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Multivariate Data Analysis. A new Insight for Thermal Mapping

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ABSTRACT

Thermal mapping has been implemented since the late eighties to determine road ice susceptibility. It consists in measuring road pavement temperature along with some other atmospheric parameters to build a susceptibility indicator to ice occurrence. Measurements are time-consuming. They had to be conducted in some specific climatic conditions during winter. Once these measurements obtained, data is processed to build a risk of ice occurrence, or to use some physical numerical models to build a forecast for pavement surface temperature. The objective of this work was to investigate a statistical approach for thermal mapping. Based on multivariate data analysis, it will forecast surface pavement temperature, and covering a wide panel of weather situations and temperature ranges. Data analysis was done through principal components analysis (PCA). PCA provided a good forecast of pavement surface temperature, covering a range between 5°C and -12°C. A validation was conducted using the large amount of measurements. Investigations indicated that few measurements on the itinerary were necessary to build a proper forecast. Some validations were conducted, and indicated possible junctions and overlaps of data for stretches monitored at different moments.

Keywords: thermal mapping, multivariate data analysis, principal components analysis.

1 INTRODUCTION. CONTEXT AND OBJECTIVES

Thermal mapping has been implemented since the late eighties to determine road ice susceptibility. It consists in measuring road pavement temperature along with some other atmospheric parameters to build a susceptibility indicator to ice occurrence [1-10], or to use some physical numerical models to forecast for pavement surface temperature. Measurements are done using a vehicle embedded into the traffic in given road weather conditions. If the dew point temperature is lower than road surface temperature there is a risk of ice occurrence, and therefore a loss of grip for circulating vehicles.

Road surface temperature is obtained with an infrared radiometer on board of a dedicated vehicle. To avoid too much influence of the sun, and to see an enhanced thermal behaviour of the pavement, thermal mapping is usually done before dawn during wintertime, with a clear sky, without wind. That is when the energy accumulated by the road during daytime is mainly dissipated and before the road structure starts a new thermal cycle. New networks are mainly concerned, or when some major pavement or road surroundings changes are made that might affect the thermal heat balance. This helps road managers to install sensors to monitor road status on specific locations identified as dangerous, or to install specific road signs. Measurements are anyhow time-consuming. A whole road network can hardly be analysed at once, and has to be partitioned in stretches that could be done in the open time window to avoid temperature artefacts due to a rising sun. Furthermore, measurements had to be conducted in some specific climatic conditions that could hardly be met or forecast during winter.

The objective of the work developed by LRPC Nancy, and the DL Clermont-Ferrand was to investigate a statistical approach for thermal mapping. It would be based on multivariate data analysis, to forecast surface

pavement temperature, and to cover a wide panel of weather situations and temperature ranges. To do so, an itinerary was analysed at least once a month, over several months. Air temperature, relative humidity and surface temperature were recorded at a 3-m spatial frequency. Data analysis was done through principal components analysis. This paper will first describe the main differences between conventional models and statistical ones. The thermal mapping procedure, instruments and objectives will be then presented. The input of multivariate data analysis will be introduced, along with the first results and their discussion, either on a global itinerary, or when a focus is made on specific road spots.
The multivariate data analysis provided a good forecast of pavement surface temperature, specifically between 5°C and -12°C. A validation was conducted using the large amount of measurements. Investigations indicated that 5 measurements on the itinerary were enough to build a proper forecast. Some validations indicated possible junctions and overlaps of data for stretches monitored at different moments.

2 NUMERICAL AND STATISTICAL APPROACHES

2.1 Existing numerical models

Road surface temperature forecast is one of the cornerstone of winter maintenance in many western countries. Such a tool hemps road managers in organizing services, in triggering de-icing operations, and in providing useful indication in potential traffic troubles. Over the years, many numerical models dedicated to road surface temperature have been developed, implemented and improved.
Over the past twenty years, many studies have been undertaken on road pavement temperature forecast on physical models [11-19]. All are based on heat transfer in the road infrastructure and on energy balance at the surface. Main differences appear on hydric phenomena and the way water is taken into consideration, or not. Some differences appear on the in input parameters, the forecast range and the performances. There are two groups of forecast models to describe road weather phenomena. The first one consists in a physical description of thermal exchanges such as conduction, convection and radiation. A global overview of existing models is provided in table 1.

