Road structural elements temperature trends diagnostics using sensory system of own design

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Abstract. A considerable funds is spent for the roads maintenance in large areas during the winter. The road maintenance is significantly affected by the temperature change of the road structure. In remote locations may occur a situation, when it is not clear whether the sanding is actually needed because the lack of information on road conditions. In these cases, the actual road conditions are investigated by a personal inspection or by sending out a gritting vehicle. Here, however, is a risk of unnecessary trip the sanding vehicle. This situation is economically and environmentally unfavorable. The proposed system solves the problem of measuring the temperature profile of the road and the utilization of the predictive model to determine the future development trend of temperature. The system was technically designed as a set of sensors to monitor environmental values such as the temperature of the road, ambient temperature, relative air humidity, solar radiation and atmospheric pressure at the measuring point. An important part of the proposal is prediction model which based on the inputs from sensors and historical measurements can, with some probability, predict temperature trends at the measuring point. The proposed system addresses the economic and environmental aspects of winter road maintenance.

1. Introduction
During winter, many roads located in cold or temperate regions are influenced by severe climatic conditions associated with snow and ice. These conditions have serious consequences on driving conditions, reducing the traffic flow dramatically, because the failure in maintaining roads in winter often leads to road closures. Ice and snow also increase the risk of accidents [1]. In this context, forecasting of road surface and traffic conditions is an important aspect of traffic safety and winter road maintenance. The weather conditions can change quickly, for example, with the onset of snowfall or during rapid temperature variations. A prior knowledge of road weather is important from a public road safety standpoint. Proper consideration of upcoming weather events also helps the road maintenance authorities to attend the roads in an effective and economical manner [2].

Several strategies can be used for winter road maintenance. Among these, the most common are 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 road pavement or spreading sand to help provide traction [3,4]. The most commonly used de-icing chemical is salt (sodium chloride, NaCl), which usually comes from mined rock salt. It is one of the most cost effective, readily available and efficient chemicals for the prevention and removal of ice and snow and is supplied in a variety of
granule size and is sometimes applied in solution. Traditionally this has been spread in dry form; known as dry salt. Another two variants are used; with the addition of some moisture either at manufacture at point of spread resulting in the pre-wetting technique, and the preparation of a brine (salt solution) that is spread as a liquid. The impact of using chemicals for winter road maintenance is a major environmental concern [4]. Studies [5,6] show that soils, vegetation, water, highway structures and vehicles are all affected, and so it is crucial that the de-icing chemicals are used wisely. The growing awareness of the environmental impacts of salt has led efforts to find ways to reduce the amounts entering the environment. There are really only two ways to achieve this. Using something other than salt or optimizing salt usage by applying it strategically [4]. Hence, there is a continual need for improvement in winter road maintenance strategy. One key component of optimized road maintenance decisions is to obtain and use accurate weather information. Weather information can be divided into two temporal categories: observations, which reflect current conditions; and forecasts, which predict future conditions [7]. The largest potential savings to be made in winter maintenance focus upon the prediction of ice formation and snow, and countries prone to icy roads can make significant annual savings [8] by optimizing weather forecasts with salt usage and other operational costs [4].

Thus, it stands to reason, it is necessary to have relevant data about the weather and road surface conditions. They can be obtained from various sources. The most important source of real time meteorological and pavement data are road weather stations (RWS) ensuring automatic data collection and transmission. Currently a wide range technologies of road weather stations are commercially available (e.g. Viasala, Lufft, CrossMet etc.) They are an essential tool for remote monitoring of weather conditions on the roads. The RWS are equipped with variable set of sensors for measuring of meteorological date. They are also equipped with road sensors connected to the station for measuring of road conditions [9]. Road surface conditions are influenced by numerous meteorological, geographical and road parameters, which can produce vast temperature variations across the road section. The most important factors are: air temperature, radiation fluxes, humidity, precipitation amount, wind, topography, properties of the road materials and traffic [10,11]. Their influence on the road is presented in detail in literature [4,12,13].

These RWS are a part of advanced systems known as the road weather information systems (RWIS) and maintenance decision support systems (MDSS). RWIS is a software tool which collects all relevant available data which can be used by dispatchers to support decision making in winter road maintenance management. The RWIS integrates current data from road weather stations, meteorological radars and satellites, cameras, mobile road weather stations, the National Weather Service (NWS) and others. The RWS ensure recording of current conditions in selected locations, but the RWIS can include forecasting module, which will allow for each RWS to generate a point forecast of important parameters in response to the measured data and general weather forecast. General weather forecasts are generally supplied by the NWS, alternatively by a commercial provider. In addition, there are specialized computational models for specialized forecast for road surface. The specialized road weather forecast model is a part of dispatcher maintenance decision support system (MDSS). MDSS as a part of RWIS is focused on special linear weather and road surface status forecast and recommendations on winter maintenance [9]. More information about RWIS and MDSS are presented in [4,9,15]. Various models for predicting meteorological conditions on the road have been developed (e.g METRo [14], RoadSurf [2], SSW model [15] etc.). Based on forecast road condition information obtained be these models, the highway engineer can determine the window of application for anti- and de-icing chemicals to be applied and for snow removal operations to commence. By strategically timing operations the safety of highways can be maintained whilst going some way to optimising the quantity of material applied to the road surface [4].

