NEXT STEPS IN FORECASTING ROAD SURFACE TEMPERATURE AND DEVELOPING MDSS

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Abstract

Snow and ice make the transportability difficult and represent a major challenge for the winter maintenance service. Optimizing winter maintenance service and safety thus requires accurate short-term forecasts of the meteorological state of the roads.

The most common approach to forecasting road conditions is energy-balance model based on one-dimensional diffusion equation. Physical models can predict the road surface temperature, which is the most important parameter for determining road surface state (i.e. dry, wet, ice, snow). However, such models can show a large degree of error at sites at which the environmental conditions are too complicated to be simulated correctly. To solve this problem, physical models are often combined with statistical approaches.

We are testing statistical method for forecasting road surface temperature based on stepwise linear regression analysis with appropriate selection of the input parameters, and with multiple models for different parts of the day. The method was tested on data from several Slovenian road weather stations and showed very promising results.

Road weather forecast is the critical point and the heart of the decision support system, which provides recommendations on road maintenance routes and actions. MDSS tailored to the Slovenian roads is under developing.

Keywords

road surface temperature (RST), stepwise linear regression, prediction models, road weather information system (RWIS), winter maintenance decision support system (MDSS), intelligent transportation system (ITS)

INTRODUCTION

During the period from late autumn to early spring, vast areas in Europe, North America and many other countries experience frequent snow, sleet, ice, and frost. Such conditions make the transportability difficult and present several challenges for the winter maintenance service. Among these challenges is the need to make effective winter maintenance decisions (treatment locations, timing, types and rates) which have a considerable impact on the roadway efficiency and the possible risk of accidents [1].

Currently, among snow ploughing, two main strategies are used for winter road maintenance: de-icing, in which chemicals are used to melt ice and snow, and anti-icing, a preventive measure that reduces ice by hindering bonds between ice crystals and the road surface. About four to ten times more salt is needed for de-icing, than for preventing roads from freezing by anti-icing [6].

An accurate prediction of road weather conditions is important for providing safer roads for the users [1, 10, 11], reducing the environmental damage from over salting [5] and for cutting the winter road maintenance costs; for example, it is estimated that the total budget for winter road maintenance in the United Kingdom is more than 140 million pounds every year, with salt corrosion causing a further 100 million of damage each year to vehicles and structures [7].

In the last decades, numerous models for predicting meteorological conditions on the road were introduced and accepted by winter maintenance personnel as an appropriate and valuable technique for effective winter road maintenance decisions. These prediction models are part of advanced systems, known as the road weather information systems (RWIS) and maintenance decision support systems (MDSS). There are many reports about savings because of the use of such systems. In State of Wisconsin in U.S. they report savings of 75,500 UDS and reduce salt usage by 2500 tons during a single winter storm [11]. In the State of Indiana in the U.S. implementation of the MDSS in the winter 2008/2009 cause savings about 11 million USD, 188 thousand tons of salt (36% saving) and 42 thousand job hours (20% savings) compared to the previous season [2].

EXISTING METHODS

Road surface temperature (RST) is influenced by numerous interacting parameters, which can produce a range of temperature variations of up to 10°C across the road section [6, 15], figure 1. Each road network is subject to a regional climate in addition to a large number of microclimates created as a direct consequence of the parameters represented in table 1. Their influence on road is studied in detail in literature [9, 14 et al.].

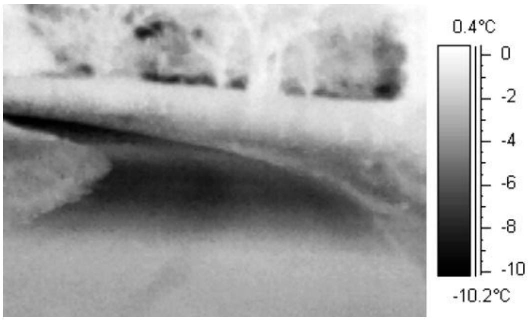

Figure 1: Thermal image of road showing a great variation of RST in relation to the shading from trees [15].

Meteorological	Geographical	Road
air temperature	latitude / longitude	thermal property of the road materials
radiation fluxes	altitude	depths of the road mat.
cloud cover and type	topography	emissivity
wind speed	shadowing	albedo
humidity / dew-point	land use	traffic
precipitation		

Table 1: Parameters with influence on RST (adapted from [8, 14]).

