Area Forecast Model for Winter Road Maintenance over a Road Network

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ABSTRACT

The likelihood of frost, ice and snow accumulation varies over a road network due to different influences of meteorological and environmental factors on road surface. These factors include precipitation, cloud cover, exposure, altitude, road construction, traffic, etc. They cause significant variation in road surface temperature and the likelihood in both temporal and spatial domains. Precise prediction of such variation and the likelihood will enable road authorities to salt and grit the road network in where and when salting and gritting is absolute needed in order to minimize winter maintenance costs. This paper presents the results of Vaisala Area Forecast model which makes 3-hour ahead forecasts of surface temperature, surface state, surface friction as well as other basic atmospheric parameters, based on digitised topographical dataset at a 200-metre spatial resolution. The model was run in both rural and urban environments and its forecasts were compared against measurements. The results are fairly accurate and consistent

Keywords: Snow and Ice, Prediction, Roads

1 INTRODUCTION

In winter road maintenance, numerical models have been used to predict temporal variation of road surface temperature (RST) and road surface state (RSS) at a specific location or forecast site [1-4]. The prediction provides valuable information about when ice, snow and frost are likely to be present at the forecast site. However, this single point, time-varying information is often not enough for highway engineers or maintenance agents to gain a complete picture about variation of RST and RSS over the whole road network or in a space domain, because RST and RSS change from one location to another due to differences in topography and terrain. Therefore, accurate information about spatial variation of RST and RSS during a winter night is highly valuable for the engineers and agents to decide not only when, but also where to target salting or gritting treatment. Such spatial variation is controlled by various factors, such as road exposure, elevation, proximity to water bodies, road materials and surface construction, traffic, and above all, weather conditions. For example, RST at a well-exposed site will be colder under clear and calm sky, but may be warmer when a warm frontal system passes by. To reveal and describe these variations, Thermal Mapping (TM) technique has been developed in the past [5-8].

TM is a technique using a vehicle-mounted infrared radiometer to measure the variation of RST. It uses vehicle-mounted infrared radiometers to detect spatial variation of road surface temperature in a road network, and plays an important role in revealing real-time spatial distribution of cold and warm road sections in a road network. Combined with a site-specific RST and RSS prediction model, the technique assists meteorologists, as well as highway engineers, in identifying time and locations of snow, ice and frost occurrence. This technique, however, is expensive and is usually applied during the nights of specific weather conditions. This means that while TM is able to describe correctly spatial variations of road surface temperature, it gives only 'snapshots' of thermal status of a road network under particular weather conditions.

Bogren *et al.* first attempted to predict RST along stretches of road by regression models [9].Chapman and Thornes developed a geomatics-based RST model [10] and recently, Bouris *et al.* combined TM and mesoscale weather forecasts to RST over a long stretch of road in Northern Greece [11]. These forecasts overcome limitation of TM by providing needed information in both time and space domains. But, they are lack of capability of providing physically consistent and constrained forecast of RSS, which is ultimately important for winter road maintenance. Also, the nature of statistical methods used in these models means that these models are likely valid only in the areas where they were developed. This will be a serious limitation for wide and easy application of the models to new forecasting areas.

This paper shows a new and fully numerical approach for RST and RSS forecasts in time and space domains. It describes a site specific RST and RSS prediction model called IceBreak, a spatial interpolation model and how these two models combined together to give RST and RSS forecasts over a road network called area forecasts. Tests are then carried out in West Midland and Glasgow city in the UK, and results are discussed.

2 METHODOLOGY

2.1 IceBreak model

IceBreak is a numerical prediction model for RST, RSS and road surface Friction Index [12]. It is based on unsteady one-dimensional heat conduction within the road sublayers, together with calculation and projection of initial and boundary condition for the model [12]. The governing equation of the model is

$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}(\kappa\frac{\partial T}{\partial z})$$

where, C is the heat capacity, κ is the thermal conductivity, and T(z, t) is the temperature at time t and depth z. It is assumed that the road surface and its underlying sublayers are horizontally homogeneous so that heat transfer in a lateral direction can be neglected.

