Real-time frost depth forecast model for thaw-induced axle load limitation management

S. Thordarson
Vegsyn Consult, Hafnarfjordur, Iceland
skuli@vegsyn.is

N. Jonasson
Icelandic Road Administration, Reykjavik, Iceland
nicolai.jonasson@vegagerdin.is

E. Sveinbjornsson
Vedurvaktin Meteorological Services, Gardabaer, Iceland
vedurvitinn@gmail.com

A. H. Thorolfsson
University of Iceland, Reykjavik, Iceland
ath68@hi.is

G. O. Bjornsson
Almenna Consulting Engineers, Reykjavik, Iceland
gudjonbj@almenna.is

ABSTRACT

Thaw weakening is a major problem for roads in Iceland. A model for road surface temperature and sub-base frost depth prognosis has been developed for the Icelandic Road Authorities. The model is connected to a frost depth and sub-base temperature sensor and an Automatic Weather Station which enables accurate real-time operation of the model. Using input data from a 5 day weather forecast, the model is capable of accurately predicting the development of freeze or thaw in the road sub-base which in turn allows the road operators to announce axle load restrictions well in advance, for the benefits of heavy goods transport operators, and less risk of excessive road deterioration. The model was also adapted to investigate the effects of future climate scenarios on the ice development in the road sub-base.

KEYWORDS

ROAD DETERIORATION / FROST DEPTH / SURFACE TEMPERATURE / AXLE LOAD RESTRICTION / CLIMATE CHANGE / FORECAST MODEL

1 INTRODUCTION

Thaw weakening is a problem on roads in cold climates in different countries around the world [1]. On the Icelandic road network, thaw weakening is responsible for excessive deterioration of the roads and frequent application of axle load restrictions. The additional costs for both the Icelandic Road Authorities (ICERA) and the transport industry are substantial. Rising mean temperatures the several past winters has led to more frequent freeze-thaw cycles in the period from December to April, increasing the number of necessary load restriction implications. Climate change is likely to further increase this problem, despite shorter winters. In order to fight breakdown of road pavement and sub-base and simultaneously minimizing the number of days with load restrictions, a precise management of load restrictions during thaw periods is important. For monitoring of frost depth in the road sub-base, ICERA commenced the development of a measurement device which is installed on more than 40 locations on the Icelandic road network and is planned for 20 more sites. For maximum utilization of the system, the current road surface temperature and frost depth forecast model has been developed as another novelty in thaw weakening management at ICERA.

2 FROST DEPTH MEASUREMENT SYSTEM

Based on measurements of temperature and electric conductivity in the road structure, a special measurement device indicates the current frost depth level in the road sub-base. Using the electric conductivity and temperature of the soil specimen surrounding the rod is a patented method for determining the frost depth. The device consists of a 1,2 m long rod that is placed in the road sub-base and a data processing unit. 16 pairs of sensors for temperature and electric conductivity are distributed with 5 cm intervals along the rod from 10 cm depth below the pavement and down to 60 cm depth, and continuing with 10 cm spacing down to 120 cm. The hourly measurements can be monitored online in real-time. Most of the measurements sites have an Automatic Weather Station (AWS) installed as well, which is a necessary combination for running the model described herein successfully. To fully utilize the benefits of the frost depth device, the relationship between the thaw depth and the road bearing capacity has to be established, i.e. by Falling Weight Deflectometer as described in [2] and [3]. Figure 1 further illustrates the frost depth device and its user interface.

