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Demonstration and Inter-Comparison of Seasonal Weight Restriction Models - Phase I

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Aurora Project 2012-05

Final Report
July 2014

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16. Abstract

In seasonal frost areas, some state departments of transportation (DOTs) take advantage of the period of higher strength in mid-winter by using winter weight premiums (WWPs) to increase the allowable weight that trucks can haul. Conversely, to reduce damage during the spring thaw, many road management agencies apply spring load restrictions (SLRs). The objective of this effort was to provide an understanding of the reliability, benefits, costs, and risks of alternate approaches to scheduling seasonal load restrictions on roadways.

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DEMONSTRATION AND INTER-COMPARISON OF SEASONAL WEIGHT RESTRICTION MODELS – PHASE I

Final Report
July 2014

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INTRODUCTION

1.1 Problem Statement

There are many miles of roads in seasonal frost areas that are highly susceptible to damage during the spring thaw period. As freezing occurs from the surface downward, moisture is drawn toward the freezing front, and ice lenses are formed. When these ice lenses, situated above still-frozen underlying layers, melt, the material is left in an undrained, unconsolidated condition. This leaves the road structure highly susceptible to damage during trafficking.

In seasonal frost areas, some state departments of transportation (DOTs) take advantage of the period of higher strength in mid-winter by applying winter weight premiums (WWPs), increasing the allowable weight that trucks can haul. Conversely, in order to reduce damage during the spring thaw, many road management agencies apply spring load restrictions (SLRs), which restrict the allowable load on the road during the critical time when the pavement is most vulnerable to damage. These load restrictions potentially pose an economic hardship to the trucking and other industries responsible for the movement of goods and services. Restrictions on movement may cause trucks to take detours that require more fuel and driving time. Restrictions may also cause trucks to opt for lighter loads, leading to more trips, additional fuel consumption, and increased driving time. The greatest impact may stem from a lack of alternate routes and/or the common practices of placing a 6-ton load limit or completely prohibiting trucking. This is typically the case for accessing timber, and it brings those hauling operations to a complete halt.

Clearly, SLRs raise sustainability and financial concerns in many regions of the nation. The challenge is to create a rational balance between infrastructure protection and roadway usage during high-stress periods such as freeze-thaw cycles.

Currently, transportation agencies use a wide range of approaches for applying WWPs and SLRs, as shown in Table 1.

Table 1. Methods for applying winter weight premiums and spring load restrictions

	Method	Comments
1	Fixed dates based on long-term experience.	Because of year-to-year variations in freezing and thawing, damage could still occur. Or, hauling may be restricted because a given date falls when conditions are fine for hauling without damage.
2	Inspection/observational approaches, where field personnel observe changes in the roadways such as water seepage from cracks, other indicators of pavement distress, or a worst-case scenario of major rutting, cracking, and breaking up of asphalt.	Too late for action; damage has already occurred.
3	Monitoring changes in pavement load bearing capacity as indicated by deflections measured in falling weight deflectometer (FWD) tests.	State DOTs typically own one FWD, possibly two, and can test only a sample of roadway segments statewide. Most other road management agencies or municipalities, such as cities and counties, do not own FWDs.
4	Monitoring subsurface temperature and/or moisture profiles beneath roadways.	Excellent for conducting studies, but as a means of monitoring for SLR and WWP placement and removal, site specific.
5	Thresholds/protocols based upon atmospheric weather data to set SLR and WWP dates.	Can be very simple to use.
6	Predictive models based upon atmospheric weather data to predict subsoil temperature and/or moisture profiles.	Can range from somewhat simple to very complex, requiring complex input. More complex models also can be expensive.

1.2 Objectives and Scope of Work

The objective of this research is to provide an understanding of the reliability, benefits, costs, and risks of alternate approaches to scheduling seasonal load restrictions.

Specifically, the approaches listed in items 5 and 6 in Table 1 will be evaluated via a field demonstration in which several protocols and/or model predictions are validated against observed subsurface temperature and moisture profiles and measurements of pavement deflection at instrumented sites in the pooled-fund highway jurisdictions (Alaska [AK], Iowa [IA], Michigan [MI], North Dakota [ND], Ontario, and Wisconsin [WI]). This understanding will improve road use management during high-stress periods such as freeze-thaw cycles and will ultimately improve roadway lifetime and usability, benefitting both state DOTs and roadway users (trucking industry, etc.).

The research was divided into two phases, as follows:

Phase 1

- Review of available models, including technical aspects, intellectual property, and implementation issues
- Identification of demonstration site requirements
- Review of available data and instrumentation
- Recommendation of models and sites
- Proposed plan for demonstration and evaluation

Phase 2

- Implementation of models at demonstration sites
- Calibration of models at all sites, if required
- Acquisition of validation data
- Validation analysis
- Presentation of results

The following sections of this report describe efforts accomplished in Phase 1 of the overall project.

2. REVIEW OF AVAILABLE MODELS

2.1 General

Many low-volume roads in the US and other countries are located in seasonal frost areas, where freeze-thaw processes and trafficking coupled with those freeze-thaw processes result in costly damage to the roadways. During the winter months, as air temperatures drop below freezing, heat and moisture move upward from subsurface soils in response to the thermal gradients. Freezing begins at the surface of the pavement and progresses downward toward the subgrade. Ice lenses may form and can cause frost heave. In some states, DOTs take advantage of the period of higher strength in mid-winter by using winter weight premiums (WWPs) to increase the allowable weight that trucks can haul.

To reduce roadway damage, many transportation agencies apply spring load restrictions (SLRs), which reduce the allowable load on the road during the critical period when the pavement is most vulnerable to damage. The challenge in SLR application is to protect the infrastructure and minimize roadway maintenance costs but also to allow commerce to flow as much as possible during the spring thaw and strength recovery period, which typically lasts six to eight weeks. Historically, many transportation agencies imposed SLRs based on set dates and/or visual inspection procedures. The problem with using fixed dates is that subsurface freezing and thawing patterns vary from year to year; thus, appropriate dates/durations for one year may not be appropriate for other years. In the inspection/observational approach, field personnel observe changes in the roadways in the early spring, such as rutting, cracking, water seepage from cracks, and/or other indicators of pavement distress. One problem with inspection/observation methods is that by the time pavement failures are observed, the agency has essentially committed to allowing some level of damage because legislation normally requires three to five days’ notice prior to applying SLRs. Additionally, these methods tend to be highly subjective.

More recently, many transportation agencies have shown an interest in using science-based decisions to establish SLR application and duration rather than relying on hard physical dates or individual judgment. Some agencies are monitoring spring thaw processes using quantitative approaches, such as measuring pavement deflections with a falling weight deflectometer (FWD) and backcalculating layer moduli or determining other indices. Some agencies have installed sensors beneath roadways to monitor subsurface temperature and/or moisture profiles during the spring thaw period.

Studies where subsurface temperature and/or moisture profiles were monitored and correlated with FWD and/or other in situ test results are reported by Van Deusen et al. (1998), Ovik et al. (2000), Kestler et al. (2007), Miller et al. (2007), Tighe et al. (2007), Marquis (2008), Eaton et al. (2009), Bradley et al. (2012), and Miller et al. (2013a). These studies indicate a strong correlation between the onset of thaw and a decrease in the strength and stiffness of the overall pavement system. They also suggest that strength and stiffness recover gradually as thawing progresses and excess moisture in the base and subgrade layers dissipates.

Although these quantitative approaches provide a rational basis for making SLR decisions, FWD testing and associated analyses are very time consuming and expensive. Installing instrumentation to measure subsurface temperature and/or moisture profiles and obtaining data from those instruments in real time can also be prohibitively expensive. Because atmospheric weather data are more readily available and much less expensive to obtain than FWD data and/or subsurface temperature data, many transportation agencies are now considering the use of SLR thresholds linked to weather-based indices and/or frost-thaw depth prediction models that can be coupled with atmospheric forecasts to provide advance warning of estimated dates when winter weight premiums or spring load restrictions should be placed and lifted. These approaches, categorized as either (a) SLR trigger thresholds or (b) frost-thaw depth prediction models, are described in the following sections.

2.2 SLR Posting Methods Based on Trigger Thresholds

2.2.1 Mahoney et al. (1986)

This method assumes that the thawing season begins once the daily average air temperature reaches the 29 degree datum for “several days.” To determine thawing, Mahoney et al. (1986) suggest computing the cumulative thawing index (CTI) using Equation 1:

$$CTI = \sum_{i=1}^{N} (T_{avg,i} - 29) \bullet \Delta t \qquad [1]$$

where

N = number of cumulative days

$T_{avg,i}$ = corresponding day’s average air temperature (degrees Fahrenheit)

Δt = period between consecutive points (1 day)

The CTI cannot be negative and is thus reset to zero if a thawing period is interrupted by a significant refreezing event. This method specifies that thin pavements *should* have the SLR applied on the day where the CTI reaches 10°F days and *must* have the SLR applied on the day where the CTI reaches 40°F days. Thick pavements *should* have the SLR applied on the day where the CTI reaches 25°F days and *must* have the SLR applied on the day where the CTI reaches 50°F days. Mahoney suggests that the “should” date correlates to when the thaw front reaches the bottom of the base layer and the “must” date correlates to when the thaw front reaches 4 in. below the bottom of the base. Pavements are considered thin if the bituminous wearing surface is 2 in. or less in thickness and the base course thickness is 6 in. or less. Pavements are considered thick if the bituminous layer and base course are more than 2 and 6 in. thick, respectively.

Mahoney et al. (1986) suggested two alternative methods for determining spring load restrictions. Both of the SLR removal methods are functions of the cumulative air freezing index (AFI), where the daily AFI is traditionally computed as the difference between the freezing temperature (32°F) and the daily average air temperature. With the cumulative AFI established for the immediate past winter, Mahoney et al. (1986) suggested lifting the SLRs using either a duration threshold (Equation 2) or a CTI threshold (Equation 3). The recommended duration (number of days the SLR should remain after the application date) is determined as follows:

$$Duration = 25 + 0.01(AFI) \qquad [2]$$

Alternately, the SLR may be lifted when the CTI (computed by Equation 1) reaches the following threshold:

$$CTI\ Threshold = 0.3(AFI) \qquad [3]$$

2.2.2 Berg/USFS Method (Berg et al. 2006)

The Berg/USFS method provides an alternative approach to applying spring load restrictions that takes into account the influence of pavement surface temperatures. This method assumes that both average daily air temperatures and average daily pavement surface temperatures can be approximated by sinusoidal functions, according to Equation 4. This method requires an initial trial and error fit for the air temperature sinusoid based upon 30-year normals of average monthly air temperature data from a weather station located near the candidate site. The National Weather Service, and its successors, define a 30-year normal as the average temperature over a 30-year period. A 30-year normal temperature may be the average daily maximum, the average daily minimum, the average monthly maximum, or the average monthly minimum. The 30-year period changes every decade. For example, the current 30-year normal period is from 1981 through 2010. Thirty-year normal data are available for several weather stations in every state and can be found at the National Climatic Data Center's (NCDC) web site, https://www.ncdc.noaa.gov/.

$$T_t = MAT + Amp * Sin\left(\left(\frac{2\Pi}{P}\right) * (t - Lag)\right) \qquad [4]$$

where

T_t = sinusoidal temperature on Julian day t

P = period of sinusoidal variation (365 days)

MAT = 30-year mean annual temperature

Amp = amplitude of temperature sinusoid

Lag = time lag of the temperature sinusoid (i.e., the amount of time it takes the temperature sinusoid to reach the MAT)

The trial and error procedure for determining the amplitude of the air temperature sinusoid is carried out in an Excel spreadsheet using a recommended value of 110 days for the time lag. Figure 1 illustrates the 30-year mean monthly air temperatures (dots) for Hettinger, ND, and daily air temperatures (solid line) computed from them using Equation [4].

