The FMI Road Weather Model

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ABSTRACT

A road weather model has been developed to forecast specific road weather related variables. The main aim in model development has been to provide FMI meteorologists with tools to determine the need for traffic condition warnings. The model not only predicts the road surface temperature but also produces a road condition interpretation which it further processes to give a three-level traffic condition index to issue traffic warnings. Moreover, road surface friction is determined. The model development has led to various spin-offs, including novelty model versions for road maintenance, pedestrian sidewalk condition forecasting and intelligent traffic applications.

Keywords: Road weather forecasting, road weather warnings, road maintenance, road condition, pedestrian safety, intelligent traffic.

1 INTRODUCTION

Forecasting of road surface and traffic conditions is an important aspect of traffic safety and road maintenance, especially during northern winter. The conditions can change quickly, e.g. with the onset of snowfall or during rapid temperature changes. Proper consideration of upcoming weather events helps the road maintenance authorities attend the roads in an effective and economical way.

Prior knowledge of road weather is also important from public safety standpoint. Finnish Meteorological Institute (FMI) is duty bound to issue warnings of hazardous traffic conditions to the general public. The main aim in the road model development was to provide FMI meteorologists with tools to define the needs for traffic weather warnings.

Road weather model development was initiated at FMI by Nysten and his colleagues in the early 1980's [1]. Activities were reinforced later when, in 1999, development of the present model was started. The model is capable not only to predict road surface temperature, but also produces a road condition interpretation which it further processes to give a three-level traffic condition index to issue traffic warnings [2]. As input, the model employs a numerical weather forecast, either directly or after modifications made by duty meteorologists, as well as observations from synoptic weather stations and the radar precipitation measurement network. The latest versions of the model are also capable to employ measurements from road weather stations. An extensive graphics output package has been developed as well.

The model has been in operational use since 2000 [3]. In addition to the basic model, several model versions have been developed for various spin-off purposes. These include the pedestrian sidewalk condition model [4], a road maintenance application to help in the timing of road maintenance actions [5], the mobile phone based warning system for heavy traffic (Driver Alert) [6], as well as research applications in several safety and intelligent transport system projects (ROADIDEA, CARLINK, WiSafeCar) [7-9]. In addition to the main road weather model, the pedestrian sidewalk condition and the road maintenance model are used in operations at FMI. The model has also been applied in a study on the effect of climate change on road maintenance needs in Finland [10].

2 MODEL DESCRIPTION

2.1 General

The model is a 1-dimensional energy balance model to calculate vertical heat transfer in the ground and at the ground-atmosphere interface, taking into account the special conditions prevailing at the road surface and in the ground below (Fig.1). The effect of traffic is also accounted for. Output from a weather forecast model, either directly or with duty meteorologist's modifications, is used as a forcing at the upper boundary.

The initial conditions for the forecast are determined by making, prior to actual forecast run, a two-day model run based on gridded weather observation data. This input also provides the horizontal coupling between the individual points. The model can be run using observed meteorological data only, e.g. for climatological research purposes [10]. The climatological ground temperature is then used as the lower boundary condition.