In this paper is presented the design and implementation of an experimental system in which the desired value of the environment such as temperature of the road are obtained by the direct method, i.e. sensors are placed directly into the road surface. In view of this data acquisition method, the model
is suitable for use in a local areas. The data are more accurate than measuring the air temperature using the weather station located near the road.

2. Experimental installation
For the verification of model described in the next section experimental installation of temperature sensors buried in the road surface was created. The sensors are divided into two groups: horizontal layer located in the road surface, and the vertical layer, where sensors are arranged in the vertical direction with a pitch of 20 cm, to the depth of 1 meter. Figure 1 illustrates the location of temperature sensors in the experimental installation. Temperature sensors were made in a special enclosure which protects them against mechanical damage during installation and subsequent use.

![Figure 1. Design of sensors placement.](image)

2.1. Technical realisation
For experimental installation following restrictions of the measurement system were defined:
- Robust mechanical enclosures of the temperature sensors to withstand the high temperature of asphalt installation and mechanical stress during the operation of the road, in which the sensors are located.
- Minimizing cabling. Since the system contains more than 10 temperature sensors, it is required to minimize the cabling.
- The temperature measuring range from -50°C to 120°C.
- Simple interface through which it is possible to view and evaluate the measurement results.

The requirement of robust mechanical design was met in the sensor enclosure (Figure 2) made of Ertalon PA66, having the following essential characteristics: melting point 255°C, thermal conductivity 0.28 W/(K.m), the short term operating temperature 200°C and long term operating temperature 80°C.

Requirement of minimizing the cabling was met using the 1-wire bus system, which needs only 2 wires to provide both power and communication with sensors. The selection of the bus is also related to the selection of sensors that are compatible with the selected 1-wire standard. As a suitable candidate which meets the requirement for the range of measured temperatures is the digital thermometer DS18B20.

For the needs of autonomous data collection has been designed and implemented system for autonomous data acquisition. The system consists of server and application parts. The server part includes an operating system service providing repeated measurements at defined time intervals, a relational database for storing measured data and interface for communication with higher-level applications. The hardware requirements for the implementation of the server are set to ensure the functionality even when using minimum hardware configuration.
3. Evaluation of the soil vertical temperature profile measurements

The object of this section is a description of the road sub-base vertical temperature profile measurement and evaluation of the measured data. The described methods can serve for the creation of predictive models to determine the surface temperature, based on the prior development of temperature and for determination of thermal parameters of the soil. The experiment was designed to measure the horizontal and vertical temperature profiles of an asphalt road. Horizontal thermometers were placed in a line milled into the road surface and fixed using low temperature asphalt mix, vertical thermometer with five sensors was placed on the side of the road.

Data acquisition was controlled by a CNT controller connected to the Internet network and data with a measurement frequency of 1 per minute were saved in the database. Data access and visualization of measurement data continuously is possible through the web interface. Advanced version of the controller allows the connection of local weather station for monitoring air temperature using radiation thermometers at selected heights, solar radiation and wind speed and direction.

Figure 2. Installation of temperature sensors in asphalt roads.

Figure 3. Measurement layout.
3.1. Data processing and results
Data processing design comes from the typical derivation of Fourier equation of heat conduction.

For heat transfer are valid general equations:

\[(Q_1 - Q_2) = (q_1 - q_2)S\Delta t = -\Delta qS\Delta t\]  \hspace{1cm} (1)
\[(Q_1 - Q_2) = mc(T_1 - T_2) = \rho S\Delta x c \Delta T\]

by comparison we get

\[-\frac{1}{\rho c} \frac{\Delta q}{\Delta x} = \frac{\Delta T}{\Delta t}\]  \hspace{1cm} (2)

by limiting transition for \(\Delta x \to 0\) and \(\Delta t \to 0\) we get:

\[-\frac{1}{\rho c} \frac{dq}{dx} = \frac{dT}{dt}\]  \hspace{1cm} (3)

Using Fourier law for heat conduction can be after its derivation, excluded immeasurable quantity \(q\) from the equation:

\[q = -\lambda \frac{dT}{dx} \to \frac{dq}{dx} = -\lambda \frac{d^2T}{dx^2}\]  \hspace{1cm} (4)

by fitting we get:

\[\frac{dT}{dx} - \frac{\lambda}{\rho c} \frac{d^2T}{dx^2} = 0\]  \hspace{1cm} (5)

