Development of Tools for Improved Spring Load Restriction Policies in Ontario

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ABSTRACT

Application of seasonal load restrictions to certain parts of the highway network can lead to lost productivity and a substantial impact on the economy. Once these restrictions are in place, the payload of certain heavy vehicles must be reduced. One of the largest challenges particularly in Northern Ontario is to design and monitor roads concisely to mitigate damage caused by seasonal effects. This is a complex problem as many of the roads are gravel or surface treated and there is limited funding available for the construction and maintenance of these facilities. Thus, it is vital that these roads are protected, particularly during the vulnerable spring thaw period. In order to properly protect these facilities, it is necessary to monitor them in a coordinated manner which utilizes both temperature and pavement data.

The advancement in data availability has been greatly enhanced with the implementation of road weather information system (RWIS). This paper describes an on-going study in Ontario which has involved the installation of two thermistor probes in Thunder Bay and New Liskeard in the Winter of 2005. At each location, a thermistor assembly was lowered into the excavated area and backfilled. The design of the two pilot sites which includes the installation of thermistor strings and soil data will be described. Initial data will be presented which attempts to relate RWIS data to that observed in the pavement structure. A preliminary thaw index will also be suggested with recommendations for continued monitoring.

INTRODUCTION

Application of spring load restrictions (SLR) to certain parts of the highway network can lead to a lost of productivity and economy. Once these SLR are placed properly, 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. There is a need, both economic and structural, to accurately determine the specific thresholds to optimize the movement of goods.

The purpose of this study is to develop a relationship to predict frost depth based on air temperatures. This will be done through field instrumentation and data collection from existing monitoring sites in the Northern Ontario region.

BACKGROUND

The cyclic nature of climates throughout a year provides challenges to transportation agencies. It is this variation in climate that will influence pavement performance. As the temperature drops in the pavement structure, the moisture that is present will freeze 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 which 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 provide 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. Certain jurisdictions allow an increased payload during this timeframe which is called a winter weight premium (WWP). 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. This study 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.

Freeze-Thaw Phenomenon

Location of freeze-thaw areas is wide spread. 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 subgrade are considered most susceptible to damage [Tighe 2004]. It is important to understand the causes of these cycles and the impact to pavement performance and deterioration. As the pavement surface temperature drops, the subgrade temperature gradient will be similar to that of Figure 1.

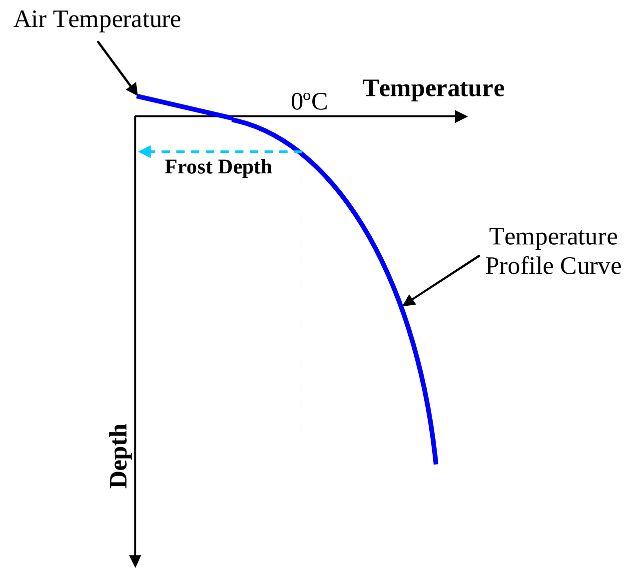

Figure 1. Typical temperature profile considering air temperature and subgrade temperatures.

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 factors that contribute to freeze-thaw 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.

In the event moisture is not permitted 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 drain. The result is a compromised pavement structure that is saturated with water. Figure 2 illustrates the lack of available drainage in the pavement structure and subgrade due to the frozen soil layer.