To run the model, an initial condition, and upper and lower boundary conditions are needed. The initial thermal condition prescribes the temperature profile within the road sublayers. The lower boundary condition (usually at a 1 m depth) is treated as a climatological constant. The upper boundary condition is, however, described by an energy balance equation

$$(1-\alpha)S + L + H + LE + G = 0 \quad (1)$$

where, S is the solar irradiance, α is the surface albedo, L is the net long-wave irradiance, H and LE are the sensible and latent heat flux densities, and G is the ground conductive heat flux density. The initial condition is derived from sensor measurements at a forecast site. The boundary conditions can be provided either by a mesoscale forecast model, or by IceBreak itself.

IceBreak can use embedded statistical models to project boundary condition in a so-called nowcasting mode. In the nowcasting mode, unlike many other models that require human intervention (e.g., providing meteorological inputs), IceBreak depends only on sensor measurements and is fully automatic. It will generate, three or six hours ahead, forecasts of road surface temperature, surface state (dry, wet, icy, snow, etc.) and surface friction index once sensor data are available or updated. The model can easily be re-run every time that new observations are available. In typical practical applications nowcasts are generated when the road surface temperature falls below a given threshold.

2.2 Spatial interpolation model

A 2-D inverse distance weighting (IDW) algorithm is used in the model

$$z_j = \frac{\sum_{i=1}^{n}\frac{z_i}{(d_{ij}+\delta)^\beta}}{\sum_{i=1}^{n}\frac{1}{(d_{ij}+\delta)^\beta}} \quad (2)$$

where n is number of neighbouring observation stations, z_j interpolated value at station j, z_i observation at neighbouring i, d_{ij} distance between stations i and j, β and δ are parameters to be optimised.

2.3 Area forecasts

Combining IceBreak with the spatial interpolation model, forecasts of RST, RSS and FI can be made at any location on a road network. In a nowcasting mode, the forecasts are made by

- Dividing a road into sections (e.g., 200m in length);
- taking in local geographical and environmental information such as grid reference, height, road type (motorway, A-road or B-road), land use (urban, woodland, water etc.);
- Projecting boundary conditions at observation stations with embedded statistical models in IceBreak;
- Interpolating initial RST and projected boundary conditions to road sections;
- Running IceBreak at all road sections and observation stations.

The combined model is called Area Forecast (AF) model because it can be virtually run anywhere in a 2-D space and not restricted to a road network. It requires two datasets to run

- GIS data;
- Roadside meteorological observations.

3 TEST DATA

3.1 GIS data

The dataset is based on the UK Ordnance Survey (OS) Meridian dataset. Using a Geographic Information System (GIS) and the spatial analysis concept of Map Algebra, the OS dataset is used to generate the following geographic features that AF requires as inputs:

- Road type identifier
  - Motorway
  - A road
  - B road
- Elevation/Height
  - Maximum height
  - Minimum height
  - Slope
  - Aspect
- Urban identifier
- Woods identifier
- Water body identifier
- Grid coordinates
  - Easting
  - Northing.

The dominant factor effecting the resolution of the data is the resolution of the underlying gridded digital terrain model (DTM). For Meridian this is 200 metres.

3.2 Roadside meteorological observations

These observation serve as inputs to IceBreak and include RST, RSS, road depth temperature(s), air temperature, dew point, wind speed, and precipitation status.

3.3 Test areas

Two areas are selected to verify the performance of the AF model. The first area selected is in West Midland of England and of the size of about 70km by 80km with 27 roadside weather stations in the area. Data were collected for about one month from 5 to 31 January 2003. The second testing area is Glasgow city in Scotland and the tests were carried out in several nights of March and April 2003.

