected. More specifically, designers and managers need to know the gross vehicle weights, axle load spectra and spacing. If the traffic loading is known, then this can be co-ordinated with the pavement structural data to ensure that the roads are not being overloaded during the weakest periods of the year.

Other types of devices can be installed in the field to measure pavement structural response under load. One such example of using in-situ measures includes a study that was carried out in Alberta by Alberta Research Council [Christian 1985] where five full depth asphalt pavements ranging in thickness from 150mm to 280mm were placed with instrumentation to measure total surface deflection and interfacial strains imposed by traffic loadings was installed at each site. The test sites consisted of sheet asphalt plates with embedded wire resistance strain gauges, to measure horizontal strains and surface set linear variable differential transformers (LVDTs) to measure total deflections. The asphalt plates were prepared in the laboratory. Each plate was 150mm square by 12mm thick and contained two 120 ohm strain gauges. Both strain carriers and differential transformers were installed in triplicate and placed in the outer wheel path as shown in Figure 3, Figure 4, Figure 5 provide show the cross sectional views of the strain transducers and deflection transducers. To ensure the transducers are not damaged during construction special pre-cautions are taken. In addition thermocouple strings are installed to monitor temperature at the pavement surface, one-third depth, two-third depths, at the base of the pavement surface layer and at intervals of 0.3m and 2.7m below the pavement surface. Measurements are recorded every twenty minutes [Christian 1985].

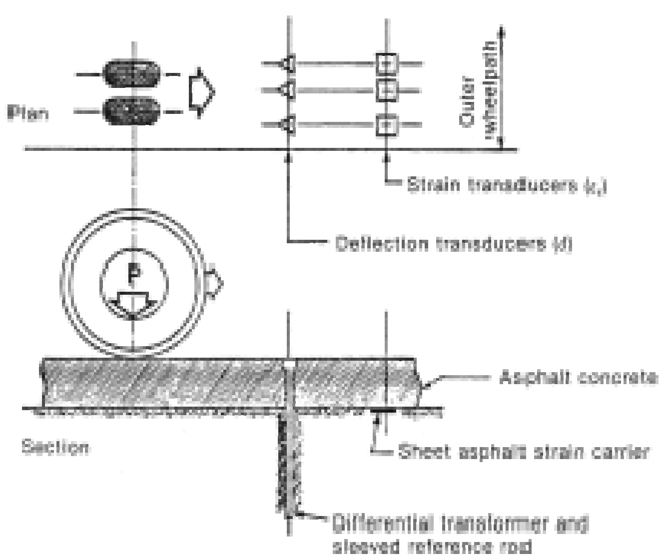


Figure 3: Schematic of Field Instrumentation

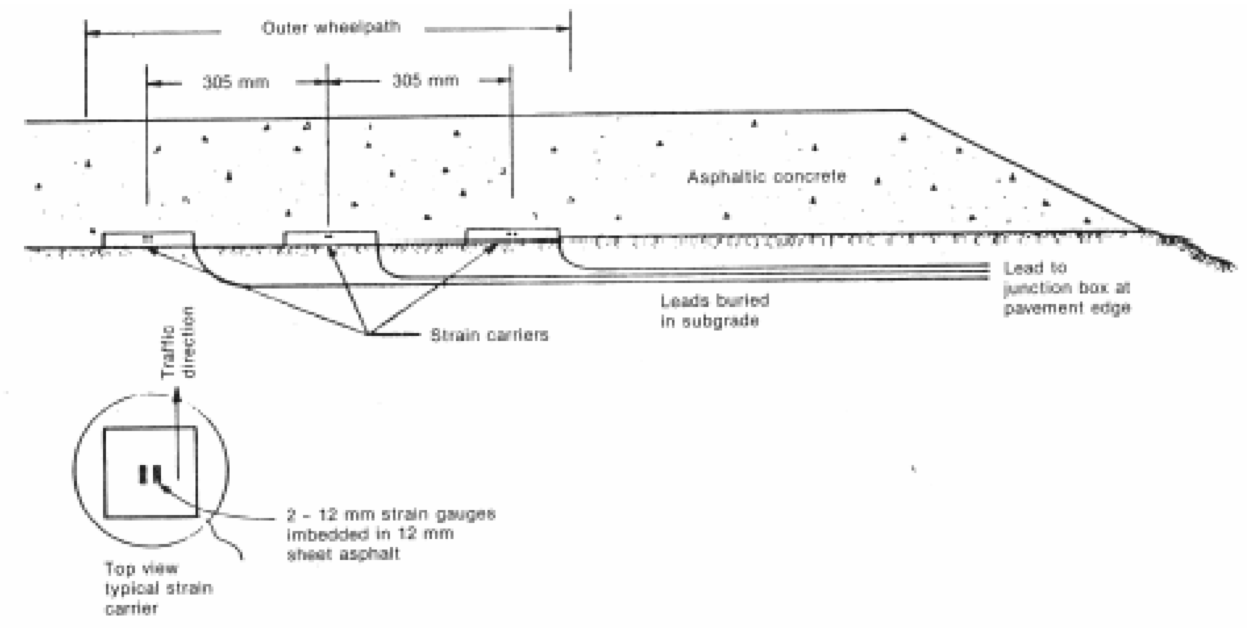


Figure 4: Strain Transducer Installation

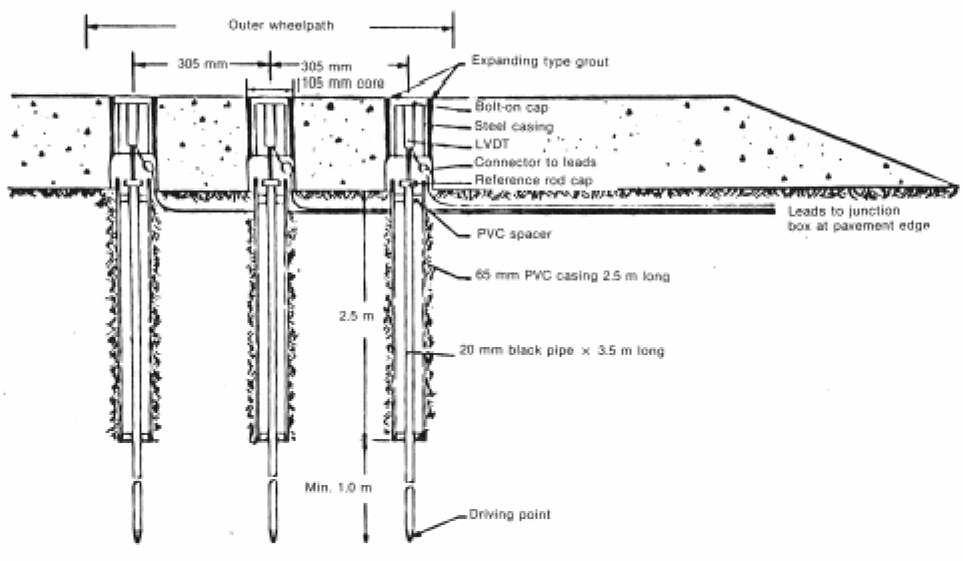


Figure 5: Deflection Transducer Installation

Overall the test sections in this example provided information on the effect of axle loads and loading configurations. It provided load equivalency factors for approximately 110 different traffic loading conditions based on pavement deflection and interfacial tensile strain measurements. In a more general sense, by using instrumentation and data acquisition systems, transportation agencies can calculate total surface deflection and pavement strain at various conditions under conventional and non-standard traffic loads. Furthermore, the influence of axle load and loading configuration on the pavement deflection and strain can be calculated. Using relative comparisons to non spring and spring time conditions, and assuming that pavement distress is a function of the response variable, in this case deflection and strain, the potential destructive effects on traffic load can be assessed. In short, it is not only essential to have information on the environment, it is also critical to have information on the truck loading and how it impacts the in-situ pavement structure and each respective layer.

## Role of Strength (Deflection) Data

Many transportation agencies base their imposition of load restrictions in visual observations of conditions such as water pumping, near cracks and shoulders. One disadvantage to this is that often once surface damage occurs, significant damage has already occurred in the lower layers.

Deflection data needs to be adjusted to account for variations in pavement layer properties relative to temperature, frost and moisture conditions. Temperature is the most significant factor impacting the modulus of asphalt. The stiffness modulus can range from 10 to 15 GPa at 0-5 °C while at high temperatures, it can be as low as 750 MPa to 1 GPA. Consequently, deflection tests must be normalized to a standard temperature. This reference temperature is usually established as 21°C. The adjustment is carried out for asphalt only and not for unbound materials as stiffness is typically not significantly affected by temperature. However, if the pavement is located in an extreme climate adjustments should be considered [TAC 1997].

Moisture has little effect on asphalt however, it does impact both the unbound base layers and subgrade. The presence of moisture can have a significant impact on the lower pavement layers as it can reduce the modulus and result in lower spring recovery periods. In addition, if a layer is saturated, it will make it difficult to properly interpret the pavement deflection basin. It is noteworthy that the moduli of wet fine grained soils can be as low as 20-30 percent of their summer values. Thus, similar to temperature, a spring reduction factor is applied to deflection data to adequately address subgrade type and moisture condition. Some consideration should also be given to a saturated unbound layers if they arte known to be weak during spring thaw. However, moisture adjustments are typically just applied based on the subgrade type [TAC 1997].

The effects of traffic loading on the structural integrity and service life although understood in a qualitative sense, are not fully quantified using state of the art mechanistic tools [Clayton 2000]. This discussion herein focuses on the current state-of –the-practice with respect to deflection data measurement and attempts to provide a basis for subsequent needs. Examples of the use of deflection data for spring load restrictions is provided.

The best known procedure which is based on Benkelman Beams is the Canadian Good Roads Association[CGRA 1962] method. The procedure was based on the relationship between deflection, actual pavement rebound and pavement life. During this initial study, approximately 2,500 pavement inventory sections from across Canada were evaluated. The following year an addition 3,000 sections were inventoried. Overall, pavement performance and strength over time were measured. Some sections had spring load restrictions while others did not. Sections with similar design conditions (ie. Traffic, subgrade soils, pavement thickness, etc) were compared using a statistical analysis. This resulted in the development of load restrictions through monitoring deflection. The study was very thorough and established several important concepts in design [CGRA 1962]. Several agencies still use this today as a basis of setting load restrictions. It should be cautioned that the Benkelman Beam is a static device and does not simulate traffic loading [TAC 1997].

Various agencies still use the Benkelman Beam Rebound (BBR) value as a basis for establishing spring load restrictions. Manitoba Transportation and Government Services (MTGS) has continued to improve and modify their spring load restriction practices since 1997 as detailed in [MHGS 2004]. The system uses a combination of Benkelman Beam Rebound Existing (BBRE) measurements to determine when the pavement is in the weakest state. If a pavement is 15 years or older and is shown to have a BBRE of more than 1.5mm but not exceeding 2.5mm then it warrants a spring road restriction. If the pavement has a deflection of greater than 1.65mm and is less than 15 years of age then it warrants a spring road restriction. Note, only RTAC secondary arterials and collectors as well as non RTAC Expressways and primary arterials are restricted while RTAC Expressways and primary arterials are not restricted.

The MHGS has also used a delayed start date as opposed to using a correlated Thawing Index (TI) (note this is an adjusted index which uses energy absorbed by the pavement due to solar radiation) to supplement the BBRE. This method uses a reference temperature and daily incremental temperature to determine the start date of spring load restrictions. This method, which is a modification procedure as suggested by the Minnesota Department of Transportation (MnDOT) as outlined in [MnDOT 2000]. The MTGS uses a reference temperature (RT) on March 1$^{st}$ of every year and the daily incremental temperature is assumed to be 0.1°C. The RT is added to a daily Thaw Index (TI) on a daily basis. Once the TI exceeds 15°C and the forecast according to Environment Canada indicates continued increases in the TI then the spring road restrictions are applied. Note, provincial monitoring is divided into two areas based on climatic conditions. Essentially if the TI indicated that the fixed date is premature, then the TI takes precedence [MTGS 2004].

British Columbia Ministry of Transportation also uses BBR to establish spring load restrictions. The restrictions are based on 50 to 60 pavement sections that were monitored for several year during the spring thaw in the late 1970's. Each test section had ten test points and were tested every week from the start of thaw to the end of the pavement recovery period. These sections were paved down in the early 1990's to approximately 30 sections. In addition to taking BBR measurements, frost tubes and thermometers were also installed. The maximum rebound (adjusted to 10°C) set at 1.6mm while others are established at 1.25mm. The BC system establishes spring load restrictions based on structural capacity, the conditions from the previous fall and whether or not it was wet or dry, amount of snow cover during winter and temperature during the spring including timing and duration of any warm weather. The main highways are usually restricted to 100% of the legal axle load, secondary highways 70% of the load and roadways in poor condition to 50% with details being made available on their website [Hein 2002].

In the 1970's, the Dynafleet and Road Rater were introduced in an attempt to improve speed. These tools also enabled transportation agencies to better examine damage by providing information on the deflection basin. This provided better indications of strength in the various pavement layers during thaw weakening. Various moduls were developed by Kelvin, Boussinesq, Burmister, etc. [Goodings 2001] to assess the stresses and strains in each respective layer. This resulted in a capacity to better predict damage from thaw weakening.

The City of Ottawa still uses the Dynaflect as a basis for establishing their spring load restrictions. The program involves testing eleven sites located across the City of Ottawa. Each site is 550m in length and has marked test locations within the site. Each site is tested weekly starting in February. The data is corrected for temperature and readings are based on average Sensor One value for each week. A plot, as shown in Figure 6 results for Winter 2004 is constructed. The City has established 0.92miles/sec, as the threshold deflection. This is related to the inflection point where the strength gain begins to plateau after the thaw has ended. This threshold is used for both the removal and implementation. Also, the city publishes a maximum end date, for 2004 it was May 17 so that businesses can plan accordingly. This date does vary from year to year depending on the thaw. For example in 2002, the removal of restrictions occurred April 29th [Goodman 2004].

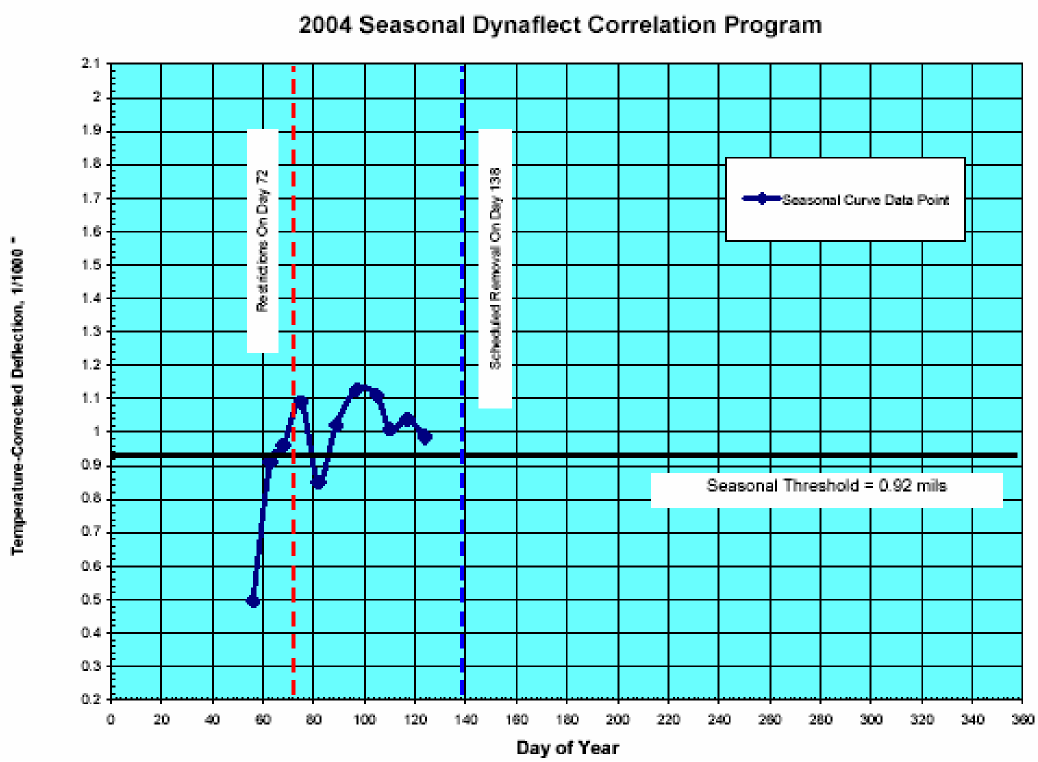


Figure 6: Seasonal Dynaflect Correlation for City of Ottawa

Although the Dynaflect can be a useful tool, one primary drawback is the device operates at low vibrating loadings. It therefore does not provide a sufficient level of detail to evaluate materials at lower layers. They have also been known to result in liquefaction of soil near saturation and thus unrealistically high damage predictions.

