A BLUEPRINT FOR 21ST CENTURY ROAD ICE PREDICTION

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ABSTRACT

This paper attempts to summarise the main research gaps evident in the field of road ice prediction. Suggestions are made for improvements to numerical road weather models, mostly by the incorporation of a spatial model component to eliminate the need for thermal mapping. It is proposed that alternative and efficient survey techniques are developed which utilise the full potential of GPS and GIS technology. The paper concludes with an example system and calls for greater collaboration between research organisations worldwide.

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1. INTRODUCTION TO ROAD WEATHER INFORMATION SYSTEMS

RWIS (Road Weather Information Systems) comprise of several linked components used to predict the variation in road surface temperature (RST) around the road network. The accuracy of road weather forecasts obtained from forecast providers is monitored by automatic weather outstations strategically placed on the highway network to collect localised 'point source' information. Outstations measure meteorological variables and road surface condition. Data transfer then takes place from sensors to a master station computer where the data are combined with regional weather information in numerical road weather prediction models. Numerous models have been developed around the world for this purpose and use either a zero-dimensional energy balance, a one-dimensional heat conduction model or a neural network approach. However, all have the same aim of producing an RST and road condition forecast from a forecast of meteorological parameters (Thornes, 1991). In the UK, this is issued at midday as a RST forecast curve. Forecast curves are then constantly updated throughout the day by forcing the model with observed meteorological data from outstations.

As forecast curves are only representative of the sensor site from which the meteorological data are acquired, the RWIS requires a means of projecting this forecast around the road network. This is often achieved by thermal mapping which surveys the spatial variations of nocturnal RST across a road network (Thornes, 1991). Surveys are conducted by RST with a vehicle mounted infra-red thermometer connected to a datalogger. Data are then displayed as thermal fingerprints showing temperature variation along a survey route on a given night. The amplitude of the thermal fingerprint displays the departure of RST from an averaged value against distance for a particular route on a particular night. Variations in RST are more defined in clear and calm stable conditions and hence standard deviation is then use to classify the fingerprints with respect to atmospheric stability (Shao *et al*, 1996).

2. LIMITATIONS OF THERMAL MAPPING

As a surveying technique, the integrity of thermal mapping is reduced by many random and systematic errors (Thornes, 1991; Gustavsson, 1999). Improvements have been made by the recent inclusion of GPS (Global Positioning Systems) to geo-locate datapoints. This has improved accuracy by removing much of the systematic error and has also facilitated the plotting of thermal data into GIS (Geographical Information Systems): a far more efficient and objective method of producing thermal maps than that by hand. However, combination of random errors such as thermometer specification accuracy and variable emissivity means that each measurement of RST is potentially only correct to within ±2.5°C. Also, from a commercial viewpoint, thermal mapping remains an expensive operation requiring five different nocturnal surveys to ensure satisfactory coverage of a range of atmospheric stability. Also, thermal maps provide just a snapshot of minimum temperatures for a few deterministic stability classes. Winter maintenance in the 21st century requires a more dynamic approach for the prediction of RST with respect to the exact time a location will dip below the 0°C threshold and at a range of atmospheric stability.

Since the 1970s work has been ongoing to develop empirical local climatological models for thermal projections between outstations in Sweden (Gustavsson & Bogren; 1993). These models are now used commercially and demonstrate that variations in RST can be accurately explained by the influence of geographical factors (e.g. Bogren & Gustavsson, 1991; Chapman *et al*, 2001a) and prevailing synoptic conditions (e.g. Bogren *et al*, 2000). Such studies have shown that sky-view factors, screening and topography control RST differences at high atmospheric stability where as altitude becomes increasingly important as stability decreases. Despite these results, thermal mapping remains the standard methodology used for interpolation between sites and is still required to validate modelling studies. Overall, the current format of RWIS has remained largely untouched for almost a decade and hence the next generation of models are long overdue.

3. NUMERICAL MODELLING OF RST WITH GEOGRAPHICAL PARAMETERS

Chapman *et al* (2001b) take the empirical research a stage further by developing a spatial component to the Thornes (1984) numerical road weather prediction model. Using the zero-dimensional energy balance approach, the model simulates the energy transfer regime of a selected site by finding the unique equilibrium temperature which balances the flow of energy across a surface:

$$(1-a)(Q+q) + sT_{sky}^{4} - sT_{0}^{4} - R_{N} = LE + H + S \tag{1}$$

where is surface albedo, Q is direct beam solar radiation, q is diffuse radiation, is the Boltzmann constant, T_{sky} is the radiation temperature of the sky hemisphere, y_s is the sky-view factor, T_0 is surface temperature, R_N is net radiation, LE is latent heat flux, H is sensible heat flux and S is heat flux to soil. The model is run on a do-loop to produce a forecast curve for each site forced by the geographical parameters in Table 1 measured by mobile (Chapman *et al*, 2001a).