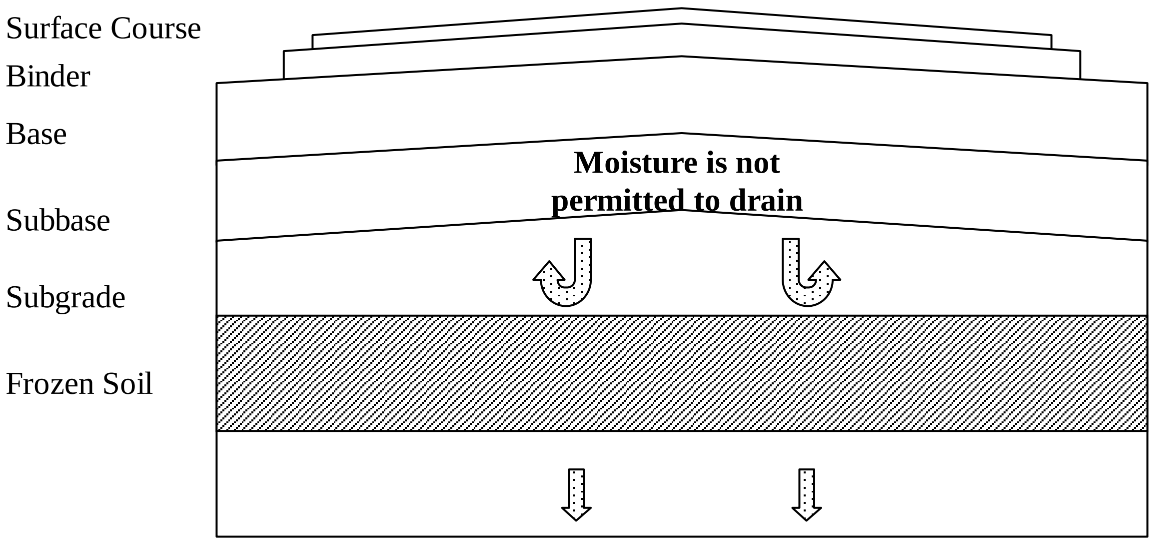

Figure 2. Illustration of the water movement during spring thaw.

Spring Load Restrictions

A pavement structure is engineered to carry an upper load limit 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 et al. [1998] state 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 to industry. In fact, compared to designing and constructing a pavement structure that is not susceptible to climate, temporary load restrictions are 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 respectively. 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 are expected to increase the service life by 62% and 95% respectively [Isotal 1993, Levinson et al. 2005].

There are three methods 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 et al. 1998].

In Ontario, load restrictions are enforced over three distinct periods that is specific to the vehicle type. 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 is enforced between the second week in March to mid-May and third week in March to the end of May respectively.

Economic Impacts of SLR

Seasonal load restrictions cause disruptions to many industries relying on utilizing the highway network to transport goods. Load restrictions may result in the need to increase the number of trips along a restricted route or to follow an alternate, potentially longer route. Both situations lead to increased costs to haulers [Goodings 2000].

As 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 night increases the stiffness of the roadbed. This practice mitigates the economic impacts to the transportation industry, especially that of the logging industry.

Alternatives to Seasonal 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.

Bradley [1997] summarizes the findings of Truebe et al. [1994 & 1995] and 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.

Removal of Seasonal Load Restrictions

An alternative option is to introduce the complete removal of SLR. 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.

In 1995, Norway 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 findings of the Norway experience provide a basis of the potential issues that must be investigated, including adequate and fair increase in transportation budgets to account for increased deterioration and reduced service life. The safety aspect in terms of rutting and provisions for complete pavement structure failures must also be investigated prior to any pilot studies.

Increasing Accuracy of Restriction Dates

Issues with most methods of setting load restrictions include a conservative duration or a delayed restriction enforcement. Therefore, many studies have investigated methods of improving the selection of these threshold dates.

Kestler et al. [1999] reveals a methodology that attempts to accurately quantify when SLR 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. The study concludes that determining the threshold dates to restrict and lift load restrictions is most effective using thermistors that provide superior accuracy at +/-0.2 C.