The falling weight deflectometers (FWD) is an impact device and is the device of choice based on speed of testing, accuracy and safety of operators. This device has enabled for various transportation agencies to better understand the impacts of thaw weakening and more specifically it is now known that maximum pavement damage can occur shortly after thawing begins. Due to the cost associated with testing, various agencies use FWD to complement air and ground temperature readings.

Ministry of Transportation of Quebec (MTQ) has used FWD to determine periodic load readings on selected pavement sections within their network. The seasonal damage is then calculated for various time intervals during the year. Factors that MTQ takes into account include [St. Laurent 2002]:

- Climate temperature, freezing, thawing (surface water, precipitation, melting snow and ice, state of stress)
- Properties of the Pavement Layers : thickness, resilient modulus, fatigue strength
- Pavement Deterioration Indicator: strain, structural number, surface curvature index

The FWD is used to measure deflection and subsequently the resilient modulus values are calculated using elastic layer theory for each respective layer. The resilient modulus values are then used to calculate pavement deterioration indicators and seasonal variations. MTQ also considers the subdivision between thawed layers and frozen layers in the analysis, as shown in Figure 7. These depths have been pre-established using frost tubes. It is noteworthy that the presence of firmer frozen layers in the lower portion of the pavement structure needs to be considered in the back calculation analysis, otherwise calculated resilient modulus values will be incorrect [St. Laurent 2002].

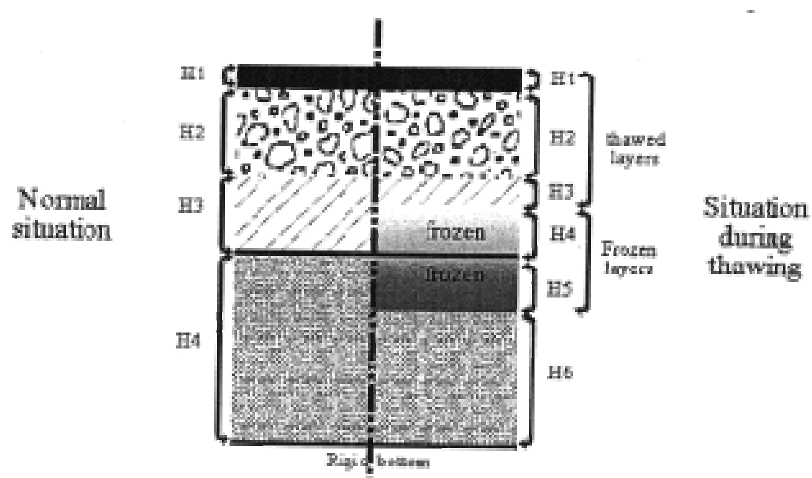

Figure 7: Subdivision of Layers for the Purpose of Back-Calculation During Thawing

The resilient modulus is then used to calculate deterioration factors based on the climatic conditions and properties of the pavement layers. Deterioration is calculated in terms of elongation at the pavement base, surface curvature index (related to fatigue cracking) and vertical strain (associated with rutting [St. Laurent 2002]. In addition, MTO considers deterioration related to the serviceability as a pavement quality index, the structural number and the resilient modulus. The MTQ then develops relative deterioration profiles related to specific times of the year when damage can occur. Data from weigh in motion (WIM) scales are also used to supplement the analytical analysis. The seasonal profile including the type of vehicle, ESAL, number of passages, number of axles and weight per axle is taken into consideration [St. Laurent 2002]. MTQ also has determined that significant damage does occur outside the spring thaw restrictions. They have also examined the duration of restrictions, deterioration in spring and summer (which is based on correlations between the dynaflect deflection and the surface curvature index), and environmental effects on pavement serviceability. Overall, the MTQ does use FWD in combination with theoretical simulations to estimate spring damage and establishes restrictions accordingly [St. Laurent 2002].

Alberta also uses FWD to monitor strength recovery to determine when spring load restrictions can be removed. The FWD evaluations are converted to equivalent Benkelman Beam rebound values using historically developed models [Lew 2000].

In the future it would be expected that heavy vehicle simulators, rolling wheel simulators and other devices could be used to better understand relationships. These devices and additional developments in laboratory devices will be used to also test new design alternatives [Goodings 2001].

The use of deflection equipment to better predict when load restrictions should be applied and removed will result in tremendous cost savings to transportation agencies. Furthermore, proper documented technical rationale and research into this area is required. The risks and associated benefits need to be quantified and understood especially in light of the recent climate changes. With these changes, there needs to be a better method of applying and removing restrictions which is not related to calendar dates but rather real time temperature and pavement data.

## Role of Environmental Data

The design of pavement sections in cold regions involve additional aspects that may need to be included in the conventional design approach, these include [Mokwa 2004]:

1. Evaluation of the depth of seasonal freezing.
2. Consideration of changes that may occur in the active layer as a result of changes in the thermal and hydraulic regime.
3. Potential damage as a result of frost heave deformation.
4. Differential settlement caused by changes in soil strength and compressibility as a result of

freeze/thaw cycles.
5. Deformation and consolidation settlement as a result of thaw.
6. Creep in ice-rich soils and permafrost.
7. Thermal interaction between the structure and the ground.
8. Thermal aspects of backfill material.

Mechanical properties of subgrade soils are greatly affected by seasonal changes in temperature and soil moisture. This compounds the difficulties in determining an accurate value of soil modulus for projects constructed in cold regions. In addition to pavement distress caused by the freezing and heave phenomena, excessive damage may occur in cold regions during the spring as a result of thaw settlement, reduced bearing capacity, and increased compressibility [Mokwa 2004].

Another recent study by Dore et al [Dore 2004] suggests that the three most important factors affecting the behaviour of pavements during spring thaw include:

1. The amount of frost heave that occurs per unit thickenss in the considered layer.
2. The rate at which the layer is thawing.
3. The rate at which the layer consolidates.

The work by Dore further suggests that a thaw weakening index should be developed to assist in predicting weakening in the pavement structure. It is proposed as:

$$TWin = (h/D) \times (X/S) \quad (6)$$

Where:
TWin = Thaw weakening index
h = Total heave resulting from frost action in subgrade soil
D = Thickness of subgrade soil affected by frost action
X = Thawing rate
S = Settlement rate

This dimensionless index incorporates several factors that have been identified as being important with respect to the weakening behaviour of a given material. The rate of thawing is identified as a function of the climatic conditions during spring, and the resulting thermal response of the material. In addition, the consolidations and volume change is incorporated into the prediction [Dore 2004].

The TWin then needs to involve a field validation which includes collection of the more specific site data [Dore 2004]:

- Thickness of the frozen soil layer (frost depth)
- Total frost heave (assuming no significant frost heave occurs in the pavement granular layers)
- Thaw progression as a function of time during the spring

- Relative elevation of the pavement structure as a function of time during spring thaw and the associated recovery period
- A measurement of the evolution of the pavement bearing capacity with time.

When thermal considerations are important, a conventional deterministic design approach may not adequately address the additional uncertainties introduced when temperatures drop below freezing. A probabilistic approach may be necessary to quantify the additional risk and uncertainty in design. Probabilistic methods such as the Monte Carlo statistical approach provide a means of rationally addressing inherent uncertainties in soil thermal properties, spatial variability of subsurface geomaterials, and stochastic variables including weather and soil pore water pressures.

Air Temperature

Weather, air temperature readings, and ground cover information are important input parameters to a quantitative frost heave model. The temperature gradient below the ground surface and the penetration of the freezing front depends in part on the magnitude and duration of the temperature differential at the air-ground interface. The air-freezing index (FI) is used to quantify the combination of freezing temperatures and duration of freeze. Other useful freeze-index parameters are the duration of freeze (number of days) and the mean annual temperature, which is usually obtained from the mean of the average daily temperatures. Similar types of parameters can be developed from weather data to analyze thaw characteristics at a site [Mokwa 2004]. A commonly used index is freezing or thawing index (FI or TI) which is calculated as

$$FI=\sum(0°C-T_{mean}) \qquad (7)$$

Where FI= Freezing Index

$T_{mean}$ = mean daily temperature

°C=1/2($T_1$+$T_2$)

$T_1$=maximum daily air temperature, °C

$T_2$=minimum daily air temperature, °C

$$TI=\sum(T_{mean}-T_{ref}) \qquad (8)$$

Where $T_{mean}$=mean daily temperature

$T_{ref}$=reference freezing temperature that varies as pavement thaws, °C

Minesota DOT has developed detailed guidelines on implementing spring road restrictions based on TI and reference temperatures during February and March at Several locations in the state [MnDOT 2000].

Ground Surface Temperature

Ground surface temperatures are different from air temperatures because of the effects of surface cover (i.e., asphalt, concrete, etc.), snow, solar radiation, wind, humidity, conduction, and convective heat transfer can be accounted for [Mokwa 2004].

For paved roads in cold regions, the surface temperature is an important measure and should be taken and used to determine FI. However, when measured ground temperatures are not available, an empirical surface correction factor index called the *N* factor can be used to convert the air FI to an approximate ground surface FI. The *N* factor is the ratio of surface-freeze index to air-freeze index. Approximate empirical values are often used in the absence of measured data.

The *N* factor approach is simple to use; however, as can be seen from the wide variation of *N* factors in this example, variables in addition to cover type need to be considered for improved accuracy. Because ground surface temperatures constitute the backbone of the analytical model, it is clear that a more refined and repeatable method for estimating ground surface temperatures would improve the accuracy of the frost heave predicative model [Mokwa 2004].

Subsurface Temperature Gradient

A number of methods are available for estimating the thermal regime (rate of freeze or thaw and temperature gradient) at a site. These can include methylene blue frost probes, thermometers, moisture sensors, prezometers and various other methods. The subsurface gradient is extremely important for assessing frost heave in the various layers and the associated rate of consolidation [Dore 2004].

Role of Environmental Data Collection and MEPDG

It is likely that the new AASHTO 2002 (also known as the Mechanistic Empirical Pavement Design Guide - MEPDG) design program will have a preformed effect on pavement design in Canada. A brief summary of environmental data requirements is presented herein. It is included in this report as it is likely that some co-ordination between data needs for pavement design and spring road restrictions can be achieved.

The MEPDG system has a revised set of standards for pavement design which include a variety of data. Required hourly information is air temperature, precipitation, wind speed, percentage sunshine (used to define cloud cover) and relative humidity. Data is also necessary in these four broad categories; general information, weather-related information, ground water related information, drainage and surface properties and pavement structure and materials [AASHTO 2002].

Most pavement designs attempt to design the pavement structure to mitigate both environmental and load associated (traffic) damage. For the purpose of this report it will focus on environmental considerations. Several design features attempt to mitigate environmental damage. These include: removal of fine grained soils prior to paving, addition of subbase and base layers to add protection for frost and the addition of drainage systems. Ultimately, pavement designers attempt to mitigate distresses by designing pavements that resist damage associated with both the environment and traffic.

Climate Data Available From Environment Canada

Environment Canada offers hourly climate data online for several Canadian cities. Daily and monthly data is also available as well as climate normals and averages. Hourly data is given for temperature, dew point temperature, relative humidity, wind direction, wind speed, visibility, station pressure, humidex, wind chill and general weather condition (rain, snow). Daily data is available by Environment Canada from January 1953 to present. Averages and normals are available for all major cities across Canada. The information for averages has been gathered from 1971 to 2000. Data that is provided includes daily average, standard deviation, daily maximum and minimum, extreme maximum and minimum, type and amount of precipitation and extreme amount of precipitation. All this information is averaged for every month. Days are also sorted by amount of precipitation received and temperature.  By using the hourly and archived data in the Environment Canada database, weather for future years can be estimated with confidence. This summary has been based on data that is available through the Environment Canada Website [EC 2004].

Figure 8 shows the larger cities that weather data is available daily by Environment Canada. Information is also available for smaller cities within each province and territory as well.


Figure 8: Map of Environment Canada Weather Stations

Since 1995, the Canadian Meteorological Centre has been creating seasonal outlooks for March $1^{st}$, June $1^{st}$, September $1^{st}$ and December $1^{st}$. The seasonal outlooks for three months in advance look at surface air temperature as well as precipitation. The air temperature predictions are divided into three categories, above, near and below the normal. Similar to the air temperature the precipitation is also divided into three categories, above, near and below normal.

To predict three to nine months in the future a statistical model called Canonical Correlation Analysis (CCA) is used. CCA predicts surface air temperature and precipitations for up to nine months in advance. The sea surface temperatures (SST) from the previous twelve months act as the main force in the predictions. Forecast of the next three to nine months are available for 51 stations for temperature and 69 stations for precipitation. These stations were chosen with the intent of being uniformly spaced across Canada.  This seasonal information along with the hourly and archived data would be useful is predicting spring loading restrictions.

Along with Environment Canada collecting hourly data across Canada all aviation sites also collect hourly data. Environment Canada strives to keep a diverse range of clients up to date on the environment conditions in their country. By using the internet they try to reach more individuals with timely and accurate information. Aviation research is done to help insure all relevant data is available to ensure safe transportation and operation at the airports.

## FREEZE-THAW PHENOMENON

Location of freeze-thaw areas is wide spread not only in North America, but also internationally. It is a function of the type of precipitation that exists, the lower temperature limit that is reached and the type of soil in the area.  An area where the frost depth penetrates and remains in the subgrade until the spring thaw, with relatively few freeze-thaw cycles, is termed a high freeze area.  Similarly, an area whereby the frost depth does not penetrate deep into the subgrade with a relatively high number of freeze-thaw cycles is termed a low freeze area.

Within Canada, areas that are classified as wet, low-freeze zones with fine grained subgrades are considered most susceptible to damage as a result of a high number of freeze-thaw cycles [Tighe 2004].  It is important to understand the causes of these cycles and the impact to pavement performance and deterioration.  Tighe [2004] and Haas [2004] note that a large amount of damage is caused by frost heaving during the freezing cycle.  As the pavement surface temperature drops, the subgrade temperature gradient will be similar to that of Figure 9.

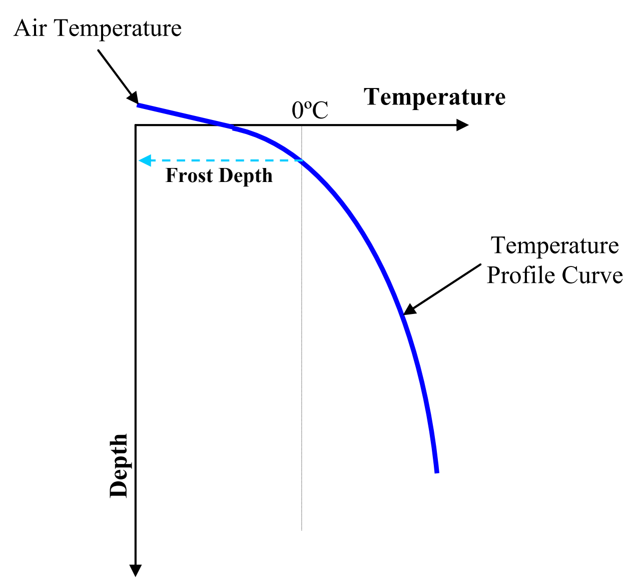

Figure 9. Typical temperature profile considering air temperature and subgrade temperatures.

