Thermal Mapping: Reliability and Repeatability

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Abstract

In winter road maintenance accurate information as to the spatial variation in minimum road surface temperature is valuable for road authorities and organisations to decide where to target salting or gritting treatment. The process to record and quantify these patterns of temperature variation is called Thermal Mapping. The technique relies on the fact that the pattern of road surface temperature is reproduced from one night to the next. This study establishes a valid statistical means of quantifying the similarity between temperature patterns captured during different Thermal Mapping surveys and is used to show that the Thermal Mapping process developed by the authors is reliable and that the pattern of temperature variation across a road network is reproduced under similar weather conditions.

1. Introduction

Winter night-time road surface temperatures can vary by more than 10°C across a road network. This variation in road surface temperature is controlled by factors such as exposure, altitude, traffic and changes in road surface construction. Most factors are spatially fixed producing a pattern of relatively warm and cold sections which is reproduced from one winter night to the next. Thermal Mapping is a process to quantify this variation and to present the data as a series of colour coded maps. It is based on the established fact that the pattern of spatial variation of minimum surface temperature is reproducible on a night by night basis, during the winter period, under similar weather types. Each Thermal Map defines the pattern of minimum road surface temperature variation which will occur under different weather conditions.

More than 100,000kms of Thermal Mapping has been carried out on roads and airports in Europe, Scandinavia, USA, Canada and Japan, where there is a requirement to ensure that roads remain free of ice and snow. The information is used by highway authorities, responsible for winter maintenance: for the redesign of salting routes to facilitate selective salting; to assess the optimum number and location of road weather stations and, in combination with Ice Prediction technology, to warn as to where and when road surface is likely to have freezing conditions. It is regarded as a valuable tool to improve road safety and cut costs in winter road maintenance.

The technique involves the collection of surface temperature data over a series of winter nights, under different weather conditions, using vehicles which have been specially equipped with infra-red thermometers and data logging equipment. From the analysis of this data and the analysis of road and weather conditions the Thermal Maps are constructed .

Since its first independent development in the United Kingdom and Sweden in 1980's (Sugrue et al. 1983; Gustavsson & Bogren 1988; Thornes 1991), there has been some research which has looked at the reliability and repeatability of Thermal Mapping under different weather conditions in complex terrain (Belk 1992). Investigations have concentrated on the data collection equipment, particularly the stability (and thus reliability) of the infra-red thermometers used and also on repeatability of the temperature pattern under similar weather conditions.

In recent years, there has been progress in the development of the Thermal Mapping process. A mathematical filter has been applied to raw Thermal Mapping data to delete random errors and to make the analysis of data easier (Shao & Lister 1995) and recent developments in micro-electronics are now enabling the design of second generation data collection equipment. In order to assess the suitability of such new designs a comprehensive study of existing techniques was required.

A vast quantity of data has been collected from Thermal Mapping practice over the last 10 years (over 80,00 km by Vaisala TMI alone). The authors' intention is to examine further the repeatability of the Thermal Mapping technique. In this paper, the re-examination was based on two research routes and focused on Thermal Fingerprints, which are the fundamental building blocks of Thermal Maps.

2. Pattern of Temperature Variation

Thermal Fingerprints are graphical representations displaying the pattern of temperature variation along a short stretch of road network on an individual night. They are generated by processing the absolute temperature data which are plotted to show their deviation from the mean. The Pattern of road temperature variation is defined by the spatial distribution of temperature variation ('peaks' and 'valleys' in a fingerprint) and the magnitude (or amplitude) of that variation

The Spatial Distribution of road surface temperature variation is dictated by factors which include topography, altitude, surface construction and weather conditions. The influence of topography, altitude and surface construction is more or less systematic at a single point. These factors are responsible for the spatial distribution of 'peaks' and 'valleys' along the Thermal Fingerprints. Topographic features tend to reduce sky-view factor restricting the exchange of longwave radiation between the road surface and the atmosphere, whilst different road constructions release heat differentially depending on their thermal properties.

Weather condition can not be regarded as a systematic factor, especially on complex terrains. The magnitude of road surface temperature variation is influenced by the prevailing weather conditions. Clear, calm conditions, when there is maximum radiative heat loss from the road, result in the greatest magnitude of variation. Total low cloud cover results in the smallest magnitude of variation as radiative heat loss is at a minimum.

In order for Thermal Mapping to be relevant on most winter nights data collection is carried out under 3 defined weather conditions. These have been assessed (Sugrue et al. 1983; Thornes 1991) to be representative of the majority of weather conditions that are likely to prevail, when Thermal Mapping data can be useful. The Thermal Fingerprints are categorised as Extreme, Intermediate or Damped accordingly. Where Extreme refers to data collected under clear calm conditions, Damped refers to data collected under conditions with extensive low level cloud cover and Intermediate refers to clear windy conditions or calm conditions with an extensive cover of medium level cloud. The Standard Deviation of road surface temperature is a useful initial indication of the magnitude of RST variation and is therefore is helpful when categorising Thermal Fingerprint types. In general, the Extreme Fingerprints will have the greatest SD, Damped Fingerprint the smallest SD and Intermediate Fingerprint a moderate SD.