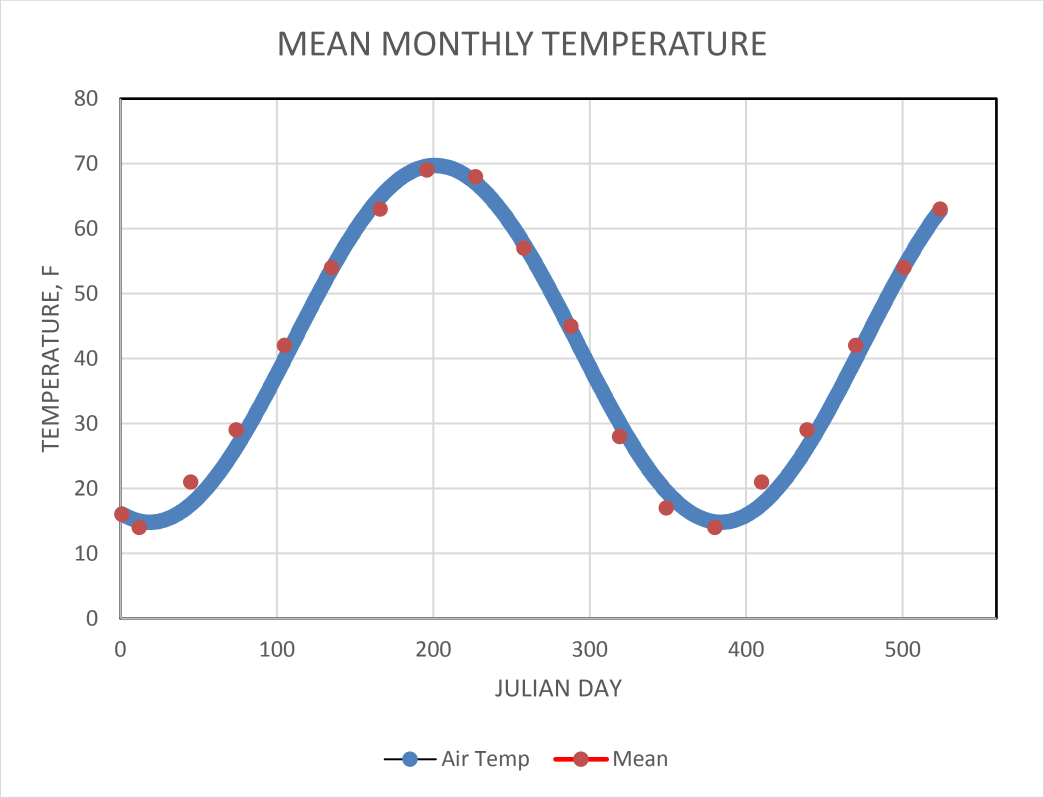

Figure 1. 30-year normal monthly air temperatures and computed daily air temperatures, Hettinger, ND

Then, the following empirical correlations are used to estimate the pavement surface temperature sinusoid:

$$SFI = n_f (AFI) \qquad [5]$$

$$STI = n_t (ATI) \qquad [6]$$

where

SFI = surface freezing index

STI = surface thawing index

n_f = n-factor applied to the air freezing index, *AFI*

n_t = n-factor applied to the air thawing index, *ATI*

Berg et al. (2006) recommend using $n_f = 0.5$ and $n_t = 1.7$ for the New England area. Additional details regarding the methodology for establishing the pavement surface sinusoidal temperature function are described by Berg et al. (2006) and Kestler et al. (2007). After the air and pavement surface temperature sinusoidal functions are established, the difference between the two can be calculated for each Julian day (1 to 365). The difference is then added to the measured average daily air temperature for a specific day to approximate the pavement surface temperature. For northern New England conditions, the daily thawing index (DTI) computation begins on February 14 according to Equation 7:

$$DTI = 32^{o}F - (Pavement \quad Surface \quad Temp) \qquad [7]$$

The DTI is then used to compute a cumulative index (CTI) using Equation 8:

$$CTI = \sum_{i=1}^{N} (DTI_i) \qquad [8]$$

This method recommends applying the SLR when the CTI increases to 30°F days above the minimum CTI value (Berg et. al 2006, Kestler et al. 2007). A protocol for removal of the SLR is not currently provided in this approach.

2.2.3 Minnesota Department of Transportation (MnDOT 2009)

The Minnesota Department of Transportation (MnDOT) recommends applying the SLR based upon a CTI threshold of 25°F days. MnDOT recommends using Equation 9 to compute the CTI:

$$\mathrm{CTI}_n = \sum_{i=1}^{n} (\text{Daily Thawing Index} - 0.5 \times \text{Daily Freezing Index}) \qquad [9]$$

The use of Equation 9 is dictated by the following conditions:

Case a: When $\left(\frac{T_{\max} + T_{\min}}{2} - T_{ref}\right) < 0^{o}F$ and $CTI_{n-1} > 0.5 \times \left(32^{o}F - \frac{T_{\max} + T_{\min}}{2}\right)$,

Then: $DTI = 0^{o}F - day$, and $DFI = \left(32^{o}F - \frac{T_{\max} + T_{\min}}{2}\right)$

Case b: When $\left(\frac{T_{\max} + T_{\min}}{2} - T_{ref}\right) > 0^{o}F$,

Then: $DTI = \left(\frac{T_{\max} + T_{\min}}{2} - T_{ref}\right)$, and $DFI = 0^{o}F - day$

where

CTI_n = cumulative thawing index calculated over *n* days (°F day)

CTI_{n-1} = cumulative thawing index for the previous day

DFI, DTI = daily freezing and thawing indices, respectively

T_{ref} = reference air temperature (°F), from MnDOT (2009)

Note that the CTI resets to zero on January 1 and on any day when $\mathrm{CTI}_n < 0$.

The use of a reference temperature in Equation 9 was recommended by MnDOT (MnDOT 2009) to compensate for the temperature differential between the air temperature and asphalt temperature. In Minnesota, it was found that the air temperature required for pavement thawing to begin actually decreases during the early spring, probably due to the increase in the elevation angle of the sun (Van Deusen et al. 1998). Therefore, MnDOT implemented the use of a floating reference temperature to account for increased solar gain. MnDOT recommends using a reference temperature of 32°F between January 1 and January 31. The solar gain is then reflected using a depression of 2.7°F during the first seven days of February and, thereafter, a further depression of 0.9°F per week (MnDOT 2009).

In Minnesota, the SLR end date for various frost zones is determined by using measured frost and thaw depths, forecast daily air temperatures, and other key indicators collected at several locations within each frost zone. Therefore, the duration of the spring load restriction varies from year to year. However, the MnDOT policy states that “the spring load restrictions will last no more than eight weeks unless extraordinary conditions exist that require additional time or route-specific signage.”

2.2.4 Manitoba Department of Infrastructure and Transportation (MIT) and FPInnovations (Bradley et al. 2012)

In Manitoba, methods for starting and ending SLRs were developed by linking weather-based indices to when pavements started to weaken and to when their strengths substantially recovered in the spring. The researchers used FWD deflection measurements and roadbed moisture content and/or temperatures as indicators of thaw weakening and recovery. Based upon their work, they recommend applying the SLR at a CTI threshold value of 27°F days. In their study, they computed the CTI (°F days) as follows:

$$CTI = \sum Daily\ Thawing\ Index = \sum \left(T_{ref} + \frac{T_{\max} + T_{\min}}{2} \right) \qquad [10]$$

where

T_{ref} = 3.06°F starting March 1 and increases by 0.108°F per day until May 31

(T_{ref} = 0°F from June 1 through February 28 in the following year)

If $(T_{max} + T_{min})/2 < 32$, then the daily thawing index (DTI) $[T_{ref} + (T_{max} + T_{min})/4]$

If CTI < 0, CTI is reset to 0 (i.e., CTI is never negative)

They recommend an ending threshold set to the earlier of two points, either 56 days (8 weeks) from start of the SLR or when CTI reaches 6 30°F days. At their study sites, the researchers also found that when the thaw front reached a depth of about 47 in., the pavement sections had substantially recovered strength (as indicated by FWD) and/or that moisture contents had essentially stabilized to summer levels. The method cannot be used in locations where the frost depth does not reach 47 in.

2.2.5 Lakehead University and Ministry of Transportation Ontario (MTO) (Chapin et al. 2013, Pernia et al. 2014)

Researchers at Lakehead University have been working in conjunction with the Ministry of Transportation Ontario (MTO) since 2005 on development of several modelling methodologies to predict frost and thaw trends at seven instrumented sites in Northern Ontario. Similar to the approaches described in Sections 2.2.3 and 2.2.4, the authors recommend applying WWPs based upon cumulative freezing index (CFI) thresholds and SLRs based upon CTI thresholds. LWD deflection data were used to confirm SLR threshold values by determining the depth associated with the weakening of the pavement structure. With the exception of one site, LWD deflection data suggested that the pavement structure was weakening to the point of permanent damage when the thaw depth exceeded 30 cm, or about 12 in. (Pernia et al. 2014).

Pernia et al. (2014) recommended using the MnDOT equations and reference temperatures (described in Section 2.2.3) for computing freezing and thawing indices. They calibrated their threshold values for applying WWPs and SLRs on a site-specific basis by determining the CFI and CTI values corresponding to the dates that the frost and thaw depths exceeded about 40 in. and 12 in. (100 cm and 30 cm), respectively. Their results are shown in Tables 2a and 2b.

Table 2a. WWP-CFI model calibration

Project Site	Region	Data Set	Date FD > 1 m	Corresponding CFI (°C days)	Site-Specific Threshold Value
Highway 527	NW	2008/2009	10/12/2008	324	347
		2009/2010	15/12/2009	262	
		2010/2011	17/12/2010	395	
		2011/2012	01/01/2012	407	
Highway 569	NE	2005/2006	18/01/2006	500	432
		2007/2008	05/01/2008	480	
		2008/2009	15/12/2008	297	
		2009/2010	08/01/2010	488	
		2010/2011	17/01/2011	530	
		2011/2012	30/12/2011	298	
Highway 599	NW	2008/2009	02/12/2008	204	224
		2009/2010	12/12/2009	206	
		2010/2011	08/12/2010	261	
Highway 66	NE	2007/2008	17/12/2007	360	560
		2009/2010	13/01/2010	565	
		2010/2011	24/01/2011	756	
Highway 643	NW	2008/2009	09/12/2008	305	306
		2009/2010	15/12/2009	289	
		2010/2011	12/12/2010	350	
		2011/2012	13/12/2011	280	
Highway 671	NW	2008/2009	-	-	269
		2009/2010	14/12/2009	257	
		2010/2011	13/12/2010	334	
		2011/2012	14/12/2011	216	
Highway 651	NE	2007/2008	16/12/2007	344	318
		2009/2010	22/12/2009	311	
		2010/2011	17/12/2010	298	

Source: Pernia et al. 2014

Table 2b. SLR-CTI model calibration

Project Site	Region	Data Set	Date TD > 0.3 m	Corresponding CTI (°C days)	Site-Specific Threshold Value
Hwy 66	NE	2007/2008	09/04/2008	66	50
		2009/2010	14/03/2010	65	
		2010/2011	02/04/2011	18	
Hwy 527	NW	2008/2009	11/04/2009	72	72
		2009/2010	15/03/2010	82	
		2010/2011	08/04/2011	58	
		2011/2012	17/03/2012	76	
Hwy 569	NE	2005/2006	29/03/2006	71	37
		2007/2008	08/04/2008	50	
		2008/2009	31/03/2009	28	
		2009/2010	11/03/2010	21	
		2010/2011	02/04/2011	18	
		2011/2012	16/03/2012	35	
Hwy 599	NW	2008/2009	-	-	55
		2009/2010	14/03/2010	64	
		2010/2011	07/04/2011	46	
Hwy 643	NW	2008/2009	16/04/2009	60	60
		2009/2010	14/03/2010	69	
		2010/2011	10/04/2011	40	
		2011/2012	18/03/2012	71	
Hwy 671	NW	2008/2009	22/03/2009	17	21
		2009/2010	10/03/2010	23	
		2010/2011	28/03/2011	0	
		2011/2012	14/03/2012	43	
Hwy 651	NE	2007/2008	07/04/2008	91	65
		2009/2010	13/03/2010	51	
		2010/2011	08/04/2011	54	

Source: Pernia et al. 2014

2.3 SLR Posting Methods Based on Frost-Thaw Depth Prediction Models

Some transportation agencies are now considering the use of predictive models to estimate frost-thaw profiles. If sufficiently accurate, the models can be used to set SLR application dates (i.e., when the pavement structure starts thawing). Where maximum seasonal frost depths are less than 3.5 ft, the SLR should remain in place until thawing is complete, or until thawing has reached a sufficient depth that excess moisture can drain from the base and upper subgrade layers. These models can rely on a variety of inputs that may include atmospheric weather data, pavement layers thicknesses, and thermal and other material properties of the pavement structure.

2.3.1 Freeze-Thaw Index Model(s)

2.3.1a Freeze-Thaw Index Model with Constant Coefficient(s)

In 2005, researchers at the University of Waterloo, Ontario, began investigating the relationship between air temperatures and depths of frost and thaw beneath roadways (Huen et al. 2006). They installed instrumentation to monitor subsurface temperatures beneath the roadway at two test locations in Ontario. Road weather information systems (RWIS) were available at these locations to measure atmospheric weather data, such as air temperature, humidity, precipitation, etc. The ultimate goal of this research was to create a localized model that could be used to predict frost profiles based upon air temperature freezing and thawing indices. The researchers developed a preliminary model relating the depth of frost penetration to the square root of the CFI and discovered a linear relationship with a coefficient of determination of 98% (Huen et al. 2006):

$$CFI = \sum (32^{o}F - T_{avg,i}) \qquad [11]$$

$$\mathrm{FD} = \mathrm{C_F}\sqrt{\mathrm{CFI}} \qquad [12]$$

where

FD = frost depth below the pavement's surface (in.)

CFI = cumulative freezing index (°F days)

C_F = frost depth coefficient

$T_{avg,i}$ = average air temperature for day *i* (^{o}F)

Huen et al. (2006) reported a frost depth coefficient, C_F, of 1.62 (for the British units shown above). In 2006 and 2007, the Maine DOT built upon the work originally conducted at the University of Waterloo, as well as work conducted by MnDOT. The Maine DOT estimated frost depths using the same methodology (Equation 12) and constant coefficient, C_F, of 1.62. The Maine DOT also estimated thaw depths in a similar fashion (Equation 13, using a C_F of 1.62), but they incorporated the CTI computations and variable reference temperatures suggested by MnDOT (2009), as described in Section 2.2.3 of this report.

$$\mathrm{TD} = \mathrm{C_T}\sqrt{\mathrm{CTI}} \qquad [13]$$

where

TD = thaw depth below the pavement's surface (in.)

