# Thermal mapping as a valuable tool for road weather forecast and winter road maintenance: An example from the Italian Alps

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## ABSTRACT

During the winter period ice is likely to form on roads, making pavement surfaces slippery and increasing accident risk. Road surface temperature (RST) is one of the most important parameters in ice formation. The LIFE+ "CLEAN-ROADS" project aims to forecast RSTs in advance in order to support road maintenance services in the timely and effective preparation of preventive anti-icing measures. This support is provided through a novel MDSS (Maintenance Decision Support System). The final goal of the project is to quantitatively demonstrate that the implemented MDSS is capable to minimize the consumption of chemical anti-icing reagents (e.g. sodium chloride) and the associated environmental (water and air) impact while maintaining the current high levels of road safety.

In the CLEAN-ROADS system RSTs have been forecast by applying the numerical model METRo (Model of the Environment and Temperature of Roads) to a network of RWIS (Road Weather Information System) stations installed on a test route in the Adige Valley (Italy). This forecast is however local and does not take into account typical peculiarities along road network, such as the presence of road sections that are particularly prone to ice formation. Thermal mapping, i.e. the acquisition of mobile RST measurements through infrared thermometry, permits to (i) identify and map those sections, and (ii) extend the forecast from a RWIS station to adjacent areas. The processing of thermal mapping signals is however challenging because of random variations in the road surface emissivity. To overcome this we have acquired several thermal mapping traces along the test route during winter seasons 2014-2015 and 2015-2016. We have then defined a "characteristic" thermal fingerprint as a function of all its historical thermal mapping signals, and used it to spatialize local METRo forecasts. Preliminary results suggest the high potential of such a technique for winter road applications.

**Keywords:** Thermal mapping, Road surface temperature, Road ice hazard, Meteorological forecast, Winter road maintenance

## 1. INTRODUCTION

When road temperatures get close to freezing point (0°C) in winter time, road engineers and maintenance authorities have to decide whether, where and when to spread anti-icing salt on roads in order to prevent road ice formation and, consequently, hazardous slippery pavements. This is the main concept at the basis of CLEAN-ROADS, a pilot project launched in late 2012 in the Autonomous Province of Trento, Italy. Co-funded by the LIFE+ program of the European Commission, the CLEAN-ROADS project aims at introducing an innovative MDSS (Maintenance Decision Support System) to optimize winter road treatments and minimize the environmental impact produced by chemical deicer on the surrounding environment[4].

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Historically, since the mid-80s the maintenance decision process has been supported by the information provided by road weather information systems (RWIS) which consist of automatic road weather stations and road weather forecasts[3]. Road weather stations measure meteorological variables, such as air temperature, relative humidity, wind speed, precipitation; they also provide road surface parameters, namely road surface temperature (RST) and state (dry, wet), through sensors embedded in the pavement. Road weather forecasts, such as the Model of the Environment and Temperature of Roads (METRo) developed by Environment Canada[1], predict the likelihood of road ice formation from the energy intake and loss at the road surface. As this energy exchange is regulated by environmental and meteorological variables, road weather forecast are based on numerical weather models that are initialized by measurements from RWIS stations.
This approach provides a knowledge that is site-specific and, as such, it might not be representative of the road condition between two or more stations. Sunlight exposure, wind, cloudiness, traffic and other factors make winter night-time road surface temperatures (RSTs) vary by more than 10°C along a road[9]. It is therefore mandatory to find a tool through which extracting information on road temperatures and conditions across a road network. This tool is thermal mapping. Thermal mapping is a technique that uses an infrared thermometer mounted on a vehicle to detect RST variations along a survey route. RST variations are usually displayed as diagrams, called "fingerprints", where the departure of RSTs from the mean is plotted against the distance sampled by the vehicle[9]. The combination of different fingerprints measured on different routes at the same night represents a "thermal map", i.e. the spatial variations of RSTs across a road network under specific weather conditions[9]. With thermal mapping, road weather forecast can be extended from RWIS stations to road stretches (spatialization), reflecting the RST variations in between. Road stretches falling below 0°C on a particular night can thus be identified in respect to other stretches remaining above 0°C. This information can be used by road maintenance authorities to adapt anti-icing strategies accordingly, i.e. to spread salt only when and where weather and road conditions require so. This would reduce maintenance cost and the impact of anti-icing salt on the environment. The use of chemicals such as sodium chloride is of major concern from this point of view. It accelerates the deterioration of road structures and the corrosion of vehicles, it increases the levels of particulate matter in the air and it alters the natural ecosystem (e.g., soil and ground water supplied) near the roadway[5].
This paper describes the usefulness and value of thermal mapping within the CLEAN-ROADS project. It first examines the acquisition and analysis of spatial RST variations as measured via thermal mapping along two test routes in the alpine Trentino region, Italy. It then describes the first implementation of acquired fingerprints in METRo road weather forecast model and its potential in predicting "thermal maps" that can assist road engineers and maintenance authorities in their decisions through RWIS.