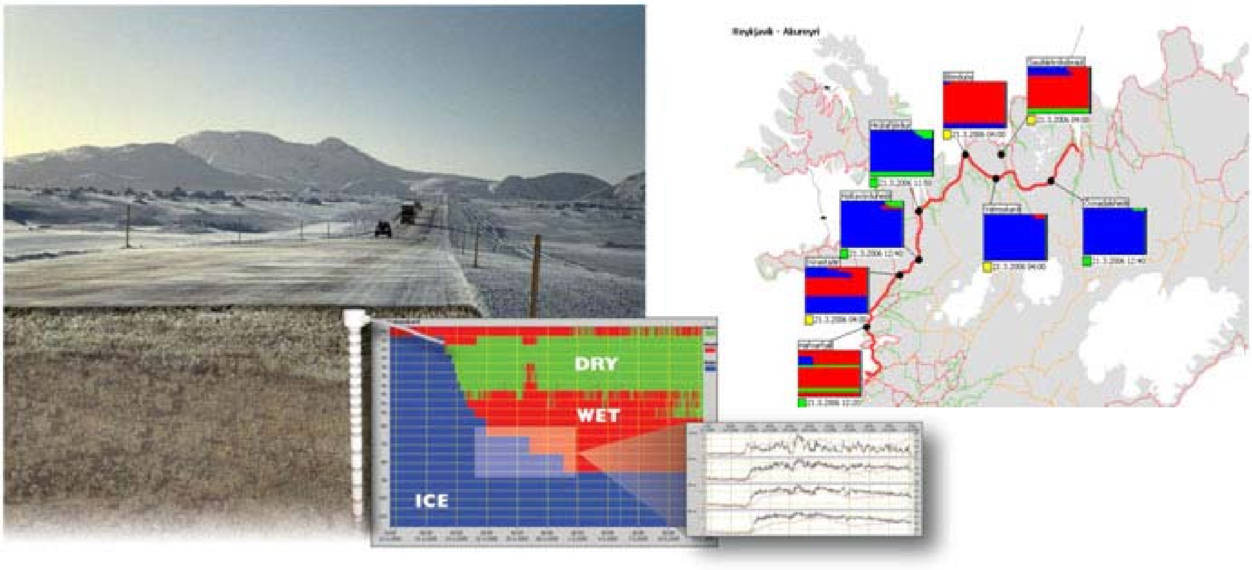

Figure 1. Left: The frost depth sensor´s placement in the road sub-base, Middle: User interface readings for electric conductivity, temperature and phase (water/ice), Right: Example of a route analysis on the road network.

3 MODEL DESCRIPTION

The model is based on thermodynamic principles for heat transfer from the road surface to it’s surroundings. Radiation from the sun and atmosphere, convection between the road surface and atmosphere and heat exchange by conduction within the road sub-base is all accounted for in. Initial- and boundary-conditions needed for running the model are forecast values for air temperature, cloud cover, wind speed and precipitation, along with real time values for air- and road surface temperature, sub base temperature and frost depth.

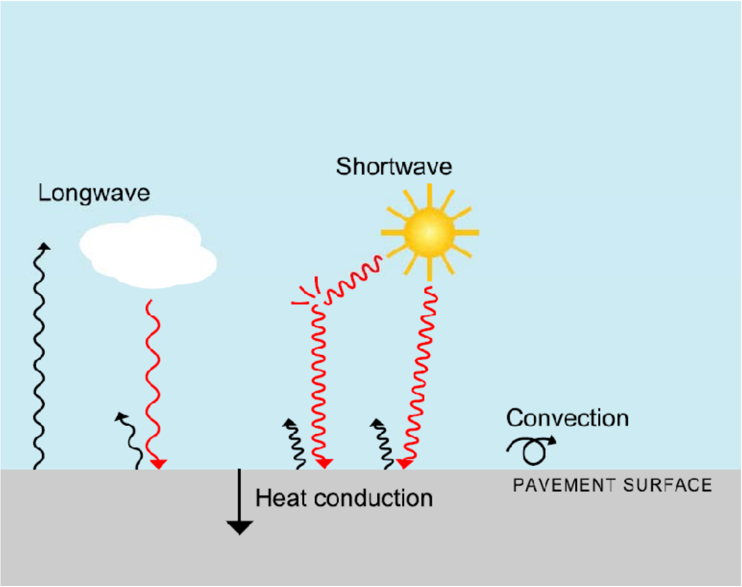

Figure 2. Schematic presentation of the energy budget of the road surface (Figure from [5])

3.1 Road surface temperature

Hermanson [4] and [5] described the approach that is favoured here for the energy budget calculation of the road surface.

The earth surface emits long wave radiation that is assumed to follow the Stefan-Boltzman principle;

$$q_r = \varepsilon \sigma T_0^4$$

Equation 1. Long-wave radiation from the surface to the atmosphere. q_r is the emitted radiation W/m^2, ε is an emission coefficient (equal to 1 minus surface Albedo, and Albedo decribes the surface reflective capacity), σ is Stefan-Boltzman constant, 5,68·10^{-8} W/(m^2 °K^4) and T_0 is the road surface temperature in degrees Kelvin.