4 RESULTS

In West Midland, the verification was carried out in such a way that every one (and only one) roadside weather station was left out or masked as a road section or point during the one-month long nowcasting period. IceBreak was run in a nowcasting mode for 3 hours ahead with 10-minute interval, and the model was run again after each hour. The nowcasts of RST made at the station in every 3 hours was then compared to measurements at the station. This process was repeated to all of the 27 stations. Results of the comparison were weighted on numbers of comparing sample at each station, and are given in Table 1. An example of 3-hour nowcasts over 24 hours at one of the 27 stations is shown in Figure 1.

Parameter	Absolute error	Bias	Standard deviation	Root-mean-square error
Surface temperature (°C)	1.04	-0.34	1.06	1.31
Air temperature (°C)	0.73	0.30	0.89	0.98
Dew point (°C)	0.63	-0.01	0.83	0.88
Wind speed (m/s)	1.56	-0.51	1.39	1.94

Table 1. Verification of 3-hour nowcasts in West Midlands after weighing on number of samples at each station (Number of samples in comparison of each parameter: 91,196)

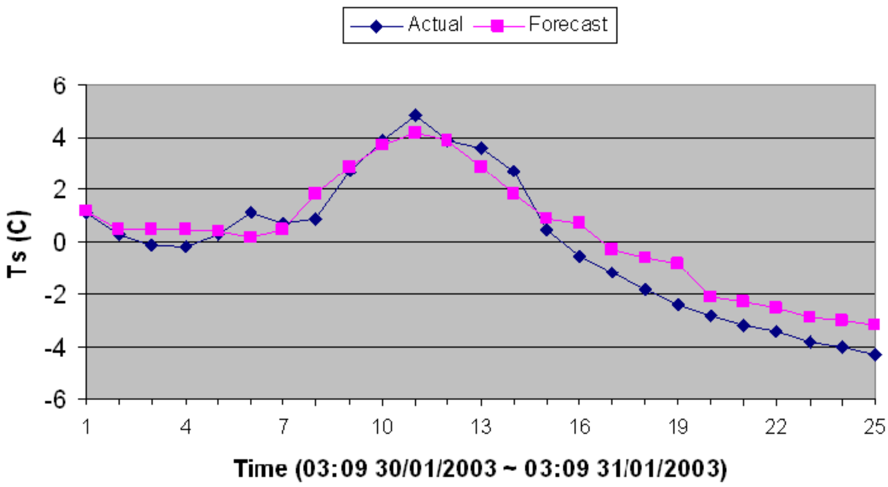

Figure 1. Comparison of nowcasts and measurements of RST at station (ID=BC004)

In Glasgow, Vaisala has carried out intensive thermal mapping surveys. These surveys provided a good opportunity to verify AF forecasts from a different angle. Within the area, 16 roadside weather stations were used by the AF model on eight nights (19-25 March 2003 and 23-25 April 2003) when thermal mapping was conducted. Weather conditions of the nights were submersed in Table 2. In the table, range of RST is the maximum RST minus minimum RST of observations among the stations. Forecast clouds are extracted from IceBreak retrospective runs at these stations, and weather types are classified according to RST range sand forecast clouds. The AF model was run at initial time 03:00am of each night in a 3-hour nowcasting mode. The results from the AF model were then shown by AreaViewer afterwards.

To view spatial variation of RST forecast by the model, an extreme night (22-23 March 2003) and a damped night (24-25 March2003) were selected for case study. Figures 2 and 3 display forecast maps of RST at 5am by the model on the extreme and damped nights respectively. It is seen from the figures that

- City centre of Glasgow is significantly warmer than rural and sub-urban areas;
- Under extreme weather condition, city centre are much warmer than other areas;
- Under damped weather condition, warm road sections are not restricted in the City Centre. Both central and northwest parts of the City is warmer than rest of the region;
- Under both extreme and damped conditions, motorways and A-roads are not necessarily colder than B-roads.