# 2. METHODOLOGY

## 2.1 Study area

Thermal mapping was carried out in Trentino region, a mountainous area in the Northeast Alps of Italy characterized by severe winter weather. Two different test routes were selected for detailed analysis. The first route is a 14 km-long stretch along a state highway (SS12), it is located in a valley bottom (Adige Valley) and it covers residential, industrial and countryside areas (Figure 1, blue route). The second route is 10 km-long stretch along a state highway (SS47) and it develops from the Adige Valley to a higher altitude valley (Valsugana Valley, Figure 1, red route). It also contains a range of different land uses, road types, lane configurations and traffic fluxes. A full dataset of thermal fingerprints were acquired along the first route in winter 2014/2015 and winter 2015/2016, and along the second route in winter 2015/2016. In addition, specific site measurements on road and atmospheric variables were acquired in the same periods by two automatic road weather stations, located along the selected routes.

## 2.2 Equipment

Thermal mapping RSTs, that is, road thermal fingerprints were obtained by an infrared radiometer set on a survey vehicle tow hook (Figure 2). The radiometer, which is based on thermopile technology, measures the energy flux density emitted by the surface by applying the Stefan-Boltzmann equation[6]. Its optical system is characterized by a field of view equal to 10°deg and by a spectral window between 5 and 12 μm. The infrared sensor has an accuracy of ± 1°C for measurements performed in a temperature range between -20°C and +40°C, and on objects with emissivity equal to 1. Thermal mapping RSTs were acquired with a maximum frequency of 6 acquisitions per second, ensuring a measurement every 20 m even with vehicle speed up to 70 km/h. Measurements were transferred from the sensor board to the vehicle unit through Bluetooth communication. The vehicle unit stored measured values locally and, at the same


Figure 1. The blue path shows the “Adige Valley” route along the SS12 state highway from Lavis town to Cadino town; the red one shows the “Valsugana Valley” route along the SS47 state highway from Trento city to Civezzano town. Map data ©2015 Google.

time, sent them to the MDSS server via an Internet connection established on the mobile network. This permitted to implement a real-time management for the collected information. The data stream was timely and geographically referenced through a GPS device, which enabled a mapped visualization through standard geographical information system (GIS) tools.


Figure 2. Thermal mapping vehicle.

### 2.3 Meteorological conditions

Meteorological conditions strongly influence thermal mapping measurements, particularly in a mountainous region as that considered in this study. In literature meteorological conditions are classified as extreme, intermediate or damped[8]. Under extreme conditions, i.e. on stable, clear and calm nights, variations in RST are the greatest and the thermal fingerprint is clearly developed as the sampled road emits infrared radiation (heat) to space and cools down. Under damped conditions, i.e. on overcast, rainy and windy nights, spatial variations in RST are the smallest and the thermal fingerprint is spatially homogeneous because heat is prevented from leaving the surface and the cooling is far less overall. Under intermediate conditions, RST variations have in-between characteristics depending upon the amount of wind and cloud. In order to best identify colder road sections against warmer road sections, thermal mapping was carried out near sunrise (i.e. when RSTs usually reach the lowest values) under extreme conditions, defined by means of the following criteria:

- wind speed ≤ 2 m/s
- cloud cover ≤ 1/8
- mean RST temperature over the entire sampled road < 0°C

Specifically, 23 and 16 “extreme” thermal fingerprints were collected along the Adige Valley route and the Valsugana Valley route, respectively in winter seasons 2014-2015 and 2015-2016. In addition, thermal mapping was carried out when extreme conditions had persisted for at least 2-3 hours before sunrise, i.e. on nights with no unsettling weather conditions that could influence RSTs on the short time scale.

### 2.4 Pre-processing stage: noise removal

Each measurement acquired via thermal mapping is characterized by a small “signal noise” perturbing acquired data on both the temporal and spatial scale[2]. A signal noise in thermally-mapped RST data might be due to different pavement emissivity (i.e. variations in roughness or color), to the presence of dirty soil on the road surface or to electronic noise, and must be removed in order to correctly identify the thermal fingerprints of the selected routes. A low-pass Gaussian filter7 has been applied for this purpose. Differently from a more common mean filter, a low-pass Gaussian filter removes signal noise without smoothing any gradient associated with a real change in RSTs. Rapid and large scale changes due to discontinuous surface features or topography variables are thus retained, as is the mean of raw thermal data. Figure 3 shows an example of thermally-mapped RST data to which a Gaussian filter was applied.