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.

Empirical Models and Indices

Developing predictive models related to frost depth to assist in the 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.

The air freezing index provides an indication of the frost duration over a given period [Leong et al. 2005]. Equation 1 provides the general method of determining the freezing index (FI). The thaw index (TI) is similar to that of the freezing index, whereby it provides an indication of the duration of warmer weather and its effect on the ground. A reference temperature, relating mean air temperatures to ground temperatures, is required. Equation 2 illustrates the general method of calculating the thawing index.

$$FI = \sum \left(0^{o}C - T_{MEAN_i}\right) \tag{1}$$

$$TI = \sum \left(T_{MEAN_i} - T_{REF}\right) \tag{2}$$

Where FI is the freezing index (^{o}C-days)
TI is the thawing index (^{o}C-days)
$T_{mean(i)}$ the mean air temperature for day i (^{o}C)
T_{ref} is the reference temperature (^{o}C)

Road Weather Information System (RWIS)

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. Road Weather Information System (RWIS) 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 RWIS 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.

OBJECTIVE OF STUDY

The purpose of this study is to provide an understanding of the current research pertaining to load restrictions in Northern Ontario. A preliminary frost depth model is one goal of this study. This model will relate ambient air temperatures to frost depth.

The long term goal of this research is to provide a means of predicting the optimal timeframe to enforce spring load restrictions in Northern Ontario. In other words, enforce load restrictions when the pavement structure is weak to minimize pavement damage while maximizing the use of the highway system. This will be completed through gathering field data at strategic sites in whereby load restrictions are enforced.

METHODOLOGY

The field instrumentation was installed in the Fall 2005. This instrumentation recorded the frost depths in two Northern Ontario sites. Corresponding RWIS data was collected to provide the ambient air temperatures around these sites. Frost and thaw indices were developed resulting in the development of a preliminary frost depth model.

Study Site Description

Two pilot sites were selected for this project. Each site currently has load restrictions in place during the spring months. The study areas are located in Northwest Ontario approximately two hours north of Thunder Bay and in Northeastern Ontario approximately 40 minutes north of New Liskeard. The physical location of the sensors will be at the centreline of the road.

Instrumentation

The instrumentation installed on site includes a thermistor assembly, a data logger and a power source. The latter two are housed in a durable weather resistant cabinet at the edge of the road. The thermistor assembly will measure the temperature profile of the pavement structure to a depth of 265 cm using 13 thermistors. As the majority of freezing and thawing occurs in the upper portion of the pavement structure, the sensors are placed closer together to facilitate a higher resolution to capture temperature fluctuations in this area.

A data logger at each site was installed to provide means of recording data at a specific time intervals. Utilities, including phone and power, were available at the Northeastern Ontario site, but not for the Northwestern Ontario site. Power for the latter is provided through a 12 V external battery. Data acquisition is set at 20 minute intervals. Data retrieval for the Northeastern site is accomplished through a dial-up modem while the Northwestern site is through memory card switch and download at weekly or biweekly intervals.

Cabinet
(Housing Data Logger
and Optional Modem)