CTI = cumulative thawing index (°F days)

C_T = thaw depth coefficient

The Maine DOT compared estimated frost and thaw depths with frost profiles measured via frost tubes at four test sites in Maine. The Maine DOT concluded that the estimated frost and thaw depths correlated very well with measured frost depths at three of the four test sites (Marquis 2008).

2.3.1b Freeze-Thaw Index Model: University of Massachusetts - Dartmouth (UMD) Method (Miller et al. 2012b)

In a follow-up to the Maine DOT study (Marquis 2008), investigators at University of Massachusetts - Dartmouth (UMD) used the same methodology to estimate frost and thaw depths at nine test sites established for a New Hampshire DOT/Forest Service SLR study (Miller et al. 2012a). While the results of that investigation were promising, the investigators concluded that calibrating the model on a site-specific basis might enable more accurate estimates of frost-thaw profiles. Subsequently, linear regression analysis was used to determine site-specific calibration coefficients for the nine NH test sites as follows (Miller et al. 2012b). The measured frost or thaw depth (dependent variable) was plotted against the square root of the corresponding CFI or CTI value (independent variable), and a linear trendline was fitted to the data to determine calibration coefficients for the prediction model. Those site-specific calibration coefficients are presented in Table 3.

Table 3. Site-specific frost and thaw coefficients for NH test sites (with zero intercepts)

Site	Years	C_F	R^2	C_T	R^2
K-1	2007-2010	2.33	0.94	1.62	0.69
K-2 and K-3	2007-2010	1.86	0.94	1.73	0.77
LT	2007-2010	1.36	0.79	1.39	0.83
NGR	2007-2010	1.20	0.91	1.33	0.88
RUM	2007-2010	1.31	0.94	1.89	0.79
SLR	2007-2010	1.18	0.76	1.34	0.38
WF	2007-2010	0.90	0.75	1.79	0.82
WS	2007-2010	1.72	0.92	1.55	0.38

Although the linear regressions were initially performed using zero intercepts, it was found that at the three Kancamagus Highway test sites (K-1, K-2, and K-3), using a non-zero intercept resulted in better thaw depth correlations. Those modified regressions yielded Equation 14 for site K-1 and Equation 15 for the combined data from sites K-2 and K-3 (with TD and CTI as defined previously). The resulting R^2 coefficients were 0.89 and 0.83, respectively, for those modified regressions. At all other sites, changing the regression analysis from a zero intercept to a non-zero intercept did not significantly affect the R^2 coefficients.

$$\mathrm{TD} = 2.98\sqrt{\mathrm{CTI}} - 30.32 \tag{14}$$

$$\mathrm{TD} = 2.29\sqrt{\mathrm{CTI}} - 10.55 \tag{15}$$

The predictive model was then used along with the site-specific coefficients to estimate frost and thaw depths, which were plotted and compared with the measured depths at each test site.

The frost-thaw patterns were reasonably estimated at most sites by the freeze-thaw index model, although the model tended to be too conservative in estimating end-of-thaw dates, with estimated end-of-thaw dates falling after measured dates in many instances (Miller et al. 2012b).

2.3.1c Freeze-Thaw Index Model: Waterloo Method (Baïz et al. 2008)

In this section, SI units are used because the original work was done in these units and changing to British units would require rerunning all of the regressions to obtain the proper coefficients. (The authors of this report do not have the original data on hand to rerun the regressions.) Building upon the preliminary model developed by Huen et al. (2006) relating the cumulative freezing index to frost depth (Equation 6), Baïz et al. (2008) developed an advanced frost model that must be calibrated on a site-specific basis using multiple years of measured frost and thaw depth data as well as air temperature data.

For any given site, Baïz et al. (2008) suggested calibrating reference temperatures on a monthly basis and then determining 12 unique, site-specific coefficients using statistical linear regression methods and best-fit algorithms such as the least squares estimation method. A transition is necessary from the use of the first set of coefficients (a, b, c, d, e, f) to the other set (g, h, i, j, k, l). That transition corresponds to the transition from a period of predominant freezing to a period during which thawing process takes over. The statistical procedures and algorithms used to compute the 12 site-specific coefficients are rather complex and are described more fully in other references (Baïz et al. 2008, Chapin et al. 2013), and the equations used to estimate frost and thaw depths are shown below.

$$0 \le i \le i_0 \Rightarrow \begin{cases} FD_i = a + b\sqrt{FI_i} + c\sqrt{TI_i}) \\ TD_i = d + e\sqrt{FI_i} + f\sqrt{TI_i}) \end{cases} \tag{16}$$

$$i \ge i_0 \Rightarrow \begin{cases} FD_i = g + h\sqrt{FI_i} + i\sqrt{TI_i}) \\ TD_i = j + k\sqrt{FI_i} + l\sqrt{TI_i}) \end{cases} \tag{17}$$

where

i number of days after the day indexed as day $i = 0$

i = 0 day on which T_{Air_i} first falls below 0℃

i_0 day after which the TI constantly rises above 0℃ days

FD_i freeze depth on day i (depth of frost from the pavement surface, negative, in cm)

TD_i thaw depth on day i (depth of thaw from the pavement surface, negative, in cm)

FI_i freezing index value on day i (in 0℃ days)

TI_i thawing index value on day i (in 0℃ days)

a, b, c, d, e, f calibration coefficients used during the winter months

g, h, I, j, k, l calibration coefficients used during the winter months

Baïz et al. (2008) presented data from one year of research at the experimental test site on Highway 569 in Ontario, Canada. Chapin et al. (2013) summarized results from three years of calibration at the Highway 569 field test site (Table 4).

Table 4. Calculated Waterloo reference temperatures and calibration coefficients for the Highway 569 study site

Monthly Reference Temperature (°C)		**2005/2006**	**2007/2008**	**2008/2009**	**Average**
November		0.03	-3.35	-4.93	-2.75
December		-4.15	-1.30	-2.94	-2.79
January		-2.21	0.79	-0.90	-0.77
February		-2.79	-0.06	-2.15	-1.67
March		-7.61	-2.05	-5.22	-4.96
April		-4.45	-5.42	-2.53	-4.14
May		-1.30	-3.68	8.58	1.20
Calibration Coefficients		**2005/2006**	**2007/2008**	**2008/2009**	**Average**
Freezing Season Coefficients (Eq. 2.25)	a	-3.63	34.28	-31.39	-0.25
	b	-4.71	-5.80	-3.96	-4.82
	c	5.14	-1.41	2.92	2.22
	d	0.19	1.93	31.74	11.29
	e	-0.01	-0.07	-0.98	-0.35
	f	-0.23	-0.85	-2.11	-1.06
Thawing Season Coefficients (Eq. 2.26)	g	791.31	53.12	-145.33	233.03
	h	-28.66	-7.43	-0.92	-12.34
	i	-0.14	4.60	0.14	1.53
	j	-861.83	-1525.79	-1425.31	-1271
	k	28.96	38.59	32.05	33.20
	l	-5.66	-0.72	1.19	-1.73
Day i_0		3/20/06	4/7/08	4/15/09	-

Source: Pernia et al. 2014

During the calibration of the Waterloo method, Chapin et al. (2013) noted that the method was highly sensitive to the algorithm calibration coefficients and that those coefficients were highly inconsistent on a yearly basis. Chapin et al. (2013) utilized the average values obtained from three years of calibration along with the recommended algorithms developed by Baïz et al. (2008) to predict frost and thaw penetration from 2009 to 2010 at the Highway 569 field test site. When used in a predictive manner for the 2009/2010 season, their study indicated that the thawing depth would exceed 0.3 m on April 14, 2010, significantly later than the date indicated by the observed conditions (March 11, 2010). As such, the predicted time required for complete pavement structure thawing at the site was also significantly offset. The researchers discovered that significant adjustments had to be made to two coefficients (g and j) on day i_0 in order for predicted frost and thaw depths to match the measured frost and thaw depths. Chapin et al. (2013) concluded that it is very difficult to develop a set of coefficients for the Waterloo method that can be used to make reliable predictions for SLR implementation, even when multiple years of calibration data are available.

2.3.1d Freeze-Thaw Index Model: Lakehead Method (Chapin et al. 2013, Pernia et al. 2014)

In this section, SI units are again used because the original work was done in these units and changing to British units would require rerunning all of the regressions to obtain the proper coefficients. (The authors of this report do not have the original data on hand to rerun the regressions.) Another variation on the freeze-thaw index method for predicting frost and thaw depths is presented by Chapin et al. (2013) and Pernia et al. (2014). As described in Section 2.2.5 of this report, they recommend using the MnDOT equations and reference temperatures (described in Section 2.2.3) for computing freezing and thawing indices. They then use those CFI and CTI values to predict frost and thaw depths using an empirical model that was developed by means of a regression analysis, as follows.

The measured frost or thaw depth (dependent variable) was plotted against the day's corresponding CFI or CTI value (independent variable) to determine calibration coefficients for the prediction model. They examined both the linear and polynomial trendlines fitted to their data and discovered that the polynomial model generally returned a better R-squared value. As such, their prediction model uses a second-order quadratic with the following form:

$$y = ax^2 + bx + c \qquad [18]$$

where

y = frost or thaw depth, respectively, below the pavement's surface (cm)

x = CFI or CTI, respectively (°C days)

a, b, and c = regression coefficients

The average frost and thaw depth coefficients determined for their prediction model based upon data collected between 2007 and 2012 are presented in Tables 5 and 6.

Table 5. Frost depth model prediction coefficients

Project Site	Polynomial A	Polynomial b	Polynomial c	R² Poly
Hwy 66	2.33E-05	-0.1799	-7.3701	0.9563
Hwy 527	0.0001	-0.3090	-3.4691	0.9876
Hwy 569	0.0001	-0.2349	-6.9967	0.9453
Hwy 599	0.0001	-0.2539	-36.0174	0.9761
Hwy 643	0.0001	-0.2375	-25.0958	0.9890
Hwy 651	0.0002	-0.2964	-17.5195	0.9082
Hwy 671	0.0001	-0.2405	-36.4742	0.9708

Source: Pernia et al. 2014

Table 6. Thaw depth model prediction coefficients

Project Site	Polynomial A	Polynomial b	Polynomial c	R² Poly
Hwy 66	7.33E-04	-0.5494	-2.0523	0.9536
Hwy 527	0.0003	-0.6534	0.3505	0.9650
Hwy 569	0.0014	-0.8878	-2.7349	0.9218
Hwy 599	0.0018	-1.1434	-1.3261	0.9333
Hwy 643	0.0013	-0.8855	-0.4598	0.9408
Hwy 651	-0.0029	-0.5080	0.9779	0.9404
Hwy 671	0.0021	-1.1434	-5.7259	0.9280

Source: Pernia et al. 2014

These models were used in a predictive mode for the 2012/2013 season. Chapin et al. (2013) and Pernia et al. (2014) concluded that this methodology for predicting frost and thaw depths produced better results in comparison with other methods that they studied (such as the Waterloo method, described in Section 2.3.1c of this report, or numerical modeling with TEMP/W, described in Section 2.3.4 of this report).

Pernia et al. (2014) noted that, because the model uses a second-order polynomial to predict the frost and thaw depths, one of its limitations is that it doesn't begin producing predictions until the depth has surpassed the c coefficient. In order to avoid this situation, an algorithm is incorporated into the model that returns a frost or thaw depth of zero until the CFI or CTI, respectively, surpasses the c coefficient. This, in turn, often creates large jumps in the early stages of frost and thaw progression (Pernia et al. 2014).

Pernia et al. (2014) suggest that their model, as with all models, should be recalibrated each year with the previous year's data. They recommend that new coefficients be determined (as described previously) and averaged with the previous ones to develop prediction coefficients for the following season. Based upon their most recent work, the coefficients that were recommended for the 2013/2014 frost depth prediction models are presented in Tables 7 and 8.

Table 7. 2013/2014 frost depth prediction coefficients

Project Site	Polynomial			R^2
	a	b	c	Poly
Hwy 66	3.5E-05	-0.1901	-6.0606	0.9649
Hwy 527	0.0001	-0.2939	-3.0646	0.9883
Hwy 569	0.0001	-0.2627	-4.8169	0.9589
Hwy 599	0.0001	-0.2645	-27.8723	0.9778
Hwy 643	0.0001	-0.2375	-25.0958	0.9890
Hwy 651	0.0002	-0.2964	-17.5195	0.9082
Hwy 671	0.0001	-0.2447	-30.7495	0.9739

Source: Pernia et al. 2014

Table 8. 2013/2014 thaw depth prediction coefficients

Project Site	Polynomial			R^2
	a	b	c	Poly
Hwy 66	8.5E-04	-0.6036	-2.3322	0.9549
Hwy 527	0.0010	-0.9435	0.0851	0.9383
Hwy 569	0.0015	-0.8821	-2.4111	0.9269
Hwy 599	0.0013	-1.0178	-1.5292	0.9312
Hwy 643	0.0013	-0.8855	-0.4598	0.9408
Hwy 651	-0.0029	-0.5080	0.9779	0.9404
Hwy 671	0.0028	-1.3064	-5.8068	0.9243

Source: Pernia et al. 2014

It can be seen in Tables 5 through 8 that the a and b coefficients are similar across all sites; however, the c coefficient varies quite dramatically. Furthermore, adding just one additional year of data to the average causes some significant changes in the c coefficient.