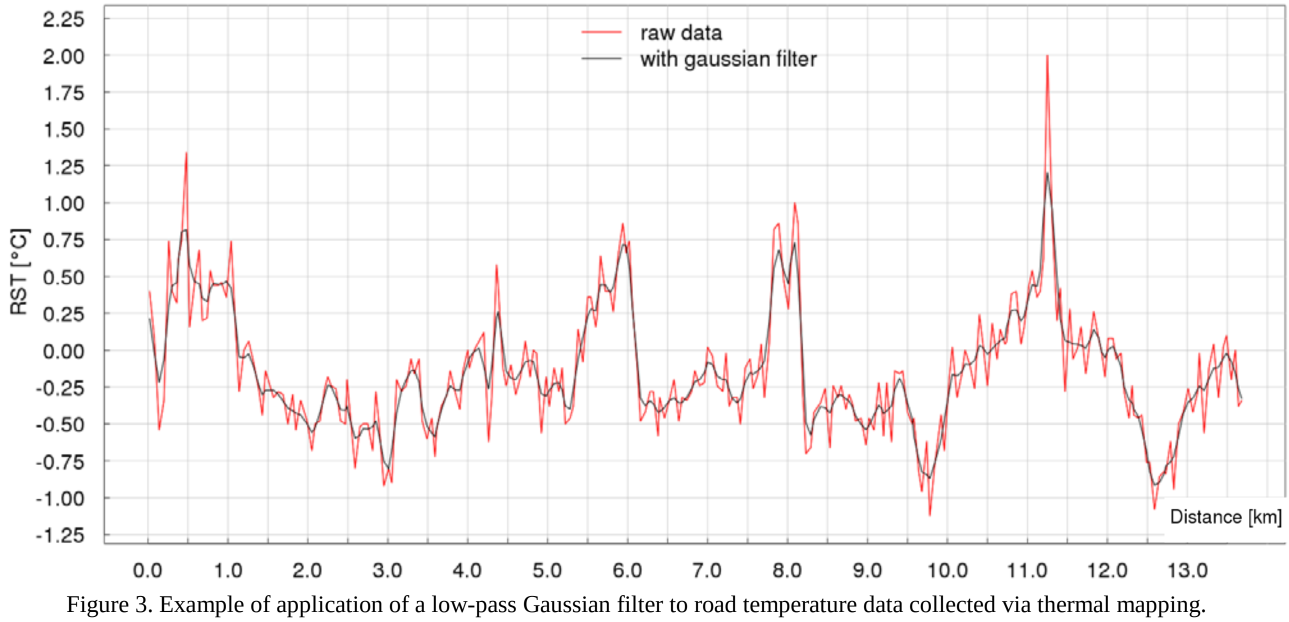


Figure 3. Example of application of a low-pass Gaussian filter to road temperature data collected via thermal mapping.

Different ranges have been tested for the window length of the Gaussian filter before choosing the correct one. Increasing the window length decreases the signal noise. However, when the window length is too wide, real RST changes get reduced too. The final choice has been to set up the window length of the filter equal to 200 m.

### 2.5 Processing stage: equivalent thermal fingerprint and spatialized forecasts

The elaboration of the equivalent thermal fingerprint was computed firstly by comparing each single thermal fingerprint to the reference RSTs measured by fixed measurement stations, and secondly by comparing different thermal fingerprints altogether, as graphically summarized in Figure 4.

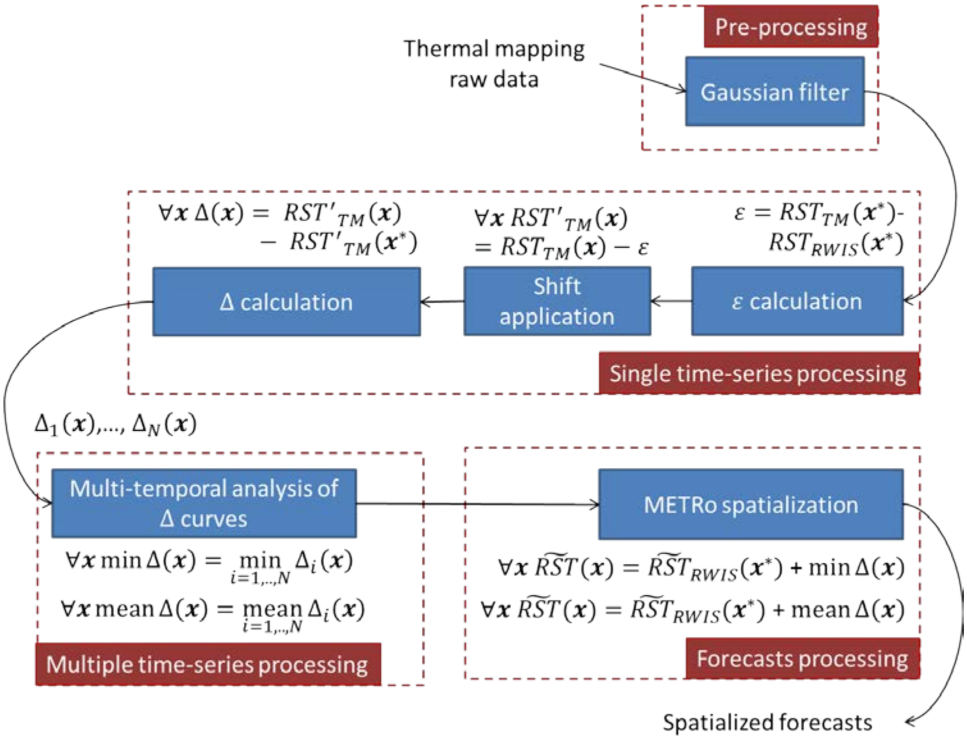


Figure 4. Methodology used in the study for the automatic processing of thermal mapping data.