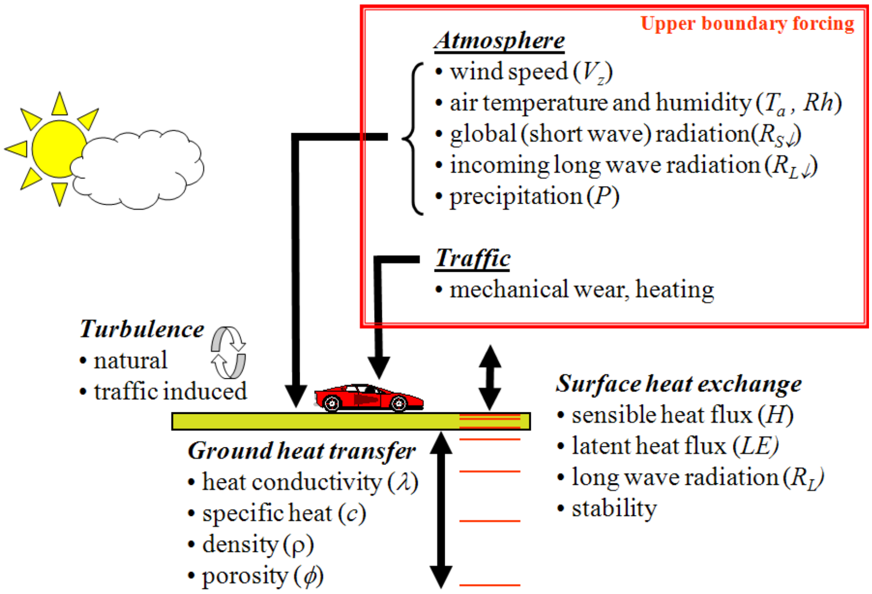

Figure 1. Model energy balance.

2.2 Model physics

Physically, the model is based on solving the energy balance at the ground surface. The energy balance equation at the surface can be written as (c.f. Fig.1):

$$G = I_{NET} - H - LE \qquad (1)$$

where G is the heat flux into the ground, I_{NET} net radiation on the surface, H is the sensible and LE the latent heat flux. The left-hand side of equation (1) describes the heat transfer and storage in the ground. The vertical heat transfer and temperature distribution are solved for a depth of about 6 metres. The heat transfer in the ground is assumed to take place by conduction of heat, only. In addition to the thermal properties of the ground, e.g. the ground porosity is taken into account. Sensible (H) and latent heat (LE) fluxes between the surface and the atmosphere are calculated using the concepts of boundary layer conductance and aerodynamic resistance [16, 17]. As to saturation vapour pressure, different formulations over the water and ice surface are used. The stability is also accounted for [11].

The right-hand side of equation (1) describes atmospheric forcing. Net radiation is in the model calculated as

$$I_{NET} = (1 - \alpha_S) I_G + \varepsilon_S I_L - \varepsilon_S \sigma_{SB} T_S^4 \qquad (2)$$

where α_s, ε_s and Ts are ground surface albedo, emissivity and temperature, respectively, and σ_{SB} is the Stefan-Bolzmann constant. The global short wave (I_G) and long wave radiation (I_L) are taken in the model as input. In cases of bare or snowy ground, albedo is approximated by using two values, one for the bare surface and another for the snow covered road surface. With icy road, a value depending on the ice thickness is used.

2.3 The effect of traffic

The traffic affects the road surface temperature and especially the road condition. Turbulent heat transfer caused by moving vehicles is approximated using a non-zero minimum value of wind. A smaller value is used during night-time. For the time being, a spatially constant traffic effect is assumed.

The main effect of traffic is through mechanical wear on the ice, snow, frost (deposit), or water on the surface. The model includes separate storage terms for these substances. The effect of traffic is either to change the size of these storages or to convert them from one form to another. E.g. with snow wear, part of the decrease in snow storage is thought to consist of snow blown away from the road, the remaining part being squeezed to ice and thus, for its part, increasing ice storage. The wear (W_i, in mm water equivalent) is described in the model by functions of type:

$$W_i = AX_i \qquad (i = \text{water, ice, snow, frost}) \qquad (3)$$

where A_i, is an empirical constant for substance i and X_i is the amount of it on the surface in mm water equivalent. The specific form of the equation was chosen to give a wear that depends on the amount of the substance on the road surface, which is in accordance with observations. The parameter values in the equation have been determined by experimenting and through discussions with road engineering and maintenance experts.

2.4 Road condition interpretation

The road condition interpretation is based on the size of the various storage terms described above. The model constantly tracks storage changes caused by melting, freezing, evaporation and condensation as well as by traffic wear. The storages may also interact with each other, e.g. the size of the water storage is increased by precipitation as well as by melting of snow or ice.

Table 1 summarizes the different ways the different storage sizes are increased or decreased. As to ice, two separate storage terms are used to describe the different wear on the different parts of the road (tracks or lanes with different amounts of traffic). One term for each was considered adequate with the other storage terms.