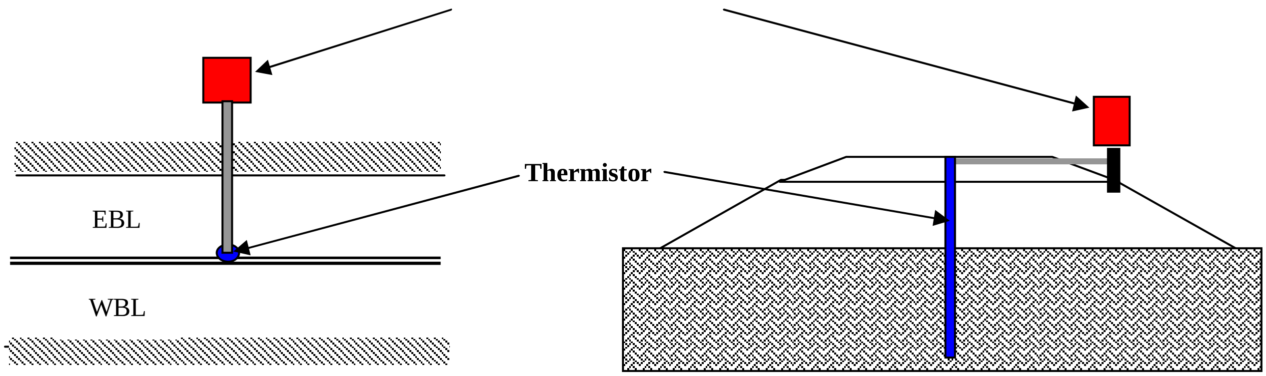

Figure 3. A schematic diagram illustrating the study site layout. Plan view (Left) and cross-sectional view (Right).

Field Data

Similar to the study performed in Quebec [Dore 1998], temperatures at various depths within the pavement structure are measured and recorded. Data acquisition commenced on December 2005 for the Northeastern Ontario site. Due to technical issues, the data acquisition from the Northwestern Ontario site began in February 2006. The preliminary frost depth prediction model will be based on the Northeastern Ontario site data. As of March 28, 2006, the Northeastern Ontario database has over 8100 data points while the Northwestern Ontario database has over 2100 data points.

RWIS data was collected through the database archives. It is important to match the RWIS data points, in terms of date and time, with that of the field frost depth data. Although an exact match is not always achievable, a tolerance of approximately five minutes was utilized in the data pairing stage.

RESULTS

A preliminary thaw index, described as Equation 3, was developed through the single season dataset from a single study site. With a reference temperature of 5.31°C, this represents a 5.3 °C lag between air temperature and pavement temperature. 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, from ARWIS stations, with the corresponding pavement surface temperatures, from thermistor readings.

$$TI = \sum \left(T_{AIR,Mean} + 5.31°\text{C} \right) \tag{3}$$

The thaw (and freeze) index is based on the common trigger date of November 11, 2005, the first day the temperature dropped below zero degrees Celsius. The method of determining an estimated reference temperature is illustrated in Figure 4. 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.