In the first step, the single thermal fingerprint was computed as follows:

- ε calculation: defined as the difference between the RST measured through the thermal mapping probe in correspondence of the fixed station located in position **x*** and the correspondent fixed RST measurement;
- shift application: removal of ε from thermal mapping signal;
- Δ calculation: defined for each point of the grid **x** as the difference between the RSTs measured through the thermal mapping probe in correspondence of **x** and **x***.

In the second step, the minimum and the mean value of Δ RST differences were evaluated and compared for each grid point of the track. If the number of acquired thermal fingerprints is enough to consider the sample statistically significant, the mean and the minimum represent the most likely and the minimum local variation of RSTs, respectively. The use of the minimum Δ RST is precautionary, as it tends to underestimate RST values and consequently overestimate the likelihood of ice formation. This is in agreement with the approach adopted in CLEAN-ROADS system, that is, to inform road operators in advance about the possibility of ice formation, especially when there is no ice risk so that they can schedule other maintenance tasks. However, when a risk is present (although minimum), road operators have to be aware that a de-icing treatment could be necessary in the following hours and must pay attention. Their final decision is supported by an automatic alarms generation tool developed on top of the real-time measurements transmitted by the static RWIS stations[4].

With the two steps above described a "thermal map" of the study area was obtained, i.e. a relative RST map that shows how much warmer and colder the rest of the routes would be in relation to RWIS station points. RST measured by RWIS stations were also used to predict overnight RSTs by means of the METRo model[1]. Together with road and atmospheric observations from RWIS stations, measured RST were used as initial conditions to run METRo and to couple it with a meteorological numerical prediction model from the European Centre for Medium-Range Weather Forecasts, ECMWF (T1279 high resolution atmospheric model, 16 km horizontal resolution, 12UTC run). The output is a site-specific forecast of overnight RST minima as expected at RWIS station locations. The combination of METRo forecast with the "thermal map" of the study area from thermal mapping measurements provided a prediction of RSTs over the entire road network at selected times (20:00, 22:00, 24:00 local time).

# 3. RESULTS AND DISCUSSION

## 3.1 Thermal mapping surveys characteristics

The "Adige Valley" route is entirely located at an average height of 220 m above the sea level. Its asphalt composition is mixed: porphyritic in some sections and calcareous in others. It presents a 2-lane configuration with 9.000 vehicles running on average for day in winter season (Table 1). One state RWIS station is installed along this route, close to a countryside area.

Table 1. Classification of the "Adige Valley" route according to land uses and road-types.

| Section n. | From – to [km] | Land use | Road peculiarity |
|---|---|---|---|
| 1 | 0.0 – 1.5 | Residential | Lavis Bridge from km 0.1 to km 0.2 |
| 2 | 1.5 – 2.2 | Industrial | Road is above an underground railway |
| 3 | 2.2 – 6.7 | Countryside | |
| 4 | 6.7 – 8.2 | Residential | |
| 5 | 8.2 – 11.2 | Countryside | Road runs parallel to Adige river |
| 6 | 11.2 – 11.6 | Residential | |
| 7 | 11.6 – 13.7 | Countryside | Road is north exposed and is shaded form mountains |

Figure 5 shows thermal fingerprints for the "Adige Valley" route acquired under extreme conditions, after they had been filtered as described in the "Methodology" chapter.

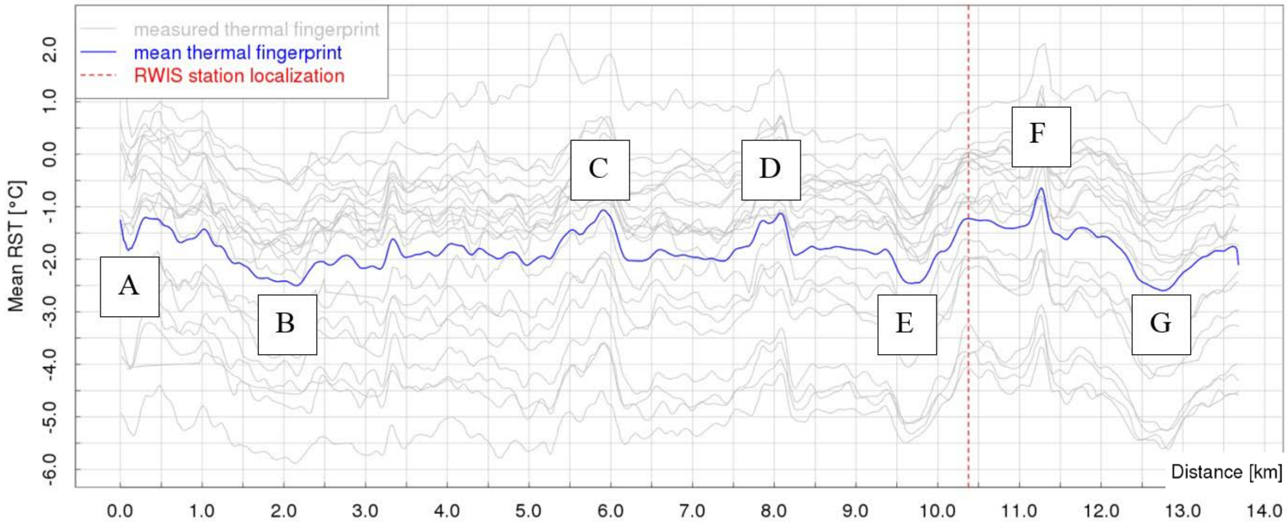


Figure 5. Thermal fingerprints for the "Adige Valley" route.