model name	***country***	***model type (statistical or physical)***	***data input nature***	***applications***	***reference***
ATMOROUTE	France		weather data	low scale forecast (1000 km^2, with climate homogeneity)	[20]
ARPEGE			weather data	weather forecast at a global scale	
PREVIROUTE			weather data, thermal fingerprint	pavement surface temperature	
GELCRO-ISBA		physical (energy balance)	données météorologiques	pavement surface temperature	[18]
NWP-DWD	Germany	physical - statistical	weather data and database	24 h weather forecast and pavement surface temperature	[21, 22]
Nimrod	England		weather data	forecast on precipitation type	[23, 24]
ICELERT			road weather data (ICELERT)	road status, surface pavement temperature	
RainCast	Switzerland		Swiss weather data and road weather data	weather forecast on a 14 km^2 mesh	[25]
unnamed			Swiss weather data and road weather data	nature of precipitations (1-2 h) (Raincast)	[26]
NEMEFO	Italy	statistical and neural network	weather data	3 h-forecast	[27]
ALWOS	USA		weather data	local weather observation	[28]

unnamed			weather data and satellites ones	discrimination of precipitations	[29]
MDSS		numerical	weather data and road weather data	road status	[30]
unnamed	Iceland		weather data and road weather data	weather conditions and short term forecast, pavement surface temperature	[31, 32]
unnamed	Korea	physical (similar to German on the numerical part)	weather data, pavement characteristics	surface pavement temperature	[33]
Road Condition Model, or DMI-HIRLAM-R	Denmark	physical	weather data and road weather data	local forecast coupling HIRLAM atmospheric model and road weather data	[34-36]
unnamed	Finland		road weather data	road weather data and alarms	[37]
unnamed	Czech Republic		Czech weather data	9 h-local weather forecast, with precipitations nature	[38]
unnamed	Pologne	numérique	road weather data	local forecast	[39]
BorrCast24	Boschung	numérique	road weather data and local meteorology	local forecast up to 24 h, road surface status	[40]
ICECAST (ROSA system)	Vaisala		road weather data	road surface status and alarms	[41]
WETTIME		numerical	weather data and pavement characteristics	determination of conditions to get a wet slippery pavement, and drying time	[42, 43]
WELS	Wels Research Corporation		weather data	weather forecast	[42-44]

Table 1. Overview of numerical models for weather and road forecast

2.2 Statistical approach

The second group of forecast models is based on a statistical analysis so as not to be fully dependent on some physical parameters. Since the 70's, many studies dealing with forecast have been conducted with statistical models, either for road pavement temperature or for road surface status. Some successful experiments could be found in the literature in the Washington state or Ottawa [45]. Precipitations forecast could be obtained with a probalistic tool using a bayesan method [46]. Another application was found on the forecast of ice occurrence [47] with Monte-Carlo chains. The forecast of an average daily temperature was also suggested with Markov chains [48].

Models based on probability or on statistics need local observation data as inputs. Each model uses a database of past climatic events which length time varies. The database is generated in the case of road weather by road weather stations installed along itineraries. Road and atmospheric parameters are selected data are considered according to their known incidence on road surface temperature variations. The most commonly selected parameters are surface temperature, water presence (liquid or solid), de-icers presence, thermal characteristics of road sub-structure, air temperature, dew point temperature, relative humidity, precipitation amount and type, and wind speed. Air temperature is prevailing since it has an influence on pavement temperature and road surface condition, and determines the precipitation type (rain, ice or snow). Furthermore, according to pavement temperature, the precipitation type does not match the water phase on the road. Some snow could either lead to water, or to ice onto the pavement. Statistical and probabilistic models must match a system which behavior is as close as possible as reality. Therefore, they do need a database which extent in type very from one system to the next. The real behavior could be reached once a learning process has been completed. The mathematical tools used could either provide the risk to reach a given temperature, etc., or they explain the pavement temperature, as an example, with some atmospheric parameters as any another forecast model. This second approach was selected, with the forecast f road pavement temperature from atmospheric data without any consideration of physics.