A valid quantitative technique is required to assess the similarity of Thermal Fingerprints once they have been initially classified using Weather Type (WT) and Standard Deviation. The authors have used Linear Correlation Coefficient (LCC) and Section Similarity Coefficient (SSC), defined in Section 3, to help categorising further. A high SSC value and high LCC value reflects close similarity and association between Thermal Fingerprint patterns.

3. Repeatability of Thermal Mapping

The analysis of reliability of Thermal Fingerprints in this paper is in twofold: correlation and similarity. For a given category of weather conditions and thus Fingerprints, there should exist a high degree correlation between any two independent and reliable runs and data series for any survey route. The linear correlation coefficient (LCC) of two data series is used to demonstrate such a dependence or reliance between them. For pairs of records (x_i, y_i), the coefficient is defined as

$$CC = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 (y_i - \bar{y})^2}}$$

where $\bar{x}$ is the mean of X, $\bar{y}$ is the mean of Y and i=1, 2, ..., N.

The other parameter used to quantify the repeatability of Thermal Mapping is called Section Similarity Coefficient (SSC). The SSC is used to measure the similarity of the spatial distribution of road surface temperature variation of Thermal Fingerprints. Here, a Section is defined by a number of sequential records with temperature difference between the Sectional Mean and each individual record less than 1.0° C. The Section is "cut-off" when its mean temperature differs from that of the next sequential record with minimum section length by more than 1.0°C. The minimum section consists of 20 metres of data records. Sections derived in this way reflect significant changes of RST along a survey route. For two independent data series (X and Y) in the same weather category, the mean temperature of a Section is compared to the Series Mean (Thermal Fingerprint mean) and is assigned either a positive (if Section Mean ≥ Series Mean) or negative (if Section Mean < Series Mean) sign in a consecutive order from the beginning to the end of the Series. If the signs of first Sections of both Series is positive (or negative), a=1 (or d=1). If the next sections keeps the same sign, a=a+1 (or d=d+1); otherwise, b=b+1 if the section temperature of series X is equal to or larger than its Series Mean and that of Series Y is less than its Series Mean, or d=d+1 on the other hand. The calculation of SSC is shown in Table 1. The higher the value of SSC between the two Series, the greater the similarity of Spatial Distribution of temperature between Thermal Fingerprints.

Table 1. Definition of section similarity coefficient (SSC)

		Series Y	
		>=mean	<mean
Series X	>=mean	a	b
	<mean	c	d

$$SSC = \frac{a + d}{a + b + c + d}$$

4. Experiments and data basis

Thermal Fingerprints were generated by conducting a series of Thermal Mapping data collection exercises across a defined set of test routes, under various weather conditions. The Fingerprints were categorised and their similarity assessed statistically.

4.1. Description of Thermal Mapping routes

In the early stages of Thermal Mapping development, an area surrounding the University of Birmingham, UK, was chosen as a research base. It consists of five research routes and covers total length of about 150 km (about 30 km for each route). Each route takes about 25 minutes to complete a single run from start to finish.. These routes are still used for the purposes of research, the testing of new equipment and training.

For the purpose of this paper, routes 3 and 5 have been chosen due to their varied topography, road construction, environment and traffic flow. Route 3 is predominantly urban running from the University of Birmingham northwards through the heart of the City along one of its main arterial roads, the A38. It travels through a series of tunnels under the City and also includes the particularly heavily trafficked 'Aston Expressway'. The route passes through Gravely Hill interchange ('Spaghetti Junction') before returning, via a similar route, southwards. In contrast, Route 5 encompasses a wide range of environments. It starts to the south of the Birmingham conurbation, running westwards along the M42 to the M5, taking in a significant area of concrete surface construction. It then turns north along the M5 before taking the A38 into the City. Before reaching the University, the route turns westwards once again to complete a circuit around the Bartley Green reservoir, covering rural and residential roads. The route then returns to the University via the suburb of Harborne.

4.2 Data Collection Procedure

On 17th December 1992, a survey for the purpose of training was carried out over the research area. Two years later, more Thermal Mapping was done in the area in order to test a new thermometer and data logging system. It should be noted that not all research routes were surveyed on any one night. Some routes, however, were run twice on the same night (called 'double-run'). Information about dates, weather and road surface conditions of these training surveys is summarised in Table 2. Each Thermal Fingerprint for a given night was categorised according to Weather condition and SD (see Table 3). Once this had been done the Fingerprint data from the same route and in the same category was compared using statistical parameters of LCC and SSC. These results are detailed in Table 4.