As such, the authors of this report believe that it is necessary to have multiple years of calibration data available in order to obtain reliable frost-thaw depth predictions for SLR implementation using any of the freeze-thaw index models (not just the model described in this section).

2.3.2 US Army Corps of Engineers Model 158

A review of various early frost prediction models is provided in a report from the US Army Corps of Engineers-New England Division (1949). Model 158, one of the equations in that report, was adapted by Orr and Irwin (2006) to compute daily frost and thaw depths.

$$X = -\frac{d}{2} + \left[\left(\frac{d}{2} \right)^2 + \frac{kI_{sf}}{L + c(v_o + I_{sf} / 2t)} \right]^{1/2} \qquad [19]$$

where

X = seasonal maximum depth of frost (ft)

k = thermal conductivity (BTU/(ft*day*°F))

I_{sf} = seasonal surface freezing index (°F days)

L = volumetric latent heat of fusion (BTU/ft^3)

d = thickness of the surface asphalt layer (ft)

c = volumetric heat capacity (BTU/(ft^3*°F))

v_o = absolute value of the difference between the mean annual temperature below the ground surface and the freezing temperature (°F)

t = annual length of time below freezing (days)

Although this model was developed before reference temperatures were introduced, this equation accounts for the difference between air and pavement surface temperatures with the surface freezing index. As originally proposed, I_{sf} is the total seasonal surface freezing index; thus, the equation would compute the seasonal maximum depth of frost. The equation accounts for the difference between the seasonal air freezing index, AFI, and seasonal pavement surface freezing index, I_{sf}, by utilizing the "n-factor" concept (Andersland and Ladanyi 2004), where n-factors of about 0.8 have typically been used for air temperatures below freezing:

$$I_{sf} = n(AFI) \tag{20}$$

The use of computer spreadsheets now enables the Model 158 equation to predict daily frost depths by using the parameter I_{sf} summed on a daily basis rather than for an entire season (Orr and Irwin 2006). The Cornell Pavement Frost Model (CFPM) described by Orr and Irwin (2006) has shown much promise for predicting frost-thaw profiles in New York state. However, the CPFM was not as successful in predicting frost-thaw profiles in northern New England.

Therefore, researchers at UMD made slightly different alterations to the original Model 158, and this "Modified Model 158" is described in Equation 21.

$$(X_f)_n = -\frac{d}{2} + \left(\left(\frac{d}{2}\right)^2 + \frac{k\,(I_{sf})_n}{L + c[v_o + (I_{sf})_n / 2t]}\right)^{1/2} \tag{21}$$

$$(X_t)_n = -\frac{d}{2} + \left(\left(\frac{d}{2}\right)^2 + \frac{k\,(I_{st})_n}{L + c[v_o + (I_{st})_n / 2t]}\right)^{1/2} \tag{22}$$

where

$(X_f)_n$ = depth of frost on day n (ft)

$(X_t)_n$ = depth of thaw on day n (ft)

$(I_{sf})_n$ = cumulative surface freezing temperature index for day n (°F days)

$(I_{st})_n$ = cumulative surface thawing temperature index for day n (°F days)

k, L, d, c, v_o, and t are as described in Equation 19.

Examination of Equations 19 and 21 shows that they are essentially the same, except Equation 19 only computes maximum seasonal freezing and Equation 21 is used to compute daily depths of frost penetration. Note that $(I_{sf})_n$ and $(I_{st})_n$ are cumulative values, summed on a daily basis, and cannot be less than zero.

As noted previously, the differences between air freezing and thawing indices and pavement surface freezing and thawing indices are accounted for by using n-factors:

$$(I_{sf})_n = n_f(CFI_n) \qquad [23]$$

$$(I_{st})_n = n_t(CTI_n) \qquad [24]$$

where

n_f = weighted average of n-factor for freezing

n_t = weighted average n-factor for thawing

CFI_n = cumulative air freezing index calculated over n days (°F days)

CTI_n = cumulative air thawing index calculated over n days (°F days)

The cumulative freezing and thawing indices are computed according to the procedures outlined in MnDOT (2009), as described in Section 2.2.3 of this report. The CFI and CTI are multiplied by weighted average values for n_f and n_t based on the depth of frost and thaw, respectively, from the previous day to determine I_{sf} and I_{st}. Weighted average values are also used for the thermal properties (k, c and L). Equation 25 shows how the weighted averages in the frost-thaw depth calculations are computed.

$$\text{Weighted Average, } P = \frac{p_1d_1 + p_2d_2 + p_3d_3}{X_{n-1}} \qquad [25]$$

where

P = weighted average value for property (n_f. n_t, k, c, L)

p_1, p_2, p_3 = property value for the asphalt, base-subbase, and subgrade, respectively

d_1, d_2, d_3 = thickness of frost penetration through the corresponding pavement layer from the previous day (ft)

X_{n-1} = total depth of frost (or thaw) penetration from the previous day (ft)

The Model 158 equation requires layer thicknesses and material properties of the pavement structure. The thermal properties necessary for this model are thermal conductivity (k), volumetric heat capacity (c), and volumetric latent heat of fusion (L). Thermal conductivity is a measure of a material's ability to conduct heat through a material (or pavement layer) per unit length per temperature degree. Volumetric heat capacity is the material characteristic that quantifies the amount of heat required to change a specific volume of a substance's temperature per degree. Latent heat is a measure of the amount of heat released or absorbed by a substance that occurs without a change in temperature and accounts for the change in energy during a phase transition (i.e., water transitioning from liquid to ice). Recommended values for the thermal properties vary from reference to reference, and they are a function of many parameters, such as soil type, density, temperature, and moisture content.

The current version of the UMD Model 158 spreadsheet, however, is not set up to incorporate changes in thermal properties as a function of those parameters (which change during the freeze-thaw process), so constant values for k, c, and L must be selected for use in that model.

2.3.3 Enhanced Integrated Climatic Model (EICM)

As a part of the American Association of State Highway and Transportation Officials (AASHTO) Mechanistic-Empirical Pavement Design Guide (MEPDG), the Enhanced Integrated Climatic Module (EICM) is a module that analyzes the climatic impacts on pavement design. This computer program has the ability to estimate subsurface temperature and moisture profiles based on atmospheric weather data. The EICM utilizes the Infiltration and Drainage Model (ID Model) developed at Texas A&M University, the Climatic-Materials-Structural Model (CMS Model) developed at the University of Illinois, and the Frost Heave and Thaw Settlement Model (CRREL Model) developed at the US Army Cold Regions Research and Engineering Laboratory (Zapata and Houston 2008, Berg et al. 1980).

This software normally uses multiple seasons of hourly atmospheric weather data from weather stations across the US, but users can utilize the historic database or import their own weather data to estimate depths of frost and thaw penetration over the winter to spring period. The climatic inputs required are air temperature, precipitation, wind speed, percent sunshine, relative humidity, and groundwater table depth. If there are gaps in the data, the software interpolates to fill in any missing values.

Similar to Model 158, the EICM requires details of the pavement structure. The user must input the thicknesses of the different layers as well as soil strength parameters. The software provides default values for properties such as thermal conductivity and specific gravity, and even the grain size distributions for different soil types.

Many studies investigating the validity of the EICM have been reported by state DOTs, the Transportation Research Board (TRB), the National Cooperative Highway Research Program (NCHRP), FHWA, and other transportation agencies. Many of these studies have compared EICM-computed data to measured pavement parameters such as temperature and moisture profiles. Results of a New Jersey Department of Transportation study did not indicate a high correlation between field-measured values and EICM-predicted temperature and moisture profiles through various pavement structures (Ahmed et al. 2005). An Ohio study also found that EICM-predicted temperature profiles did not match measured field data, but the range of values computed by the model was considered to fall within an acceptable range. This research found that there was not a good relationship between the modeled and measured frost-thaw depths in the bounded base material sections (such as cement or asphalt stabilized base layers), but there was a noticeable relationship for unbounded base material layers (Liang 2006).

A project sponsored by the FHWA through Clarus developed an “automated tool” as part of the Clarus Use Case #2 Project in North Dakota, South Dakota, and Montana (FHWA 2011). That tool utilizes the EICM to simulate pavement, subbase, and subgrade conditions (including temperature, moisture, and strength/stiffness) based on observed and forecasted weather parameters. The tool provides graphic profiles of subsurface conditions down to 48 in. and provides forecasts for about three weeks into the future. The authors of the FHWA report concluded that “the Clarus Use Case #2 seasonal load restriction tool demonstration can be viewed as reasonably successful and perceived by state DOTs and motor carriers as having great potential value.” However, they expressed a need to validate the forecasts through the use of more probes and sensors and concluded that “a verification and validation approach for this use case tool is needed and can provide significant impetus for increased support and adoption” (FHWA 2011). This current study can be used to conduct the verification and validation using a small sample of test sites.

2.3.4 Finite Element Program TEMP/W

TEMP/W, a two-dimensional finite element program, was used by Lakehead University under contract with the Ministry of Transportation Ontario (Chapin et al. 2009, Chapin et al. 2010, Chapin et al. 2013, Pernia et al. 2014). The work was accomplished to estimate frost and thaw penetration, subsurface temperatures, moisture contents, and ice contents beneath pavements where temperature sensors had been installed. The program also attempted to determine when to place and remove SLRs by using data output from the computer program. Inputs at the upper boundary for TEMP/W can be similar to those for the EICM; however, other conditions can also be used, such as temperature only. Like the EICM, TEMP/W requires initial temperature and moisture conditions and lower boundary temperatures with time. Measured lower boundary conditions or an assumed constant temperature at a depth of several feet can be used. They assumed adiabatic conditions at the sides of the two-dimensional space to obtain what is essentially a one-dimensional temperature and moisture solution.

The authors used two types of temperature conditions at the upper boundary. One type was using air temperatures and applying n-factors of 0.8 when temperatures were below freezing and 2.0 when temperatures were above freezing. The n-factor concept was developed by the US Army Corps of Engineers about the time Aldrich and Paynter developed the Modified Berggren equation and Equation 158, mentioned earlier in this report. Andersland and Ladanyi (2004) discuss n-factors in more detail. Chapin and his colleagues indicated that modifying the air temperatures similarly to the MnDOT method of adjusting air temperatures was most successful when comparing measured and computer-predicted subsurface temperatures and frost and thaw depths. Chapin et al. (2009) and (2010) also state that correlations between measured and computed temperatures were best when they applied measured lower boundary temperatures.

2.4 Intellectual Property and Implementation Issues

In general, SLR and WWP timing methods can be broken down into two broad categories: (1) SLR trigger thresholds and (2) prediction models that estimate frost and thaw depths. A summary listing of the various methods is provided below.

(a) SLR Posting Methods Based on Trigger Thresholds (From Section 2.2)

2.2.1 Mahoney et al. (1986)

2.2.2 Berg/USFS method (Berg et al. 2006)

2.2.3 Minnesota Department of Transportation (MnDOT 2009)

2.2.4 Manitoba Department of Infrastructure and Transportation (MIT) and FPInnovations (Bradley et al. 2012)

2.2.5 Lakehead University and Ministry of Transportation Ontario (MTO) (Chapin et al. 2013, Pernia et al. 2014)

Initial efforts to devise a method based on trigger thresholds were made by Mahoney et al. (1986). Their method has been revised, and several variations have been used since that initial effort. The most notable revision is the procedure currently used by MnDOT, as described by Van Deusen et al. (1998) and MnDOT (2009). These methods (and variations of these methods) are generally based on the accumulation of degree-days computed from average daily air temperatures. Some methods use cumulative thawing degree-days directly to determine the time to place SLRs. These methods frequently use a reference temperature other than 32°F, the freezing point of pure bulk water, to consider differences between the air and pavement surface temperatures and increases in incoming shortwave radiation during the spring and early summer. These models are relatively simple to apply and can be accomplished using spreadsheets. There are no significant issues with regard to intellectual property or software fees with any of these methods.

The only notable implementation issues for some of the SLR posting methods based upon trigger thresholds relate to calibration. The Berg/USFS method (Berg et al. 2006) requires 30-year normals of average monthly temperatures from a weather station near the candidate site for initial setup. Although this information is generally available for several long-term weather stations in each state, it adds another step to the process. Although the methods suggested by MnDOT (2009) and by MIT/Bradley et al. (2012) do not specify any specific calibration, it is possible that the reference temperatures utilized by those agencies might not be applicable to other regions with very different climates, such as Alaska. The SLR application methodology recomended by MTO/Lakehead University (Chapin et al. 2013, Pernia et al. 2014) uses an approach identical to that suggested by MnDOT (2009), with the following exception: these researchers recommend calibrating the threshold values for applying WWPs and SLRs on a site-specific basis by determining the CFI and CTI values corresponding to the dates that the frost and thaw depths exceeded about 40 and 12 in. (100 and 30 cm), respectively.