The atmosphere absorbs radiation and emits to the earth surface as long-wave radiation. A portion of this radiation is absorbed by the surface as:

$$q_a = \varepsilon_a \sigma T_2^4$$

Equation 2. Long wave-radiation absorbed by the surface, q_a (W/m^2). The constant ε_a describes the surface absorptivity and is also depending on the cloud cover, T_2 is the 2 m air temperature.

The sun emits short-wave radiation which is partially absorbed by the surface for heating and partially reflected and absorbed by the atmosphere. According to global position and time, the maximum magnitude of the perpendicular radiation upon a horizontal plane can be assessed. This radiation then needs to be corrected with respect to surface Albedo and cloud cover. Here, we use the widely used model of Bird and Hulstrom*, which has been

---

* Richard E. Bird and Roland L. Hulstrom A Simplified Clear Sky Model for Direct and Diffuse Insolation on Horizontal Surfaces. SERI/TR-642-761, Solar Energy Research Institute, Golden, Colorado, USA, February 1981.

compiled for a spreadsheet application [6]. The short-wave radiation, q_{GL} (W/m^2), absorbed by the surface is;

$$q_{GL} = q_{Bird} \cdot (1 - alb) \cdot \left(1 - \frac{NH}{8}\right)$$

Equation 3. Short-wave radiation absorbed by the surface. Calculated solar radiation for standard atmospheric conditions, upon a horizontal surface is q_{Bird} ,*alb* is the surface Albedo and *NH* is cloud cover on the scale 0 to 8 (0 on a bright day, 8 on fully overcast day)

Heat exchange to the atmosphere by convection, q_c (W/m^2) is;

$$q_c = h_c (T_0 - T_2)$$

Equation 4. Convective heat exchange between the surface and atmosphere. T_0 and T_2 are road and air temperature as before and h_c is depending on temperature and wind speed;

$$h_c = 698{,}24a\left(bT_m^c U^d + 0{,}00097\left|T_0 - T_2\right|^e\right)$$

Equation 5. Convection parameter. *U* is wind speed and *a* through *e* are experimental constants.

The road pavement exchanges heat with the sub-base by heat conduction;

$$q_N = -kA\frac{(T_0 - T_{d10})}{\Delta z}$$

Equation 6. Heat conduction, q_N, (W/m^2), between a unit area, *A*, of surface pavement and the road sub-base. The thermal conductivity is *k* and T_{d10} is the temperature at 10 cm depth (Δz).

Heat conduction further down in the road sub-base is according to the heat equation;

$$\frac{\partial T}{\partial t} = \alpha \cdot \frac{\partial^2 T}{\partial z^2}$$

Equation 7. The heat equation.

The thermal diffusivity, α, is defined as

$$\alpha = \frac{k}{\rho C}$$

Equation 8. Thermal diffusivity of a soil specimen where *k* is the thermal conductivity , ρ is the density (kg/m^3) and *C* is the material specific heat in KJ/(kg °C)

Initial- and boundary conditions are necessary to solve the heat equation numerically. These are given by the frost depth sensor described in the previous chapter.

When all the heat fluxes for a given time step in the calculation have been calculated (1 hour time step is used, same as the frost depth sensor logging), these are added up, Δe, and the resulting temperature change of the pavement surface, ΔT, can be solved for;

$$\Delta e = S \cdot C \cdot m \cdot \Delta T$$

Equation 9. Sum of all heat fluxes to and from the pavement surface on the left, (q_r, q_a, q_{GL} q_c *and* q_N), *C* is the pavement specific heat, *m* is the mass of an arbitrary volume of pavement. The parameter *S* is here applied to account for freeze and thaw of moisture and ice on the pavement surface.

The parameter *S* is high when surface temperature is around 0°, thus slowing the temperature evolution when heat is required for freezing or thawing of surface moisture such as water or ice on the road pavement.