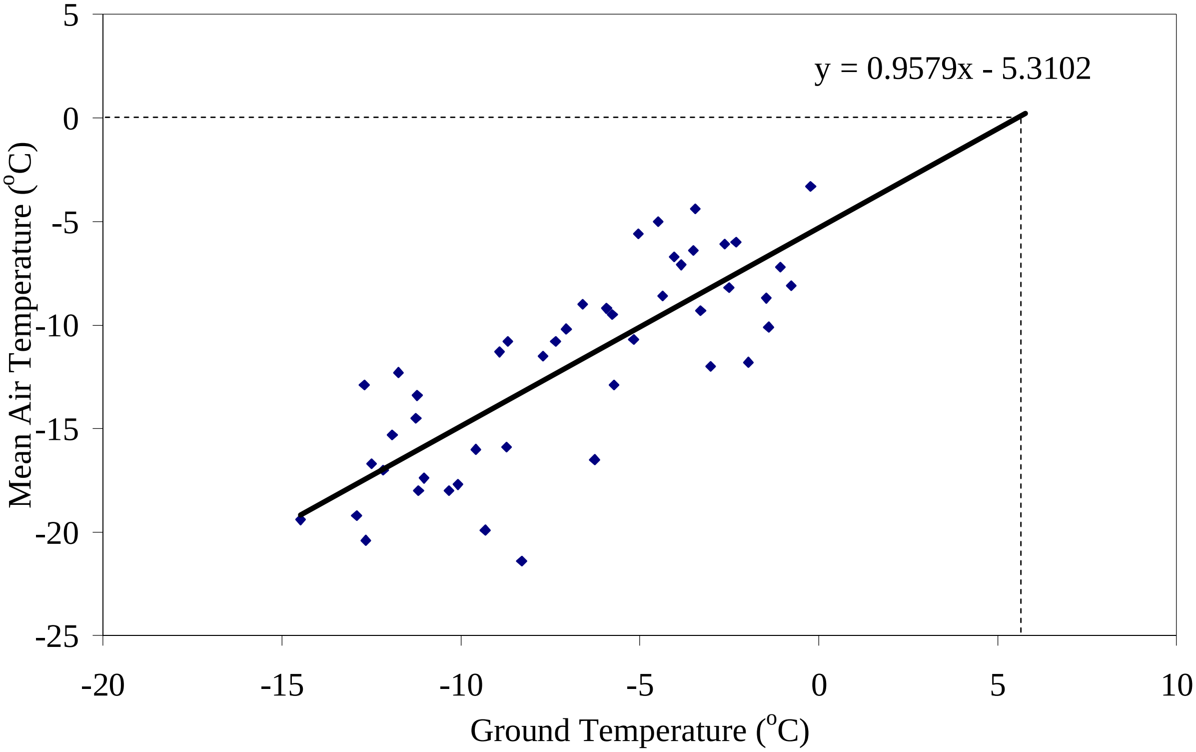

Figure 4. Reference temperature for Northeastern study site.

Figure 5 illustrates the data collected from the Northeastern Ontario 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 at greater amplitude. At lower depths, the temperature fluctuation decreases and is relatively stable. Figure 5 illustrates the temperature lag between the air and various depths in the pavement structure during the frost period.

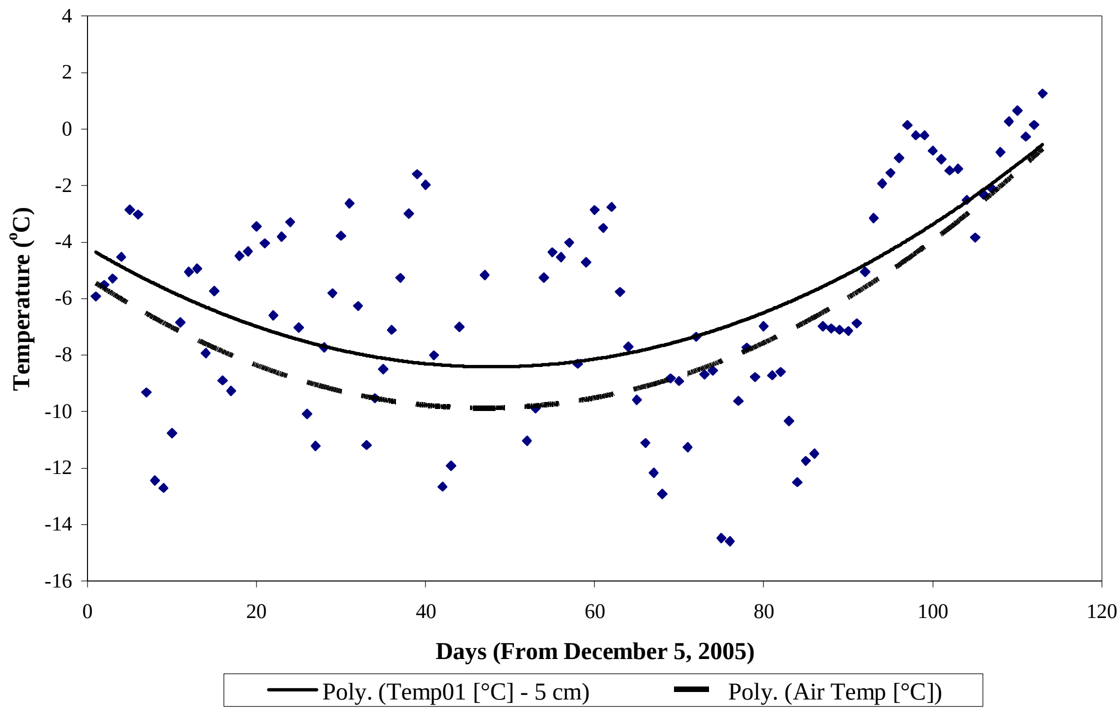

Figure 5a. Daily thermistor values at 5 cm below pavement surface in Northeast Region site. (Note: Red curve indicates mean air temperature while black curve indicates ground surface temperature.)