It also indicates the thermal fingerprint representative for the route, i.e. the mean of all extreme thermal fingerprints, and the location of the RWIS station installed along the route (km 10.4). Interesting areas are pointed out on the mean thermal fingerprint with capital letters and can be identified as follows: (A): Lavis bridge in a residential area; (B): road stretch above an underground railway in an industrial area; (C): road stretch in a countryside area near a rock face heated up on the south side by sun during the day; (D): road stretch in a residential area surrounded by buildings; (E): road stretch in a countryside area; (F): narrower road stretch in a residential area surrounded by tall buildings; (G): road stretch in shade and in a countryside area. A, B, E and G are cold spots, while C, D and F are hot spots.
The "Valsugana Valley" route develops from a mountainous/hill area to a valley bottom and crosses residential, industrial, countryside and mountainous areas. The route starts at a height of 480 m above the sea level and reaches a height of 200 m above the sea level. Its asphalt composition is mixed: porphyritic in some sections and calcareous in others. It presents two different lane configurations, and the average daily traffic flux is about 43.300 vehicles for day in winter season (Table 2). One state RWIS station is installed along this route, close to a countryside area.

Table 2. Classification of the "Valsugana Valley" route according to land uses, road-types, lane configurations and traffic fluxes.

| Section n. | From – to [km] | Land use | Road peculiarity | Lane configuration |
|---|---|---|---|---|
| 1 | 0.4 - 2 | Mountainous/hill | Road runs parallel to Fersina river with Corona tunnel from km 1.6 to km 1.7 | 4 lanes |
| 2 | 2 - 3 | Mountainous/hill | Crozzi tunnel from km 2 to km 3 | 4 lanes |
| 3 | 3 – 4.3 | Mountainous/hill | Crozzi viaduct from km 3 to km 3.6 | 4 lanes |
| 4 | 3.6 – 8.0 | Mountainous/hill | Road exposed to the Adige Valley with Ponte Alto tunnel from km 4.3 to km 4.6 and with Laste tunnel from km 5.6 to km 5.8 | 2 lanes |
| 5 | 8.0 – 9.9 | Industrial | Canova viaduct from km 9 to km 9.7 | 4 lanes |

The dataset of extreme thermal fingerprints for the "Valsugana Valley" route and the corresponding mean thermal fingerprint are shown in Figure 6 after noise removal. The location of the RWIS station installed along the route is indicted (km 1.4). Interesting areas can be identified as follows: (A): stretch of road located below an embankment; (B): bridge over the "Rio Farinella" with a stretch clear from trees; (C): "Corona" tunnel; (D): "Crozi" tunnel; (E): "Crozi" viaduct; (F): "Ponte Alto" tunnel; (G): Track exposed on the Adige valley and sheltered by mountainside rocks; (H): "Laste" tunnel; (I): Track sheltered by mountainside rocks and (L): Canova viaduct. A, B, E and L are cold spots while G and I are hot ones. C, D, F and H are tunnels.

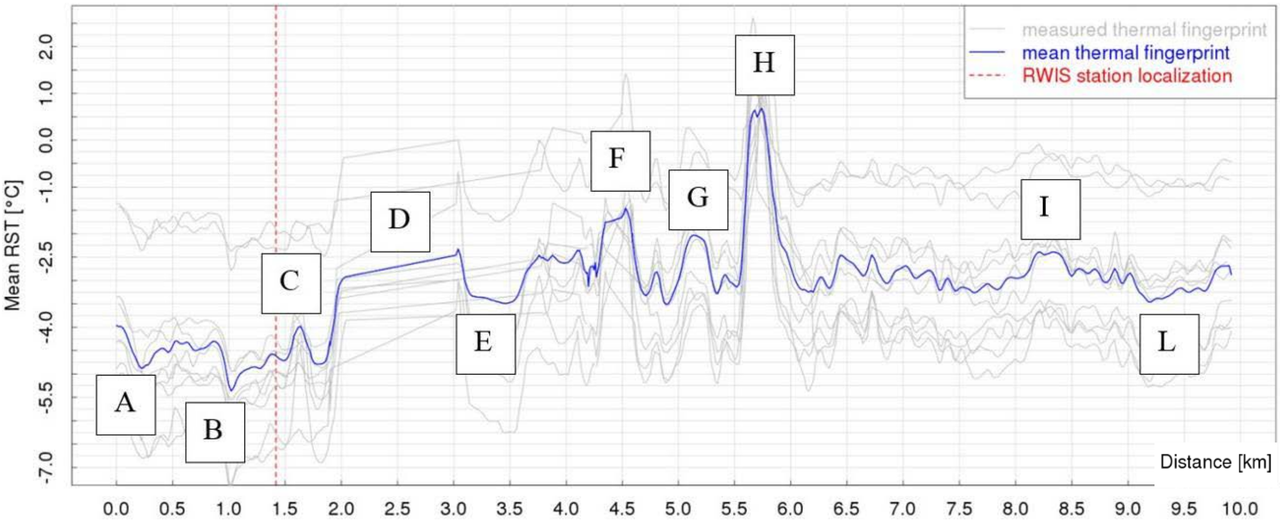


Figure 6: Thermal fingerprints for the "Valsugana Valley" route.