3.2 Frost depth

The temperature of the road surface controls the ice development in the road sub-base. This is modelled by the Stefan equation as described in [7] and validated for one hour resolution by Thorolfsson [8]:

$$L\frac{dX}{dt} = k\frac{v_s}{X}$$

Equation 10. Stefan equation.

Analytic solution of the equation is straight forward;

$$X = \sqrt{\frac{2k}{L}\int v_s dt}$$

Equation 11. X is the vertical displacement of the ice-edge in a time interval dt, during which the difference between surface temperature and the soil freezing (or melting) point is v_s. L is the latent heat of the soil and k is the thermal conductivity.

The Stefan equation assumes that only the latent heat of the soil needs to be removed to freeze the soil moisture (reverse for thawing). Hence, volumetric heat stored in the soil specimen is neglected which leads to overestimation of modelled frost penetration into the ground. However, the real-time data feed from the sub-surface thermometers built into the frost measuring rod allows the software to compensate for this, forcing the model to not allow freeze or melting until the soil temperature is reasonable.

4 RESULTS FROM REAL-TIME APPLICATION

The forecast model has been validated for National Road no. 31 at Skálholt in South-Iceland and was run on a daily basis from December 2008 to April 2009, until spring thaw. For model input, a 5 day weather forecast was used. Thanks to the real-time monitoring of pavement surface temperature and frost depth by the instruments, calibration can be done quite effectively and the mean error of the predicted surface temperature is below one degree centigrade. The resulting 5 day frost depth prognosis is reliable for the purposes of axle load management on the road system. Figure 3 shows the model results for the testing period and Figure 4 shows the same results for the last three weeks of the period. Note that the green bar with arrow in each end denotes the concurrent prognosis period, during which only weather forecast and no measurement data was yet available.