The freezing of the subgrade will occur from the top-downwards. The rate of frost penetration is a function of the air temperature and the moisture in the soil.

The cyclic freezing and thawing introduces fatigue damage to the pavement structure. Capillary forces and lack of drainage through the pavement structure due to top down thawing are examples of factors that contribute to freeze-thaw fatigue and damage [Tighe 2004, Tighe 2000]. In the event thawing occurs in the pavement structure, as vehicle loading is not distributed and transferred as per the design, deformation of the pavement structure occurs. If the thaw progresses into the subgrade, significant strength reduction occurs resulting in the need of spring load restrictions to be enforced to mitigate damage.

The freeze-thaw effect can lead to significant volumetric changes within the structure over a short period of time. Industries relying on the road network to transport goods can find a significant advantage after the freezing period in winter has reached a steady state. Once the temperatures begin to rise, the subgrade is susceptible to damage due to a decrease in structural carrying capacity. In other words, the excess moisture reduces the maximum weight permitted on the road before deformation occurs.

## Moisture Related Issues

In the event moisture is not allowed to drain from the pavement structure, the consequences can become severe. In terms of structural adequacy, moisture induces consolidation that will negatively affect the pavement surface. The frost that accumulates underneath the pavement structure increases the structural capacity as the moisture freezes. However, during the spring thaw, top-down thawing will occur when the pavement surface temperature is consistently above the freezing temperature. This will allow the soil near the pavement surface to thaw and translating ice to liquid water. As the soil below this liquid moisture is still frozen, this liquid is trapped and not permitted to be drained as normal. The result is a compromised pavement structure that is saturated with water. Figures 10 and 11 provide an illustration of the movement or lack of movement of moisture in the pavement structure and subgrade.

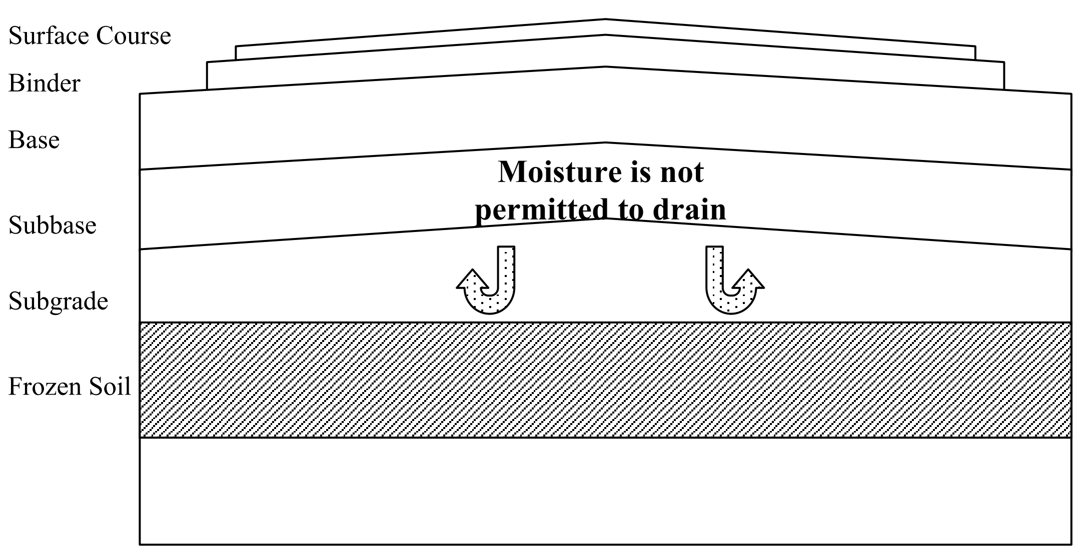

Figure 10. Illustration of the water movement during spring thaw.

During the spring, the melting of the ice lenses and the additional moisture from rain and melting snow causes the subsurface layers to become saturated. This saturation decreases the bearing capacity of the pavement layers. Excess moisture in either the pavement or the supporting structure changes the modulus of the layers which affects the resistance to deformation. The result is potential damage in the form of potholes, alligator cracking, or rutting. The extent of damage caused during this period varies, however reports have stated that 90% of pavement damage occurs during this period [Janoo 2000].

In their study, Hanek et al. [2001] concluded that moisture content is a good indicator to trigger the lifting or removal of load restrictions. Once the excess moisture has dissipated, the potential damage dramatically decreases. However, it was recommended that prior to resuming “normal” loads on the facility, a safety factor be incorporated on the lifting of the restrictions. In other words, the load restriction is recommended to be in place one week following the trigger moisture content being achieved. The recovery of the base course modulus and decrease in corresponding damage is gradual, not an instantaneous change at the onset of thaw.

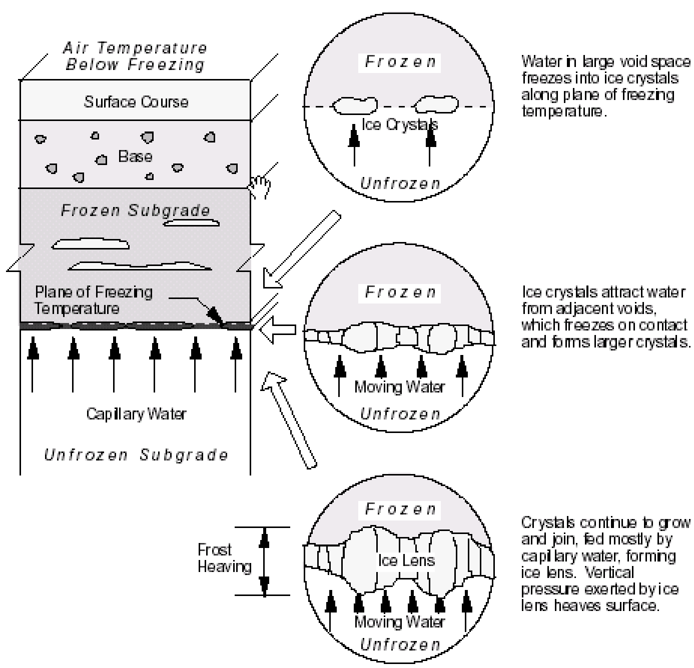


Figure 11. Movement of water and ice in a pavement structure and subgrade. Courtesy of WAPA Asphalt Pavement Guide.

## Temperature Related Issues

Another factor related to a compromised pavement structure is the increase in ambient temperatures. This warming trend heats the ground surface leading to a gradual thaw of the subgrade. An increase in subgrade moisture content will result. At the same time, as the heave subsides and the base and soils begin to consolidate, a dramatic decrease in pavement strength occurs. Soils and aggregate base materials are in a weakened state during and immediately following the thaw period. [Goodings 2000]

The mechanism that causes frost heaving is related to the volumetric expansion of moisture in the soil forming ice lenses also known as ice segregation. These ice lenses are formed from the top downwards and are a function of the material and environmental thermal and hydraulic properties as well as the type and magnitude of stress applied to the area [Tighe 2004]. There are three primary categories of frost heaving including capillary rise theory, secondary heave theory and segregation potential theory. The following was adapted from Tighe [2004] and Mokwa [2004].

Capillary Rise Theory

Capillary rise theory was introduced by Martin in 1959. The theory is that negative pressure, as a result of the ice formation, induces suction at the ice-water interface. Capillary rise is driven by surface tension at the interface between ice and pore water [Rempel et al. 2004]. The result is water movement towards ice lenses. Figure 12 illustrates the movement of water towards the ice formation.

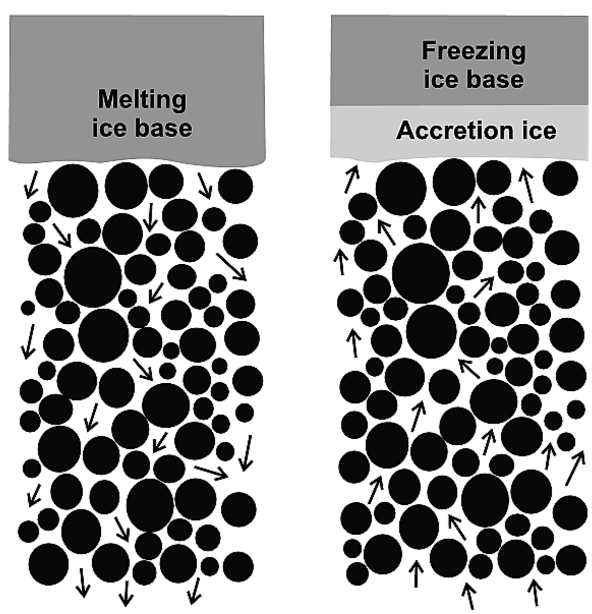


Figure 12. Illustration of water movement due to capillary action [Christoffersen and Tulaczyk, 2003]

Secondary Heave Theory

Ketcham and Black [1995] describes the division of a body of soil into three regions based on a theory developed by Miller in the 1970s: already frozen, frozen fringe and unfrozen. A frost fringe is an area whereby ice and water coexist in the pores of the soil. In the event these three layers exist, this comprises the Secondary Heave theory. The premise of this theory is that water travels through a frost fringe which is an area that is partially frozen. Modeling the rate of water migration is a limitation of this theory as it is difficult to predict pressures, material properties such as hydraulic conductivity, within this fringe area.

Secondary frost heave is characterised by the existence of a partially frozen zone, underlying the frozen soil, in which ice and water coexist in the pore space, also illustrated in Figure 13.

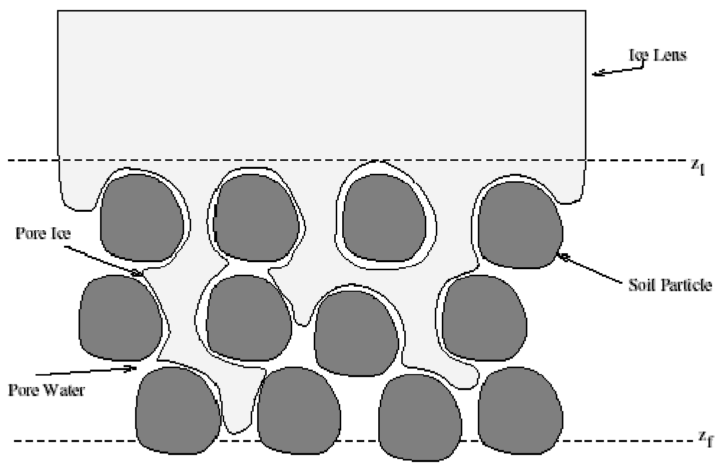


Figure 13. Illustration of the frost fringe or ice lens pertaining to the secondary heave theory [Noon 1996].

Segregation Potential Theory

Uneven heat flow at the frost fringe as a result of various temperature changes is the basis of this theory. The segregation potential theory attempts to simulate the heat and mass transfer in frozen soil based on laboratory tests.

This theory is defined as the ratio of moisture migration to the temperature gradient in a frozen soil near the 0°C [Watanabe 1999]. Water flow is the result of suction at the growth surface of the ice lens and the hydraulic conductivity, based on the amount of liquid water, near the surface (in the frozen fringe).

## The Freezing and Thaw Indices

The freezing index (FI) is the accumulation of the daily mean temperatures. However, the trigger is when the mean daily temperature first falls below 0°C. At this point, the equation below is employed daily with a constraint that the freezing index must be greater or equal to 0°C.

$$FI = \sum \left(0^{o} C - T_{MEAN_i}\right)$$

During the thawing period, a thaw index (TI) can be used to understand the approximate level of thaw based on air temperature and a reference temperature. The state of Minnesota uses the following equation to determine the thaw index.

$$TI = \sum \left(T_{MEAN_i} - T_{REF}\right)$$

## SPRING LOAD RESTRICTIONS

A pavement structure is engineered to carry an upper limit in terms of loading to balance economics and service life. Implementation of maximum vehicle weights and dimensions for various heavy vehicle types is the result [MTO 1997]. This is based on adequate drainage and the type of traffic utilizing the facility. In the event the regulations are exceeded, damage to the pavement surface and structure is likely to occur [Taylor et al 2000, MTO 1997].

Spring thaw provides a challenge to engineers and highway maintenance personnel. As the carrying capacity of the pavement structure is compromised as a result of excess moisture, deformation and distresses will occur. Kestler [1998] states that a handful of heavy vehicles travelling on compromised pavements can inflict comparable damage as that over one entire year. The result is significant pavement maintenance and rehabilitation costs throughout its service life. One option is to impose load restrictions on the approach and during the spring thaw.

Enforcing load restrictions during this period is perceived to be a cost effective means of retaining an adequate and acceptable service life of a facility whilst mitigating the economic impact of the transportation industry. In fact, compared to designing and construction of a pavement capable of carrying expected stresses regardless of the climate and time of year, enforcing these temporary reduced load restrictions is extremely cost effective [Goodings 2000]. Up to a 9 percent and 14 percent reduction in overall annual facility cost was realized by Levinson et al. [2005] by implementing 7-ton and 5-ton restrictions on affected facilities. Benefits of SLR include increasing the service life of the facility. A United States (US) study found that a 20% and 50% weight reduction during the thaw period is expected to increase the service life by 62% and 95% respectively [Isotal 1993, Levinson et al. 2005].

Each jurisdiction will have their own method to estimate the threshold dates to impose and lift load restrictions. There are three general categories to determine the threshold dates: field testing, prescheduled restrictions and empirical models. All are based on historical data to determine the general time frame to begin detailed analysis concerning frost depth [Goodings 2000 & Kestler 1998].

## Field Testing

One method of understanding the state of the pavement structure is to perform field testing. Field testing requires physical testing at a given facility at regular intervals to provide engineers and technicians an indication of the short term trends. It is important to note that field testing has its limitations.

Deflection testing and visual observations are limited since maximum damage can occur shortly after thawing begins [Goodings 2000]. A methelyne-water solution frost tube can be installed in the centerline of a road to determine the frost depth. Pavement strength measurements, using a falling weight deflectometer (FWD) for example, can also assist in understanding the strength of the facility to bear or carry significant loads [Leong et al. 2005]. The premise of the FWD test is to drop a known weight onto the pavement surface and geophones placed at set distances from the impact site will measure the sound waves emitted from the pavement surface. The basis of these types of testing is to determine the modulus of the supporting structure and whether it has reached a value that will result in permanent deformation if the current loads remain.

In each case, personnel must arrive on site and perform these types of tests. On the approach to application of WWP, measurements are taken frequently. During the frost (WWP) and load restriction periods, the frequency of measurements is increased until the approach of warmer weather whereby daily field testing will be required until the conclusion of the weak period.

Limitations to this include the time required by personnel to perform these tests. Considering the length and vastness of the highway network, travelling to test sites can be onerous and at times dangerous. In the event the testing reveals the critical thaw depth has been reached, the road agency typically must give sufficient notice to the transportation industry to accommodate rerouting procedures. Unfortunately, severe damage may be occurring during this notification stage and the critical thaw depth may have been exceeded during this time frame.

## Prescheduled Restrictions

Many jurisdictions utilize fixed dates to allow WWP and enforce SLR. SLR in Manitoba begin on March 23 and April 15 for the Southern and Northern zones respectively while the restrictions are lifted on May 31. SLR in southern and northern zones in New Brunswick are enforced between the second week in March to mid-May and third week in March to the end of May respectively. Other jurisdictions in Canada utilize a combination of prescheduled restrictions and field testing. For example, in Quebec specific dates are set with respect to the zone (north, central and south). However, it is noted that timing can be advanced or delayed based on field data [Leong et al. 2005]. The Canadian perspective of setting these restrictions is summarized in Table 1.