### 3.2 Spatialization model results

For the “Adige Valley” route the minimum value of the road temperature correction is approximately 0.5 °C lower than the mean value (Figure 7), with the exception of a cold spot after the RWIS station (km 12.75) corresponding to a screened zone (Figure 6, G point). Here the difference between the two curves is in the order of 1°C. For the “Valsugana Valley” route, the difference between minimum and mean curve is on average approximately 0.5-0.8 °C (Figure 8).

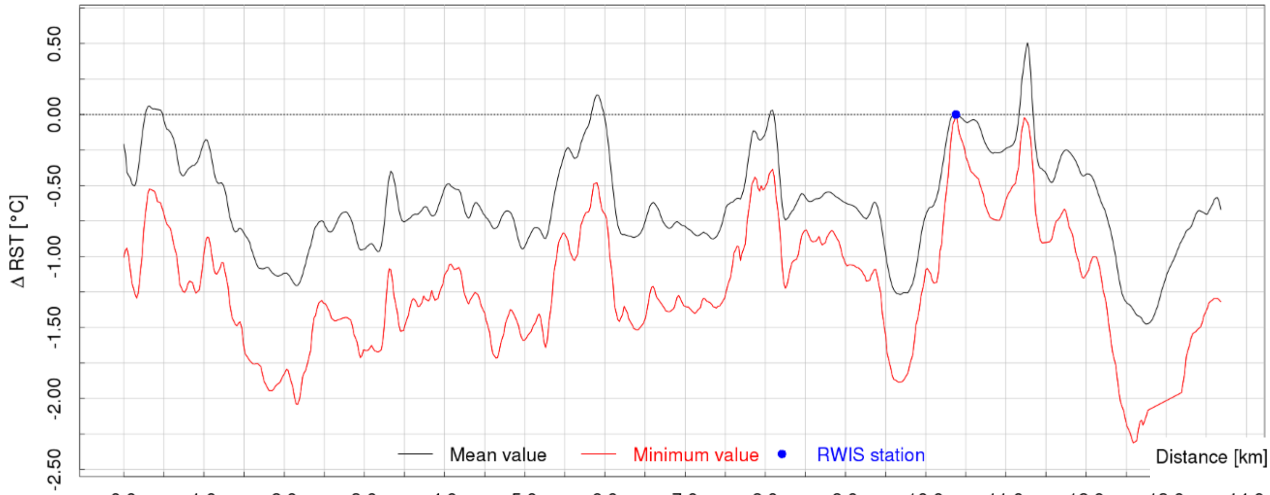


Figure 7: Minimum and mean values of Δ RST for the “Adige Valley” route.

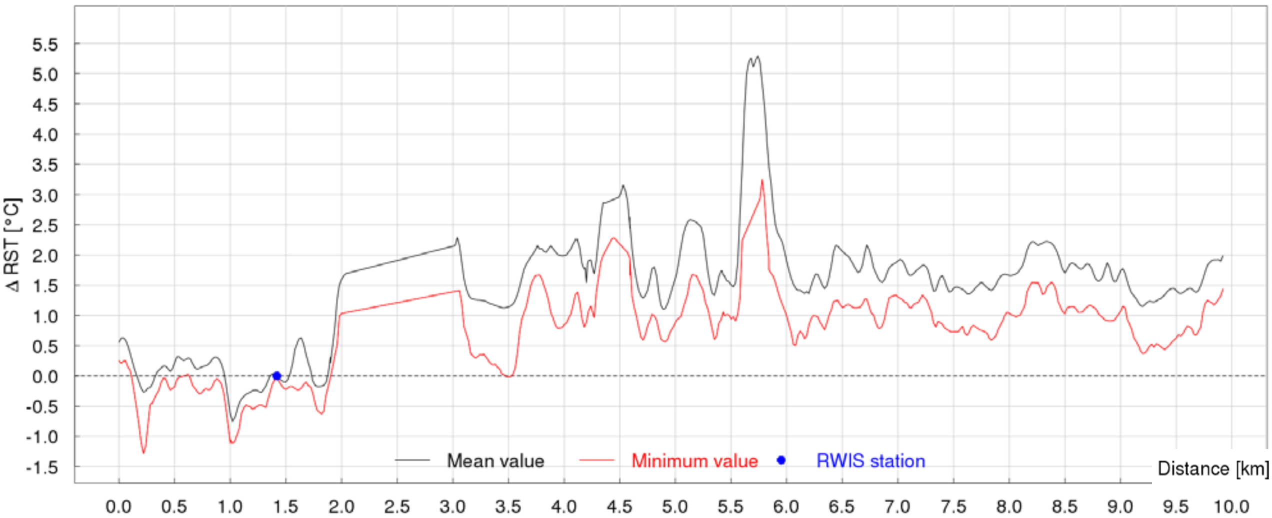


Figure 8: Minimum and mean values of Δ RST for the “Valsugana Valley” route.