Storage term	Increased by	Decreased by
Snow	snowing	squeezing to ice traffic "blow off" melting to water
Ice	squeezing from snow freezing of water	traffic wear melting to water
Frost (deposit)	deposition	traffic wear melting to water
Water	rain condensation melting of snow/ice/frost	traffic wear evaporation runoff

Table 1 : Storage interactions

The model makes the road condition interpretation based on the sizes of the different storage terms and the calculated road surface temperature, i.e. it determines the status of the road surface. Eight different road surface classes are used:

1. dry
2. damp
3. wet
4. wet snow
5. frost (deposit)
6. partly icy
7. icy
8. dry snow

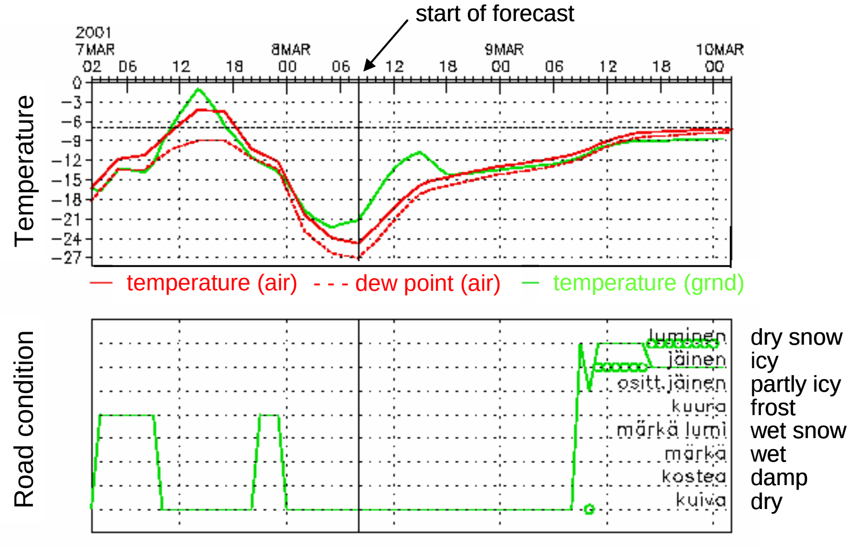

Figure 2. Example of road surface temperature (upper plot) and road condition interpretation (lower plot, solid line; green circles denote secondary condition) produced by the model.

Damp and wet classes differ only by the amount of water on the surface. The 'partly icy' case means conditions in which only part of the road surface (e.g. lanes with less traffic) is covered by ice. It is also used to describe the uneven wear of the road surface, which may cause a snow-free track on a lane otherwise covered with snow or ice. In such cases, a secondary road class index is determined to indicate the road condition in the ice free tracks. The secondary index is also used to describe cases with water or snow on ice.

2.5 Traffic condition index

The model further combines information about the road condition, storage sizes and certain weather parameters to produce a three-level traffic condition index to describe traffic conditions in more general terms:

1. normal
2. difficult
3. very difficult

The index classes are used by FMI to issue road weather warnings. The index is determined by first defining a basic value using the information about road condition and then adding a correction factor based on wind speed, precipitation phase and intensity as well as on lighting conditions. The procedure has been designed to mimic the instructions and decision logic of a duty meteorologist as closely as possible.