Table 1. Provincial methods of determining load restrictions [Leong et al. 2005]

| PROVINCE | START/END DATES | TESTING |
|---|---|---|

| | | |
|---|---|---|
| **British Columbia** | **Mid-February to Mid-June** | Frost probes, weather synopsis, Benkelman Beam data for 20+ years, other historical data |
| **Alberta** | **Start Date:** 30 cm thaw and a heat flow model<br>**End Date:** Determined with FWD testing | FWD |
| **Saskatchewan** | **Start Date:** Second or third week of March (weather dependent)<br>**End Date:** Maximum six weeks after start date | Benkelman Beam |
| **Manitoba** | **Start Date:**<br>Southern Zone: March 23<br>Northern Zone: April 15<br>**End Date:** May 31 | Benkelman Beam |
| **Ontario** | Variable start and end dates. Typically first Monday in March to Mid May (Southern Region) | |
| **Quebec** | **North:** March 24 to May 25<br>**Central:** March 6 to May 12<br>**South:** March 21 to May 19<br>Timing can be advanced or delayed based on frost probe data. Start of restrictions at 300 mm thaw and ending at 5 weeks after 900 mm thaw below road surface | 81 frost probes (1.5 m to 3.5 m depth) Measured weekly during freeze, daily during thaw, and then weekly at end of thaw. |
| **New Brunswick** | **Southern Zone:** Second week in March to mid-May<br>**Northern Zone:** Third week in March to end of May<br>Timing varied according to severity of winter and spring conditions. | Dynaflect testing on 40 affected control sections on weekly basis during restriction period. |
| **Prince Edward Island** | **March 1 to April 30**<br>Timing varied according to severity of winter and spring conditions | Dynaflect testing on random sections throughout restriction period. |
| **Nova Scotia** | **Southern Region:** March 2 to April 24<br>**Central/Northern Regions:** March 2 to April 27 | Dynaflect testing on random control sections (all classes) from mid-February to end of April. |
| **Newfoundland** | **February to April** | |

In the United States, several jurisdictions including Washington, Alaska, South Dakota and Minnesota, use deflection tests, measurements of thaw depth, average daily air and pavement temperatures, historical records and engineering experience to assist in determining thresholds of spring load restrictions [MnDOT 2000]. Further detail on SLR in the US is summarized in Table 2.

Table 2. Spring Load Restrictions for Selected US States [Levinson et al. 2005]

| State | Start SLR | End SLR | Restrictions | Justification |
|---|---|---|---|---|
| North Dakota | March 15 | June 1 | Varies between trunk highways and county roads | Deflection measurements and experience |
| South Dakota | February 28 | April 27 | 6-, 7-ton per axle | Deflection measurements and experience |
| Iowa | March 1 | May 1 | No overloads | Road Rater and experience |
| Wisconsin | March 10 | May 10 | No overloads | Deflection measurements and experience |
| Michigan | Early March | Late May | 70% of gross weight for HMA facilities | Experience |
| Minnesota | March | May | 5-, 7-, 9-ton per axle | Design testing and experience |

## Empirical Models

Developing predictive models related to frost depth which relates to application of load restrictions is important to transportation agencies. Empirical models utilize field data to develop a relationship to allow predictive abilities. Instrumentation can be installed to monitor the pavement structure to determine the frost depth with external air temperature recorded by a separate or internal system [Dore 1998]. Once data is acquired, calibration and validation of the proposed model is completed. It is important to note that each jurisdiction will have its unique empirical model due to unique environmental and soil type characteristics. The calibration stage will yield unique coefficients and offsets to account for these variances in location characteristics.

Although the majority of empirical models utilize average air temperatures, relating to both freezing and thawing indices, the soil type is indirectly accounted for in the unique coefficients generated. For example, determining the frost depth is a function of the freezing index. Quebec and Minnesota have unique soil and moisture characteristics resulting in unique frost penetration and temperature gradients as different soil types will retain moisture differently [Craig 1997]. Clays will retain moisture more aggressively compared to sandy soils.

Advantages to empirical modelling are the ability to use air temperature and/or moisture accumulation to predict the probable critical timeframe whereby the soil strength is compromised. In addition, through forecasting, the estimated removal of the restriction time frame can also be predicted. This will provide an economic benefit not only to the transportation agency, through mitigated pavement damage, but also to the freight industry.

It is difficult to linearly transfer a model from one jurisdiction to another as there are external factors that differ. A jurisdiction will have unique soil, climatic and traffic loading parameters. The result is a potentially different model. Therefore, care must be taken when investigating employing a model from another jurisdiction.

## Economic Impacts of SLR

Spring load restrictions cause disruptions to freight haulers, therefore some transportation agencies are now attempting to study its associated costs and benefits. Load restrictions may result in the need to make increased trips along a restricted route or to follow alternate, potentially longer routes. Both situations lead to increased costs to haulers that are passed on to the consumer [Goodings 2000].

As spring load restrictions place the owners of heavy vehicles that travel these roads into a situation of a reduced payload, there have been instances whereby the drivers can avoid penalties. Kestler et al. [1998] reveal that the majority of jurisdictions in the US enforce SLR through penalties. However, a few states indicated that, during the overnight hours between midnight and 5:00 am, heavy vehicles are permitted to exceed the upper load limit. Justification from the enforcement officers include the drop in temperatures during nighttime hours increases the stiffness of the roadbed. This practice mitigates the economic impacts to the transportation industry, especially that of the logging industry.

## Pavement Damage

The role of spring load restrictions is to mitigate the damage to the pavement structure. As mentioned, the presence of excess moisture causes structural inadequacies that must be mitigated. Four main types of distresses can occur: longitudinal cracking, transverse cracking, rutting and roughness. Each are dependant on the traffic loading, structural strength and temperatures that are encountered in an annual basis. For instance, the onset of longitudinal cracking can provide an indication of the onset of fatigue cracking as illustrated in Figure 14. As the cyclic loading of heavy vehicles is applied to the pavement structure, the loss of subbase and subgrade support is likely occurring as a result of excess moisture within the structure.

Figure 14. An example of fatigue cracking (Courtesy of the Washington Asphalt Pavement Association)

# AVAILABLE MODELS

There are many jurisdictions, both in Canada and the United States, that have attempted to model the effects of freeze and thaw. Canadian jurisdictions such as Quebec and Manitoba and Minnesota in the United States have developed models. In the majority of cases, field testing to determine an empirical model was performed at several satellite test sites. The following is a brief summary of the relationships developed.

Although the models listed below are currently in use in their respective jurisdictions, the direct transfer of a model to another jurisdiction is not recommended. As described earlier, the models are empirically based. Therefore, calibration for each model is specific to the originating area. Climate and soil conditions differ among all regions and therefore, are accounted for in the coefficients within the model. For example, Quebec has a unique suite of climatic trends as well as soil characteristics, both moisture and type. Compared to Minnesota, where the climate is significantly different in terms of precipitation and temperature, the coefficients in Minnesota model are different to the Quebec model.

## Quebec

Within the province of Quebec, a study conducted by Dore et al. [1998] to investigate ground frost. A field experiment was developed and completed to predict the frost depth in relation to ambient air temperatures. The instrumentation used in this experiment included a thermistor assembly that is placed into the roadbed to measure the vertical temperature profile.

In developing the empirical model, the following relationships were also employed into the model created by Dore et al. [1998]. The mean air temperatures, in centigrade, is calculated.

$$T_{MEAN} = \frac{T_{MAX} + T_{MIN}}{2}$$

where $T_{MEAN}$ - Mean daily air temperature (ºC)
$T_{MAX}$ - Maximum daily air temperature (ºC)
$T_{MIN}$ - Minimum daily air temperature (ºC)

In the event the mean air temperature is not zero, the corrected surface temperature must be calculated:

$$T_{CORR} = 0 \qquad \text{if } T_{MEAN} = 0$$
$$T_{CORR} = T_{MEAN} + \left[\left(T_{MAX} - T_{MIN}\right) \cdot F\right] + CONST \qquad \text{if } T_{MEAN} \neq 0$$

where $T_{CORR}$ - Corrected pavement surface temperature (ºC)

| | |
|---|---|
| $T_{MEAN}$ | - Mean daily air temperature (ºC) |
| $T_{MAX}$ | - Maximum daily air temperature (ºC) |
| $T_{MIN}$ | - Minimum daily air temperature (ºC) |
| F | - Regression constant |
| CONST | - Regression constant |

To determine the freezing index, the following incorporates the corrected temperature for a given day and the freezing index of the previous day. Conditional inequalities apply to this relationship.

$$FI_i = T_{CORR_i} + FI_{i-1} \qquad \text{if } T_{CORR_i} + FI_{i-1} > 0$$
$$FI_i = T_{CORR_i} \qquad \text{if } T_{CORR_i} + FI_{i-1} \le 0 \text{ and } T_{CORR_i} > 0$$
$$FI_i = 0 \qquad \text{if } T_{CORR_i} + FI_{i-1} \le 0 \text{ and } T_{CORR_i} \le 0$$

where $T_{CORR}$ - Corrected pavement surface temperature (ºC)
$FI_i$ - Freezing Index for a day i (ºC-days)
$FI_{i-1}$ - Freezing Index for previous day (i-1) (ºC-days)

The depth of frost is related to this empirical equation involving a constant F and the freezing index.

$$P = F \cdot FI^{0.5}$$

where P - Projected frost depth (cm)
F - Regression constant
$FI_i$ - Freezing Index for day i (ºC-days)

The final corrected frost depth model for Quebec is determined through the following relationship. The related factors include constants, sum of square errors, freezing index, and thaw depth and was developed through statistical regression. In this case, a confidence of level of 60% was selected.

$$P_i^* > 0 \qquad \text{if } P_i = P_{i-1}$$
$$P_i^* = P_i \qquad \text{if } P_i \ne P_{i-1}$$

$$P_{CORR} = P^* + \left[ c \cdot S_e \cdot \left(1 + \frac{1}{398}\right) + \left( \frac{\left(FI^{0.5} - X_{MEAN}\right)^2}{\sum \left(X_i - X_{MEAN}\right)^2} \right)^{0.5} \right]$$

where $P_{CORR}$ - Corrected frost depth – includes regression constants and statistical variables

$P^*$ - Projected frost depth (cm) (must be greater than zero)

c - Confidence interval for a population mean
A function of Significance Level (alpha = 0.4), one standard deviation and a sample size of one.

$S_e$ - Sum of squared errors

FI - Freezing Index (ºC-days)

$X_i$ - Observed frost depth (cm)

$X_{MEAN}$ - Average Observed frost depth (cm)

## Manitoba

Within Manitoba, a specific method in determining the thaw index is employed. This method utilizes a modified mean air temperature value as well as a reference temperature based on March 1 at a value of 1.7ºC. A trigger value of TI = 15 will result in the enforcement of reduced loads on specified roadways.

$$T_{MOD} = \frac{T_{MEAN}}{2} \qquad \text{if} \quad T_{MEAN} < 0$$

$$T_{MOD} = T_{MEAN} \qquad \text{if} \quad T_{MEAN} \geq 0$$

$$TI_i = TI_{i-1} + T_{MOD} + T_{REF}$$

$$T_{REF} = 1.7 + 0.06i$$

where $T_{MOD}$ - Modified Temperature (ºC)

$T_{MEAN}$ - Mean air temperature (ºC)

$T_{REF}$ - Reference air temperature (ºC) – 1.7ºC

$TI_i$ - Thaw index for day i (ºC-day)

$TI_{i-1}$ - Thaw index for day i-1 (ºC-day)

i - Number of days since March 1

## Minnesota

The state of Minnesota has investigated the impacts of SLR thoroughly. A variety of models are discussed in Levinson et al. [2005]. This includes air and subgrade temperature models. In general, an empirical model requires data to be fit onto a curve, through parametric coefficients. Surface temperature is estimated through the minimum daily air and the daily mean air temperatures as represented by the following models.

$$T_{Surf} = 0.859\,T_{Min,Air} + 1.7$$

$$T_{Mean} = 0.859\,T_{Air} + 7.7$$

where $T_{Min,Air}$ - One Day Minimum Air Temperature (ºC)
$T_{Air}$ - Mean Daily Air Temperature (ºC)
$T_{Mean}$ - Mean Pavement Surface Temperature (ºC)
$T_{Surf}$ - Pavement Surface Temperature (ºC)

The following is a model that estimates the temperature within the soil as a function of depth and time is also described [Levinson et al. 2005]. It is important to note that with the level and type of input required for this relationship, the use of such would be on a micro-level or area specific basis. It is not suitable for network level management. Thermal diffusivity is a measure of the ability of the soil to transmit a thermal disturbance. In other words, a high thermal diffusivity results in a rapid transmission of either high or low temperatures through the soil medium.

$$T(x,t) = T_{Mean} + A\,\exp\left(-x\sqrt{\frac{2\pi}{P\alpha}}\right)\sin\left(\frac{2\pi}{P}t - x\sqrt{\frac{2\pi}{P\alpha}}\right)$$

where $T(x,t)$ - Soil temperature as a function of depth and time
$x$ - Depth below surface (m)
$t$ - Time when the measured air temperature is greater than the mean surface temperature (days)
$T_{Mean}$ - Mean surface temperature (ºC)
$A$ - Maximum temperature amplitude ( $T_{Max} - T_{Mean}$ ) (ºC)
$\alpha$ - Thermal diffusivity of the soil (m²/days)
$P$ - Period of cycle (days)

Temperature profile in pavement layers can be computed using the following developed by Witczak [1972]:

$$T_P = T_A\left(1+\frac{1}{z+4}\right)-\left(\frac{34}{z+4}\right)+6$$

where $T_p$ - Average seasonal pavement temperature (ºF)
$T_A$ - Average seasonal air temperature (ºF)
z - Depth of predicted temperature (in) – typically z = 1/3 of HMA thickness

Leong et al. [2005] utilized Canadian long term pavement performance (C-LTPP) data to establish a reference temperature of 3.4ºC and a threshold thaw index of 13ºC-Days through regression. Levinson et al. [2005] refers to a model developed by Chisholm and Phang [1977]. This model relates freezing index to frost depth (P).

$$P = -0.328 + 0.0578\sqrt{FI}$$

where P - Frost depth (m)
P* - Projected frost depth (cm) (must be greater than zero)
c - Confidence interval for a population mean
A function of Significance Level (alpha = 0.4), one standard deviation and a sample size of one.
$S_e$ - Sum of squared errors
FI - Freezing Index (ºC-days)

## ADVANCED ROAD WEATHER INFORMATION SYSTEM

Allowing transportation agencies and the maintenance contractors to monitor real-time conditions on highways is not only a convenient but also contributes to safer roadways. Advanced Road Weather Information System (ARWIS) in Ontario monitor the following parameters:

- Air temperature
- Dewpoint temperature
- Relative humidity
- Air pressure
- Average wind speed & direction
- Visibility
- Precipitation amount and type
- Road surface conditions
- Surface and subsurface temperatures
- Active warnings

The purpose of ARWIS systems is to provide real time road surface data to management. This data is used by maintenance personnel to determine when to dispatch the appropriate countermeasures. For example, as the surface temperature approaches the designated freezing temperature, an ice warning will be relayed to the dispatcher.

## MECHANISTIC EMPIRICAL PAVEMENT DESIGN GUIDE

Software is available to predict the performance of pavement given pavement characteristics and climatic conditions. The MEPDG is an evolution of the AASHTO 1993 Design Guide. A limitation with the previous versions of the design guide is the level of input for material properties. This interactive software provides the user the ability to run simulations of various parameters and predict the long term effects of such conditions prior to huge investments being made.

The purpose of the MEPDG is to increase the range of possible solutions designers can assess, analyze both new and existing pavement design issues and be user friendly. As mechanistic procedures can better incorporate the effects of climate, age and vehicle loading to provide an idea of the performance, the impact of materials and its usage on roadways can be evaluated and predicted. The output of the MEPDG is the pavement performance in terms of cracking, rutting and surface roughness.

Employing the MEPDG as an analysis tool to determine the impact of spring load restrictions on certain roadways can be done. To simulate the freezing effect during the winter, the stiffness of the subgrade and pavement layers must be achieved. To adjust the stiffness of a given subgrade layer, manipulation of various structural parameters such as the California Bearing Ratio (CBR) will accomplish this.