Table 2. Weather and road surface conditions of Thermal Mapping surveys
(Research routes, Birmingham, UK)

Test number	Date	Cloud amount (oktas)	Cloud type	Wind speed	Visibility	Road surface
1 and 2	24/01/1995	7	low	moderate	good	dry
3 and 4	19/04/1995	2	high	light	good	dry
5	03/01/1995	0	-	calm	good	dry
6	17/12/1992	0	-	calm	good	dry
7	27/01/1995	0	-	calm	good	damp (dew)

Table 3. Minimum, maximum, mean and standard deviation (SD) of road surface temperature (deg C) and category of Thermal Mapping Fingerprints of routes 3 and 5

Test	Route 3					Route 5					
	Min	Max	Mean	SD	Category		Min	Max	Mean	SD	Category
1	4.2	9.4	5.5	0.7	D		4.4	7.7	6.1	0.6	D
2	4.2	9.2	5.1	0.8	D						
3	3.7	12.5	6.5	1.4	I		-	-	-	-	-
4	3.8	12.4	6.4	1.4	I						
5	-	-	-	-	-		-4.9	.2	0.3	2.0	E
6	-1.2	11.6	3.0	2.1	E		-2.2	6.8	2.5	2.1	E
7	-1.3	7.7	1.5	1.4	E						

Note: D - Damped; I - Intermediate; E - Extreme.

Table 4. Correlation Coefficient (CC) and Section Similarity Coefficient (SSC) (All correlation coefficients are significant at α=1%)

Category	Route 3				Route 5			
	No. of records	CC	No. of sections	SSC	No. of records	CC	No. of sections	SSC
Damped	3178	0.87	10	0.90	-	-	-	-
Intermediate	5602	0.97	19	0.95	-	-	-	-
Extreme	5607	0.90	27	0.78	8373	0.79	18	0.89
Average	4796	0.91	19	0.88	-	-	-	-

5. Analyses

In this reliability and repeatability analysis, either a double-run or two runs on different dates under the same weather type is regarded as two independent runs. For the double-runs at damped and intermediate nights, data series of the first run is compared to that of the second run (for route 3 only). For extreme Fingerprints, date series obtained on different nights are compared for both route 3 and route 5. The results of the analysis are given in Table 4. It is seen from the table that strong correlations exist in damped, intermediate and extreme Fingerprints, with a minimum correlation coefficient 0.79. The significance of correlation is tested by t-test. Before the t-test, however, the assumption that N observation pairs come from a normal population is tested by the Kolmogoroff- Smirnoff (K-S) method (Sachs, 1978). The results show that the population underlying the samples obey a normal distribution function and all correlation coefficients which varies from 0.79 to as high as 0.97 are significant at the α level 1%. The interpretation of the results of tests is that each record in the second data series is highly predictable based on the first data series. In other words, the two series are highly associated and reliable. The section similarity coefficient varies from 0.78 to 0.95 with a mean 0.88. This mean that the pattern of distribution of the data series compared are repeatable for the same Thermal Mapping category. It is clear from the table that both double-runs (in Damped and Intermediate categories) which were made on the same route on the same night and the separate runs (in Extreme categories) which were made on different nights are highly similar and repeatable.

6. Discussion and summary

It is critical that the statistical technique and methodology is used in its entirety to assess levels of similarity. For example the test data series 6 and 7 from Route 3 illustrate that it is not enough just to compare the LCC and SSC values. Its LCC and SSC values are high, 0.90 and 0.78 respectively, as one might expect as both sets of data where collected under the weather condition described as Extreme. A comparison of the SD reveals that the Thermal Fingerprint for Test 6 is 1.4°C and for Test 7 it is 2.1°C. Such a difference casts some doubt as to whether these two tests of Route 3 should be put in the same category. Whilst the weather condition was Extreme on 27th January 1995 (see Test 7), in that weather conditions were clear and calm, the road surface itself was damp as a result of dew formation. The effect of moisture on the road surface is, usually, to reduce the magnitude of temperature variation. From an operational perspective this emphasises the importance of having a full appreciation of the conditions under which Thermal Mapping data is collected and the impact they will have on the Thermal Fingerprints.

The results clearly show that Standard Deviation is a useful additional indicator, to the observed weather conditions, for categorising the Thermal mapping data into the relevant weather type. Section Similarity Coefficient and Correlation Coefficient, together, are good indicators of the similarity of Thermal Fingerprints within a category. The data illustrates that the Thermal Mapping technique used by the authors produces reliable results and that the pattern of road surface temperature is reproduced at the time of minimum temperature under similar weather conditions.

In conclusion, this paper shows that the products of Thermal Mapping of road surface temperatures under strict quality control are reliable and repeatable, in terms of Correlation and Similarity Coefficients (with both mean values 0.88).

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