A study route covering two transects from Birmingham city centre to rural Worcestershire, UK was thermally surveyed 20 times over the 1999-2000 winter to provide validation data to test the performance of the outlined numerical model. Analyses were conducted at a range of atmospheric stability using retrospective meteorological data. The results are shown in Figure 1 and are expressed in r (the linear correlation coefficient between predicted and observed RST), bias (the nature of the error) standard deviation of bias and root mean square error (RMS).

Table 1 *Inclusion of geographical parameters into the numerical model*

Parameter	Survey Technique	Model Incorporation
Latitude	GPS	Used in radiation geometry to calculate Q and q in equation (1)
Altitude	GPS	Used to quantify air temperature variations with respect to the environmental lapse rate
Topography	GPS	Cold air pooling index applied in valleys located by differentiating altitude data (Chapman *et al*, 2001a)
Sky-view factor	Frame-grabbed digital imagery	Calculated by methodology in Chapman *et al* (2001c) and used in (1).
Screening	Frame-grabbed digital imagery	Calculated by methodology in Chapman *et al* (2001c). $Q = 0$ if location is in shade
Landuse	Inferred by surveyor	Used to parameterise roughness length
Road construction	Inferred by surveyor	Used to parameterise sub-surface temperature
Traffic	Inferred by surveyor	Used to parameterise anthropogenic heat

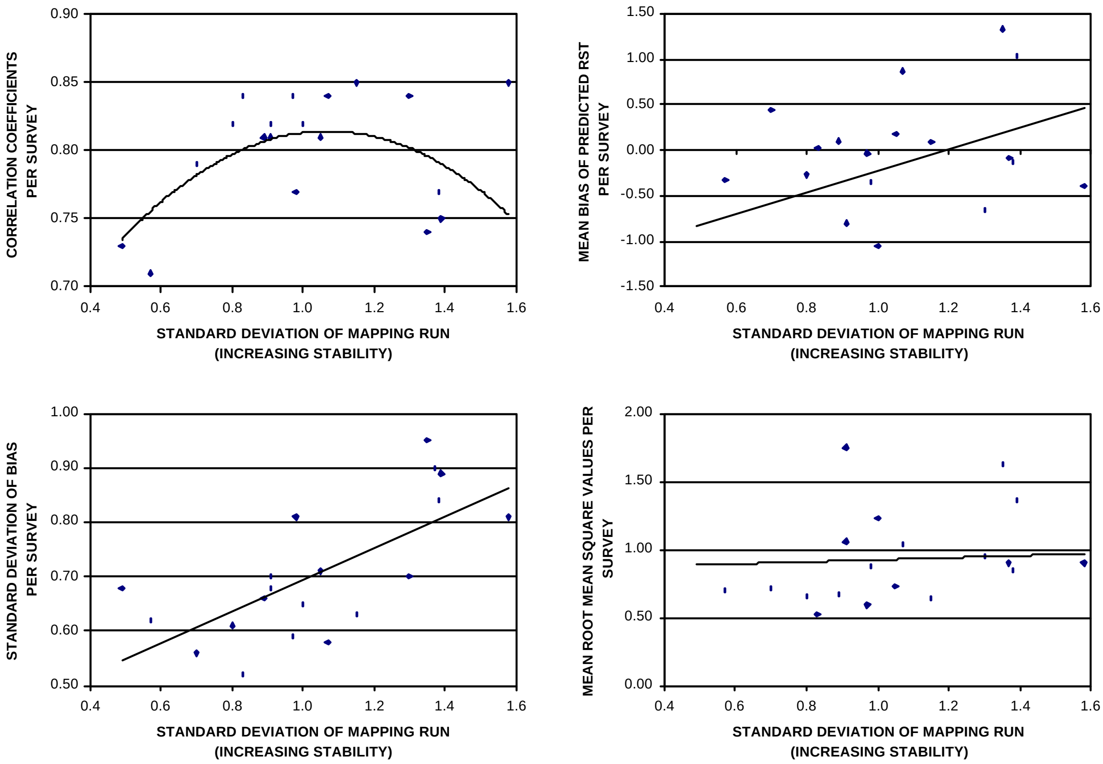

Figure 1 *Model performance quantified in correlation coefficients, bias, standard deviation of bias and RMS at different levels of atmospheric stability.*

The performance of the model in predicting trends in RST around the route is considered to be good and r = 0.69 to 0.85. Average bias around the route is just -0.19ºC, standard deviation of bias is 0.70ºC and RMS is 1.00ºC. These results are comparable with the performance achieved by other UK road weather models in a study by Thornes & Shao (1991), which was based around model performance at the forecast site (Table 2). Hence, the acquisition of similar results with a numerical model which projects RST *away* from an outstation is very encouraging although care must be taken as the models are not compared using the same data.