Simulating cyclic climatic events is another major component in the MEPDG. As strengthening and weakening of the pavement structure occurs in a cyclic manner, the enhanced integrated climatic model (EICM) provides the basis of the climatic influence on the entire highway network. The previous generation incorporated less than 5% of its analysis dealing with climatic influence. The current version raises this to 38% of the overall analysis [Wagner 2005].

## ALTERNATIVES TO SPRING LOAD RESTRICTIONS

### Reduced or Active Tire Pressures

The effect of tire pressures with pavement damage has been studied by many researchers. Pressure applied to the pavement is dependant on the tire-pavement contact area while the load remains constant. Larger tire area results in a slightly lower pressure and vice versa. To achieve a greater tire contact area, a lower tire pressure can be used. Typical tire pressure is rated at 690 kPa (100 psi) [Bradley 1997]. The theory is that a greater tire contact area to the pavement results in the distribution of the load over a larger area, reducing the active damage caused by heavy vehicles. This area is typically generated by increasing the sidewall deflection.

Controversy to this type of practice exists. The environmental impact of decreased tire pressures will result in increased consumption of fossil fuels as a result of tire flex, heat generation and increased rolling resistance. In fact, an increase of 1% in fuel consumption is the result of a truck tire 10 psi below the recommended pressure. Uneven tread wear will result in increased maintenance cost, unpredictable handling in adverse road surface conditions and increased frequency of tire failures [USEPA 2004a].

Related to increasing the tire-pavement contact area, a single wide based tire is a possible alternative. The advantages of employing a single wide based tire are the reduction of weight, reduction of costs and reduction of pavement damage. The typical dual tire assembly has two steel rims on each tire assembly, except for the steering axle. Therefore, the weight reduction can be realized. Fuel consumption is reduced by about two to five percent compared to conventional dual tires saving over 400 gallons of fuel per year [USEPA 2004c]. The environmental benefit, specifically reduction of greenhouse gases, can be realized. Pavement deterioration is reduced as a result of the increased contact area.

Several studies have looked at pavement deterioration or deformation with respect to varying tire pressures. It was found in Raad et al. [1998] that the pavement damage caused by increased tire pressures increased. In fact, this study indicates the majority of damage will be in the base and subbase layers for thin asphalt overlays.

Bradley [1997] summarizes the findings of Truebe et al. [1994] and Truebe et al. [1995] whereby 20% of the damage, namely rutting, was observed in the subgrade. The remainder of the damage occurs as a result of densification and aggregate shear. Rutting also occurs at a reduced rate with vehicles using the central tire inflation (CTI) system. Lateral movement of the tread blocks results in an increase in tire temperatures leading to an increase in tire pressures. The CTI is an onboard system whereby the tire pressures are actively adjusted to maintain a set level at any given speed and distance travelled.

## Complete Removal of Spring Load Restrictions

An alternative option is to introduce the complete removal of spring load restrictions in the highway network. The premise of this is to realize the maximum social-economic outcome. While it is understood that a proportion of the highway network will deteriorate at a rapid rate, the economic benefits can outweigh this cost.

However, it is not as simple as lifting all seasonal restrictions. Transportation budgets must be augmented to compensate for the increased deterioration rate. An increased maintenance and intervention schedule must be followed to maintain the service life and the status of the highway network at a reasonable level. Without this, reconstruction may be required earlier as well as at higher frequencies.

There have been several studies that have investigated the feasibility of lifting seasonal restrictions and others summarize the impacts of lifting these restrictions in several jurisdictions. In 1995 Norway has eliminated the load restriction component over the entire highway network. With a road network at approximately 53,000 km in length, a study was initiated in 1990 to investigate any means of optimizing the use of the bearing capacity of the road network [Refsdal 1998]. The results of the 1990 study provided an understanding the cost/benefit analysis between the effects of reducing the service life and extra annual costs to maintain the facility, with the potential gains industries will realize.

Simply lifting the weight restrictions can be performed. However, the designs of heavy vehicles have progressed over the decades. In fact, most jurisdictions have seen the following transitions in the truck design as directly quoted [Refsdal et al. 2004]:

- Triple tandem axles
- Radial tires instead of diagonal tires
- Air suspension
- Increased tire inflation pressures
- Single wide tires instead of dual tires

The extra costs to maintain the facility at a reasonable level was an important issue for the Norwegian transportation agency. In contrast, the savings to the road users, particularly the trucking industry, may outweigh the extra costs. The government initiated a benefit-cost analysis. It was found that $330 Million NOK (Norway Kroner) ($59 Million CDN equivalent) was the estimated annual road user benefit while road agency costs amounted to approximately $145 Million NOK ($26 Million CDN) annually [Refsdal 1998]. Benefit was defined as the summation of direct profits, indirect profits and time savings. This study also included an annual penalty of $210 Million NOK ($37 Million CDN) can be realized if maintenance budgets were not adjusted to mitigate the increased damage rate.

Apart from the economics, the highway network appears to have suffered relatively minor damage compared to what was predicted. In fact, in 1998, the extra funding has prevented the majority of failures at an average of $8 Million NOK ($1.5 Million CDN) for each of the 19 jurisdictions since the restrictions were lifted.

In the Ontario realm, lifting spring load restrictions is an option that requires extensive investigation in terms of vehicle loading patterns, soil conditions, and climate compared to Norway. As the logging and mining industries are prevalent in Northern Ontario, often load restricted facilities are used for these industries. The findings of the Norway experience provide a basis of the potential issues that may be raised or observed, including adequate and fair increase in transportation budgets to account for increased deterioration and reduced service life. Threshold dates for the release of these budgetary increases as the Norwegian Government has done. Of course, the safety aspect in terms of rutting and provisions for complete pavement structure failures must be investigated prior to any field testing.

## Vehicle Component Weight Reduction

It is possible to reduce the overall truck weight by 3000 lbs by replacing heavy components with lighter weight ones. For instance, cast aluminium wheels can save approximately 40 lbs each, aluminium axle hubs, centrifuge brake drums, aluminium clutch, composite front axle leaf spring etc. can provide a cumulative weight savings resulting in increased fuel economy. In terms of environmental impact, two to five metric tons of greenhouse gases can be eliminated annually as well as 200 to 500 gallons of fuel annually per vehicle [USEPA 2004b]. Although this weight reduction appears to be insignificant compared to the spring load restrictions, the reduction of annual maintenance costs and emissions given the same payload is an interesting situation.

## Increasing Accuracy of Restriction Dates

Issues with most methods of setting load restrictions is that in the majority of instances, the load restriction duration are either conservative or applied not on time. Therefore, many studies have investigated alternative methods of improving the selection of these threshold dates.

Kestler et al. [1999] reveals a methodology that attempts to accurately quantify when spring load restrictions should be lifted by relating pavement stiffness and soil moisture. Their findings utilized time domain reflectometry (TDR) and radio frequency to measure soil moisture on a field test site. TDR sends a high frequency wave through the soil and the amount of time required for the signal to return to the unit is used to determine the dielectric constant of the material or soil being measured. Determining the threshold dates to restrict loads and to lift restrictions is most effective using thermistors the study concludes. Thermistors provide superior accuracy at +/-0.2 C.

Hanek et al. [2001] performed a similar study revealed that environmental monitoring with moisture sensors, in combination with thermistors, can provide a viable means of identifying periods of lowered pavement strength during thaw. This information would be helpful in determining optimal timing and duration of load restrictions. Van Deusen [1998] also performed field trials on low volume asphalt roads to attempt to correlate and forecast the load restriction duration using frost depth and air temperature. This study developed a duration relationship with an R-squared of 50% and an error of +/- 8 days.

In their study on moisture and its effect on the subsurface layer moduli Janoo et al. [2000] observed that the moisture content in the base and subgrade rapidly increased when the ground temperature was approximately -2°C. This led the authors to conclude that if the thaw-weakening process is solely based on ground temperature, then the thaw-weakening period can be over when the ground temperature is above 0°C. They also observed that not all the moisture present in the pavement structure freezes, and that the unfrozen moisture content is a function of depth.

## Minimizing Frost Effects by Design

Preventing the issue of reduced load carrying capacity in the design phase of a facility is one means of eliminating the need to impose load restrictions [Goodings 2000]. Avoiding fine soils within the pavement structure and the subgrade will assist in preventing common structural issues. Another possible method is to remove frost susceptible soils from underneath the roadbed and replace this soil with acceptable aggregate or soils. Reducing the pore water pressures by providing a drainage route for the moisture in the soil will retain the structural strength of the roadbed and subgrade.

# Field Instrumentation

This section will provide a basic background into the selection of test sites and equipment for the project. The basic equipment required includes a thermistor assembly, a data logger, and housing for the data logger with a power source.

## INVESTIGATION SITES

Two pilot sites were selected for this project. Each site has load restrictions in place during the spring months. The study areas are located in Northwest Region approximately two hours north of Thunder Bay and in Northeast Region approximately 40 minutes north of New Liskeard. Figures 15 and 16 illustrate the approximate locations of each installation. Physical location of the sensors will be at the centreline of the road with the cabinet housing the recording equipment located a sufficient distance away from the pavement edge to prevent damage to the cabinet during snow removal. The final location of the cabinet was at the discretion of the MTO staff on site.

The Northwest Region pilot site is located approximately 0.5 kilometres north of Highway 811 (Approximate Station is 29+600) on Highway 527. The total road width is 6.5 metres or 3.25 metres in each direction. It is a two-lane road constructed out of asphalt. The asphalt thickness is approximately 50 mm. Due to the location, utilities such as hydro and communication were not readily available. Therefore provisions to provide power to the data logger were made.

The Northeast Region pilot site is located approximately three kilometres east of Highway 11 on Highway 569. The total road width is approximately 6.5 metres or 3.25 metres in each direction. It is a two-lane road constructed out of asphalt. The asphalt thickness is approximately 50 mm. Availability of hydro and communication (via. Phone line) provides flexibility on power management and data acquisition at this site.

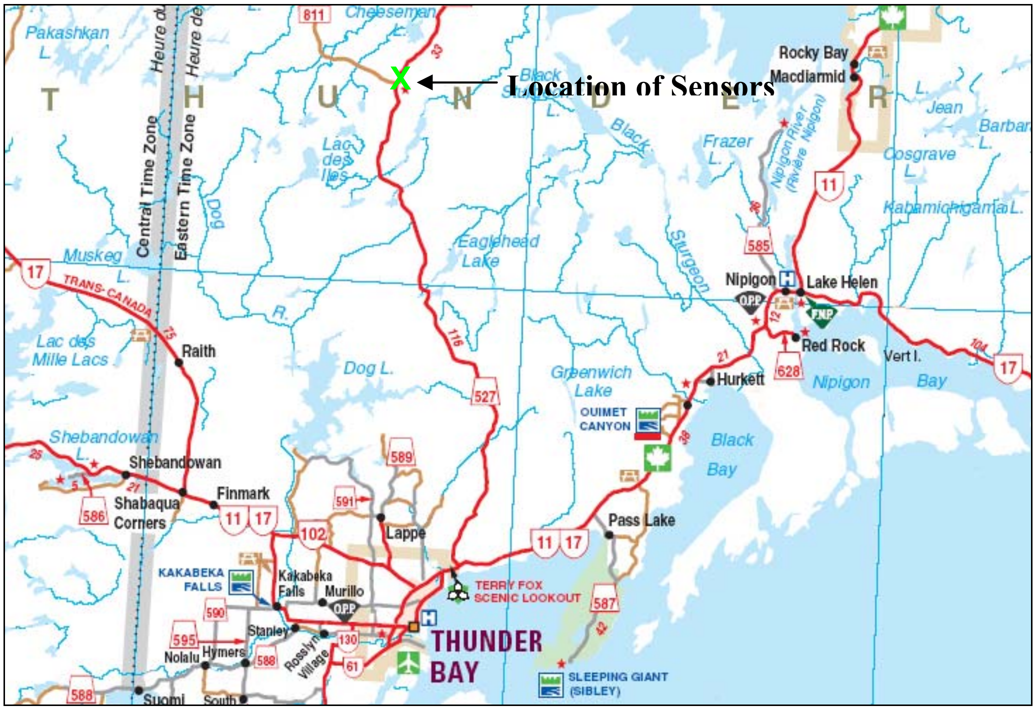


Figure 15. Location of thermistor installation in Northwest Region.

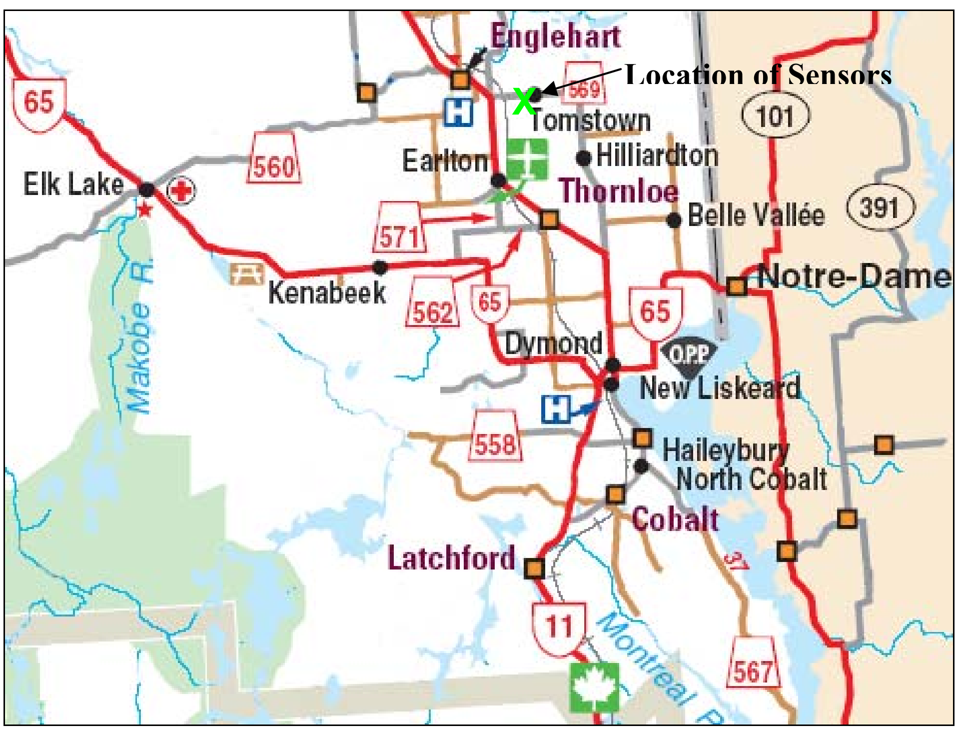


Figure 16. Location of thermistor installation in Northeast Region.

# THERMISTOR ASSEMBLY

There are various methods to determine the state of a pavement structure. Focus in this study will be on sensors that will be installed in the pavement structure to capture the temperature as a function of depth relative to the pavement surface. These devices, known as "thermistors", are constructed to withstand external forces such as damage due to backfilling, slight volumetric changes in the surrounding soils and weather extremes. Thermistors are highly temperature sensitive devices that results in a resistance measurement that can be correlated to an equivalent temperature. Unlike thermocouples, the resolution of the thermistor output is more precise. Therefore, minute changes in temperature can be captured by the thermistor. This is essential in understanding the dynamics within a pavement structure during critical times in the year where structure can either be compromised or enhanced.

For this project, the monitoring device will consist of several thermistors located at various depths. The entire thermistor assembly is illustrated in Figure 17. The total depth of monitoring will consist of 2.5 m. The thermistors in the top 1 m will be spaced at 15 cm intervals. In the lower 1.5 m, they will be spaced at 30 cm intervals. Figure 18 illustrates the spacing of the thermistors within the assembly. The primary reason for placing the upper sensors at a closer spacing is to provide better resolution of what is actually occurring in this area. It is important to have several sensors as some thermistors do fail so it is important to build some redundancy into the system. Overall, the life expectancy of the thermistors is typically 4-5 years. The thermistors can provide readings beyond 5 years but accuracy may become an issue due to corrosion or ingress of moisture. Therefore, replacement of the thermistor assembly may be required at this point. The two thermistors were assembled in Laval University in Quebec through the supervision of Dr. Guy Dore and Dr. Sylvain Juneau.