(b) SLR Posting Methods Based on Frost-Thaw Depth Prediction Models (From Section 2.3)

- 2.3.1 Freeze-Thaw Index Model(s)
  - 2.3.1a Freeze-Thaw Index Model with Constant Coefficient(s)
  - 2.3.1b Freeze-Thaw Index Model: UMD Method (Miller et al. 2012b)
  - 2.3.1c Freeze-Thaw Index Model: Waterloo Method (Baïz et al. 2008)
  - 2.3.1d Freeze-Thaw Index Model: Lakehead Method (Chapin et al. 2013, Pernia et al. 2014)
- 2.3.2 US Army Corps of Engineers Model 158
- 2.3.3 Enhanced Integrated Climatic Model (EICM)
- 2.3.4 Finite Element Program TEMP/W

In terms of SLR posting methods based on frost-thaw depth prediction models, there are several procedures based upon freezing and thawing indices, as described in Section 2.3.1. These methods can generally be set up to run on spreadsheets (and thus have no associated intellectual property issues or software fees), but all of them (other than the constant coefficient model described in Section 2.3.1.a) require several years of measured frost thaw data to achieve the most accurate calibration, as well as some amount of statistical analysis to determine the calibration coefficients. The models described in Section 2.3.1b (Miller et al. 2012b) and Section 2.3.1d (Chapin et al. 2013, Pernia et al. 2014) require only minimal statistical analysis, which can be done fairly easily using Excel spreadsheets. The model described in Section 2.3.1c (Baïz et al. 2008), however, requires a much more rigorous set of statistical tools in order to determine the 12 site-specific calibration coefficients.

A modified version of US Army Corps of Engineers Model 158 has been developed to predict daily frost and thaw depths using an Excel spreadsheet, as described in Section 2.3.2. Input for that model considers cumulative degree-days (based upon average daily air temperatures), as well as the thermal properties and thickness of the pavement layers. There are no intellectual property issues, software fees, or notable implementation issues associated with that model.

The remaining set of numerical models (EICM and TEMP/W), described in Section 2.3, computes frost and thaw depths on a daily basis. While these models are very robust and should be more accurate than the degree-day methods, they are also much more complicated and fairly expensive. There is one version of the EICM embedded in the AASHTOWare Pavement Design ME (formerly DARWin-ME, formerly MEPDG). Another version of the EICM is the Clarus Use Case #2 seasonal load restriction tool, described in Report No. JPO-11-117 (FHWA 2011).

The AASHTOWare Pavement Design ME software is fairly expensive: $5,000 per station per year. A 30-day trial version of the software was obtained for preliminary evaluation by the research team on this project. This version of the software includes a database with atmospheric weather data from multiple locations around the country, but it only includes data up until about 2005. There are no automated real-time data feeds. A major limitation of this version of the EICM is that there is no way to enter daily average values (as opposed to hourly values) for the required atmospheric data. Additionally, the required “percent sunshine” data is not easily obtained from traditional weather stations and is not well defined. Due to the very tedious process required to prepare input files for this version of the EICM, the research team concluded that this software would not likely be used by any DOTs to predict frost-thaw profiles in real-time analyses for SLR application and/or removal.

An alternative version of the EICM is the Clarus Use Case #2 seasonal load restriction tool (FHWA 2011). A public domain set of files related to that tool is available from FHWA; however, those files cannot be directly implemented on a typical Windows-based computer without a substantial amount of additional software and programming. The developer of the Clarus Use Case #2 SLR tool was contacted by the research team. For potential evaluation of this EICM-based tool for this project, the developer has agreed to set up and run simulations for four of the Aurora sites for one freeze-thaw season (2014-2015) for a fee of approximately $20,000. In terms of future implementation of this model/tool by DOTs, it would be necessary for them to negotiate fees directly with the developer of the *Clarus* Use Case #2 SLR tool on a case-by-case basis.

TEMP/W is a finite element software program owned by Geo-Slope International, Ltd. The cost for TEMP/W depends upon whether one purchases a standalone license or a network license and whether one chooses a perpetual license or a subscription. The licensing options can be explained as follows:

- A standalone license is installed on an individual desktop or laptop computer, whereas a network license is installed on a computer chosen as the network license server computer and is thus accessible by all computers on the network.

- A perpetual license entitles one to use the software indefinitely, although there is a yearly maintenance fee. Subscription licenses (also known as leased licenses) are available for short-term projects (one-month or one-year terms are available), such as this one.
- Currently, the initial purchase price for a standalone, perpetual license is $4,495, with an annual maintenance fee of $900. Additional pricing information can be obtained from the Geo-Slope website (http://www.geo-slope.com/).

In addition to the intellectual property issues (software fees), there are some implementation issues associated with the TEMP/W software. Specifically, there is a fairly rigorous learning curve typically associated with the use of this or any type of finite element software.

3. IDENTIFICATION OF DEMONSTRATION SITE REQUIREMENTS AND PROPOSED SITES

3.1 Demonstration Site Requirements

Based on the authors' experience in developing procedures and models to determine when to apply and remove SLRs, it is necessary for demonstration sites to have certain attributes regarding the pavement structure and to have instrumentation installed to provide air temperature, pavement surface and subsurface temperature, and subsurface moisture data (although the need for moisture data is not as great as the need for temperature data). It is also desirable to have a groundwater well at or near the site to monitor movement of the groundwater table throughout the winter and spring. For evaluation of the EICM, various additional atmospheric data are required, as discussed in subsequent paragraphs.

Temperature sensors should extend below the maximum depth of frost penetration expected at the site. Individual temperature sensors should be more closely spaced near the pavement surface (ideally, 3 in. spacing) but can be more widely spaced beneath a depth of about 12 in. (Spacing of 6 in. is desired for the upper 48 in., and 12 in. spacing below that depth is adequate.) If moisture sensors are installed, a typical configuration would involve three or four moisture sensors that are installed to a maximum depth of about 30 to 36 in. The exact spacing of moisture sensors is usually determined on a site-specific basis dependent upon base and subgrade material types and layer thicknesses.

Because a form of the EICM is planned for evaluation in this study, the necessary atmospheric data include air temperatures, precipitation, wind speed, percent sunshine, and relative humidity. The EICM requires atmospheric data and the groundwater depth on an hourly basis starting several months before freezing commences and extending to when the SLRs are removed. As noted in Section 2.3.3 of this report, the version of the EICM embedded in the AASHTOWare Pavement Design ME software would not likely be used by any DOTs for predicting frost-thaw profiles in real-time analyses for SLR application and/or removal due to the very tedious process required to prepare the input files for that software. In addition, there is no procedure for obtaining forecast data of the necessary atmospheric and groundwater data.

The other version of EICM software considered for this study is embedded in the Clarus Use Case #2 seasonal load restriction tool. The developer of that tool has stated that the tool can be set up to automatically download the necessary atmospheric data from an RWIS station at or near the candidate site.

In terms of site attributes, the ideal site would be on a low-volume road with a pavement structure such that some amount of thaw-weakening is exhibited during the springtime. The pavement should have minimal cracking in the areas around the instruments. Sufficient data regarding pavement layer thicknesses and material types should be provided down to a depth of about 6 ft. If that pavement profile data is not available (or does not extend to sufficient depth), then it is recommended that a borehole be advanced to obtain soil samples and standard penetration test N-values.

For model validation purposes, specifically with regard to timing decisions for SLR removal, testing with either an FWD or a lightweight deflectometer (LWD) is recommended. If an LWD is to be used at a site, a location with a relatively thin pavement should be selected for the most effective use of the LWD. A grid of FWD or LWD locations should be located near the subsurface temperature sensors. Ideally, FWD or LWD testing would be conducted prior to the start of winter, once a week for the first three weeks of winter, and two times per week during the spring thaw and strength recovery period. Because the transportation agencies will be responsible for this testing, the candidate site should be in a location that is convenient for the use of FWD or LWD equipment and for operating personnel.

3.2 Proposed Demonstration Sites and Available Data and Instrumentation

At the start of Phase 1, a project Technical Advisory Committee (TAC) was established by the Aurora Consortium. The research team convened with the majority of the TAC via a conference call to provide an overview of the project and outline demonstration site requirements. Subsequently, numerous individual contacts via phone and email were made between individual research team members and individual TAC members. The sites listed in Table 9 have been proposed for demonstrations.

Table 9. Proposed demonstration sites

	Highway Jurisdiction	**Probable Site Identification**	**Cross-Section**	**Comments: Desired Additional Information ***
1	Alaska	Whittier Access Road at Tunnel MP 6.5	2 in. asphalt atop 3 in. crushed aggregate base atop 6 in. select material atop fill	Borehole data required to determine information regarding virgin aggregate base
2	Michigan	Republic	3.5 in. asphalt atop 11 in. of aggregate over 58 in. of brown medium sand	Website with temperature probe data
3	North Dakota	Bowman US-85 at MP 12.2	6 in. asphalt atop 16 in. blend of recycled asphalt and virgin aggregate base	Borehole data required to determine information regarding virgin aggregate base
4	Wisconsin	RWIS Site # 101051 Thermistor to be installed	TBD	Borehole data will be obtained during thermistor installation
5	Ontario	Highway 599 near Dryden	1.5 in. asphalt atop 14 in. sand and gravel atop sand.	

*Groundwater wells and soil moisture sensors at each site are desirable (although not critical).

An RWIS station providing atmospheric weather data is located at each of the sites listed, and all sites (except for Wisconsin) currently have a thermistor string installed to measure subsurface temperatures down to a depth of about 6 ft. In general, individual temperature sensors are located in the asphalt surface and just below the asphalt layer, at 3 in. intervals from the bottom of the asphalt down to a depth of 12 in., and then at 6 in. intervals down to a depth of 72 in. The Wisconsin Department of Transportation (WisDOT) is planning to install a similar thermistor string at their proposed low-volume road demonstration site for Phase 2 of this study.

At all sites (with the exception of Ontario), it is recommended that a borehole be advanced down to a depth of about 6 ft. with soil samples classified and logged, layer thicknesses estimated, and standard penetration test N-values recorded. This is necessary to provide sufficient data regarding pavement layer thicknesses and material types.

4. RECOMMENDATION OF MODELS TO BE EVALUATED AT DEMONSTRATION SITES

4.1 SLR Posting Methods Based on Trigger Thresholds (degree-day methods)

Based upon the review of available models described in Section 2.2 of this report, the authors believe that most of the SLR application methods based upon trigger thresholds (degree-day methods) are simple to use and do not require a large amount of time to apply. To review, these models consist of the following:

a. Mahoney et al. (1986)
b. Berg/USFS method (Berg et al. 2006)
c. Minnesota Department of Transportation (MnDOT 2009)
d. Manitoba Department of Infrastructure and Transportation (MIT) and FPInnovations (Bradley et al. 2012)
e. Lakehead University and Ministry of Transportation Ontario (MTO) (Chapin et al. 2013, Pernia et al. 2014)

Methods c, d, and e are almost identical in terms of SLR application, with the following exceptions. The method suggested by Bradley et al. (2012) utilizes slightly different reference temperatures, as well as a slightly different equation for computing the CTI compared to the MnDOT (2009) protocol. The Lakehead University method uses the same equations and same reference temperatures suggested by MnDOT (2009). The only difference between those two methods is that MnDOT recommends applying the SLR when the CTI is predicted to surpass 25°F days for at least several days. The Lakehead University protocol suggests using variable threshold values for applying WWPs and SLRs, which must be calibrated on a site-specific basis by determining the CFI and CTI values corresponding to the dates on which the frost and thaw depths exceeded about 40 and 12 in., respectively.

For the Phase 2 work, the authors are proposing to utilize the MnDOT (2009) model for predicting SLR application dates at all proposed sites for both years (2014-2015 and 2015-2016). Because the Lakehead University protocol for applying WWPs and SLRs has already been calibrated at the Ontario site (Highway 599) based upon several years of measured frost and thaw depth data, it is proposed that that model only be run at the Ontario site during 2014-2015. At all other sites, the data obtained during 2014-2015 will be used to calibrate the Lakehead model for each site, and then that model will be run in a predictive mode at each of those sites during the 2015-2016 season.

The (a) Mahoney et al. (1986) and (b) Berg/USFS method (Berg et al., 2006) models have been omitted for the following reasons. In studies conducted by Miller et al. (2013a, 2013b), it was concluded that for SLR application dates, the Berg/USFS method and the MnDOT method yielded very similar results. For 8 of the 15 SLR determinations, both methods yielded exactly the same SLR application date. For 7 of the determinations, the MnDOT method yielded an application date that was one to three days earlier than the Berg/USFS method. Because the methods yielded very similar results and the MnDOT method does not require 30-year normal data for its initial setup, the MnDOT (2009) protocol was chosen for the study.

In terms of the method suggested by Mahoney et al. (1986), the studies conducted by Miller et al. (2013a, 2013b) suggested that this method tended to be less conservative than both the Berg/USFS and MnDOT methods, yielding SLR application dates up to 21 days later than those estimated by the latter two methods. At the New England test sites, the Mahoney et al. (1986) method often yielded SLR application dates that fell after thawing had commenced and after the pavement structure became significantly weakened (as indicated by FWD data). As such, this model has been omitted from our recommendations for the Phase 2 work.