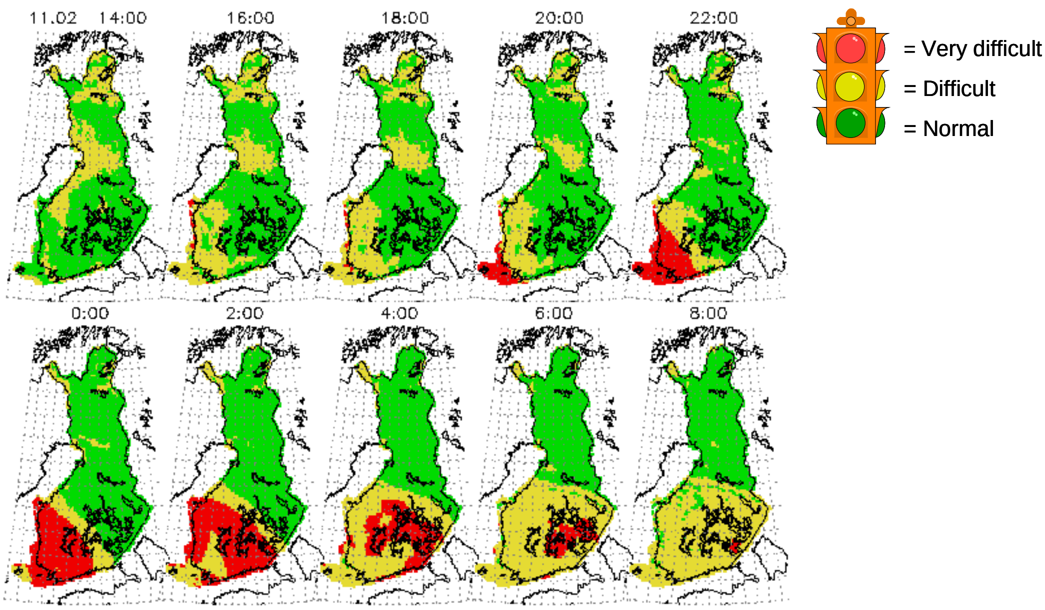

Figure 3. Example of traffic condition index map time series produced by the model.

2.6 Surface friction

An explicit method to estimate surface friction by the model has been derived quite recently. This statistical-numerical friction model [12, 13] is based on a large data set of road surface friction measurements by the Vaisala DSC111 sensor. The resulting regression equations are based on observations from four Finnish road weather stations during winters 2007/08 and 2008/09. The equations have been validated with independent data from winter 2009/10. The observational data was provided by the Finnish Transport Agency.

The underlying idea of the methodology (so-called Perfect Prog method) is that the friction model utilizes the road weather model output as predictor variables (assuming them to represent perfect forecasts) in the regression equations. The resulting statistical friction model equations are:

Snowy and/or icy roads: $CF_{si} = a_1 f(X_S) + b_1 f(X_I) + c_1 f(T_r) + d_1$ (4)

Wet road surface: $CF_w = a_2 f(X_W) + d_2$ (5)

Dry road surface: $CF_d = 0.82$ (constant) (6)

where a_i, b_i, c_i, and d_i are regression coefficients and T_r is road surface temperature. X_S, X_I and X_W are thickness of snow, ice and water layers (in equivalent water mm), respectively. The function f is either a square root or a logarithmic function.

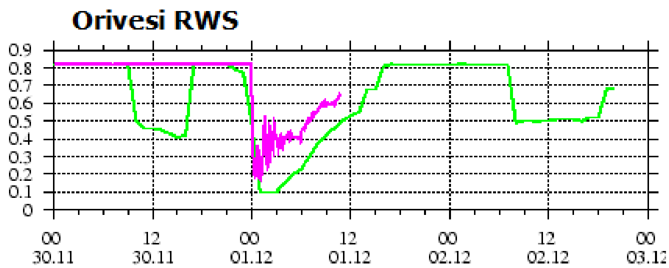

Figure 4. Example from the on-line verification system at FMI: forecasted (—) and observed (—) surface road friction coefficient time series for Orivesi, southern Finland.

3 NUMERICAL SOLUTION

The ground has been divided into 15 layers with varying thicknesses, the thinnest ones (1-10 cm) being next to the ground surface where the temperature changes are the largest and swiftest. The first few layers below the ground are assumed to consist of asphalt or related material, while the rest of the layers are described as porous ground. Appropriate density, heat conductivity, heat capacity, and porosity properties for each ground type are used. Temperature dependency of these properties is also accounted for.

Heat transfer equations are written numerically using a time-centred Crank-Nicholson scheme. The resulting tridiagonal matrix system is solved iteratively using the Thomas Algorithm [14]. The one-point model is solved in a 10 x 10 km grid covering mainland Finland and resulting in a total of 3551 points to be solved.