Classical meteorological weather forecasts are inadequate for this purpose, since they are based on data from weather stations, which can be far from the road system and do not reflect the weather conditions on the road. For obtaining good forecasts it is important to include historical data of the measurements of the road weather stations and the short-term weather forecasts of good temporal and spatial resolution.

The most common approach to forecasting road conditions is physical energy-balance model and since the 1980s, several such models with reasonably high accuracy have been developed for this purpose [i.e. 3, 4, 6, 12, 13]. Physical models can predict the RST based on one-dimensional diffusion equation:

$$\frac{\partial q}{\partial t} = -K\frac{\partial^2 q}{\partial x^2},$$

where q is heat flux in the road, t time, x depth and K heat capacity of the road.

These models take weather forecasts and measurements of the road weather stations as inputs, and predict RST using the energy-balance equation, which describes the fluxes of energy between the atmosphere and the road surface.

The initial temperature profile is interpolated with the measurements of the road weather stations at the surface and different depth levels. The lower boundary condition is treated as a constant temperature at some depth. The upper boundary condition is expressed by an energy balance equation. The prediction of road surface state, such as dry, wet, frost, or ice, is determined by whether there is a critical amount of moisture or water remaining on the surface and whether surface temperature is above or below 0°C.

Such models still show a large degree of error at sites at which the environmental conditions are too complicated to be simulated correctly. To solve this problem, physical models can be improved with further parameterisations of some important phenomena [19] or combined with statistical approaches [11, 17]. In [11] they use a three-layer neural network which is generally able to improve the accuracy of physical model forecasts of road surface temperature by learning from the historical data, especially at the problematic sites.

DATA

On Slovenia roads, there are near 90 road weather stations (RWS), situated mostly on motorways and regional roads (figure 2). All of them are equipped with embedded or remote road sensors and meteorological sensors. Most common measurements on RWS are: road temperature (on surface and in different depth; figure 3), thickness of water film, salt concentration, freezing point temperature, road condition, air temperature and humidity, dew point, air pressure, amount and type of precipitation, visibility, wind speed and direction.

Figure 2: Road weather station *Mislinja*.

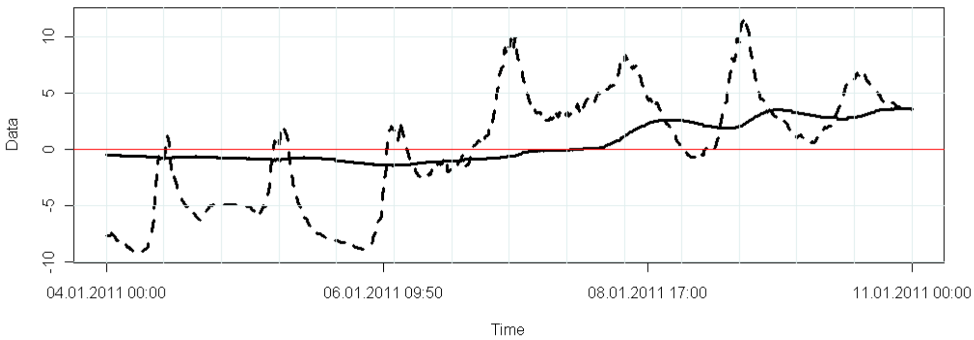

Figure 3: Road surface (dashed line) and subsurface (solid line) temperature measurements on RWS *Mislinja* from 4 to 11 January 2011.

Another important data source are weather forecasts obtained from INCA (Integrated Nowcasting through Comprehensive Analysis) system, which has been developed primarily as a means of providing improved numerical forecast products in the nowcasting and very short time range (up to 12 hours) and good spatial resolution

(1 km) [18]. INCA analysis and nowcasting fields include temperature, humidity, wind, precipitation amount, precipitation type. Radiation fluxes, pressure and cloudiness data were obtained from ALADIN numerical weather prediction model with smaller spatial resolution (9.5 km).