Figure 17. Thermistor assembly prior to installation.

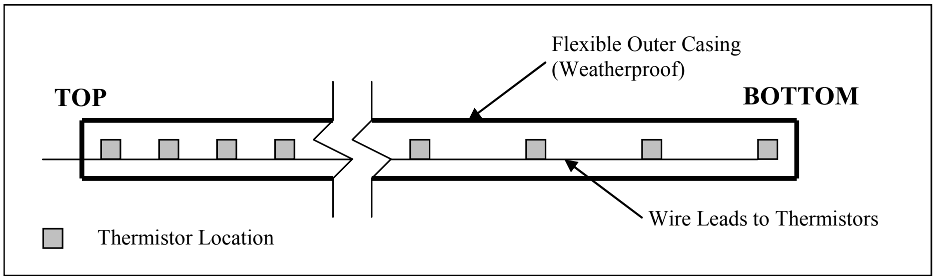


Figure 18. General schematic of the thermistor assembly.

## DATA LOGGERS

Capturing data for future use in research is part of the mandate of this project. To do so, an automated system must be in place to provide accurate and reliable capturing of data at regular intervals. This will reveal important trends within the pavement structure concerning critical thresholds for vehicle loadings. A data logger would meet all of the requirements. However, given the number of readings to be taken at each data capture, sufficient channel capacity is required. In addition, a redundant internal power supply as well as sufficient data storage will reduce maintenance activities resulting in a nearly stand alone system.

A robust and reliable data logger was needed for this research. Environment Canada has recorded that the area of the field test site in Northwest Region, the air temperature ranged between -35°C to +33°C in 2003 and 2004. The Northeast Region has recorded -34°C to +32°C in 2003 and -37°C to +29°C in 2004. Therefore, a logging system that is physically rated to handle such extreme temperatures is required.

Table 3 summarizes the specifications of the selected data logger to be used to capture data from both test sites. The data logger will be enclosed in a weather resistant cabinet but will be subject to the temperature and weather fluctuations of the area.

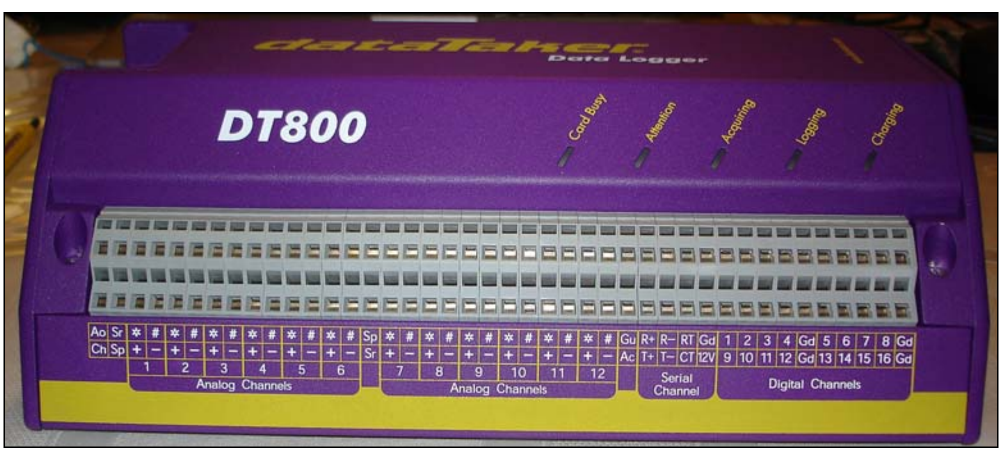


Figure 19. The Datataker DT800.

Table 3. Summary of specifications of data logger for the study.

| | |
|---|---|
| **Make** | Datataker |
| **Model** | DT800 |
| **Serial Number** | 081725 (Northwest Region)<br>081726 (Northeast Region) |
| **Environmental** | -45°C to +70°C, 85% RH |
| **Physical** | Powder coated fabricated steel<br>260 x 110 x 90 mm, 3.1 kg |
| **Power Inputs** | 110/240 V AC, 11-28 V DC, 1 Amp |
| **Power Consumption** | 5 W @ Normal Mode / 5 mW @ Sleep Mode |
| **Channels** | 12-42 Channels (Analogue / Digital) |
| **Data Storage** | 2 MB Internal, ATA Flash PC Card Expansion |
| **Communication** | Ethernet, USB<br>RS232 – 57,600 Baud with Modem Support |
| **Accuracy (Resistance)** | 0.04% @ +25°C<br>0.20% @ -45°C to +70°C |
| **Accuracy (DC Voltage)** | 0.02% @ +25°C<br>0.10% @ -45°C to +70°C |
| **Bios Version** | 4.10.0001 (2006/01/25) – SN 081725<br>4.08.0001 (2004/12/16) – SN 081726 |
| **Supplier** | Dalimar Instruments Inc. |

## INSTRUMENT ENCLOSURE

It is important to protect the instrumentation from the elements while on site. Water entering the equipment, be it the data logger, the thermistor leads, or even the power source can result in erroneous data or degradation of the equipment. Therefore, a weather resistant enclosure, preferably a cabinet, is required to house and protect such equipment. Table 4 summarizes the recommended enclosure to be installed at the test site.

## EQUIPMENT INSTALLATION

The sequence of events that occurred during the installation include providing adequate traffic control, site selection, excavation, installation, backfill and equipment testing. Traffic control was necessary to meter vehicles through the undisturbed lane. The study site must be representative, in a load restriction area, provide adequate depth for the thermistor probe, and provide accessibility for maintenance purposes. Excavation at the centreline is proposed followed by the installation and backfilling of the thermistor assembly. Testing the equipment through the data logger to ensure proper readings are taken completes the overall installation.


Figure 20. An example of the instrument enclosure with DT800, power source and telephone access.

Table 4. Summary of specifications for the instrument enclosure.

| | |
|---|---|
| **Make** | Intertec |
| **Model** | Multibox Type 100 |
| **Material** | Hot-pressed glass fibre reinforced polyester |
| **Dimensions** | 640 x 440 x 430 mm |
| **Weight** | 9.5 kg |

The facility at each installation was both a two lane rural highway. Traffic control at the site was the responsibility of the maintenance contractor. In the Northwest and the Northeast Regions, TWD Roads Management Inc. and Integrated Maintenance and Operations Services (IMOS) Inc. were responsible for traffic controls. The Northwest region site required extra attention as there is a high proportion of heavy logging trucks using this facility. Compounding the situation is the horizontal and vertical curves that surrounded the test site. Therefore, traffic control personnel were placed at a significant distance away from the actual construction site to ensure the safety of the workers as well as that of the travelling public.

The general procedure to install the equipment on site is described below. Due to the variation of the sub-grade and pavement structure, adaptation of these instructions may be necessary.

## STAGE 1: Thermistors String Installation in the Ground

1. Drill a hole of 2.75 m (9 feet) deep and 0.30 m (12 inches) in diameter.

2. As you drill the hole, keep on the side the materials you have excavated to use them to fill the space around the tube. Stock the materials on the side according to the various layers of soil recovered.
3. Place the tube containing the thermistors string into the hole. Ensure the bottom of the hole is levelled.
4. Place the tube at the selected height starting from the surface.
5. Fill the hole by the layers of soil you have recovered previously.

## STAGE 2: Thermistors String Wires Installation in the Asphalt

1. With a proper saw, make a groove in the asphalt to pass the conduit with all the thermistor wires that will be connected in the data acquisition system.
2. Place the conduit into the groove. Patch the groove with cold patch or cracks seal.
3. Dig a channel to pass the conduit in the shoulder. Bring all the wires to the cabinet. Fill the channel.

## STAGE 3: Cabinet Installation

1. Drive a wood post in the ground to hang the cabinet. Make sure the cabinet is placed above snow level to facilitate its access. It is suggested to place it about 1.75 m (6 feet) above the ground.
2. Bring all the wires placed in the conduit to the cabinet.
3. Pass the wires into a little hole in the cabinet to bring all the wires to the data acquisition system (Datataker DT800).
4. Connect the thermistors in the data acquisition system.

Excavation at the site location requires several stages. Firstly, to accommodate the thermistor assembly, a one metre diameter hole is required at a depth of at least 2.75 metres. This is done through an auger equipment. As the various soil types are excavated, it is important to segregate them to allow for proper backfilling. Secondly, a shallow trench is required to install the conduit that will house the leads from the thermistor. The depth of the trench should be sufficient to allow the top of the conduit to be below the asphalt layer. Finally, excavation on the shoulder to the location of the cabinet is required to feed the wires and conduit through. In addition, securing the cabinet to prevent accidental or malicious movement of the equipment relative to the thermistor assembly location is necessary.

Installing the thermistor may, due to site conditions, require a variation from the original installation procedure. Once the thermistor assembly is placed in the excavated hole, the proper soil is backfilled and compacted. This secures the thermistor from movement and provides direct soil contact to the equipment. A 90° PVC joint is installed onto the top of the thermistor assembly to direct the leads 90° to run across the lane width through the conduit pipe. The joints are secured with the appropriate sealant once the final alignment was determined.

Backfilling the areas excavated was performed to recover the appropriate pavement structure. This included backfilling and compacting the appropriate soil type (in sequence) and applying layer of cold mix to replace the excavated asphalt surface. The shoulder profiles were recovered to pre-construction specifications.

Based on past experiences, failures can occur in the wires that transport the data from the thermistors to the data loggers. A robust product is required to transmit data to the data loggers. Therefore, for this project, a military grade wire will be used. The lead wires from the thermistor to the data logger will be encased by PVC conduit for protection during backfill, weather and distributing loads around these wires.

The thermistor probes will be placed in at the centerline of the roadway. A trench will be cut in the road and the wires will be placed in a conduit and run to the edge of pavement, and out to the edge of right of way where the data logger will be located.

As an aside, if one did want to increase the service life to 7-10 years, it would be recommended that a second string of sensors be included in the installation. The double system would be installed and hooked up at a later date. This in effect is built in redundancy but it does improve the life cycle.

For the purpose of this research project, the five year period should be ample. In fact given that this project is only a one year project at this point, the suggested system is more than adequate.

**Table 5. Summary of wiring configurations for each installation site.**

| **Site A - Northeast Region (New Liskeard)** | | | **Site B - Northwest Region (Thunder Bay)** | | |
|---|---|---|---|---|---|
| **Wire ID** | **Thermistor ID** | **Wire Colour** | **Wire ID** | **Thermistor ID** | **Wire Colour** |
| A1 (WG) | - | - | B1 (WG) | - | - |
| | A1 | WG | | B1 | WG |
| A2 (WG)<br>A3 (RB) | A2 | WG | B2 (WG)<br>B3 (RB) | B2 | WG |
| | A3 | RB | | B3 | RB |
| A4 (WG)<br>A5 (RB) | A4 | WG | B4 (WG)<br>B5 (RB) | B4 | WG |
| | A5 | RB | | B5 | RB |
| A6 (WG)<br>A7 (RB) | A6 | WG | B6 (WG)<br>B7 (RB) | B6 | WG |
| | A7 | RB | | B7 | RB |
| A8 (WG)<br>A9 (RB) | A8 | WG | B8 (WG)<br>B9 (RB) | B8 | WG |
| | A9 | RB | | B9 | RB |
| A10 (WG)<br>A11 (RB) | A10 | WG | B10 (WG)<br>B11 (RB) | B10 | WG |
| | A11 | RB | | B11 | RB |
| A12 (WG)<br>A13 (RB) | A12 | WG | B12 (WG)<br>B13 (RB) | B12 | WG |
| | A13 | RB | | B13 | RB |

*RB = Red and Black* *WG = White and Green*

The first thermistor of each string (A1 and B1) is located 5 cm from the top of the thermistor string tube. It should be installed so the first thermistor is at the bottom of the asphalt layer as shown in Figure 21. Figure 22 is a schematic of the proposed installation of the thermistor assembly with each thermistor at specific depths from the pavement surface.

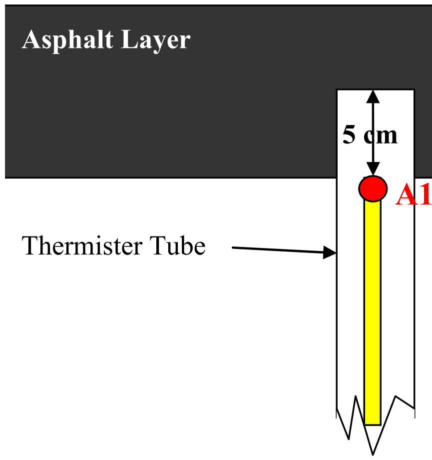


Figure 21. Detail schematic of thermistor installation below the asphalt surface.

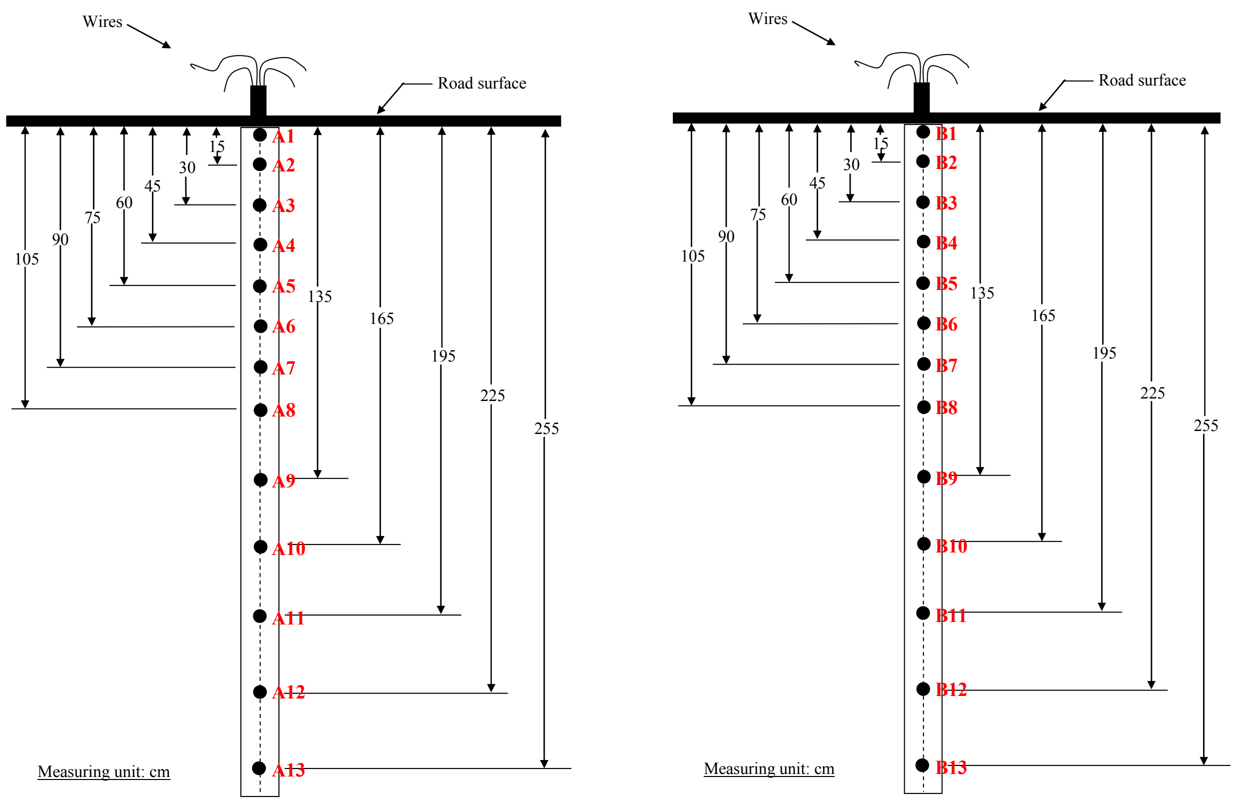


Figure 22. Schematic of thermistor installation at Northeast Region (Left) and Northwest Region (Right).