4.2 SLR Posting Methods Based on Frost-Thaw Depth Prediction Models

A summary listing of the available models described in Section 2.3 of this report is presented below:

- 2.3.1 Freeze-Thaw Index Model(s)
    - 2.3.1a Freeze-Thaw Index Model with Constant Coefficient(s)
    - 2.3.1b Freeze-Thaw Index Model: UMD Method (Miller et al. 2012b)
    - 2.3.1c Freeze-Thaw Index Model: Waterloo Method (Baïz et al. 2008)
    - 2.3.1d Freeze-Thaw Index Model: Lakehead Method (Chapin et al. 2013, Pernia et al. 2014)
- 2.3.2 US Army Corps of Engineers Model 158
- 2.3.3 Enhanced Integrated Climatic Model (EICM)
- 2.3.4 Finite Element Program TEMP/W

Based upon a review of the models, the authors believe that the various freeze-thaw depth prediction models described in Section 2.3.1 require several years of measured frost and thaw depth data in order to properly calibrate the model coefficients. At most of the proposed test sites, those data either are not available or the available data have too many gaps to make such calibration feasible. As such, the researchers recommend the following freeze thaw index models:

- At the Ontario site (Highway 599), we are proposing that the Lakehead model be run for both the 2014-2015 and 2015-2016 seasons (because that model has already been calibrated based upon several years of measured frost-thaw data).
- At all other sites, data obtained during 2014-2015 will be used to calibrate the Lakehead freeze-thaw index model for each site and then to run the models in a

predictive mode at those sites during the 2015-2016 season. The 2014-2015 data will be used to determine calibration coefficients according to the statistical procedures suggested by Miller et al. (2012b) and to run the predictive model using those coefficients during 2015-2016 for comparison.

Additionally, for all sites where sufficient subsurface information is available (i.e., as provided from a borehole), the researchers propose to run the US Army Corps of Engineers Model 158 (modified as per the UMD spreadsheet, described in Section 2.3.2) and the alternative version of the EICM that is embedded in the Clarus Use Case #2 seasonal load restriction tool (FHWA 2011). The researchers propose to run the Modified Model 158 for both 2014-2015 and 2015-2016. For the EICM, it is proposed that the SLR tool be run at a maximum of four sites for 2014-2015 only. Note that for any sites where sufficient subsurface information is not available to a depth of at least 6 ft., neither of these models can be run.

5. PROPOSED PLAN FOR PHASE II DEMONSTRATION AND EVALUATION

5.1 Pre-Phase II Preparatory Activities

The following summary of preparatory activities by the DOTs for Phase II will facilitate the work of the project and improve the final product. (For example, borehole profiles with layer and material information are required for certain models, so those particular models can only be run at sites for which that information can be provided.) A few activities are critical; others would simply be very helpful, and are so noted. Required information is also referenced in Table 9.

- In some instances, installation of equipment or instrumentation is required. For example, WisDOT plans to install subsurface temperature sensors by Fall 2014.
- All DOTs that have not already done so are asked to provide to the research team borehole data to a depth of 6 ft. or more, including layer and material information such as densities and moisture content. (Ontario borehole data are already available.) This information is required for models that compute frost and thaw depths.
- Although not critical, it would be helpful to have groundwater wells to a depth of 7 to 10 ft and three or four time-domain reflectometry (TDR)-type moisture sensors at the monitoring sites. (There is no need for a groundwater well at the Ontario site because no groundwater was encountered during borehole advancement.)
- Although also not critical, it would be very helpful if agencies could make arrangements to provide subsurface temperature data to the research team in a format similar to that of the North Dakota subsurface data. A sample of the arrangements made by North Dakota with its RWIS vendor is provided in Appendix A. Data in Appendix A were provided to the research team by the North Dakota Department of Transportation (NDDOT) for the site at Mile Post 12.2 on US 85 near Bowman, ND. The RWIS site number is 597019. Apparently, NDDOT requested that its RWIS vendor for this site, Vaisala, sort and average the multiple hourly scans from the RWIS to obtain these data. It would be helpful if other agencies could also request that their RWIS vendors do similar sorting and averaging to provide this type of data. The Alaska Department of Transportation and Public Facilities (Alaska DOT&PF), and possibly the Ministry of Transportation Ontario and other agencies, collect their subsurface temperature data independently from the RWIS data and can provide data similar to those in Appendix A using a different approach. All data of this type should be either emailed to the research team or be made available via a web site.

5.2 Proposed Phase II Test Plan

The following summarizes proposed Phase II test plan activities, most of which have also been covered in previous sections.

Each of the highway jurisdictions participating in the study has designated one potential test site, as listed in Table 9. Throughout the monitoring season, data for each of the selected sites will be collected from subsurface temperature sensors, nearby RWIS sites, and possible soil moisture sensors and groundwater wells. The EICM/SLR tool needs the data on an hourly basis, but monthly measurements made by hand can be interpolated daily to provide adequate data because levels do not change rapidly.

Each agency should have a plan to run FWD or LWD tests on a grid around the subsurface temperature sensors. Ideally, FWD or LWD testing would be conducted prior to the start of winter, once a week for the first three weeks of winter, and two times per week during the spring thaw and strength recovery period.

Simulations will be run using the following models (also shown in Table 9 and previously discussed in detail):

- The MnDOT procedure will be applied at each of the five test sites during the 2015 spring and the 2016 thawing season. The MnDOT procedure will be initiated on about February 1 for each of the five test sites during each of the two spring thawing seasons.

- Because the Lakehead University protocol for applying WWPs and SLRs has already been calibrated at the Highway 599 site in Ontario based upon several years of measured frost and thaw depth data, the researchers propose to run that model only at the Ontario site during 2014-2015. At all other sites, the data obtained during 2014-2015 will be used to calibrate the Lakehead model for each site, and then that model will be run in a predictive mode at those sites during the 2015-2016 season.

- The research team plans to use the Lakehead model (Chapin et al., 2013; Pernia et al., 2014) and modified Model 158 to determine frost and thaw depths using cumulative freezing and thawing indexes. The modified Model 158 will be run at all five test sites for both the 2014-2015 and 2015-2016 winter and spring seasons, provided that there are adequate descriptions of the layers beneath the pavement.

- The research team plans to apply the Clarus tool to a maximum of four sites for the 2014-2015 winter only. This is due to the expense in contracting for the use of this tool. The contractor will require the researchers to supply the material properties, but the contractor will gather all of the other data required to execute the model.

Using the selected models described above, data collected from RWIS, and supplemental instrumentation information, dates for imposing and removing WWPs and SLRs will be determined. Computed dates will be compared with stiffness data obtained from FWD or LWD tests. Finally, based on accuracy, simplicity of use, and cost, a decision matrix will be developed to aid road management agencies in selecting the model that is most appropriate for their intended purposes, personnel, and specific conditions.

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APPENDIX A. AVERAGE DAILY SUBSURFACE TEMPERATURES IN BOWMAN, ND, JANUARY THROUGH MAY 2014

Data in this appendix were provided to the research team by the North Dakota Department of Transportation (NDDOT) for the site at Mile Post 12.2 on US 85 near Bowman, ND. Apparently, NDDOT requested that its RWIS vendor for this site (RWIS site number 597019), sort and average the multiple hourly scans from the RWIS to obtain this data. It would be helpful if other agencies could also request that their RWIS vendors do similar sorting and averaging to provide this type of data. The Alaska Department of Transportation and Public Facilities (Alaska DOT&PF), and possibly the Ministry of Transportation Ontario and other agencies, collect their subsurface temperature data independently from the RWIS data and can provide data similar to that in Appendix A using a different approach. All data of this type should be either emailed to the research team or be made available via a web site.

Table A.1. Bowman, ND, average daily air and subsurface temperatures, January 1 through May 8, 2014

		Depth below Pavement Surface (in.)															
Date	Air	0	5	8	11	14	17	23	29	35	41	47	53	59	65	71	77
1/15/2014	32.79	34.80	34.77	34.78	34.84	34.87	34.88	34.88	34.88	35.02	35.06	35.09	35.24	35.28	35.42	35.42	35.02
1/16/2014	28.60	33.60	33.58	33.62	33.64	33.65	33.74	33.84	34.17	34.53	34.92	35.31	35.76	36.05	36.56	36.74	34.65
1/17/2014	24.50	27.89	28.51	29.31	29.78	30.07	30.57	30.92	32.23	33.26	34.52	35.96	37.22	38.30	39.74	40.46	33.25
1/18/2014	32.17	29.82	29.50	29.54	29.70	29.94	30.58	30.92	32.30	33.25	34.51	35.91	37.05	38.12	39.56	40.29	33.40
1/19/2014	36.34	31.13	30.49	30.30	30.24	30.21	30.70	30.98	32.36	33.26	34.47	35.78	37.04	38.10	39.44	40.18	33.64
1/20/2014	24.00	31.73	31.18	30.85	30.64	30.48	30.77	31.06	32.36	33.17	34.36	35.77	36.88	37.96	39.34	40.06	33.77
1/21/2014	18.60	27.02	28.18	29.28	29.98	30.34	30.91	31.10	32.36	33.22	34.34	35.72	36.86	37.85	39.22	39.93	33.09
1/22/2014	15.44	27.91	28.31	28.95	29.48	29.96	30.74	31.10	32.36	33.13	34.34	35.60	36.74	37.79	39.12	39.78	33.02
1/23/2014	0.59	19.93	22.64	25.23	27.30	29.00	30.63	31.10	32.36	33.16	34.34	35.60	36.68	37.76	39.02	39.72	31.63
1/24/2014	34.30	25.44	25.05	25.54	26.49	27.84	30.08	31.10	32.36	33.18	34.34	35.60	36.68	37.75	38.93	39.56	32.00
1/25/2014	37.91	31.43	30.15	29.61	29.37	29.40	30.20	31.08	32.36	33.21	34.33	35.59	36.63	37.57	38.84	39.55	33.29
1/26/2014	26.56	33.29	32.03	31.21	30.62	30.28	30.58	31.10	32.36	33.12	34.26	35.47	36.50	37.56	38.77	39.39	33.77
1/27/2014	-0.48	22.53	25.72	27.99	29.34	30.10	30.76	31.10	32.36	33.11	34.17	35.42	36.50	37.40	38.66	39.35	32.30
1/28/2014	3.57	17.06	19.74	22.59	25.19	27.64	30.31	31.10	32.36	33.08	34.16	35.42	36.40	37.40	38.59	39.20	30.68
1/29/2014	23.23	20.00	20.81	22.38	24.25	26.31	29.52	30.99	32.36	33.08	34.16	35.40	36.35	37.36	38.50	39.18	30.71
1/30/2014	12.12	25.31	25.49	25.97	26.56	27.40	29.43	30.83	32.35	33.08	34.15	35.34	36.32	37.23	38.47	39.03	31.80
1/31/2014	5.47	19.43	21.41	23.51	25.36	27.03	29.51	30.74	32.24	33.04	34.10	35.24	36.27	37.22	38.33	38.99	30.83
2/1/2014	6.22	19.14	20.70	22.55	24.32	26.17	28.99	30.62	32.18	32.94	34.01	35.24	36.17	37.16	38.30	38.88	30.49
2/2/2014	1.97	16.18	18.26	20.70	23.02	25.30	28.55	30.43	32.12	32.90	33.98	35.14	36.14	37.04	38.20	38.83	29.78
2/3/2014	8.59	18.20	19.32	20.99	22.81	24.81	27.85	30.16	32.00	32.90	33.93	35.06	36.10	37.00	38.12	38.78	29.87
2/4/2014	1.29	18.05	19.59	21.43	23.22	25.03	27.76	29.99	31.90	32.82	33.80	35.05	35.96	36.90	38.10	38.66	29.88
2/5/2014	-7.85	14.36	16.88	19.57	22.01	24.35	27.44	29.81	31.76	32.72	33.71	34.90	35.94	36.86	38.10	38.55	29.13
2/6/2014	-10.33	8.78	12.07	15.72	19.17	22.54	26.62	29.45	31.63	32.54	33.62	34.87	35.82	36.75	37.98	38.55	27.74
2/7/2014	-6.31	7.61	10.28	13.70	17.17	20.81	25.43	28.83	31.41	32.45	33.53	34.74	35.76	36.68	37.88	38.42	26.98
2/8/2014	3.60	14.23	15.16	16.84	18.82	21.16	24.86	28.06	31.16	32.26	33.39	34.64	35.62	36.59	37.79	38.31	27.93
2/9/2014	-3.08	13.94	15.67	17.81	19.88	22.03	25.16	27.71	30.82	32.06	33.20	34.48	35.51	36.48	37.71	38.22	28.04
2/10/2014	-6.19	12.84	14.65	16.95	19.25	21.64	24.97	27.48	30.55	31.89	33.04	34.35	35.38	36.36	37.60	38.15	27.67
2/11/2014	15.93	16.46	17.04	18.34	19.92	21.80	24.75	27.19	30.30	31.74	32.91	34.20	35.25	36.27	37.55	38.06	28.12