Measurements of RST over Glasgow city and surrounding areas by TM in the past were used to compare with the forecast maps in the figures. Figure 4 shows distribution of the measurements under extreme weather condition. Figure 5 shows the distribution under damped condition. Figures 4 and 5 are colour-banded with red representing the warmth and dark blue the coldness. The comparison is done in twofold: general pattern and selected spots. By comparing Figure 2 to 4 and Figure 3 to 5, we can see that the pairs of the maps fit to each other very well in general trends. The next step of comparison is to select and mark three spots on each of the TM maps and compare them against forecasts in Figures 2 and 3 by zooming into and picking up forecast values from road sections. The results are given in Table 3 and demonstrate a high degree of consistency between forecasts and measurements at under extreme weather condition. At damped night, forecasts and measurements fit well at points A and B on Figure 5, but not so at point C.

Night	RST range (°C) at 03:00am	Forecast clouds at 03:00am		Weather type
		Amount	Type	
19-20/03/2003	2.3 to 7.2	7	1	Damped
20-21/03/2003	3.4 to 8.4	6	1	Damped
21-22/03/2003	-0.3 to 6.2	3 to 4	1	Extreme
22-23/03/2003	-1.5 to 4.9	2 to 3	1	Extreme
23-24/03/2003	0.5 to 6.2	5	1	Intermediate
24-25/03/2003	5.2 to 10.2	7	1	Damped
23-24/04/2003	3.5 to 11.8	5	1	Intermediate
24-25/04/2003	5.4 to 10.0	5	1	Intermediate

Table 2. Weather conditions at the nights for AF model verification in Glasgow

Extreme night (23 March 2003)					
Point	**Easting**	**Northing**	**Road**	**Colour band on TM map**	**Temp. range on forecast map**
A	2581	6711	A879	Red	Warm (3.5-3.7°C) and mild (1.3-1.7°C) sections
B	2525	6661	A8	Dark blue	Mostly cold (0.2-0.4°C) sections
C	2585	6637	A728	Dark blue	Cold (0.3°C) section with mild (1.7-1.9°C) sections
Damped night (25 March 2003)					
Point	**Easting**	**Northing**	**Road**	**Colour band on TM map**	**Temp. range on forecast map**
A	2542	6665	A739	Red	Warm (7.8-9.0°C) sections
B	2603	6641	A749	Yellow	Mild (6.5-7.7°C) sections
C	2548	6696	A739	Dark blue	Warm and mild sections

Table 3. Comparison of RST on spots between measured and forecast maps in Glasgow

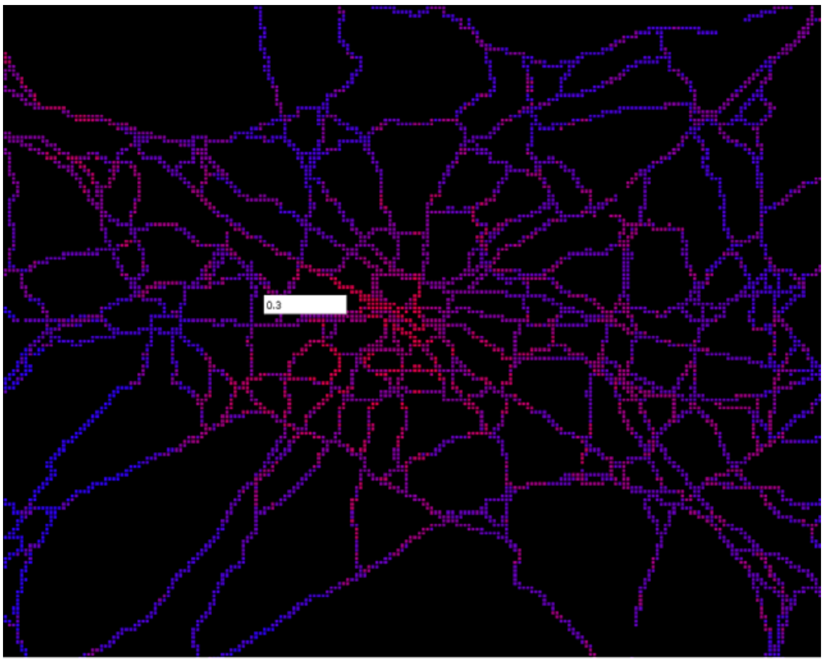

Figure 2. Forecast RST map of Glasgow by AF model at 06:00am, 23 March 2003 (Extreme)