To increase the statistically relevant number of thermal fingerprints considered in the calculation of the mean thermal fingerprint, an extended definition of the extreme weather conditions has been introduced. This includes surveys carried out when one of the three defining meteorological criteria, described in the paragraph concerning methodology, is not fulfilled, i.e. a wind speed higher than 2 m/s, a cloud cover larger than 1/8 or a mean RST temperature over the entire sampled road higher than 0 °C. A comparison between thermal fingerprints acquired under extreme conditions and under “extended” extreme conditions is shown in Figure 9. The difference between these two thermal fingerprints is not significant. The temperature profile along a particular thermal mapping route is usually relatively similar in pattern, also under different weather conditions[8]. Different meteorological conditions, that are uniform on the whole route, affect the amplitude of the relative temperature differences between cold and warm sections but do not alter the main pattern of the thermal fingerprint. For this reason, the whole thermal fingerprints obtained under "extended" extreme meteorological conditions had been adopted for the spatialization procedure, since they are statistically more representative.

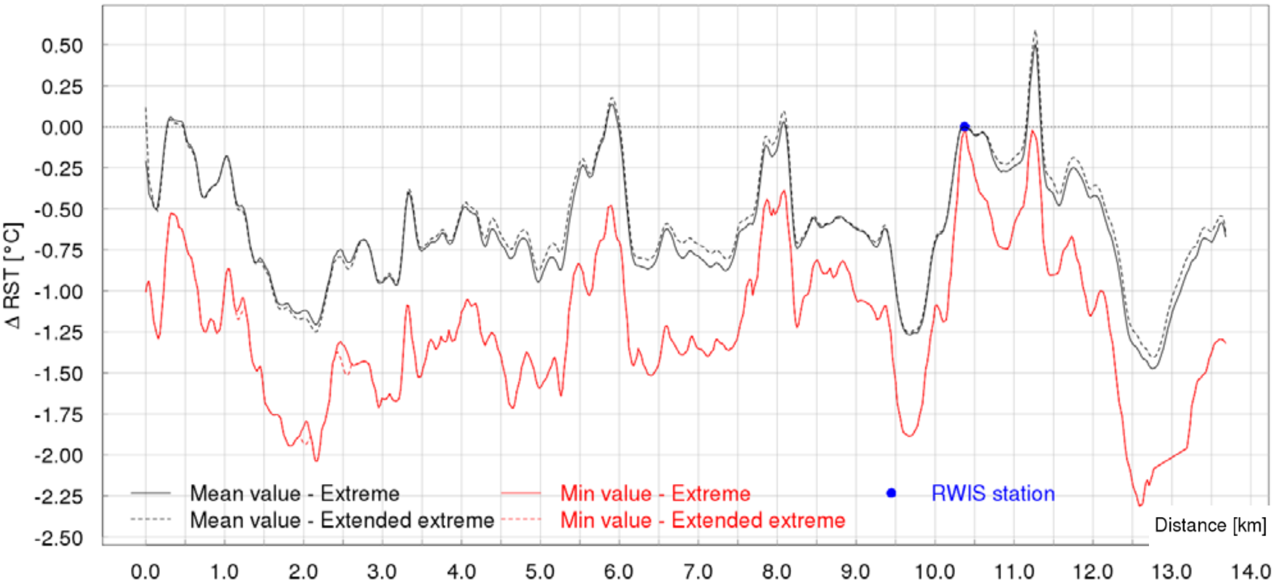


Figure 9: Comparison between minimum and mean values of the Δ RST for the "Adige Valley" route under extreme conditions and "extended" extreme conditions.

Spatialization was applied to the RSTs forecast by the METRo model at the points where static RWIS stations are installed. Specifically, minimum RSTs were first predicted automatically every night at the reference sites through METRo. Forecast minimum RSTs were then extended to the entire route by keeping into account the location of cold and hot spots as indicated by the mean/minimum referenced thermal fingerprint. Figure 10 shows the result of the first example in the Alpine area of a predicted "thermal map". METRo-predicted RSTs at the RWIS station on the "Valsugana Valley" route for January 26th, 2016 are spatialized over the entire road. Using a color code, road stretches where RSTs are forecast to go below 0°C are indicated in blue, road stretches with forecast RSTs between 0°C and 2°C are indicated in yellow, and road stretches with forecast RSTs above 2°C are indicated in red.


Figure 10: Example of the spatialization for RST minimum values predicted by the METRo model along the "Valsugana Valley" route on January 26th, 2016.