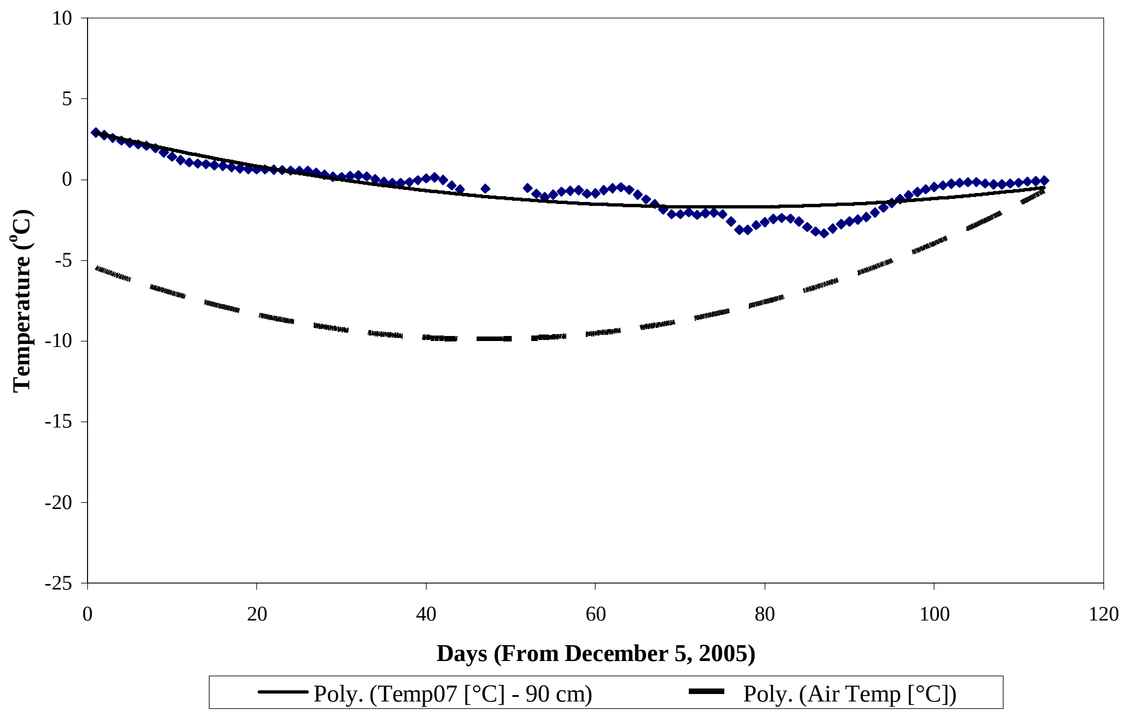

Figure 5b. Daily thermistor values at 90 cm below pavement surface in Northeast Region site.