The output of the thermistors, when powered, is a resistance measurement (in Ohms). Once this resistance measurement is recorded by the data logger, conversion to a temperature is required for meaningful interpretation. As each thermistor is unique, specific calibration equations must be used to perform this resistance to temperature conversion. To find the temperature T (in ºC) of each thermistor, you enter the corresponding resistance R (in kOhms) registered by the Datataker (DT800) into the calibration equations listed in Table 5.

Table 5. Calibration equations for each thermistor assembly.

| **Site A - Northeast Region (New Liskeard)** | | | **Site B - Northwest Region (Thunder Bay)** | |
|---|---|---|---|---|
| **Thermistor ID** | **Calibration Equation** | | **Thermistor ID** | **Calibration Equation** |
| A1 | T = -18.528 x Ln R + 3.5446 | | B1 | T = -17.827 x Ln R + 2.1020 |
| A2 | T = -18.517 x Ln R + 2.5648 | | B2 | T = -18.299 x Ln R + 3.3148 |
| A3 | T = -18.252 x Ln R + 2.5968 | | B3 | T = -18.115 x Ln R + 2.7840 |
| A4 | T = -18.479 x Ln R + 2.5973 | | B4 | T = -17.856 x Ln R + 2.7612 |
| A5 | T = -18.014 x Ln R + 2.7899 | | B5 | T = -17.805 x Ln R + 3.2600 |
| A6 | T = -17.924 x Ln R + 2.9998 | | B6 | T = -18.004 x Ln R + 2.4003 |
| A7 | T = -18.051 x Ln R + 3.2426 | | B7 | T = -17.594 x Ln R + 3.5649 |
| A8 | T = -18.002 x Ln R + 2.1608 | | B8 | T = -18.482 x Ln R + 3.2510 |
| A9 | T = -18.202 x Ln R + 3.7788 | | B9 | T = -19.283 x Ln R + 3.9856 |
| A10 | T = -18.611 x Ln R + 1.8692 | | B10 | T = -18.254 x Ln R + 2.4623 |
| A11 | T = -18.297 x Ln R + 2.6563 | | B11 | T = -18.375 x Ln R + 3.3392 |
| A12 | T = -18.505 x Ln R + 2.5649 | | B12 | T = -20.152 x Ln R + 3.5366 |
| A13 | T = -17.724 x Ln R + 2.7238 | | B13 | T = -18.374 x Ln R + 2.3756 |

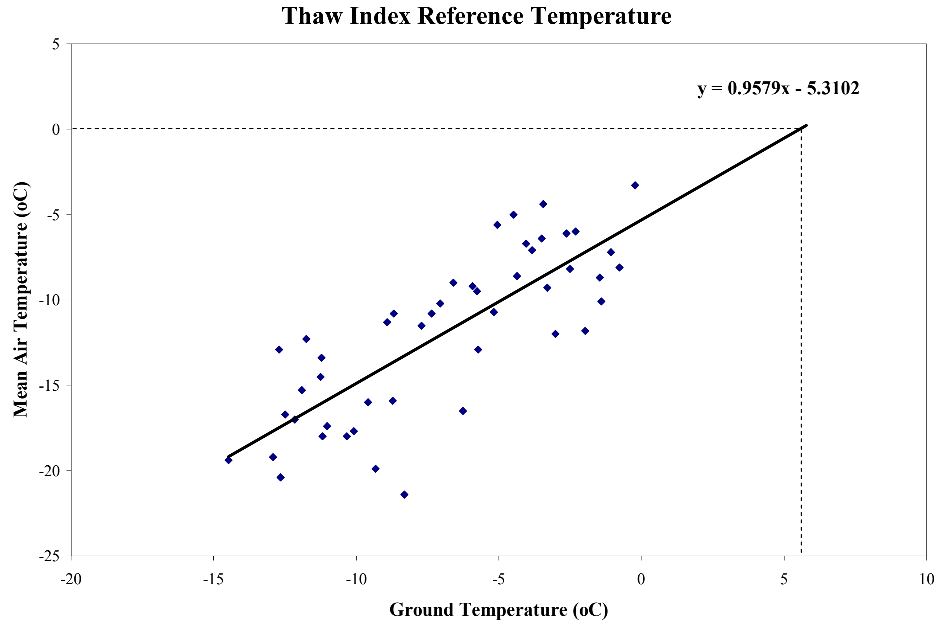


Figure 23. Reference temperature for Northeastern study site.

Figure 23 illustrates the data collected from the Northeastern site from December 5, 2005 to March 28, 2006. The progression of the frost penetration is as expected whereby the upper portion of the pavement structure fluctuates in temperature while at lower depths, the temperature is relatively stable. Figure 24a illustrates the temperature lag between the air and the ground during the frost period.

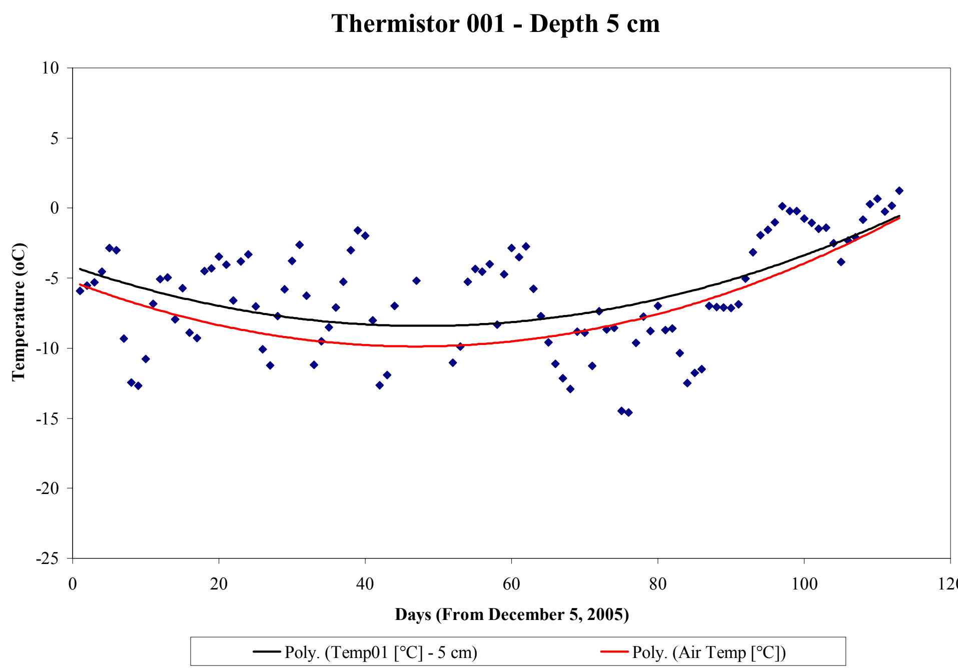

Figure 24a. Daily thermistor values at 5 cm below pavement surface in Northeast Region site. (Note: Red curve indicates mean air temperature while black curve indicates ground surface temperature.)

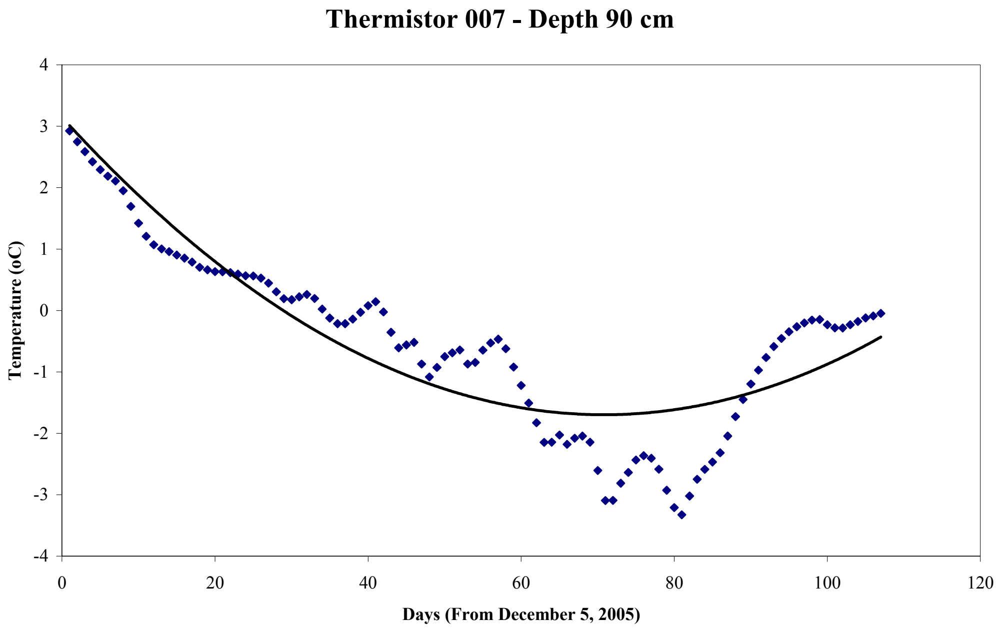


Figure 24b. Daily thermistor values at 90 cm below pavement surface in Northeast Region site.

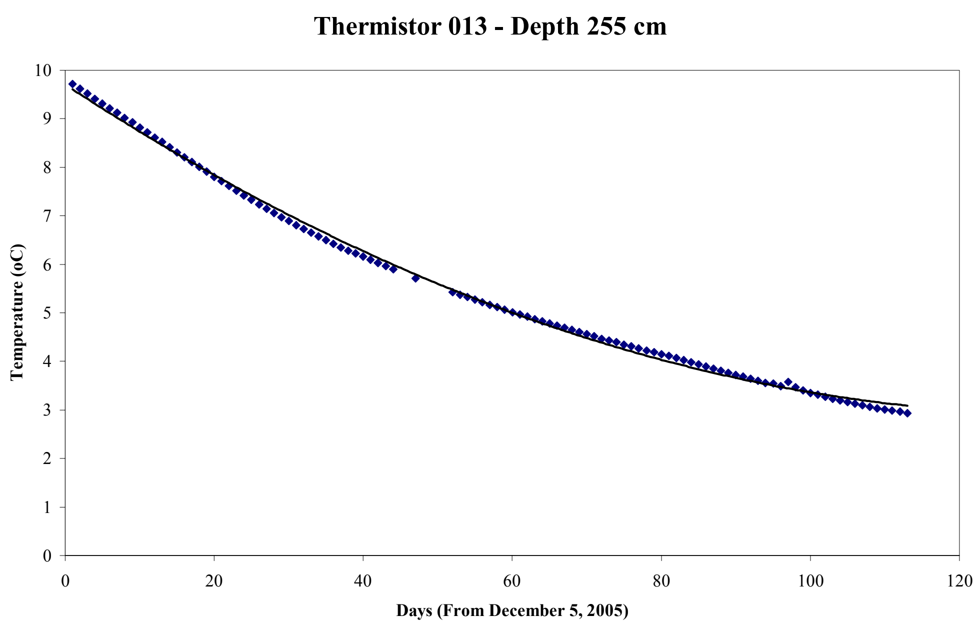


Figure 24c. Daily thermistor values at 255 cm below pavement surface in Northeast Region site.

# Phase One Results

The objective of Phase I is to install equipment to monitor field temperatures and frost depth, develop a preliminary reference temperature based on field data, and develop a preliminary frost depth model, similar to that performed in the province of Quebec. This section will illustrate these preliminary results.

It is important to have sufficient data to provide a reliable prediction model. Due to technical hardware issues, the freeze-thaw dataset is limited as the majority of the data was unattainable during the Fall-Winter 2005 in both sites. However, the thaw data was available for the Northeastern site and therefore a preliminary model was developed based on this data. To generate a refined Ontario based model, freeze-thaw data over several seasons is required. Therefore Phase II will provide a refined reference temperature and frost depth model.

## PRELIMINARY THAW INDEX

A preliminary thaw index, described as Equation 1, was developed through the single season of data acquired from one study site. With a reference temperature of 5.54$^{o}$C, this represents a 5.5 $^{o}$C lag between air and pavement temperatures. It is important to note that, due to variations in climate throughout Ontario, the reference temperature will be unique for each jurisdiction. This reference temperature was developed through relating daily air temperatures with the corresponding pavement surface temperatures as measured by the thermistors.

$$TI = \sum \left( T_{AIR,Mean} + 5.31°\mathrm{C} \right) \tag{1}$$

| | | | |
|---|---|---|---|
| Where | TI | - | Thaw Index ($^{o}$C) |
| | $T_{AIR,Mean}$ | - | Daily Mean Air Temperature ($^{o}$C) |

The thaw (and freeze) index is based from November 11, 2005, the first day the temperature was below zero degrees Celsius. The method of determining an estimated reference temperature is illustrated in Figure 23. Further field data is required to provide an accurate generalized reference temperature. However the R-squared for the curve is 63.07% and will improve as the database is developed.

## PRELIMINARY FROST THICKNESS MODEL

Development of a frost depth and thickness model was desired based on the field data. During the freezing phase of the season, the frost depth is equal to the frost thickness, where frost depth is a measure from the pavement surface to the bottom of the frost fringe. The thawing phase during the onset of spring provides a challenge as there are several factors that will affect the depth of the upper frost fringe depth. This includes higher ambient temperatures, solar radiation, humidity, wind speed, etc. Therefore, further seasonal data is required to provide a reliable upper frost fringe depth.

$$T = 5.537 \cdot \sqrt{FI} \tag{2}$$

Where T - Frost Thickness (cm)
FI - Freezing Index ($^{o}$C-days)

A root transformation was performed on the Freezing Index as it provided an improved relationship with the frost thickness. Due to the various influencing factors including ambient temperatures, solar radiation and wind speed, the external environmental effects do not instantaneously and proportionally affect the ground temperature profile. For instance, a sudden drop in ambient temperature, significantly below freezing, resulted in a modest increase in frost depth. Similarly, an acute short-term ambient air temperature increase resulted in a slight thaw to occur. In each case, the ambient temperature fluctuations, no matter how severe were, their effects were significantly dampened in the soil or pavement structure. Transforming the Freezing Index in this way provides a means of dampening the temperature fluctuation effects.

In developing this model, only one Ontario site was used. This site, specifically the Northeastern Region site, had a significantly large database as data acquisition was at 20 minute intervals continuously. Therefore, the data point that corresponds to 12:00 PM each day was used in this regression. It was important to select a specific daily time rather than utilizing a daily average as fluctuations over the day, simply with or without sunlight, will occur. This provided a straightforward and understandable model. In addition, RWIS data is collected in discrete 20 minute intervals as well. Matching the frost depth recorded on site to the air temperatures from the RWIS station was also required as the RWIS database has data gaps. Smoothing of the data, through interpolation was required to ensure the frost depth at a given time was not relating to an ambient air temperature of zero. Fortunately, the data gaps were not more than 24 hours. However, in the event several days worth of RWIS data was missing, an alternative interpolation method may be required but will not be discussed in this report.

The significance of this model is very high. This is due to the fact that the number and trends of observations were as expected. A coefficient of determination of 98.9% was achieved. This means the majority of the residuals have been accounted for in the model itself given 107 observations (or data points). Once another freeze-thaw season occurs and the data is collected from both sites, the model developed and calibrated from one site can then be verified utilizing the data from the second site.

Figures 24 and 25 illustrate the freezing index (FI) and thawing index (TI) for the Northeast Site. Both the FI and TI commenced on November 10, 2005, the first day the temperature dropped below zero in the region. As one can see, the FI accumulates until late-March and early-April. During this time, the temperature began to rise above zero consistently throughout the day. Figure 25 illustrates the period of frost that occurred during the winter months. The slight accumulation of the thawing index in November 2005 is due to the ambient temperatures did not fall below zero frequently.