3 DESCRIPTION OF THERMAL MAPPING MEASUREMENTS

The LRPC Nancy has been using a vehicle for thermal mapping early after the technique appeared. The vehicle is illustrated and detailed elsewhere in the literature [50]. Although the whole device has great performances, such radiometer could only analyse one lane at a time. Furthermore, measurements being usually run before dawn, all road events are obtained making measurements during daytime. The road surface temperature obtained is then used to establish a rough cooling speed, aspect not detailed in this work.

The infrared radiometer is a PRT5 from Barnes pyrometer, and its characteristics are summarized in table 2. It was mounted on the front bumper of a car, in a compartment which temperature is regulated around 18°C. The compartment is located at about 40 cm above the road surface. During the measurements, usual atmospheric parameters such as air temperature, relative humidity and atmospheric pressure were monitored. Measurements were provided by a SSBC probe designed to be installed on moving vehicles, including aircrafts wings [51].

Detector type	bolometer detector
Spectral bandwidth	9.5 - 11.5 µm
Thermal range	-40°C to + 70°C
Sensitivity	0.1°C below 0°C, 0.05°C above 0°C
Accuracy	± 0.5°C
FOV	20°
Time response	50 ms
NET	0.005 °C for a time response of 50 ms on a body at 25°C

Table 2. Characteristics of PRT5 radiometer.

The road network chosen for the test was almost 30 km long. It included several configurations, from single lane road to multiple lanes highway, passing above and below bridges, with and without roadside trees. Measurements were run in various weather conditions, from a clear sky and up to global cloud cover, and a large panel of temperatures, at different seasons of the year. The vehicle remained in the right lane when the driving was done on highway. A large distance with the preceding vehicle was maintained to avoid its thermal signature. Results nearly 50 thermal fingerprints were monitored. The surface temperature profiles are more or less constant, with an offset due to local temperature, and local distortions, due environment heterogeneities. One objective would be to determine if a generic thermal fingerprint of this itinerary does exist. If so, it would be used to build the ones in other different weather conditions.

4 PRINCIPAL COMPONENTS ANALYSIS OF THERMAL FINGERPRINTS. RESULTS AND DISCUSSION

4.1 Description of the PCA method and objectives

Principal Component Analysis (PCA) is a statistical sensitivity analysis method that enables to deal with a large set of data. It is commonly used in spectroscopic analytics where the spectral responses of a sample have a similar form of the signal when a little variation is applied.

Data analysis is included in multivariate statistical data analysis. It is a set of descriptive techniques, which mathematical main tool is matrix algebra, without guessing any probabilistic model. They allow using and summarizing large amounts of data thanks to their correlations. The statistical tool used is the correlations matrix, or the variance-covariance matrix. It helps giving a meaning to large collected data. It seeks what are the correlations within the dataset. Multivariate analysis considers related variables as a single entity an attempts to produce an overall result taking the relationship among the variable into account.

The method relies on data-analytic technique. Linear transformations of a group of correlated variables are obtained in such a way that certain optimal conditions are obtained. The most important of these conditions is that the transformed variables are uncorrelated.

PCA is one technique among many. It is a descriptive one, based on a NIPALS ("Nonlinear estimation by Iterative PArtial Least Squares") algorithm. In the PCA approach, the physics that generates the variations is "lost" for a mathematical one. It is then a linear combination of current physical factors. Data is transposed in another space build on real physical factors. Calculations are conducted to identify the space leading to the lower variance, meaning axis along which data tend to gather [51, 52].

We used this method to analyse a large series of data that we could not interpret manually and to confirm or not if the thermal response of a road section is reproducible.
We also used this method to evaluate if it possible to build forecasts of road surface temperature in climatic conditions that have not been obtained during measurement sessions. Then, it would be possible to compute at any moment a winter risk indicator at each position of a studied route.

4.2 Results of PCA

4.2.1. Whole itinerary analysis

The survey route was 31890 meters long that corresponds to 10632 measurement points according to the 3 m spatial frequency. To enable a PCA numerical computation (statistical software processing-cost limited to 5000 points) the input data were preprocessed. A regular sampling of 1 point extracted from 9 of the raw dataset to create was applied first and a moving average on 7 points was used on the sample to smooth the fingerprint. NIPALS algorithm has been used.