4 MODEL INPUT AND OUTPUT

The model input consists of time series of data from observations and weather forecast, the latter either directly from a NWP model or from a model forecast with modifications made by duty meteorologists. The model itself does not make any distinction as to the source of the data. The input parameters include (c.f. Fig.1):

- ambient temperature (T_{2m})
- relative humidity (Rh_{2m})
- wind speed (V_{10m})
- short-wave radiation (I_g, global radiation)
- downwelling long-wave radiation (I_L)
- precipitation
- precipitation phase

The precipitation and radiation input may consist of cumulative or instantaneous values. The precipitation phase may be provided either as phase interpretation or as the amount of snow precipitation. With no phase information available, the model makes a phase interpretation itself using a correlation based on temperature and humidity [15]. Special routines for including weather radar based precipitation observations are included in the model.

The model produces as its output surface temperature, road condition (primary and secondary), traffic index, road friction, and the storage sizes, both as plain ASCII text and as a binary file for the GrADS visualisation software (Grid Analysis and Display System, http://grads.iges.org/grads/head.html). The ASCII data can be used for further post-processing, whereas GrADS is used to produce on-line special graphical web pages for forecast monitoring, development and forecasting guidance.

5 MODEL VERIFICATION

Model performance has been assessed in the past [3]. The verification data covered winters 1997/1998 and 1998/1999. Periods of a few days duration were selected to represent contrasting winter weather types and data from four road weather stations in the south-western part of Finland were used. Test runs of the model were made as hindcasts: measurements at the road weather stations were used to provide upper boundary weather forcing for the simulation. Cloud observations from the nearest SYNOP weather stations were used to derive the radiation components for the test sites.

The mean error between simulated and measured road surface temperature was 0.3°C with root mean square error 1.35°C under conditions in which severe icing could be expected, i.e. rapid air temperature rise towards zero or wet surface freezing with temperature dropping below zero. Correspondence of time periods when icing was detected by the Vaisala road sensor and when ice was predicted by the model was qualitatively good. The timing of icing could be predicted to within a few hours compared to the road sensors. The large variation of the surface temperature was generally well simulated during cloud-free days in the spring when daytime heating from the sun was significant. Accurate determination of the night-time minimum (to within 1°C) was observed, but with slight underestimation of the daytime maximum surface temperature. Part of this can be explained by the linear interpolation of global radiation intensity between the SYNOP observation times and with the SYNOP observation not covering the time of maximum solar radiation in the early afternoon.

Recent verification results of the friction forecasting component of the road weather model are reported in [18].

6 OPERATIONAL USE

Four versions of the model are presently run operationally, once an hour, and the model area covers Finland in a 10x10 km grid. Observational and forecast data are interpolated into this grid using the Kriging method.

The operational model run consists of two parts to avoid the problem of initial state definition. The first one is based on observations and the second one on the forecast. The purpose of the first run ("observation phase" in Fig.5) is to set the initial state of the forecast-based run ("forecast phase") that follows it and starts from the final state of the observation-based run. The length of both runs is 24-48 hours depending on the amount of available input data. Technically, there is just one computer run, where the input source changes from observations to forecast when the end of the observations is reached.

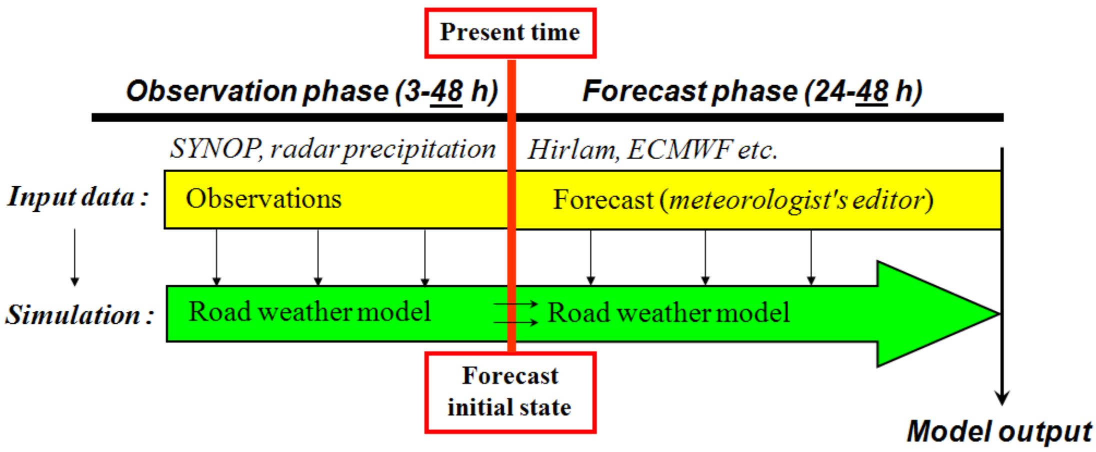

Figure 5. Operational road model run schematic.