Table 2 *Summary statistics of road weather model performance (Thornes & Shao, 1991) including data for the model described.*

	Chapman *et al* (2001b)	ICEBREAK	Thornes	Met.Office
No of hours	N/A	2164	2164	2164
Bias	-0.19	-0.29	-0.61	-1.14
Standard deviation	0.70	0.96	1.28	1.05
RMS	1.00	1.00	1.42	1.54

Overall, the predictive ability of the model is greatest at intermediate levels of atmospheric stability. A fall in model accuracy at high levels of atmospheric stability is considered to be due to the oversimplification of topography as an index. Decreases in model accuracy during unstable conditions could be a result of problems of parameterising traffic density, road construction and lapse rates which become more influential when radiative processes are not dominant. The magnitude of the calculated values for bias, RMS and standard deviation of bias each increase in line with atmospheric stability (Figure 1). This indicates that although the model is less accurate at low levels of stability, the predictions are more precise. The greater potential variation in RST at higher levels of stability provides more margin for error and accounts for the increase in values according to the standard deviation of surveys. Indeed, minor forecast errors will significantly effect the precision of the model. For example, if a forecast is too warm (e.g. skies clear later than expected) or too cold then this reflects in the bias and RMS values.

4. THE BLUEPRINT

The study by Chapman *et al* (2001b) has laid the foundations for future research and development with respect to ice prediction. Forecast minimum temperatures from thermal maps and deterministic stability classes have been abandoned in favour of dynamic forecasting in GIS. This paper continues by presenting ideas for future research in 21st century road ice prediction.

Digital Terrain Models: Topography and altitude are major controls on rural RST (Bogren & Gustavsson, 1991). Although accurate altitude datasets can be collected using GPS systems, the accuracy of topographical indices derived from such data are limited (Chapman *et al*, 2001a). It is anticipated that improved data can be generated from digital terrain models (DTM). The cost of DTMs has fallen recently to the extent that high resolution models are available for free to the academic community and will instantly provide an accurate altitude dataset. A major advantage of using DTMs is that algorithms can be developed to enable dynamic modelling of the influence of topography such as katabatic drainage. For example, Laughlin & Kalma (1990) use a DTM to produce an index of frost risk. Although, yielding a static value of temperature reduction, additional numerical modelling (e.g. Kondo & Okusa, 1990) could be implemented to enable a dynamic solution. DTMs have the added advantage of providing the boundary conditions for:

Mesoscale Modelling: The zero-dimensional energy balance approach of the model is limiting as there is no simulation of advective processes. This problem can be improved by using a mesoscale forecast model. For example, the UK Met.Office use a high resolution version of a unified model modified for site specific RST forecasts. Trials are underway around the world and show a considerable improvement in forecast accuracy (Maisey *et al*, 2000). Improved forecast accuracy is critical to the success of RWIS. Wind-speed and in particular, cloud are notoriously hard to forecast being variable both spatially and temporally. Mesoscale models improve this situation as the parameters are not being forecast for a single outstation.

Satellite Landuse Classifications: The use of satellite imagery can provide a useful source of landuse data to provide parameterisations for models with respect to roughness length, albedo and traffic densities (e.g. Bradley *et al*, 2001a).

Road Classifications: Vector map products for use in GIS are now commercially available such as the UK Ordnance Survey Meridian data product. By providing a national vector dataset at a street level resolution, vector data represent an instant objective solution to roadtype classification. Further research is then required to improve road construction parameterisations.

Sky-view factors and screening: The sky-view factor is consistently shown in studies to be the dominant control on RST. Any accurate model will include sky-view data, but the actual acquisition of data is difficult as imagery can only be taken in a limited 'surveying window' of homogeneous cloudy conditions. This problem can be eliminated by surveying during the night (possibly simultaneously with thermal mapping) by using near infra-red fish-eye imagery. Temperatures of elements within the hemisphere could be sensed and it is anticipated that the large thermal differences between warm buildings and the cold sky hemisphere will allow for easy processing. Techniques need to also be developed to measure sky-view factors in real time. For this to achieved, measurement techniques by proxy may offer a viable alternative (e.g. Postgård & Nunez, 2001; Bradley *et al,* 2001b).

Figure 2 shows the synergy of how the individual components discussed in this paper link up in a GIS to provide a mesoscale ice prediction system providing up to the minute information over the internet to winter maintenance engineers.