PCA has been conducted on 3 different datasets :
[1] Case 1: the whole measurements, corresponding to 53 measured thermal fingerprints ;
[2] Case 2: the measurements conducted during the cold season corresponding to a range between -12°C and 5°C average surface temperature values, that corresponds to 8 fingerprints ;
[3] Case 3: 5 fingerprints selected from this “cold” range values.
The objective was to evaluate the capability of the approach to lead to a good representation of the fingerprints according to the number of data and the thermal range dependence. PCA results are given in Table 3. Thermal fingerprints from PCA results will integrate all weather conditions effects met during the measurements used for the calculations.

Case study	Case 1 All measurements (53)	Case 2 All measurements under 5°C (8)	Case 3 5 selected measurements under 5°C
Number of principal components (PC) used	10	6	3
Percentage of explained variance (with 1st PC)	98%	99%	99%
Outliers detected (number of data points)	1000	91	94

Table 3. PCA statistical indicators for the 3 cases

Global results were promising. For each case, the first principal component (PC) allowed to obtain a good fit with statistical description : 98% of variance is explained with the first principal component for all measurements (Case 1). The first component is statistically associated with the average.
To illustrate the quality of th model, we compared the raw measurements to the PCA statistical model obtained for the 5 selected fingerprints under 5°C (Case 3) (Figure 1).
PCA lead to a well representation of the real surveys, but some bias did locally appear, mainly for surveys 3 and 4, between 5000 and 6000, between 9000 and 11000, between 13000 and 16000, between 18000 and 19000 and between 21000 and 26000 meters. This discrepancy could be explained by the difference between vehicle-paths during the campaign. From one survey to another, measurement points did not really overlap.
Moreover, thermal phenomena that occurred in different weather conditions are not necessarily reproducible on every road segments at the scale of 32000 meters.

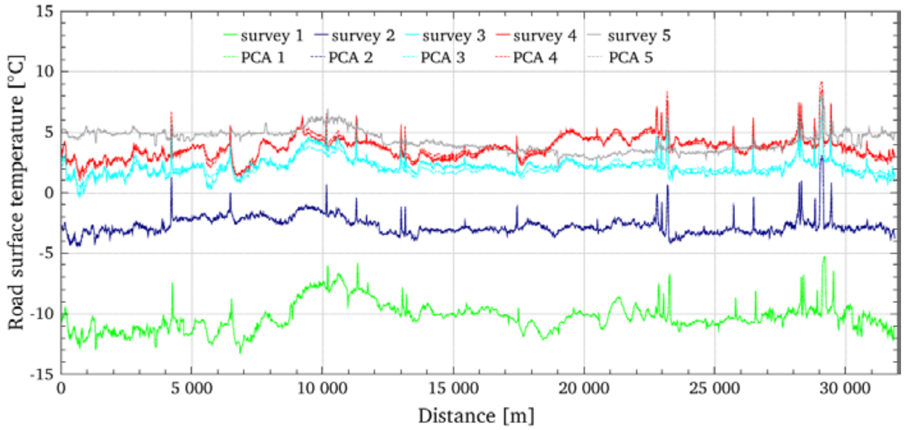

Figure 1. Comparison of raw measurements and corresponding PCA modelled fingerprints under 5°C (Case 3)

4.2.1. Itinerary sections analysis

In the last part of this work, the whole itinerary was studied according to four road sections (Figure 2):

- Section 1: a slope (1500 m)
- Section 2: a bridge (40 m)
- Section 3: a hill (2400 m)
- Section 4: a hill (3200 m)

Partitioning the itinerary into sections permits to obtain an homogeneity with the road infrastructure or to isolate specific climatic phenomenon due to land occupation and to conserve the maximum of data to exploit for PCA computations. Each isolated section has its own winter maintenance specificity.