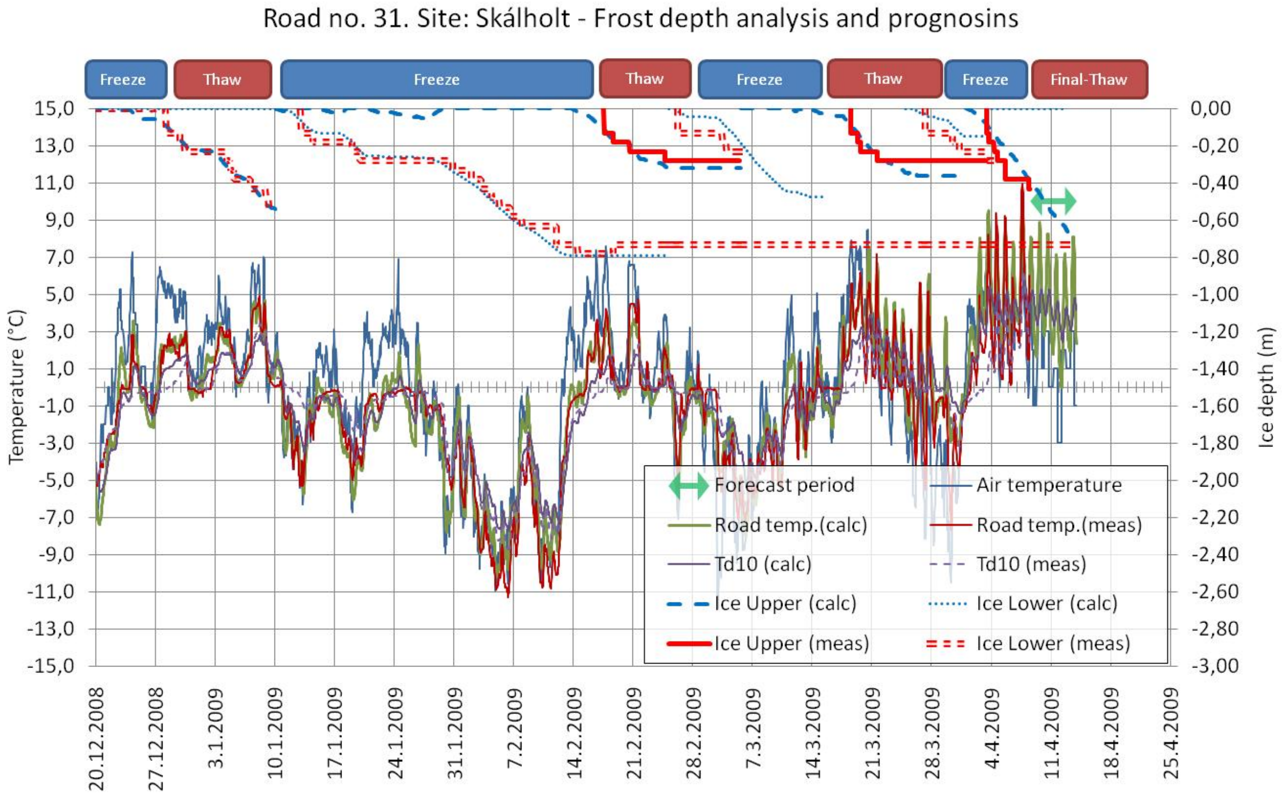

Figure 3. Model results for the testing period. Three thaw episodes occurred, all of which lead to axle load limitations on the road network in the area.

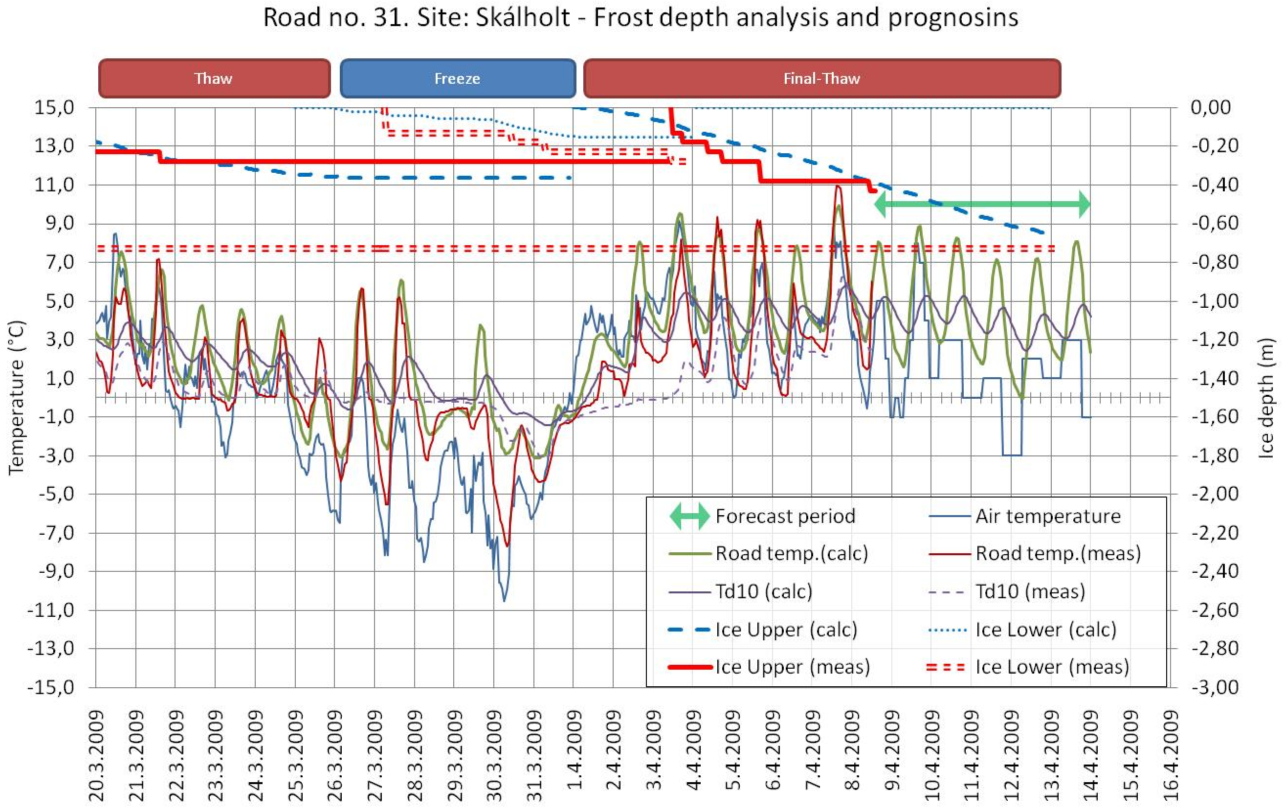

Figure 4. The figure shows clearly how the diurnal solar radiation fluctuations govern the road temperature late winter. The quality of the cloud cover forecast is thus extremely important to predict the road surface temperature correctly.