Value \(a = \lambda / \rho c\) is the coefficient of thermal conductivity and expresses how "easy" are temperature differences compensated in given substance. Measurement of the vertical soil temperature profile can be considered as one-dimensional case of heat conduction. In this case, it is possible under constant environmental parameters, obtaining a solution of the equation

\[\frac{1}{a} \frac{\partial T}{\partial t} = \frac{d^2T}{dx^2}\]  \hspace{1cm} (6)

In analytic form:

\[T(x, y) = T \ast er f\left[\frac{x}{\sqrt{4at}}\right]\]  \hspace{1cm} (7)

The unknown quantity is the thermal diffusion coefficient \(a\), that characterizes the environment in which is the thermal energy spread. From its definition is clear that it is depending on the material parameters of the environment which may not be constant over time.

To experimentally determine the thermal diffusion coefficient, can be used data from the vertical thermometer. For the evaluation we will develop a formula (6) using central difference formula into
differential form, the indication referred by Figure 5 for linear environment \( a_i = a_{k+1} = a \), index \( k \) is a time period:

\[
T_i^{k+1} = T_i^k + 2(T_{i-1}^k - 2T_i^k + T_{i+1}^k) \frac{a \Delta t}{\Delta x^2}
\]  

(8)

by fitting we get:

\[
T_i^{k+1} = rT_i^k + \left(1 - 2r\right)T_{i-1}^k + rT_{i+1}^k
\]

\[ r = \frac{a \Delta t}{\Delta x^2} \]  

(9)

To verify the functionality of the measurement system, the validity of data and the experimental determination of the coefficient \( a \), we will use a block of the measurement data of Figure 6. T1 correspond to placement Vert.1. in Figure 1 and Figure 3, T2 correspond to Vert.2 etc.

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![Figure 6. Temperatures chart for autumn 26.8.-29.9.2016.](image)

From the data block we use thermometers T1, T2 and T3. By recursive calculation of the equation in Figure 5 with parameter \( a \) we calculate the value \( T_2^* \) and by using least square method we are looking for such a parameter value at which the deviation of calculated from the measured temperature values is minimal. Constant parameter value during the entire monitored period was assumed in the calculation. The result is shown in Figure 7, the detail in Figure 8. For \( \Delta x = 20 \text{ cm} \) was determined as the optimal value of the thermal diffusion coefficient

\[ a = 2.1 \times 10^{-7} [\text{m}^2 \text{s}^{-1}] \], \quad \Delta x = 20 \text{cm}. \]
Similarly was calculated thermal diffusion coefficient for winter season with temperatures course in Figure 9, the coefficient value was

$$a = 3.1 \times 10^{-7} [m^2 s^{-1}], \quad \Delta x = 20 cm.$$

Conclusions

It is clear from the above that from measurements of the vertical temperature profile it is possible to determine the thermal diffusion coefficient, by extension of the described method to further depths. From the detailed Figure 8 is obvious that the assumption of constant coefficient is probably not correct, because after a significant change in temperature, likely accompanied by the rainfall, the coefficient changed (day 24-26). Based on fixed marginal conditions (T1, T2), calculated temperature $T2^*$ was equal to measured temperature T2 with accuracy better than 0.5°C.

A key factor which influences the thermal diffusion coefficient is the water content in the environment. Clearly, heat transfer will be described as non-stationary and non-linear problem. Knowledge of the current coefficient value is fundamental to determine the road surface temperature, since it determines the speed at which the heat from the road surface transfers to the sub-base or vice versa. Following the above, it is likewise possible that, at a suitable calibration of diffusion coefficient
parameters and knowledge of the sub-base (i.e., the structure and composition) could be obtained information by measuring the dynamics of temperature changes on the amount of water and its height profile in the sub-base. Verification of this assumption needs to implement further relevant experiments and verification in real practice.

Knowledge of the thermal diffusion coefficient and its dependence on the depth provides the basis for creation of the predictive model of temperature changes, the structure of the model is shown in Figure 11. The model consists of two Kalman filters. Filter KF1 calculates into current time on the basis of data flow from thermometers and weather stations (solar radiation, air temperature and wind direction and speed) vector of diffusion values. The actual value of the diffusion coefficient and temperature are used at feedforward simulation in the second filter KF2 as initial values and filter based on knowledge of the course of solar radiation and meteorological forecast estimates a vector of temperatures.

The proposed model, due to its potential can be implemented in MDSS systems and as its part can thus leads to improvement of economic and environmental aspects of road winter maintenance.

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