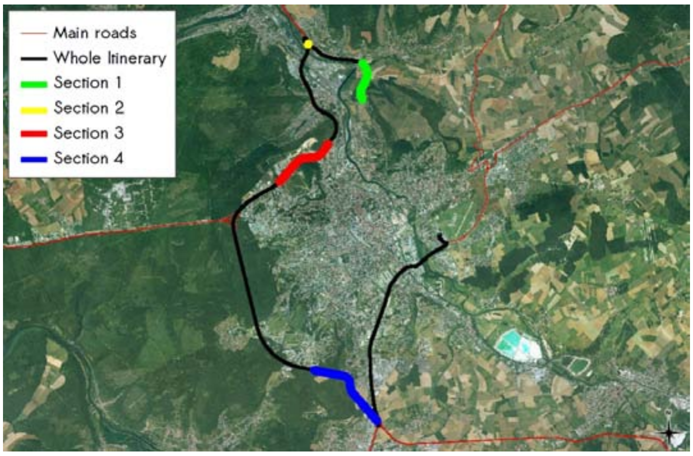

Figure 2. The whole itinerary and the four studied sections

PCA computations were conducted using the entire dataset (no sampling, nor moving-average) for each road section, which means one surface temperature record contains data points at a 3 meter distance frequency.

We studied first the influence of the account of the number of survey in PCA representativeness for the full range of temperature, so taking sequentially 20, 10, 5, 4 and 3 surveys for computations.
Results were suitable until the account of 5 surveys. Below this limit a loss of information was observed.
We also focused on the low temperature range (Ts < 5°C). As in part 4.2.1., 5 fingerprints have been used. PCA and raw measurements were compared. Results for section 3 are presented Figure 3.

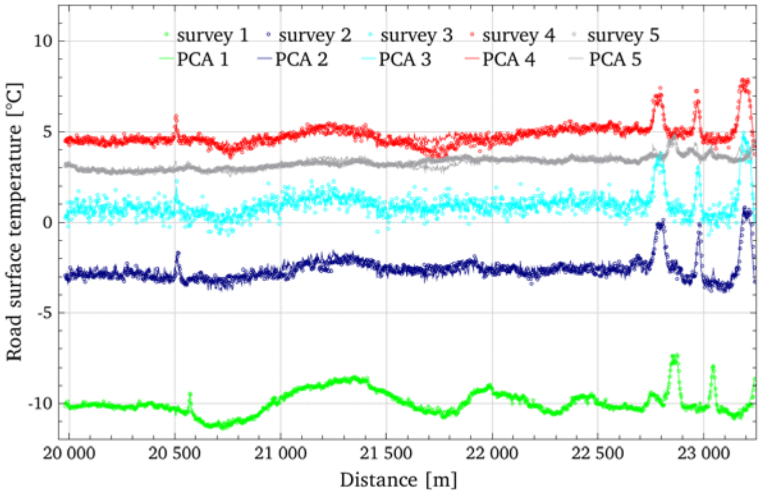

Figure 3. Comparison between raw measurements and corresponding PCA modelled fingerprints under 5°C for road section 4

One of the objectives was to build proper road surface temperature forecasts for different weather conditions. We tested here a method to build representative fingerprints that have not been available during measurement campaigns.

Under 5°C temperature range we re-considered the 8 measurements surveys, so the 5 taken into account for PCA computations and the 3 remaining ones. Among those, survey 6 road surface temperatures were always upper survey 3 values and below survey 5 values.
We compared survey 6 real measurements to the "re-built" fingerprint ($Pedicted_6$) from PCA values of survey 3 (PCA_3) and 5 (PCA_5) according to this relation : $Pedicted_6 = k\ PCA_3 + (1\text{-}k)PCA_5$
with k = 0.58, this parameter has been adjusted to obtain the same average temperature value for the measurement fingerprint and the predicted one along the road section 4. Figure 4 shows that prediction is very close to real measurements even if survey 6 did not participate to PCA computations. There, survey 3 and 5, do not have the same variability but the same form. This kind of prediction should be interesting to evaluate in the case of very different fingerprints in the same temperature range.