5 RESULTS FOR FUTURE CLIMATE REFLECTIONS

The model was modified to run on a 24 hour basis, enabling the use of daily mean temperature series from downscaled climate scenario simulations. Data from the ENSEMBLES project was used for the experiment [9]. The climate model is METO-HC 25 km HadRM3Q0 by the Hadley Centre. Firstly, a simulated climate scenario for the decade 1991 – 2000 was considered. As the downscaled climate model is run on a 25 km grid, choosing a suitable location for the analysis is possible. A model point near Skálholt in South Iceland was chosen. The climate scenario is simulated using real weather observations as initial and boundary conditions. One representative winter from the 10 year simulation was chosen. The resulting 24 hour air temperature series (one temperature value each day) was put into the frost depth model for a control run. Surface Albedo, wind speed and cloud cover was kept constant for the period. Results are shown on Figure 5. Freezing of the road sub-base starts on November 16th. The total frost penetration in the road is 63 cm (curve "Ice Lower") and no thaw episodes are observed until the spring thaw settles in. Thaw reaches 40 cm into the ground on March 10th (ideally the criteria for terminating axle load restrictions) and the road is ice-free on May 25th.

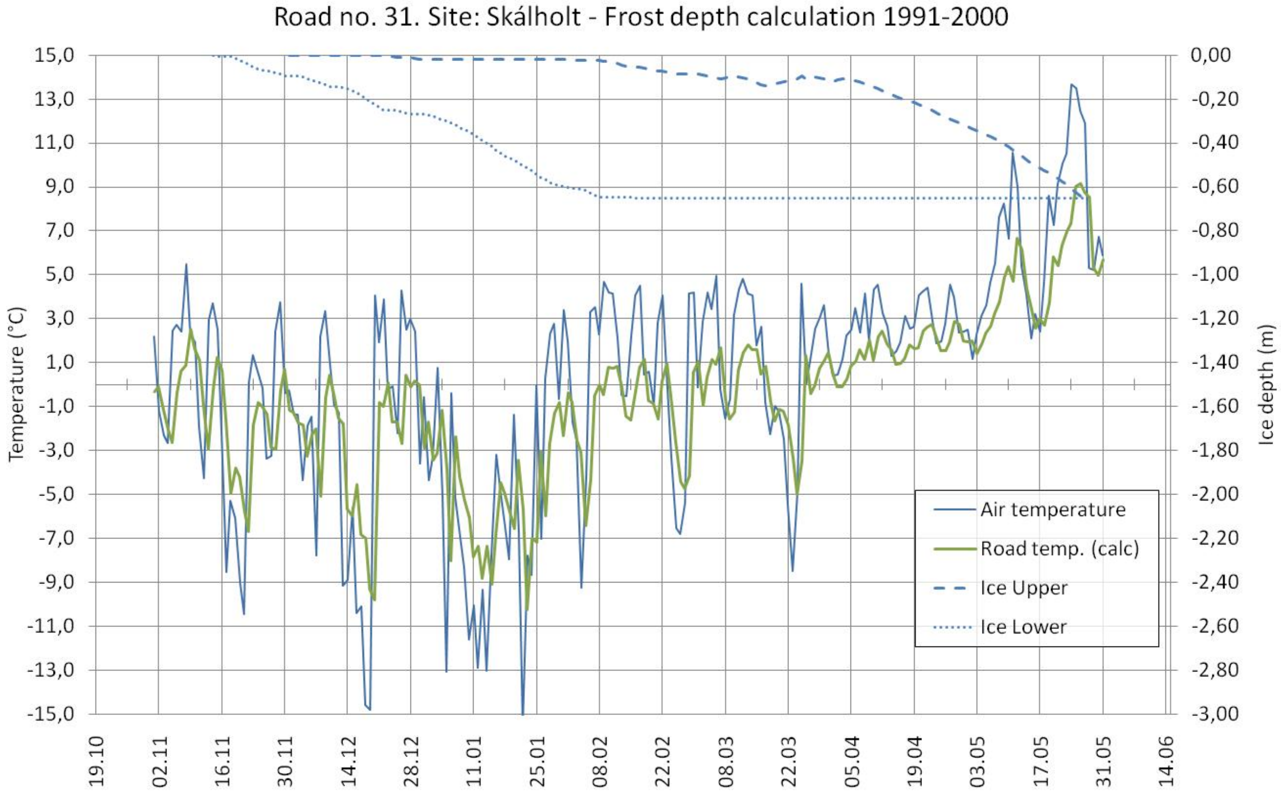

Figure 5. Frost depth model results for a typical winter from a simulated climate scenario for the period 1991 - 2000

For a possible future climate scenario, results for the A1B1 scenario defined by IPCC were chosen. That scenario assumes an increase of 2,2°C in the mean annual temperature in South-Iceland by year 2060 compared to year 2000. The results from the frost depth model are shown on Figure 6. As before, the road starts to freeze around middle of November. However, the maximum frost penetration is only 35 cm into the road sub-base. One thaw period lasting for two weeks is observed, melting the uppermost 10 cm in the road. Spring thaw is complete on April 18th.

In general, the temperature series from the simulated climate scenarios do not reflect the character of the temperature fluctuations observed in South Iceland during the last decade. Each winter, the real weather results in several thaw periods which last up to two weeks, a trend that is missing from the ENSEMBLES simulations. However, this exercise has shown that the current frost depth model is capable of reflecting the effects of future climate on the frost behaviour in the road sub-base and the resulting bearing capacity challenges, as soon as more suitable model results for future climate simulations become available.