		Depth below Pavement Surface (in.)															
Date	**Air**	**0**	**5**	**8**	**11**	**14**	**17**	**23**	**29**	**35**	**41**	**47**	**53**	**59**	**65**	**71**	**77**
2/12/2014	17.93	22.06	21.99	22.33	22.86	23.66	25.46	27.27	30.05	31.56	32.82	34.08	35.14	36.14	37.40	38.01	29.39
2/13/2014	28.34	26.11	25.22	24.94	24.94	25.24	26.44	27.67	30.02	31.46	32.71	33.95	35.01	36.00	37.30	37.83	30.32
2/14/2014	24.60	27.86	27.16	26.89	26.75	26.74	27.41	28.35	30.07	31.32	32.54	33.80	34.88	35.90	37.21	37.75	30.97
2/15/2014	32.74	30.38	29.39	28.73	28.23	27.89	28.30	28.81	30.20	31.28	32.54	33.68	34.74	35.78	37.04	37.74	31.65
2/16/2014	23.06	31.00	30.30	29.82	29.35	28.94	29.02	29.21	30.30	31.28	32.37	33.62	34.66	35.63	36.91	37.58	32.00
2/17/2014	32.14	30.61	30.10	29.89	29.67	29.38	29.49	29.54	30.41	31.27	32.36	33.50	34.52	35.56	36.83	37.46	32.04
2/18/2014	34.24	32.37	31.16	30.57	30.09	29.78	29.82	29.77	30.56	31.28	32.36	33.44	34.52	35.43	36.71	37.40	32.35
2/19/2014	30.68	32.63	31.79	31.13	30.59	30.13	30.08	29.95	30.64	31.28	32.34	33.44	34.36	35.41	36.68	37.24	32.51
2/20/2014	25.87	30.99	30.85	30.76	30.54	30.23	30.25	30.04	30.74	31.28	32.27	33.38	34.34	35.25	36.53	37.19	32.31
2/21/2014	25.72	30.03	30.03	30.20	30.25	30.18	30.38	30.20	30.77	31.28	32.22	33.28	34.33	35.24	36.50	37.04	32.13
2/22/2014	14.86	29.20	29.60	29.99	30.13	30.13	30.39	30.23	30.85	31.29	32.25	33.28	34.24	35.17	36.41	37.00	32.01
2/23/2014	11.83	25.56	26.57	27.78	28.78	29.55	30.32	30.35	30.92	31.31	32.33	33.27	34.21	35.11	36.33	36.95	31.29
2/24/2014	5.15	25.71	26.50	27.44	28.26	29.06	30.04	30.23	30.92	31.37	32.31	33.26	34.16	35.06	36.32	36.86	31.17
2/25/2014	-0.12	20.07	22.08	24.19	25.98	27.71	29.71	30.18	30.92	31.38	32.30	33.26	34.16	35.06	36.21	36.85	30.00
2/26/2014	6.39	18.26	20.02	22.15	24.18	26.15	28.87	29.89	30.92	31.40	32.30	33.26	34.16	34.96	36.14	36.69	29.29
2/27/2014	6.50	20.78	21.64	22.91	24.27	25.77	28.14	29.53	30.79	31.43	32.33	33.26	34.15	34.92	36.14	36.68	29.52
2/28/2014	10.11	23.40	23.75	24.41	25.16	26.13	27.79	29.22	30.64	31.41	32.32	33.26	34.11	34.89	36.10	36.66	29.95
3/1/2014	-8.17	17.55	19.73	22.00	23.88	25.60	27.70	29.07	30.56	31.31	32.23	33.26	34.01	34.88	35.99	36.53	28.95
3/2/2014	-10.58	15.13	16.98	19.34	21.67	23.98	26.86	28.72	30.41	31.29	32.22	33.18	34.02	34.86	35.97	36.50	28.07
3/3/2014	-0.69	16.98	18.19	19.87	21.62	23.51	26.21	28.18	30.18	31.27	32.18	33.10	33.98	34.78	35.96	36.50	28.17
3/4/2014	9.98	22.08	22.01	22.48	23.21	24.23	26.18	27.71	30.02	31.17	32.15	33.08	33.97	34.73	35.90	36.44	29.02
3/5/2014	20.07	24.11	23.88	24.19	24.66	25.29	26.69	27.92	29.91	31.09	32.12	33.08	33.94	34.70	35.87	36.35	29.59
3/6/2014	35.79	31.14	29.47	28.34	27.53	27.02	27.45	28.33	30.02	31.01	32.00	33.06	33.80	34.65	35.78	36.32	31.06
3/7/2014	21.88	32.08	31.12	30.30	29.59	28.90	28.74	28.90	30.05	30.93	31.99	32.90	33.80	34.56	35.76	36.27	31.73
3/8/2014	31.97	32.77	31.26	30.60	30.07	29.54	29.40	29.35	30.21	30.92	31.88	32.90	33.70	34.52	35.62	36.14	31.92
3/9/2014	44.90	38.18	35.18	32.70	31.14	30.23	29.88	29.69	30.38	30.92	31.85	32.90	33.63	34.49	35.60	36.14	32.86
3/10/2014	42.31	40.91	38.47	35.99	33.40	31.40	30.32	29.97	30.54	31.03	31.82	32.90	33.62	34.46	35.58	36.12	33.77
3/11/2014	35.24	38.07	36.59	35.19	33.59	32.02	31.01	30.14	30.62	31.07	31.82	32.90	33.62	34.34	35.56	35.97	33.50
3/12/2014	36.39	37.94	36.44	35.07	33.62	32.18	31.17	30.38	30.74	31.10	31.82	32.87	33.59	34.34	35.42	35.96	33.51

		Depth below Pavement Surface (in.)															
Date	Air	0	5	8	11	14	17	23	29	35	41	47	53	59	65	71	77
3/13/2014	41.27	40.00	37.96	36.15	34.28	32.45	31.13	30.48	30.76	31.10	31.82	32.83	33.53	34.32	35.42	35.93	33.88
3/14/2014	38.29	41.14	39.09	37.13	35.07	32.91	31.34	30.58	30.92	31.10	31.82	32.86	33.47	34.29	35.40	35.89	34.20
3/15/2014	30.87	41.77	40.19	38.24	36.05	33.61	31.68	30.90	30.92	31.10	31.82	32.86	33.45	34.23	35.36	35.80	34.53
3/16/2014	32.92	34.61	33.95	33.59	33.11	32.43	31.80	31.30	31.02	31.12	31.84	32.82	33.44	34.17	35.26	35.78	33.08
3/17/2014	39.68	40.38	38.49	36.75	35.02	33.29	31.66	31.06	31.10	31.24	31.91	32.87	33.44	34.17	35.25	35.78	34.16
3/18/2014	32.98	36.75	36.13	35.52	34.60	33.39	31.94	31.08	31.11	31.27	31.90	32.88	33.44	34.16	35.24	35.78	33.68
3/19/2014	33.89	36.69	35.46	34.58	33.72	32.82	31.83	31.10	31.13	31.28	31.94	32.86	33.44	34.16	35.24	35.71	33.46
3/20/2014	37.02	40.89	38.89	37.15	35.47	33.76	31.82	31.10	31.13	31.28	31.95	32.84	33.44	34.16	35.23	35.62	34.31
3/21/2014	29.46	40.16	39.15	37.87	36.34	34.48	31.87	31.10	31.13	31.28	32.00	32.89	33.44	34.16	35.21	35.60	34.45
3/22/2014	15.10	33.77	33.96	34.00	33.73	33.11	31.98	31.10	31.22	31.28	32.00	32.87	33.44	34.16	35.17	35.60	33.16
3/23/2014	16.98	32.11	32.27	32.29	32.17	31.97	31.86	31.10	31.25	31.28	32.00	32.89	33.44	34.16	35.13	35.60	32.63
3/24/2014	21.95	31.10	31.22	31.59	31.66	31.66	31.73	31.10	31.27	31.29	32.00	32.90	33.44	34.14	35.07	35.60	32.38
3/25/2014	18.47	30.04	30.53	31.14	31.56	31.66	31.70	31.10	31.28	31.38	32.00	32.90	33.44	34.13	35.07	35.57	32.23
3/26/2014	28.33	32.00	31.33	31.29	31.40	31.64	31.64	31.10	31.28	31.34	32.00	32.90	33.44	34.13	35.06	35.52	32.41
3/27/2014	26.11	34.77	33.28	32.32	31.80	31.61	31.64	31.10	31.28	31.35	32.03	32.90	33.44	34.07	35.06	35.46	32.81
3/28/2014	25.29	36.55	35.65	34.71	33.57	32.31	31.64	31.10	31.28	31.44	32.05	32.90	33.44	34.08	35.06	35.44	33.41
3/29/2014	38.32	34.81	33.70	33.17	32.74	32.27	31.66	31.11	31.28	31.46	32.08	32.90	33.44	34.05	35.06	35.43	33.01
3/30/2014	41.44	43.90	41.37	38.95	36.70	34.47	31.82	31.12	31.28	31.46	32.15	32.90	33.44	34.11	35.06	35.42	34.94
3/31/2014	20.90	36.41	36.72	36.56	35.89	34.65	32.10	31.17	31.30	31.46	32.18	32.90	33.45	34.07	35.06	35.42	33.95
4/1/2014	7.83	29.55	31.02	31.92	32.14	32.15	32.04	31.26	31.34	31.46	32.18	32.90	33.44	34.13	35.06	35.42	32.40
4/2/2014	21.20	31.63	31.16	31.32	31.63	31.64	31.87	31.28	31.29	31.47	32.18	32.90	33.45	34.01	35.06	35.42	32.42
4/3/2014	25.95	30.71	30.86	31.18	31.45	31.64	31.82	31.28	31.34	31.51	32.18	32.90	33.45	34.05	35.06	35.42	32.32
4/4/2014	22.81	33.68	31.98	31.49	31.48	31.59	31.70	31.27	31.37	31.57	32.24	32.90	33.50	34.09	35.04	35.42	32.62
4/5/2014	32.48	39.71	37.35	35.36	33.63	32.34	31.66	31.26	31.39	31.64	32.21	32.95	33.46	34.04	35.03	35.42	33.83
4/6/2014	40.62	46.68	43.65	40.88	38.28	35.80	32.13	31.28	31.44	31.64	32.33	32.98	33.50	34.10	35.04	35.42	35.68
4/7/2014	42.38	48.82	46.19	43.57	40.87	38.05	33.62	31.29	31.45	31.64	32.35	32.99	33.56	34.11	35.02	35.39	36.60
4/8/2014	42.09	47.92	45.85	43.80	41.54	39.03	35.10	31.47	31.46	31.65	32.36	33.07	33.60	34.14	35.04	35.41	36.76
4/9/2014	55.82	51.99	48.37	45.36	42.62	39.93	36.18	31.85	31.46	31.78	32.36	33.08	33.60	34.14	35.04	35.40	37.54
4/10/2014	43.58	50.72	48.78	46.67	44.31	41.63	37.80	34.22	32.27	32.17	32.58	33.08	33.62	34.15	35.04	35.39	38.16