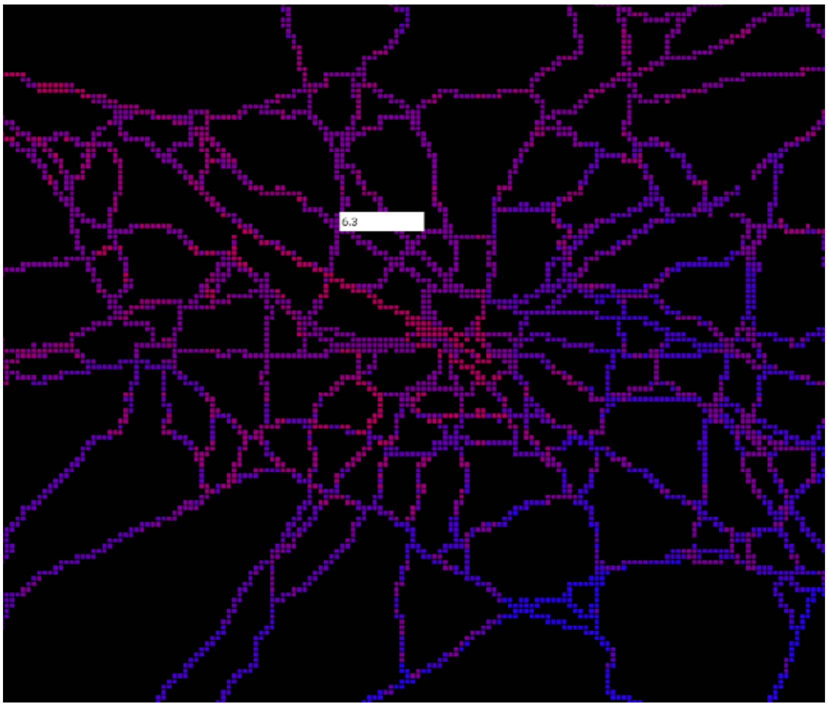

Figure 3. Forecast RST map of Glasgow by AF model at 06:00am, 25 March 2003 (Damped)