At present, the observational part of the operational run is based on meteorological SYNOP observations and on weather radar precipitation data. Radar data is used wherever available. Synoptic observations are used when no radar data is available. The radar network of Finland is very comprehensive and covers most of the country.

The forecast-based part of the run uses output from a weather forecast model with duty meteorologist's corrections. This main version of the model is run hourly. Another operational suite with input directly from HIRLAM (http://hirlam.org/) weather forecast model is provided for comparison and as a backup. It is run at synoptic hours at 3-hour intervals.

6 MODEL SPIN-OFFS AND FURTHER DEVELOPMENTS

6.1 Pedestrian warning system

The pedestrian warning version of the model [4] aims at predicting sidewalk conditions from the viewpoint of the pedestrians. The surface condition interpretation and the related warning system has been modified in co-operation with the Finnish Institute of Occupational Health, which performed in-situ foot gear friction measurements using a special stepping robot [4].

FMI has been issuing warnings of slippery sidewalks for pedestrians operationally since 2004. The model is used in this service as guidance for the meteorologist when considering the need to issue warnings. Hospitals have shown interest in this model application for the purpose of advance planning of personnel availability in case of approaching bad sidewalk conditions and a possible rush of patients.

6.2 Road maintenance scheduling

The basic road weather model does not include the effects of road maintenance, providing thus a kind of “what-if-nothing-is-done” scenario. A special version of the model has been developed to ease the planning of road maintenance actions [5]. The model has been provided with enhanced snow storage handling including ploughing of the roads. Two road classes with different road maintenance needs are simulated operationally by the model. The maintenance needs include the maximum allowed amount of snow on the surface as well as time limits during which certain road maintenance actions need to be performed.

6.3 Driver alert for heavy traffic

A special mobile phone based warning system for transport traffic called Driver Alert was developed during 2004-2007 as part of the national AINO R&D programme [6]. The system was based on early warnings produced by the road weather model – the model issues a warning when dangerous traffic conditions, e.g. rapidly changing weather conditions are expected to develop. Traffic entering the danger area is determined using mobile phone based localisation or GPS techniques. A voice message giving the warning and detailing the situation is then sent to the mobile phones or the driver computer in the appropriate vehicles.

6.4 Intelligent traffic (ITS)

The road weather model has been adapted for piloting in various recent intelligent traffic projects, for example the CARLINK and the WiSafeCar projects [8, 9].

The objective of the international CARLINK [8] (Wireless Traffic Service Platform for Linking Cars) was to develop an intelligent wireless traffic service platform between cars, supported with wireless transceivers along the roads. The FMI road weather model was integrated in the system to provide up-to-date road weather data.

A platform for data transfer between vehicles and infrastructure was developed for the pilot study of the international WiSafeCar project [9]. The data provided for the system included road weather and emergency information. Data were transferred wirelessly between cars or between cars and infrastructure (e.g. traffic management centres) to enable the most urgent data to be delivered to drivers in real-time.

Weather information can be utilized in ITS applications like route planning which is the case in the new EU FP7 project FOTsis (www.fotsis.com) in which FMI road weather know-how is applied in a European context [19].

7 CONCLUSIONS AND FUTURE

The road weather model has been operational since 2000 and, with all its spin-offs and applications, a total of c. 60 model runs are now performed daily. The model is very robust and reliable and has performed generally well.

The present main operational model is limited to one road type, the Finnish main road network, with no maintenance information included. It provides a generic forecast as basis of road weather forecasting and decision-making. The localisation of model forecasts can be improved by including observations from road weather stations. Further planned future enhancements include to better account for locally and temporally varying traffic and environmental conditions and inclusion of road maintenance information.

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