5 CONCLUSIONS

This paper has highlighted the increased role of GPS and GIS technologies in winter road maintenance. The ice prediction system outlined in Figure 2 is currently just a vision, but many individual components already exist. With increased collaboration between weather companies and research organisations, ideas can be developed together to provide a new solution which:

1. Provides dynamic RST forecasts for any time at any location and at any atmospheric stability.
2. Reduces the original five thermal mapping surveys into a single survey to collect y_s data, either by camera or by proxy. Surveys are envisaged to be combined with thermal mapping technology, as despite its limitations thermal mapping remains a useful validation tool.
3. Has the potential to link to gritters fitted with GPS enabling the tracking of vehicles and accurate selective salting with respect to location and rate; all monitored in a GIS.

By comparison, the current road weather information system outlined in the introduction of this paper is looking very dated. It is time for a change.

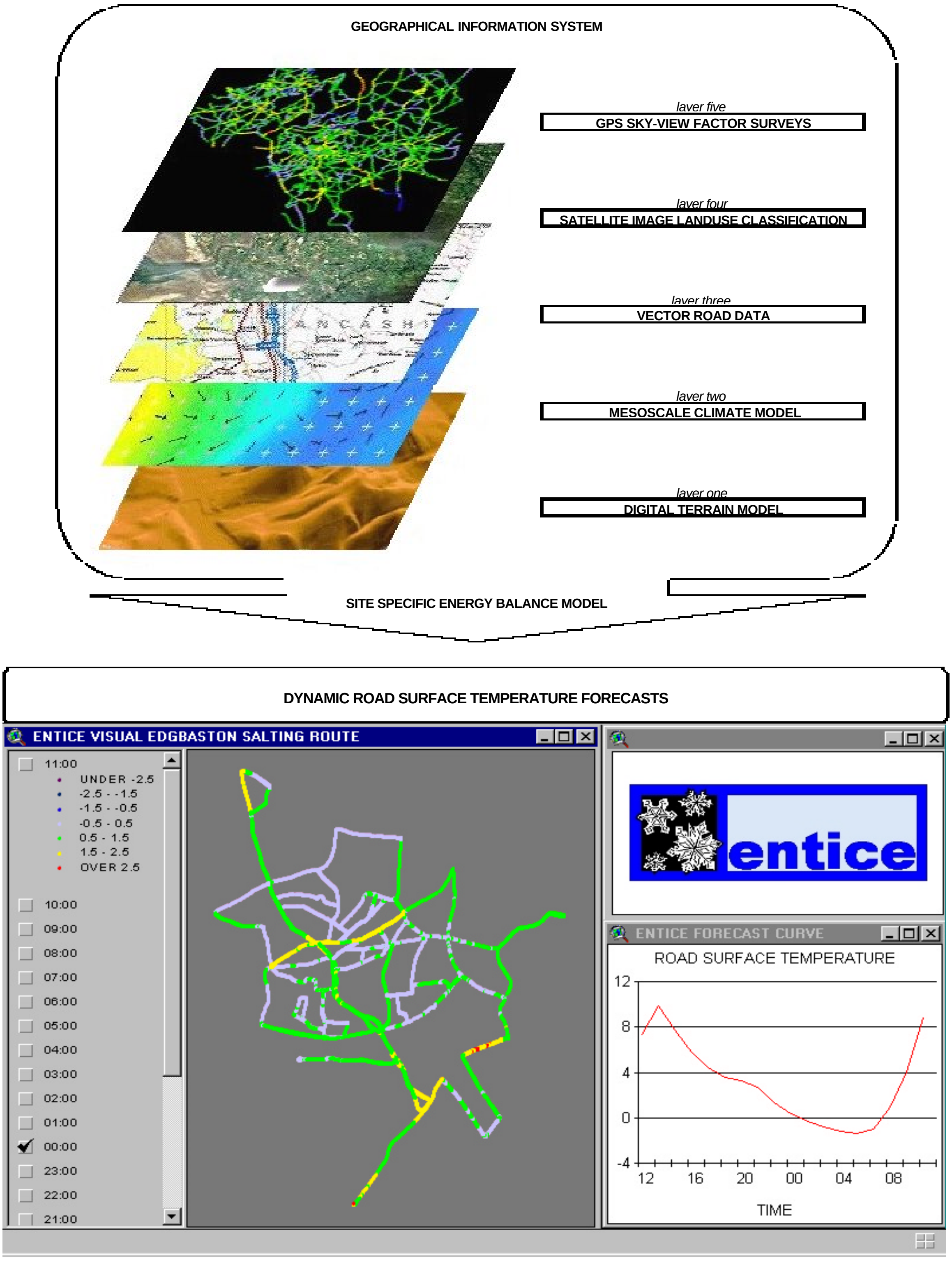

***Figure 2** A blueprint for 21st century road ice prediction.*

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