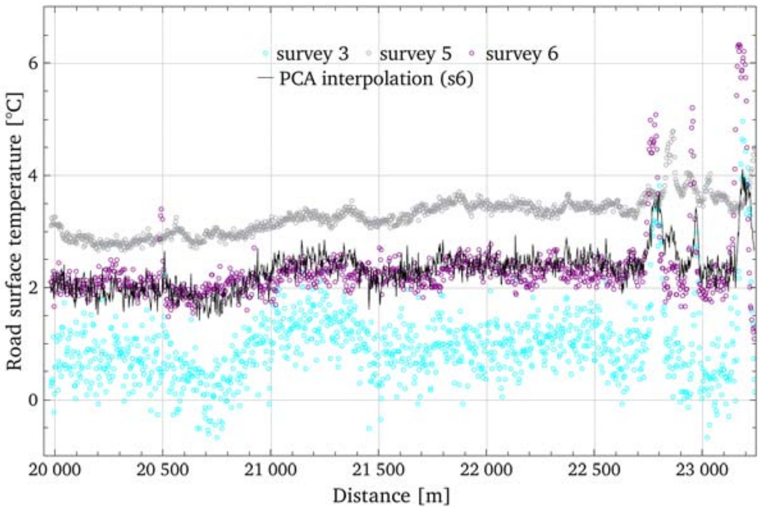

Figure 4. Comparison of survey 6 raw measurements and interpolated ("predicted") values from PCA computations

The results were promising and let suggest to us that any road thermal mapping could be reproduced on specific sections the sections for which we have enough reference measurements. The recalibration of the model could also be refined by a few local records of road weather stations.

4.3 Dynamic susceptibility of ice occurrence

Many possibilities exist in the calculation of the susceptibility of ice occurrence of an itinerary. One commonly employed consists in using the average parameters of the itinerary (air temperature Ta, relative humidity HR, pavement temperature T_s, dew point T_d) and analyse how far or close the measurements are from these averages. Indeed, when surface temperature is below the dew point, condensation could occur. And if surface temperature is below 0°C, some slipperiness might appear, and generating a danger for road users. The susceptibility of ice occurrence could then be the sum of two risks, one on surface temperature, and a second one on dew point. It was then defined in this study according to Eq. 1, for each data point, giving more weight to the variation of surface temperature. With such definition, a risk exists each time the surface temperature drops below the dew point, with a negative surface temperature. The greater the difference in such configuration, the greater the susceptibility.

$$\begin{aligned}&\text{ice susceptibility} = 2.\text{susceptibility}(T_s) + \text{susceptibility}(T_d),\\&\text{with susceptibility}(T_s) = 0 \text{ if } -0.5°C \leq T_s - T_{s,average} < 0°C; 1 \text{ if } -1°C \leq T_s - T_{s,average} < -0.5°C; \ldots\\&\text{and susceptibility}(T_d) = 0 \text{ if } 0°C \leq T_d - T_{d,average} < 0.5°C; 1 \text{ if } 0.5°C \leq T_d - T_{d,average} < 1°C; \ldots\end{aligned} \quad (1)$$

As shown in the previous paragraphs, surface temperature variations could be obtained through a PCA analysis. Air temperature of the itinerary could either be measured, or obtained from a meteorological forecast. An itinerary could easily be illustrated using a geographical information system (GIS). Therefore, using PCA surface temperature estimation along with air temperature, one could easily build ice susceptibility dynamic maps that could be regularly updated and refreshed.

5 CONCLUSION

Thermal mapping is a common tool used in winter maintenance. It is based on the measurement of pavement and atmospheric parameters such as surface temperature and air temperature. A susceptibility of ice occurrence is build with these measurements to help road managers. The objective of this work was to analyse to which extent multivariate data analysis, and more specifically principal components analysis, could be used to get a susceptibility indicator to ice occurrence. Such approach would avoid time-consuming measurements, in specific climatic conditions during winter.
This statistical approach has indicated a good ability to obtain thermal fingerprints of an itinerary on the base of a set of some fingerprints in a 5°C to -12°C temperature range. When applied to a whole itinerary, the explained variance exceeded 90 %, and mainly with one principal component. Some discrepancies remain due to local specificities. The approach was then applied to very specific locations known to be winter maintenance problems, as bridges and slopes are. The itinerary was partitioned into sections to which PCA was applied. Results indicated again the ability to PCA to explained data variance through mainly one component. Based on these statistical thermal fingerprints, extrapolated ones were obtained using interpolations and covering into details a full temperature range. These thermal fingerprints statistically contain various weather conditions. A good agreement was obtained between these results on sections and field measurements.
PCA appears to be a proper way to later build dynamic maps of susceptibility of ice occurrence of itinerary to hemps road managers in avoiding major traffic disruptions and congestions, or accidents due to poor road conditions.

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