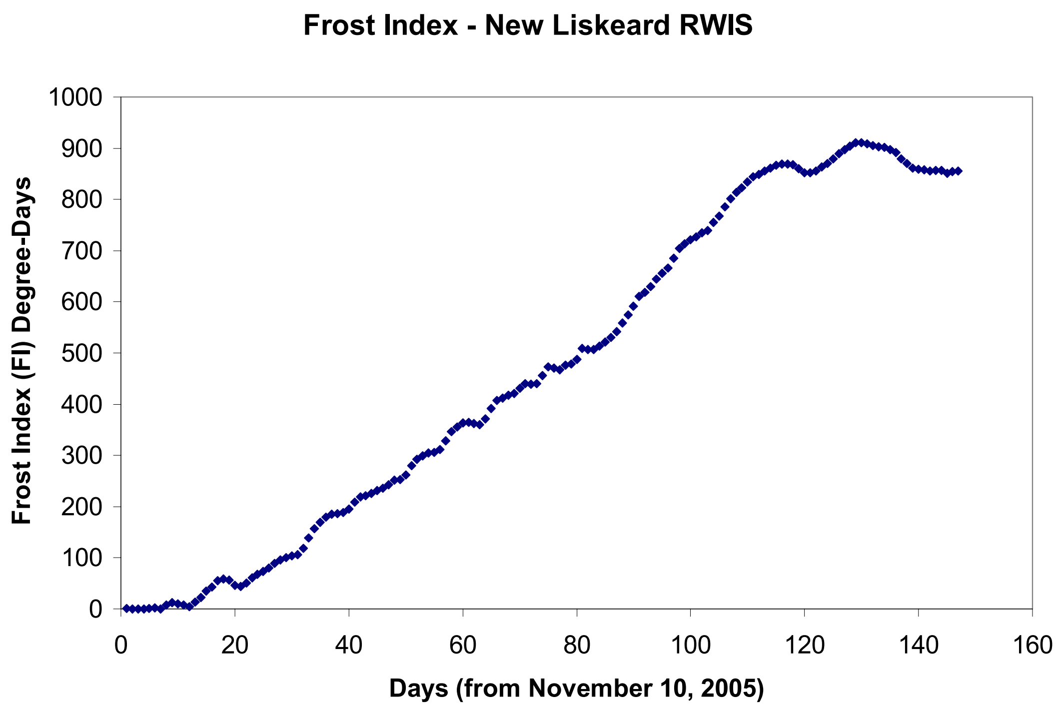


Figure 24. Field data illustrating the cumulative frost index for the NE Region site.

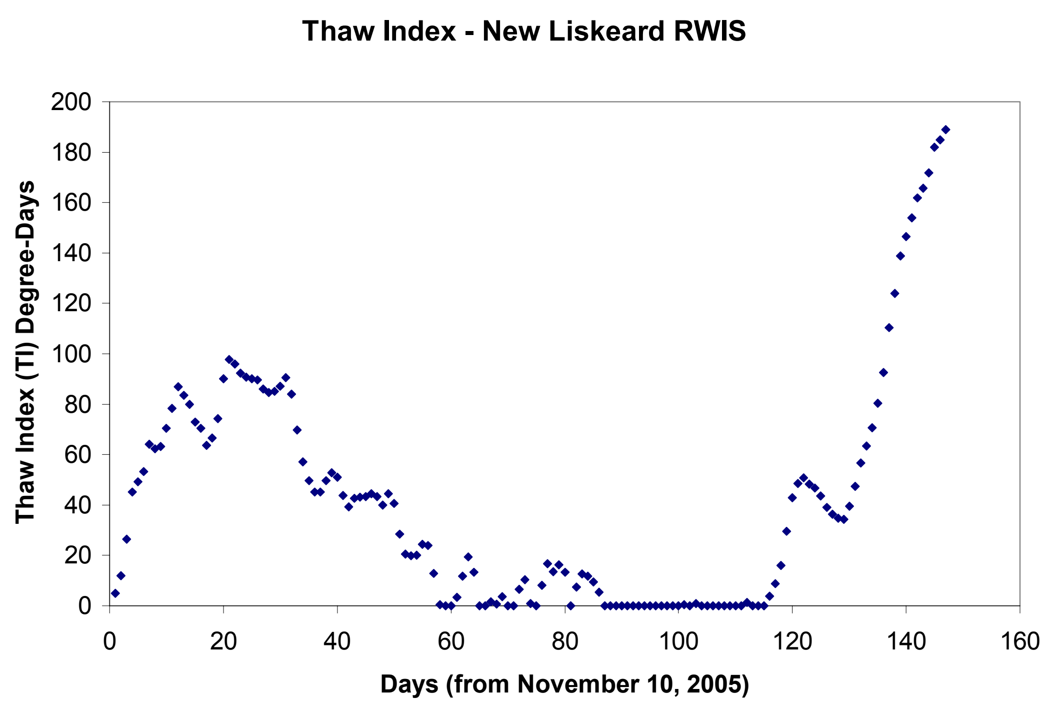

Figure 25.  Field data illustrating the cumulative thawing index for the NE Region site.

# Strategy for Phase II

The purpose of this section is to provide a road map of the short- and long-term work to be completed and delivered to the Ministry of Transportation. The short-term strategy in this project is to firstly, collect relevant data including ARWIS and thermistor. This in turn will be employed in developing an Ontario model to predict thaw depth given ambient air temperatures. Developing thresholds to enforce winter weight premiums and spring load restrictions is the final objective. As the developed models are based on actual data, testing the final models with historical data will provide a means of the accuracy and relevancy of the models developed.

Given the mandate of the project, the literature review and the development of preliminary Ontario models was performed concurrently. The subsequent tasks such as developing and validating the final Ontario specific models as well as the life cycle costing require a sequential approach. In other words, future tasks are dependant on the completion of previous tasks. Figure 26 is a breakdown of the future progress of the project. Currently, the literature and development of preliminary models specifically in Ontario is nearly complete. Refinement of the literature review throughout the project is to be completed. Finalization of the Ontario model will be completed once a sufficient database is acquired, specifically after the spring thaw period. Long term calibration may be required to account for the variance between seasonal thaw.

## TIME SCHEDULE

The following approximate time schedule, which allows for some flexibility. A great deal was accomplished already in terms of design and instrumentation of the two sites. Future focus will be primarily on analysis and justification of indices. The following is a summary of the projected milestones for the successful completion of this research.

### Task 1: July 1, 2006 to Nov. 30, 2006

Further validate the current available ARWIS data and the pilot site data. In developing the experimental design procedure in Phase 1, the initial premise was to utilize ARWIS stations in the study area. Although this data is crucial to the outcome of the project, additional instrumentation to these study sites can provide complementary data to both assist in model development and to substantiate the existing data set already in use, namely the interpolation or extrapolation of ARWIS data. Examine further instrumentation of the two pilot study sites with a temperature and solar radiation sensor and work with MTO to add these sensors to the existing sites.

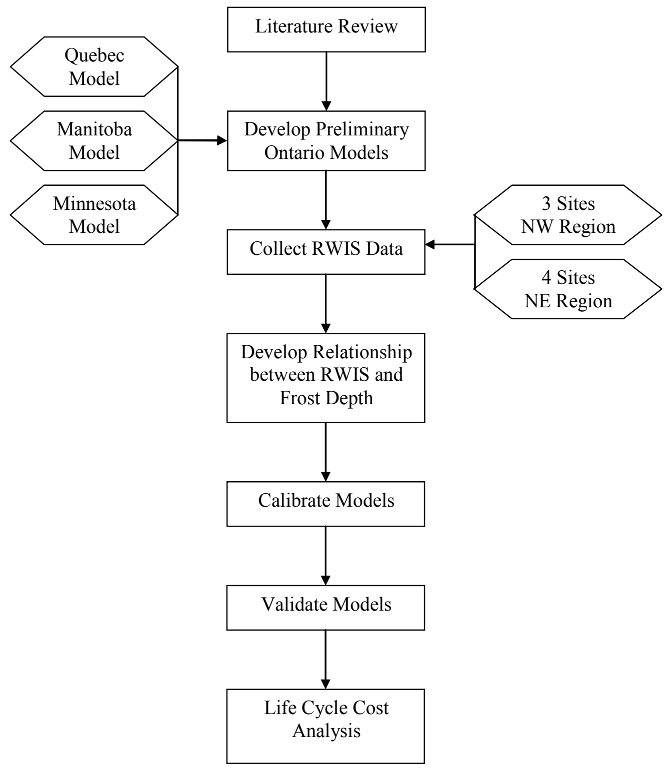


Figure 26. General breakdown of progression of research project.

## Task 2: July 1, 2006 to Dec. 31, 2006

Carry out a detailed pavement cracking prediction scenario using the new AAHSTO MEPDG guide. This will involve development of climatic data files, traffic spectra, subgrade characteristics and their respective impact on pavement performance during the spring thaw and freezing period. Ultimately relate cracking associated with spring thaw to various thaw depths for typical Northern Ontario soil and traffic conditions.

## Task 3: July 1, 2006 to Dec. 31, 2006

Carry out a sensitivity analysis using the Ontario Pavement Analysis of Costs (OPAC 2000) to determine the long term impacts of allowing traffic to run on weak pavement structures. This damage will be calculated in terms of loss of pavement performance but also as a life cycle cost.

## Task 4: Jan. 1, 2007 to April 25, 2007

Collect data for a second season for the two pilot sites. Develop a preliminary probability based model using both the first and second season of thermistor and ARWIS data.

## Task 5: Jan. 1, 2007 to April 25, 2007

Analyze the results of Tasks 3 through 6. Essentially, this will result in a pavement damage model associated with not applying SLR and/or WWP using appropriate statistical procedures. Appropriate modification to the initial models will be recommended with recommendations for continued monitoring.

### Task 6: Jan. 1, 2007 to April 25, 2007

Develop recommendations, based on the results of previous Tasks, for use at MTO. Work with MTO to develop a plan for continued improvement to models.

### Task 7: May 31, 2007

Prepare a technical report on the foregoing tasks and make a presentation to the MTO technical committee.

## DEVELOPMENT OF WWP AND SLR MODEL

Determination of the frost and thaw duration will ultimately provide policy makers the ability to appease the trucking industry whilst mitigating the overall damage of the roadway. This will provide the ability to accurately apply WWP and SLR which are important both economically and mitigating pavement damage.

## LIFE CYCLE COSTING

From an agency perspective, the economics of a given facility must be determined. Material, maintenance and construction life cycle costs are important. The maintenance data for the study sites provide an estimate of the possible cyclic maintenance activities that are required. Figure 27 summarizes the point at which spring load restrictions and winter weight premiums affects the life cycle cost of a facility due to heavy vehicle pavement damage.

The importance of the spring load restriction and winter weight premium duration is profound in terms of possible pavement damage. Excessive loads, as a result of winter weight premiums, can be detrimental once the subgrade strength drops below a certain threshold. Similarly, if SLR is not enforced during low strength periods, damage can occur to the highway infrastructure. Once damage occurs, the annual maintenance cost increase in an attempt to mitigate significant deterioration. The long term effects include moderate and major interventions as well as reconstruction ahead of the initial projected service life. This will cost the transportation agency significantly as the full value of the infrastructure was not realized over its life cycle.

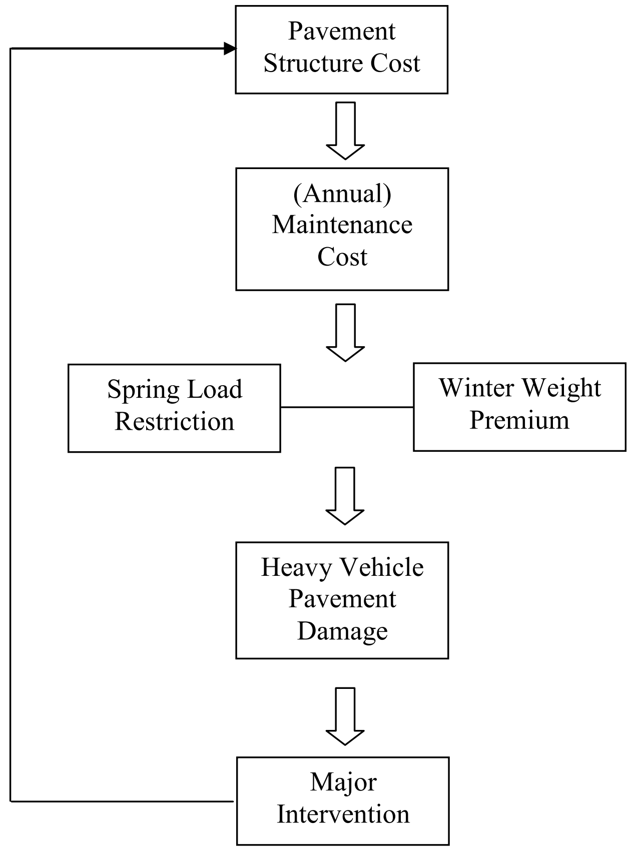


Figure 27. General life cycle cost structure.

## POTENTIAL FUTURE INSTRUMENTATION

Accurate and real-time data is a benefit to field testing. In developing the experimental design procedure, the initial premise was to utilize ARWIS stations in the study area. Although this data is crucial to the outcome of the project, additional instrumentation to these study sites can provide complementary data to both assist in model development and to substantiate the existing data set already in use, namely the interpolation or extrapolation of ARWIS data.

As most of the infrastructure is currently available, including the extra channel capacity of the data loggers, as well as the housing to protect the instrumentation, implementation of this extra sensor is relatively simple and cost effective. Reprogramming the data logger is also relatively simple with the requirement to be on-site to upload the new user defined program to capture the channel of the new sensor.

Placement and protection of the proposed sensors is important for long-term reliability. As it is presumed the sensors will be placed external to the housing, protection from direct sunlight, rain, snow and any projectile objects including snow removal, must be considered. In addition, area wildlife and the potential exposure to harmful chemicals in the event they ingest all or part of such a device must also be considered.

Costs of these types of sensors are relatively low when comparing to the thermistor and data logger costs. Discussions are on going in terms of which manufacturer to purchase the sensor from. However, finalization of this issue is expected by mid February 2006. Upon approval, installation of this sensor at each study site can be completed shortly after the arrival of the sensors. The goal is to have the system active in all capacities prior to the spring thaw, as it is the crucial timeframe for this study.

## Air Temperature Sensor

Ambient air temperature is crucial in determining the relationship for frost depth. Instrumenting each study site with a temperature sensor, specifically that of one or two metres above the pavement surface, would provide on-site temperatures. The benefit of this is to both ensure the calculated (extrapolated / interpolated) temperatures are reasonable, and to provide the ability to analyze the data in a statistical manner. For example, the latter benefit can be used to understand the magnitude of error in extrapolation of ARWIS data. Study sites that are remote in nature, such as the site in Northwest Region, will benefit significantly with this on-site temperature sensor.

## Solar Radiation

The amount of daily sunlight can become an important factor when determining the pavement structure and subgrade temperatures. Solar radiation provides the energy to increase the temperature of the pavement surface. In doing so, the pavement structure and subgrade can be affected in the same way. Therefore, a sensor to provide the magnitude of solar radiation the pavement perceives along with the thermistor temperature probes will allow the understanding of the effects of solar radiation and frost depth.

## Precipitation / Moisture Sensor

There are two types of sensors that measure climatic moisture: precipitation and humidity. Measuring precipitation as well as relative humidity can provide an idea of the amount of moisture that may be entering the subgrade at any given time during the year. A period of high precipitation may lead to higher moisture content in the subgrade leading to a higher potential for thaw damage during the spring.

Precipitation in the form of snow is another important factor that will influence ground temperature. Snow, due to its nature and air voids, provides a means of insulating the ground when a sufficient amount has fallen and remains. Although most facilities have the pavement surface cleared of snow during the winter months, the adjacent ditch banking and surrounding ground remain insulated with the accumulated snow. Therefore, measuring the real-time effects of the amount of precipitation can prove useful.

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