METHODS

We propose entirely statistical method for forecasting road surface temperature based on stepwise linear regression analysis. The classical linear regression model can be written mathematically in matrix notation as:

$$\boldsymbol{y} = \boldsymbol{X\beta} + \boldsymbol{\epsilon},$$

where $\boldsymbol{y}$ is $n \times 1$ vector of response variable, $\boldsymbol{X}$ is an $n \times p$ matrix of observable variables, $\boldsymbol{\beta}$ is a $p \times 1$ vector of parameters (estimated from data), $\boldsymbol{\epsilon}$ is an $n \times 1$ random error vector (for which we suppose to have independent normal distributions with mean 0 and standard deviation σ), p is the number of parameters and n number of data examples. For this equation, the least squares estimate is the $\widehat{\boldsymbol{\beta}}$ that minimizes the sum of squared errors, $\sum_{i=1}^{n}(y_i - X_i\widehat{\boldsymbol{\beta}})^2$, for the given data $\boldsymbol{X}, \boldsymbol{y}$:

$$\widehat{\boldsymbol{\beta}} = (\boldsymbol{X}'\boldsymbol{X})^{-\mathbf{1}}\boldsymbol{X}'\boldsymbol{y} \ ,$$

where $'$ means matrix transposition operation. Stepwise regression includes regression models in which the choice of parameters is carried out by Akaike information criterion:

$$AIC = vk - 2log(L) ,$$

where v represents the number of variables in the fitted model, weight $k = 2$, L is the likelihood and $-2\log(L)$ is computed from the deviance. The goal is to find a value of v that minimize AIC.

For each hour of the day we calculate regression model M_i and determine parameters by AIC on train set. To reduce the number of models and to increase robustness we propose an algorithm for merging.

e_i is RMS error calculated for each M_i on training set.

Er_i is real error calculated on merged data sets of two neighbours models M_i and M_{i+1}.

Et_i is theoretical error calculated as a weighted errors of two neighbour's error:

$$Et_i = \frac{e_i \cdot |S_i| + e_{i+1} \cdot |S_{i+1}|}{|S_i| + |S_{i+1}|},$$

where $|S_i|$ is the number of elements of the training set S_i for the model M_i.

All errors are calculated with cross validation approach. In each step, neighbour models with $min(Er_i - Et_i)$ are merged, determined new parameters by AIC, and calculated new RMS error. In the beginning $i = 1, \dots, 24$ and decreases with every step. Situation right before the RMS error rise up drastically is chosen as final models set at the end.

RESULTS

Input parameters were hourly measurements from selected Slovenian RWSs: *Jeprca, Mislinja, Črmošnjice*. Meteorological data was obtained from INCA/ALADIN weather forecasts on the locations of the RWSs. Time frame of the train set was from 1st December 2009 to 1st April 2010 and for test set from 1st October 2010 to 1st February 2011. All input parameters were standardized by subtracting the mean and dividing by 2 standard deviations. Main goal was to predict RST for 6 hours in advance. Models were built as described in METHODS section and used on test set. Results are presented in tables 2, 3 and figure 4.