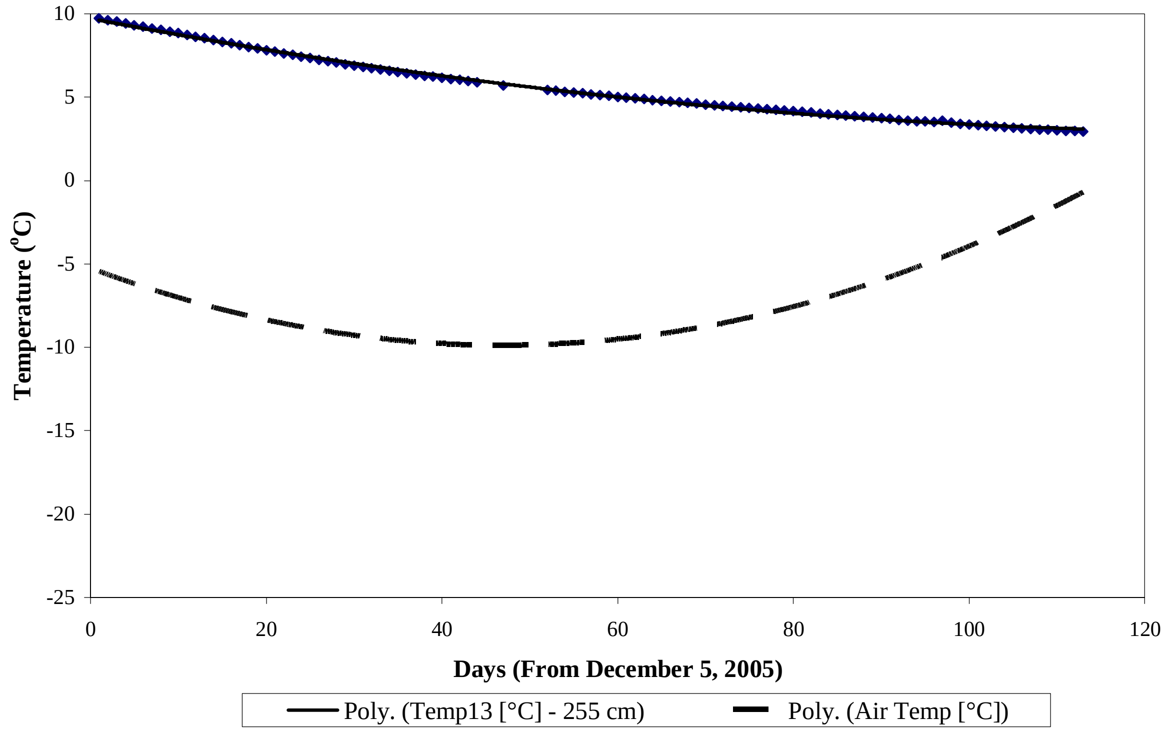

Figure 5c. Daily thermistor values at 255 cm below pavement surface in Northeast Region site.

The RWIS dataset was limited as there exists many air temperature gaps. In the event air temperature is not available for the corresponding frost depth, this data point is omitted from the frost depth model analysis. Although interpolation between two known air temperature data points is possible, it would add to the uncertainty of the final model. Given only one season of data, the goal was to minimize this uncertainty.

A preliminary frost depth model relating cumulative thaw index and frost depth is given in Equation 4. This model is based solely on the Northeastern Ontario pilot site.

$$FD = 5.537 \cdot \sqrt{TI} \qquad (4)$$

Where FD = Frost Depth (cm below pavement surface)
TI = Cumulative thaw index (^{o}C-days)

Equation 4 is based on 107 data points. This preliminary frost depth prediction model has a coefficient of determination of 98.0%. With one seasons worth of data to develop this model, the authors understand the predictive limitations. Therefore, further calibration will be performed based on the 2006-2007 freeze-thaw season.

CONCLUSIONS

The instrumentation installed at the two study sites are performing as expected. With the preliminary freezing and partial thawing data collected, the field trends provide an indication of the effects of low temperature during the winter. Crucially, an indication of the thaw depth will provide personnel an indication of when to impose and lift seasonal load restrictions.

This study is on-going and models will be developed to predict thaw depth based on freezing and thawing indices. As the field database grows, the calibration of these models will improve for these sites. Prediction and forecasting of future key dates, namely imposing and lifting winter weight premiums or seasonal load restrictions, is the long-term goal of this study based on several years of accumulated data.

Instrumentation of strategic sites to record pavement structure and subgrade temperatures is extremely useful. Providing personnel a supplemental tool to understand the state of the highway, in terms of carrying capacity, will allow for increased accuracy of proper seasonal load restriction application and lifting. The end result is reduced damage to the pavement structure as well as maximized revenues for industries that rely on the highway network to transport goods.

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