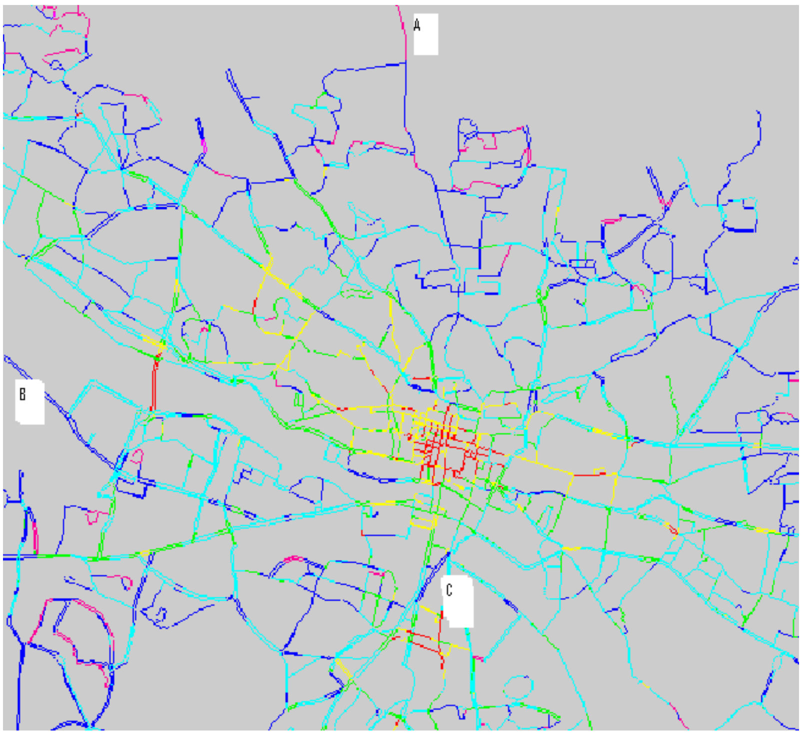

Figure 4. Measured RST distribution at Glasgow by Thermal Mapping (Extreme)

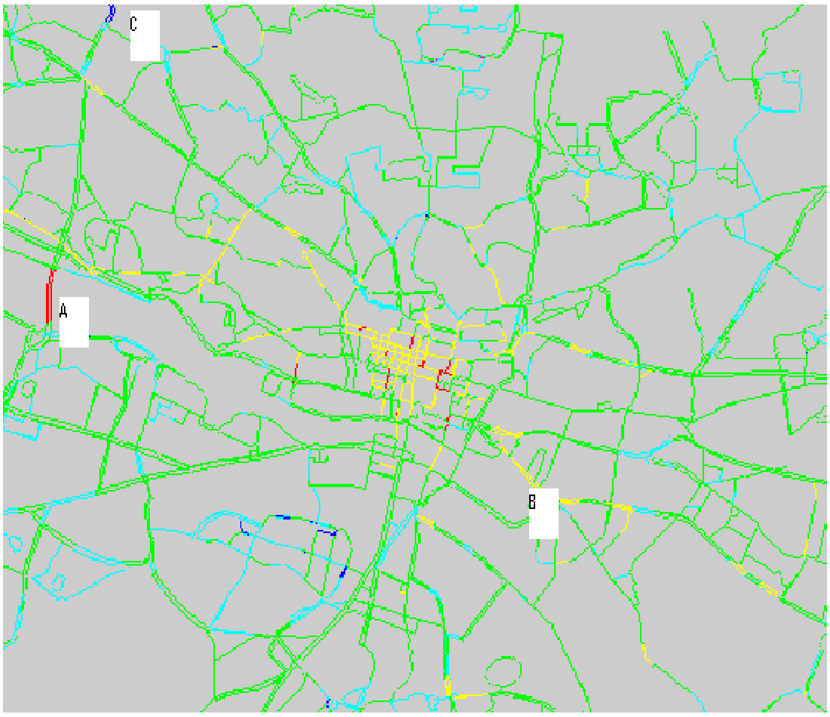

Figure 5. Measured RST distribution at Glasgow by Thermal Mapping (Damped)

5 SUMMERY

By combining the site specific ice prediction model (IceBreak) and the spatial interpolation model based on 2-D inverse distance weighting (IDW) algorithm, we can generate automated nowcasts of road surface temperature, road surface state and road surface friction index based on sensor measurements alone. With external meteorological inputs, the forecasts can be extended to days ahead. Using observation data from multiple roadside weather stations in West Midland and Thermal Mapping survey data in Glasgow, we have shown that good accuracy and consistency have been achieved in not only rural, but also urban environment. Because of lack of friction measurements and time constraint, the verification is limited to surface temperature forecasts.

The benefits of the numerical model discussed in the paper are that

- It provides physically sound and consistent prediction of road surface temperature, as well as surface state and surface friction;
- Unlike statistical models, the Area Forecast model can be instantly deployed to a new area without the need for a learning period.

Because of lack of friction measurements and time constraint, the verification is limited to surface temperature forecasts. Further work on verification of surface state and surface friction forecasts is needed. Additionally, by using DTM data from the Shuttle Radar Topography Mission (SRTM), it would be be feasible to increase the spatial resolution of the AF Model to 30 or 90 metres depending upon the location in the world.

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