		Depth below Pavement Surface (in.)															
Date	**Air**	**0**	**5**	**8**	**11**	**14**	**17**	**23**	**29**	**35**	**41**	**47**	**53**	**59**	**65**	**71**	**77**
4/11/2014	42.80	50.07	48.34	46.50	44.52	42.26	39.04	36.15	34.41	33.33	33.11	33.34	33.70	34.16	35.05	35.39	38.62
4/12/2014	45.24	50.04	48.03	46.23	44.44	42.50	39.86	37.26	35.60	34.34	33.85	33.83	33.98	34.32	35.07	35.41	38.98
4/13/2014	29.13	48.13	47.40	46.37	45.04	43.29	40.72	38.10	36.53	35.21	34.58	34.36	34.32	34.49	35.16	35.43	39.27
4/14/2014	27.30	44.15	43.78	43.46	42.91	42.12	40.74	38.72	37.32	36.02	35.29	34.90	34.71	34.77	35.32	35.53	38.65
4/15/2014	33.94	44.92	43.94	43.19	42.42	41.56	40.41	38.76	37.70	36.59	35.89	35.44	35.16	35.06	35.52	35.67	38.81
4/16/2014	32.80	47.99	46.69	45.34	43.94	42.47	40.76	39.01	37.98	37.02	36.37	35.91	35.57	35.41	35.81	35.86	39.74
4/17/2014	30.97	41.71	42.08	42.31	42.27	41.87	41.06	39.45	38.40	37.42	36.76	36.31	35.92	35.68	36.03	36.05	38.89
4/18/2014	42.45	43.90	42.63	41.93	41.40	40.92	40.44	39.35	38.65	37.76	37.14	36.70	36.28	36.01	36.28	36.27	39.04
4/19/2014	47.28	50.34	48.03	46.10	44.41	42.75	41.03	39.51	38.72	37.92	37.39	37.03	36.61	36.29	36.53	36.49	40.61
4/20/2014	48.00	54.82	52.34	50.01	47.76	45.46	42.70	40.44	39.26	38.25	37.67	37.30	36.87	36.56	36.77	36.70	42.19
4/21/2014	48.48	56.74	54.28	52.07	49.89	47.58	44.50	41.78	40.17	38.86	38.09	37.59	37.18	36.82	37.02	36.92	43.30
4/22/2014	51.44	60.56	57.79	55.09	52.50	49.75	46.23	43.13	41.22	39.68	38.71	37.99	37.48	37.09	37.24	37.13	44.77
4/23/2014	52.35	59.53	57.86	55.90	53.76	51.32	47.86	44.55	42.34	40.58	39.40	38.54	37.83	37.37	37.47	37.35	45.44
4/24/2014	48.60	55.79	54.20	53.06	51.99	50.65	48.44	45.59	43.39	41.52	40.19	39.15	38.32	37.74	37.74	37.55	45.02
4/25/2014	51.59	59.37	56.91	54.88	53.03	51.12	48.61	46.02	44.07	42.28	40.93	39.82	38.87	38.13	38.07	37.77	45.99
4/26/2014	53.71	62.58	60.48	58.19	55.84	53.33	49.91	46.87	44.72	42.89	41.56	40.38	39.39	38.55	38.41	38.11	47.41
4/27/2014	42.69	56.56	56.74	56.14	55.18	53.74	51.09	47.98	45.68	43.66	42.21	40.96	39.88	39.02	38.80	38.44	47.07
4/28/2014	34.52	46.22	47.49	48.66	49.58	50.06	49.93	48.15	46.32	44.35	42.86	41.56	40.40	39.44	39.17	38.76	44.86
4/29/2014	33.55	45.03	45.92	46.68	47.26	47.60	47.92	47.07	46.05	44.60	43.30	42.08	40.90	39.89	39.54	39.12	44.20
4/30/2014	39.32	44.42	44.23	44.63	45.20	45.71	46.44	46.04	45.52	44.42	43.49	42.40	41.29	40.32	39.95	39.47	43.57
5/1/2014	46.37	51.32	49.43	48.17	47.30	46.59	46.14	45.36	44.95	44.15	43.40	42.61	41.58	40.66	40.30	39.82	44.79
5/2/2014	47.87	55.93	54.30	52.65	50.95	49.24	47.27	45.68	44.92	44.04	43.34	42.62	41.74	40.93	40.60	40.10	46.29
5/3/2014	42.94	51.84	51.38	50.94	50.35	49.49	48.15	46.47	45.35	44.21	43.44	42.73	41.90	41.13	40.83	40.39	45.91
5/4/2014	39.80	51.21	50.88	50.50	49.99	49.24	48.17	46.69	45.69	44.50	43.68	42.91	42.09	41.31	41.04	40.63	45.90
5/5/2014	46.72	51.26	49.97	49.30	48.88	48.45	47.92	46.73	45.79	44.73	43.89	43.13	42.29	41.52	41.26	40.83	45.73
5/6/2014	52.26	59.27	56.87	54.73	52.68	50.77	48.56	46.86	45.82	44.87	44.05	43.30	42.51	41.69	41.48	41.04	47.63
5/7/2014	42.37	56.28	56.04	55.29	54.13	52.57	50.20	47.88	46.46	45.24	44.28	43.53	42.71	41.93	41.70	41.27	47.97
5/8/2014	38.19	47.99	49.00	49.87	50.39	50.47	50.01	48.37	47.02	45.67	44.60	43.77	42.90	42.11	41.89	41.43	46.36

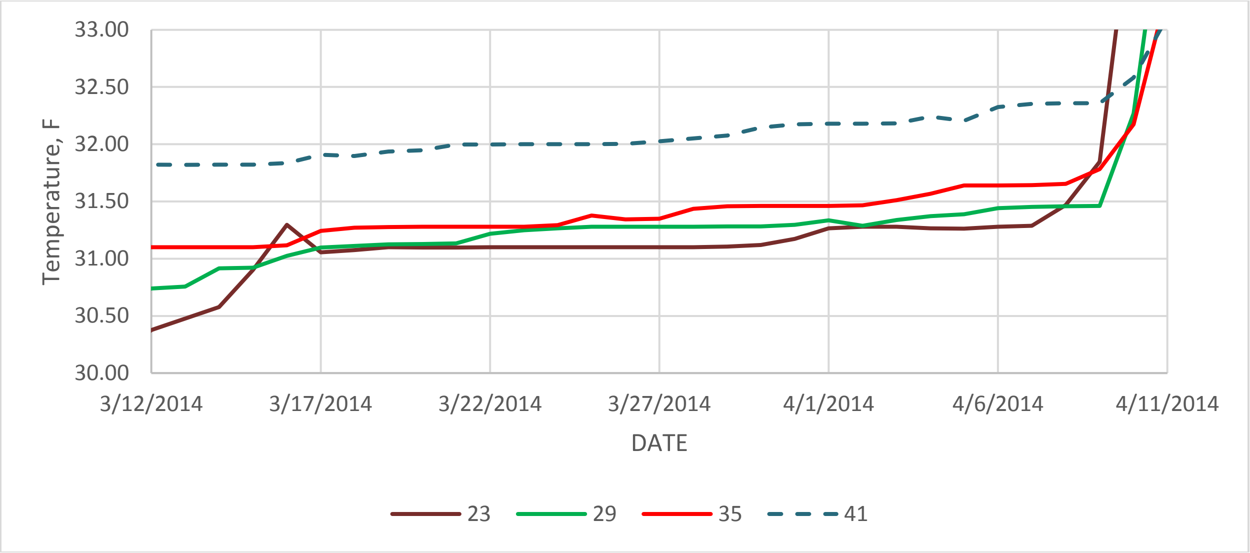

Table A.1. End of freezing

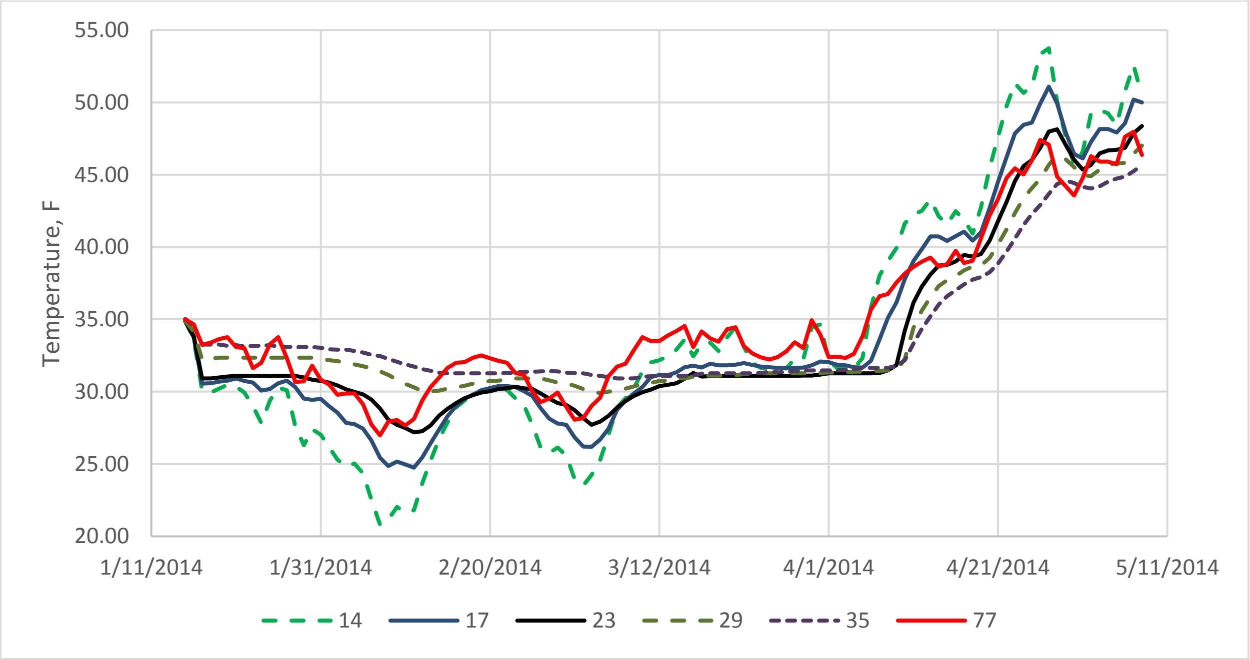

Table A.2. Question 77 in. sensor

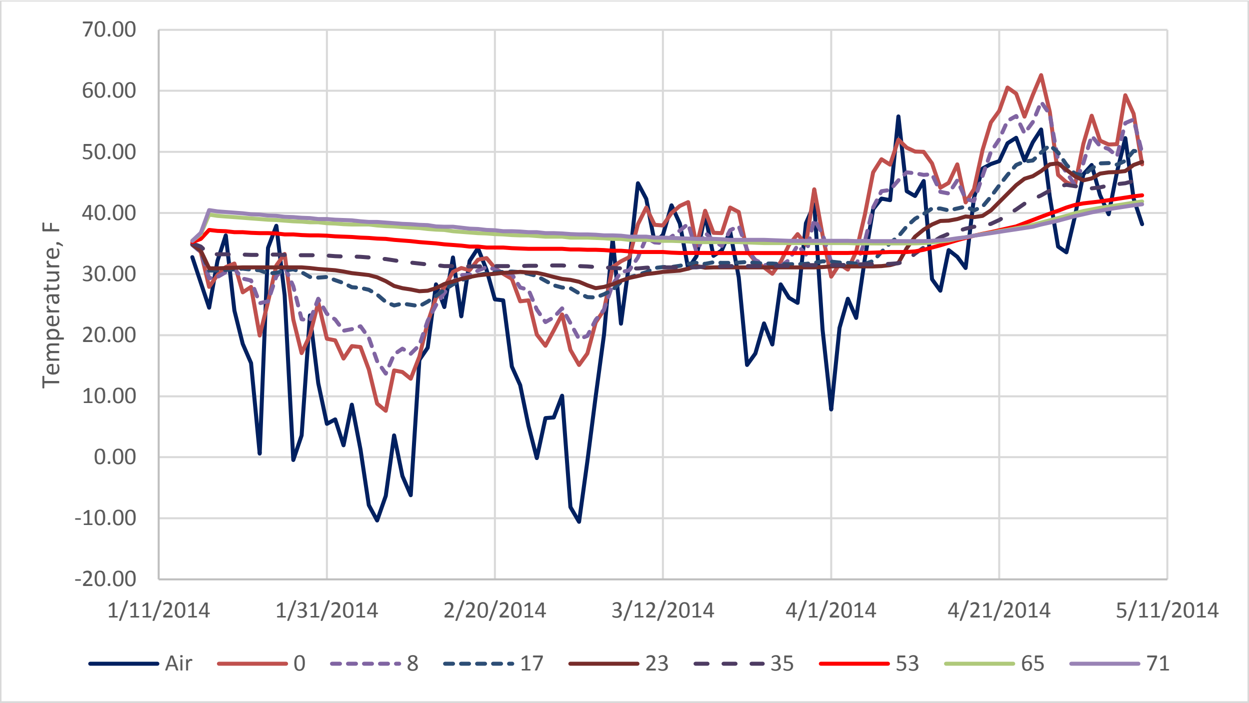

Table A.3. Selection top to bottom

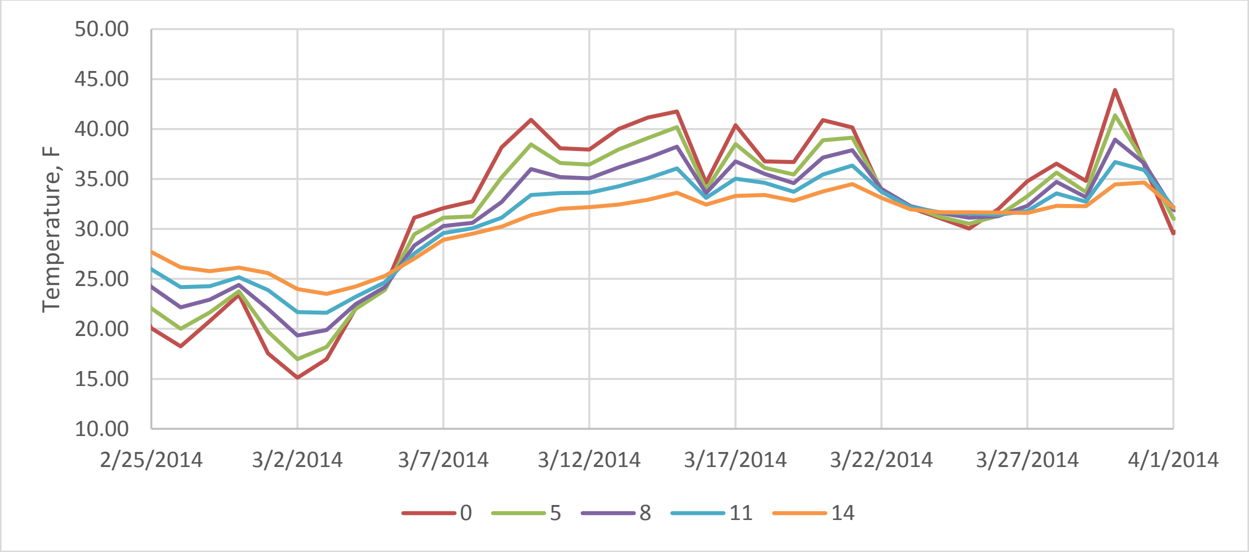

Table A.4. Temperatures to 14 in.

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