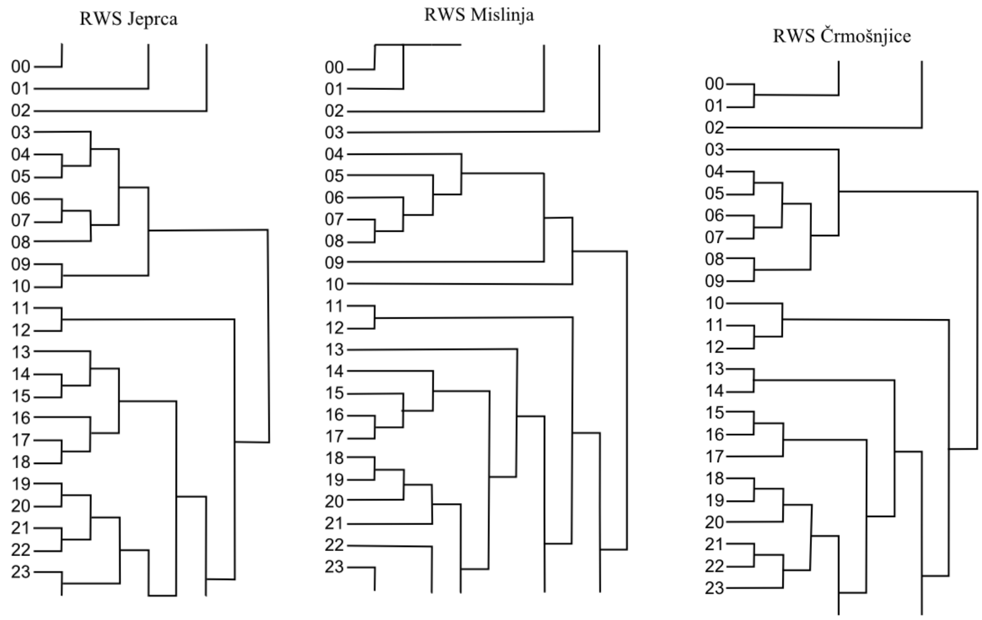

Figure 4: Merging schemes of the hourly models on every RWS.

For RWS *Jeprca* four models are obtained. Only model for hours from 03 to 08 has significant percent of the prediction error larger than 4°C (15%) which can be considered as unacceptable. There is model (from 13 to 02) with large time frame for late afternoon and night predictions with very high accuracy.

Similar situation is on RWS *Črmošnjice*. Model for hours from 04 to 09 has significant percent of the prediction error larger than 4°C (15%). There is model just for one hour (03), since its merging with others cause poor results. Other models show very high prediction accuracy.

On RWS *Mislinja* we have two models just for one hour (03 and 10) with different set of input parameters. We can understand them as mediate models between two large models (from 04 to 09 and from 11 to 02).

Table 3 shows that some input parameters are important in almost every model: air temperature, RST, road subsurface temperature, precipitation, shortwave radiation.

RWS		*Jeprca*				*Mislinja*				*Črmošnjice*			
Models time frame	**From** **To**	03 08	09 10	11 12	13 02	03 03	04 09	10 10	11 02	03 03	04 09	10 12	13 02
RWS measure-ments	air temperature	x		x	x	x	x		x	x	x		x
	RST	x	x	x	x		x	x	x			x	x
	road subsurface temp.	x		x	x	x	x	x	x	x	x	x	x
	air humidity	x	x	x	x			x					x
	thickness of water film				x					x	x	x	x
INCA/ ALADIN forecasts for 6 hours	air temperature	x	x	x	x	x	x	x	x	x	x	x	x
	air temp. (for 3 hours)	x		x	x	x			x		x	x	x
	air humidity	x	x					x	x			x	x
	wind speed	x	x		x					x	x		x
	precipitation amount	x	x	x	x		x				x	x	x
	longwave radiation	x			x		x	x					x
	shortwave radiation	x	x	x		x	x	x		x	x	x	x
	cloudiness	x			x	x				x	x	x	

Table 2: Selected input parameters for individual merging models.

RWS	Models time frame (UTC hours of the beginning of the prediction)	RMS error on test set	Percent of the predictions on test set with error larger than 2°C	Percent of the predictions on test set with error larger than 4°C
Jeprca	from 03 to 08	2.86	43 %	15 %
	from 09 to 10	1.63	22 %	2 %
	from 11 to 12	1.41	16 %	0 %
	from 13 to 02	1.55	20 %	0 %
Mislinja	03	1.99	30 %	5 %
	from 04 to 09	3.21	48 %	21 %
	10	1.70	24 %	1 %
	from 11 to 02	1.33	13 %	0 %
Črmošnjice	03	1.30	13 %	0 %
	from 04 to 09	2.73	41 %	15 %
	from 10 to 12	1.49	17 %	1 %
	from 13 to 02	1.30	12 %	0 %

Table 3: Results for 6 hours RST predictions on selected RWSs.

CONCLUSIONS

The method was tested on data from several Slovenian road weather stations and showed very promising results. Nevertheless, there are still large errors for predictions around noon and further research should focus on reducing this RMS error. Proposed method is presented as an independent approach but can also be combined with any physical models.

The heart of the decision support system which provides recommendations on road maintenance routes and actions is accurate and reliable road forecast which should be adjust to geographic area in question. Therefore developing of MDSS tailored to the Slovenian roads shows the applicability and naturally suggests next steps for future research.

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