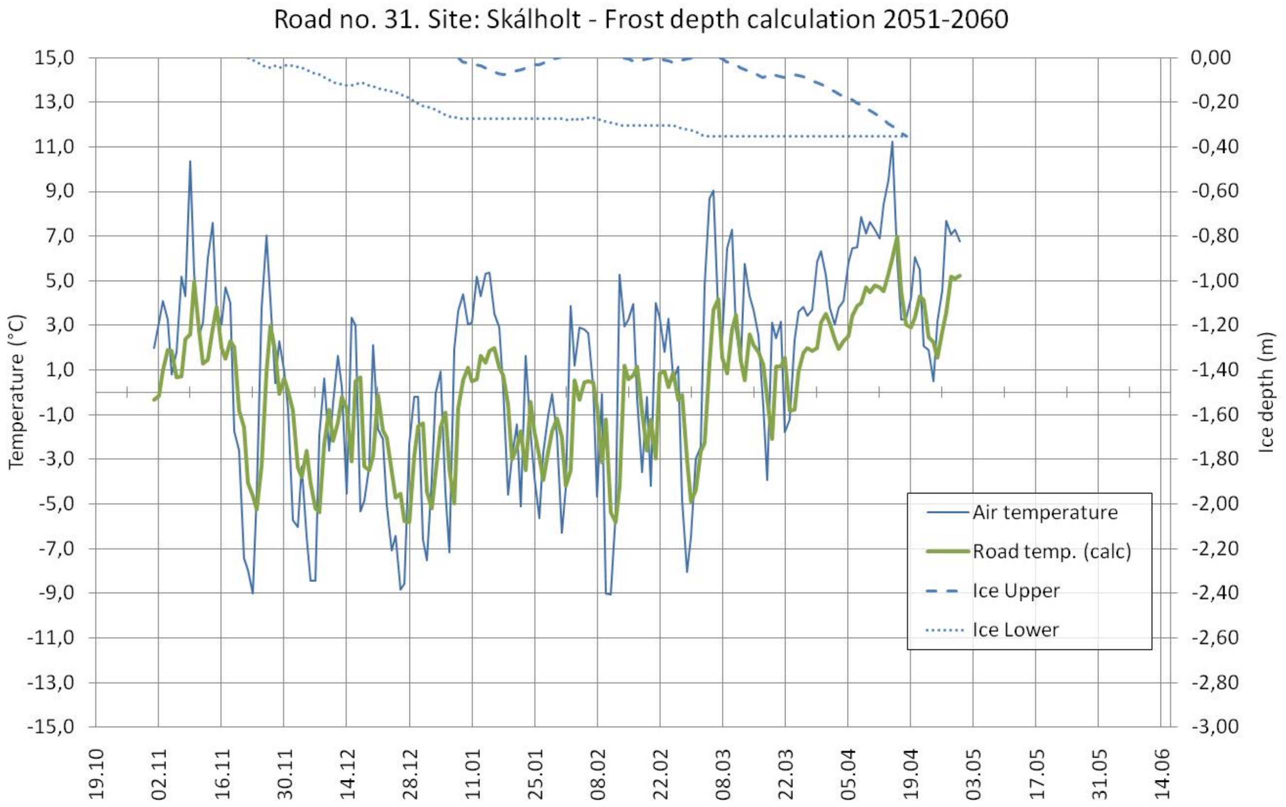

Figure 6. Frost depth model results for a typical winter from a simulated climate scenario for the period 2051 – 2060 based on the A1B1 Green House Gas Emission scenario by IPCC.

6 CONCLUSIONS

A model for road sub-base frost depth prognosis was developed. The model is connected to on-site instruments; an Automatic Weather station and an electronic frost depth measuring rod. Using a 5 day weather forecast, the model is capable of predicting ice movements in the road reasonably well in order to allow for a sound axle load management on the road system. Ideally the model gives an opportunity to announce axle load limitations 2 or 3 days in advance, which allows the transport operators to reorganize timely.

Software that allows automatic model run on a daily basis with continuous feed from weather forecast is under development. It is foreseen that the model will run on 60 sites around the Icelandic road network in the near future.

In a separate experiment, a modified version of the model was run on series for daily average temperatures from a future climate scenario. The results show that the model is quite useful for estimating the effects of future climate on possible changes in the ice development and resulting effects on road bearing capacity and pavement deterioration.

ACKNOWLEDGEMENTS

We acknowledge the ENSEMBLES project, funded by the European Commission's 6th Framework Programme through contract GOCE-CT-2003-505539. We also thank Dr. Halldor Bjornsson at the Icelandic Meteorological Office for providing the ENSEMBLES future climate data and facilitating the use of it in this experiment. Finally we thank the Icelandic Road Authorities Research Fund for financing the project.

REFERENCES

[1] Gudjon Örn Björnsson, 2006; *Thaw induced axle load limitation*. MSc. thesis, Civil and environmental engineering, University of Alberta, Edmonton.

[2] Skuli Thordarson and Anton H. Thorolfsson, 2007: *Kvörðun frostdýptarmæla út frá falllóðsmælingum. Áfangi ársins 2007*. ("Calibration of frost depth measurement device by Falling Weight Deflectometer bearing capacity measurements"). Report to the Service Department, Icelandic Road Authorites, funded by ICERA Research Fund (In Icelandic).

[3] Skuli Thordarson, 2008: *Burðarþolsmælingar við frostmælistöðvar á vegum 2008*. ("FWD measurements at frost depth measuring sites 2008"). Report by Vegsyn Consult for ICERA Service Department (In Icelandic).

[4] Åke Hermanson, 2002: *Modeling of frost heave and surface temperatures in roads*. PhD thesis, Luleå University of Technology, apríl 2002.

[5] Åke Hermanson, 2004: *Mathematical model for paved surface summer and winter temperature: comparison of calculated and measured temperatures*. Cold Regions Science and Technology, 40. p. 1-17.

[6] Greg Pelletier: *A solar position and radiation calculator for Microsoft Excel/VBA*. Washington state Department of Ecology.

[7] Orlando B. Andersland og Branko Ladanyi, 2004. *Frozen Ground Engineering*. John Wiley and Sons Inc.

[8] Anton Heidar Thorolfsson, 2008: *Spálíkan fyrir frostdýpt í burðarlögum vega*. ("Prognosis model for frost depth in the road sub-base"). Report to the Icelandic Student Innovation Fund (In Icelandic).

[9] Hewitt, C. D. and D. J. Griggs, 2004: *Ensembles-based Predictions of Climate Changes and their Impacts*. Eos, 85, p566.