An evaluation was performed on the quality of the METRo prediction. In Figure 11 RST values measured via thermal mapping along the "Adige Valley" route and RST values predicted by METRo model for the same route on January 26th, 2016 are compared.

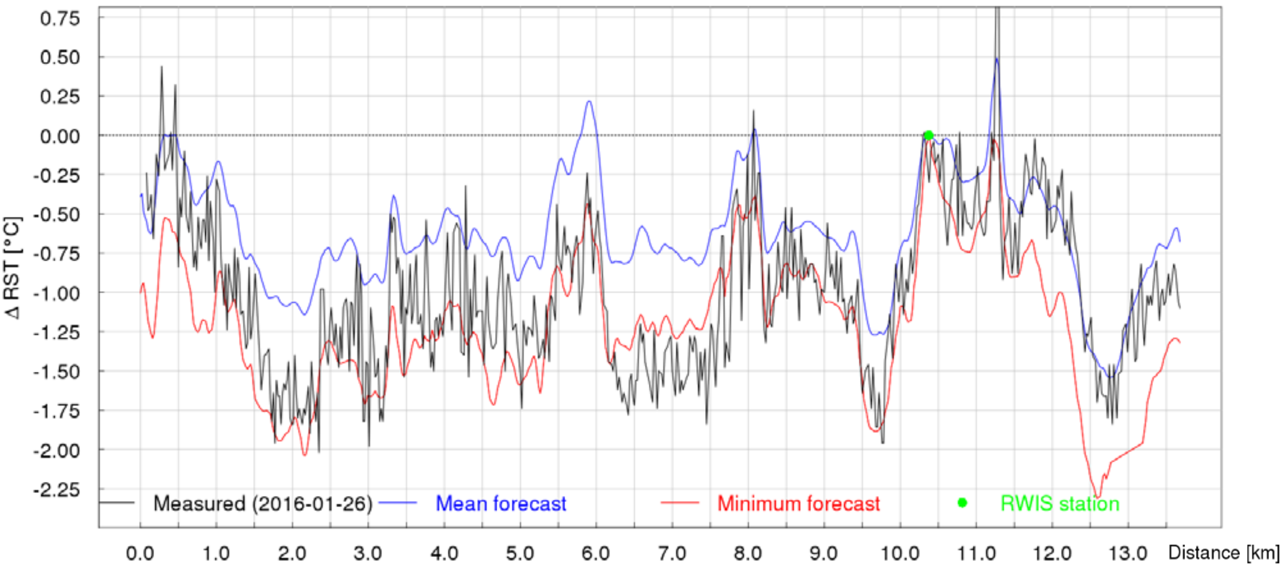


Figure 11: Comparison between forecast (mean in blue; minimum in red) and measured (black) RST values for the "Adige Valley" route on January 26th, 2016. The location of the static RWIS station is plotted for reference.

Forecast RST minimum values are observed to well reproduce RST measured values. Cold spots can be identified and are in agreement with those correspondingly described. The considered mean thermal fingerprint is the one evaluated on the basis of the "extended extreme" thermal fingerprints acquired before 26$^{th}$ January. These fingerprints constitute the training data set used to predict reasonable values of the RST correction. The thermal fingerprint acquired on 26$^{th}$ January is used as a testing data set. As it can be seen, RST measured values are for the most part of the route comprised between mean and minimum forecast RST, with a very small exception for the stretch between C and D hot points, where RST measured values are slightly smaller than the minimum forecast RST. For this reason, the use of the RST minimum thermal fingerprint can be encouraged in order to avoid possible local underestimation of the RST.

## 4. CONCLUSIONS AND DISCUSSION

This paper presents a novel procedure for exploiting the potential of thermal mapping for road winter maintenance. The acquisition of RSTs via an infrared thermometer mounted on a vehicle permits to identify the pattern and distribution of warm and cold sections along a road. We demonstrate with this study that knowing an "equivalent temperature fingerprint" is the key to conscious road maintenance behaviors. With the acquisition of thermal mapping data along two selected routes in the Italian Alps we have confirmed that even in a mountainous areas RST is not spatially homogeneous within a road network and cold spots are clearly observable due to topography and road-related variables. T Distance [km] are the ones that deserve special attention from road engineers, as suitable conditions for ice formation are particularly prone to occur there. Being able to predict cold spots is therefore mandatory. At this scope we have combined the information from temperature fingerprints acquired in specific weather conditions with a weather forecast model, called METRo. In this way, daily minimum RST forecasts over the two selected routes have been provided and sections with predicted RST minima below freezing displayed. We have thus obtained a forecast "thermal map" in a complex terrain area, where the local variations of the meteorological parameters can be significant and this technique can show its full potential. This perspective is going to be further reinforced in a near future, thanks to the plenty of RST data which the connected vehicles will be able to collect and transmit. In this future scenario, the research challenge is likely to turn in the understanding of how it's possible to best fuse RST data collected through heterogeneous measurement techniques and equipment. Our pilot activities have in fact specifically drawn our attention to the challenge of extracting valuable information through the combination of RST data collected through thermal mapping and by fixed monitoring stations.

## ACKNOWLEDGEMENTS

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