Meteorol. Appl. 3, 325–330 (1996)

Thermal mapping: reliability and repeatability

J Shao, P J Lister, G D Hart and H B Pearson, *Vaisala TMI Ltd, Vaisala House, Bristol Road, Birmingham, UK*

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 similar night. 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 in a county. This variation in road-surface temperature (RST) 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 for quantifying this variation and presenting the data usually as a series of colour-coded maps. It is based on the established fact that the pattern of spatial variation of road-surface temperature is reproducible on a night-by-night basis, during the winter period, under similar weather types. For the purpose of winter road maintenance, this technique is used shortly before dawn to measure minimum surface temperature. Each Thermal Map defines the pattern of minimum road-surface temperature variation which will occur under different weather conditions.

More than 100 000 km of Thermal Mapping has been carried out on roads and airports in Europe, 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 the road surface is likely to have freezing conditions. It is regarded as a valuable tool for improving road safety and cutting 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 the 1980s (Sugrue *et al.*, 1983; Gustavsson & Bogren, 1988; Thornes, 1991), there has been some research which has looked at the value of the application, and the reliability and repeatability of Thermal Mapping under different weather conditions in complex terrain (Bogren *et al.*, 1992; Gustavsson & Bogren, 1993). Some other 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 (Belk, 1992), and recent research has been carried out to improve the quality of raw Thermal Mapping data (Shao & Lister, 1995).

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. 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. In this paper, a Thermal Fingerprint is a graphical representation of the departure of RST (y-axis) from its mean against distance (x-axis) for a particular route on a given night.

2. Pattern of temperature variation

Thermal Fingerprints display 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 the sky-view factor (Oke, 1978), restricting the exchange of long-wave radiation between the road surface and the atmosphere, whilst different road constructions release heat differentially depending on their thermal properties.

Weather condition cannot 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, combined with humid air (and strong winds), results in the smallest magnitude of variation as radiative heat loss is at a minimum (and horizontal advection and vertical air mixing are at maxima).

In the United Kingdom, in order for Thermal Mapping to be relevant on most winter nights, data collection is carried out under three 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. 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 (SD) of road-surface temperature is a useful initial indication of the magnitude of RST variation and is therefore 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 according to weather type and SD. The authors have used Linear Correlation Coefficient (LCC) and Section Similarity Coefficient (SSC) (defined in section 3) to help categorising further. It will be seen from their definitions that high SSC and LCC values reflect close similarity and association between Thermal Fingerprint patterns.

3. Repeatability of Thermal Mapping

The analysis of reliability and repeatability 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 of correlation between any two independent and reliable runs and data series for any survey route. The LCC, which varies between −1 and +1, is therefore used to describe such a dependence or reliance between two data series. The higher the LCC value, the more reliable the series.

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 (or 'pattern') 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 (20 metres) by more than 1.0 °C. To form a new section, it is required that the section consists of at least 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 $\geq$ series mean) or negative (if section mean < series mean) sign in a consecutive order from the beginning to the end of the series.

Let a (or d) denote the number of sections of both X and Y being above (or below) average, b (or c) the number of sections above (or below) average in X with every corresponding section in Y below (or above) average (see Table 1). If the signs of the first sections of both series are positive (or negative), $a = 1$ (or $d = 1$). If the next sections keep 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

Table 1. *Definition of section similarity coefficient (SSC)*

		Series Y	
		$\geq$ mean	$<$ mean
Series X	$\geq$ mean	a	b
	$<$ mean	c	d

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

shown in Table 1. The value of SSC varies from 0 (indicating no 'match') to 1 (perfect 'match'). The higher the value of SSC between the two series, the greater the similarity of spatial distribution of temperature between the two Thermal Fingerprints.

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 a 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

On 17 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 along the same direction as that of the first run on the same night (called 'double-run') immediately after completing the first run and returning to the initial point (in about 30 minutes from the beginning of the first run). Most of the runs were started and finished between 0230 and sunrise. Information about dates, weather and road-surface conditions of these training surveys is summarised in Table 2. One example of a Thermal Fingerprint is shown in Figure 1. It is seen from the figure that the temperature was dramatically higher when the survey vehicle went into tunnels and temperature dropped significantly when the survey was undertaken on the elevated Aston Expressway. Existence or lack of roadside trees and buildings also results in a significant change of RST.

Each Thermal Fingerprint for a given night was categorised according to weather condition and standard deviation of surface temperature (see Table 3). Once this had been done the Fingerprint data from the same route and in the same category were compared using statistical parameters of LCC and SSC.

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, the data series of the first run is compared with that of the second run (for Route 3 only). For extreme Fingerprints, data series obtained on different nights are compared for both Route 3 and Route 5. The number of data pairs in the comparison is about 5600 for Route 3 and 8300 for Route 5. The results of the analysis are given in Table 4. It is seen from the table that strong correlation exists in damped, intermediate and extreme Fingerprints, with a minimum correlation coefficient 0.88 for damped Fingerprint. This means that under damped weather condition, the variation of RST from one point to the next along the road stretch is less significant or 'sharp' than those under intermediate and extreme conditions, leading to a 'vague' relationship and thus low LCC between the two runs.

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, 1982). The results show that the population

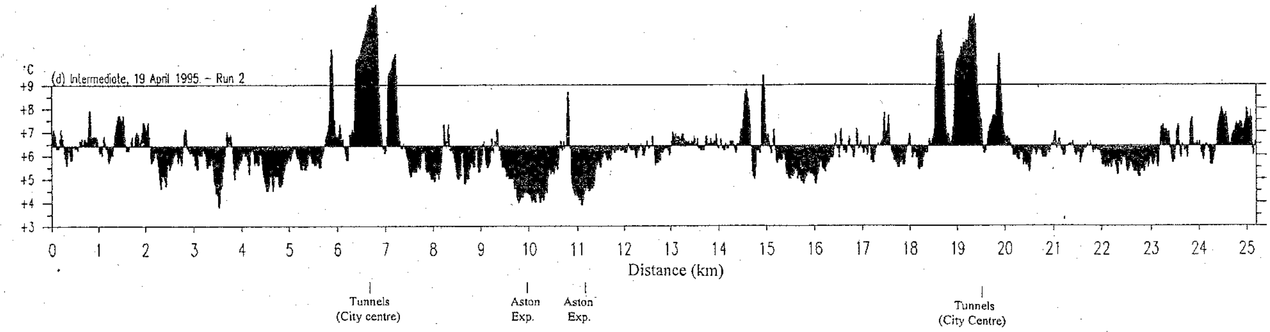

Figure 1. *Fingerprint of intermediate run (Route 3, 19 April 1995).*

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

Test number	Date	Cloud amount (oktas)	Cloud typle	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 (°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. *Linear correlation coefficient (LCC) and section similarity coefficient (SSC) (all correlation coeficients are significant at* $\alpha = 1\%$*)*

Category	Route 3				Route 5			
	No. of records	LCC	No. of sections	SSC	No. of records	LCC	No. of sections	SSC
Damped	3178	0.88	9	1.0	—	—	—	—
Intermediate	5602	0.98	40	0.95	—	—	—	—
Extreme	5607	0.90	23	0.74	8373	0.88	42	0.86
Average	4796	0.92	24	0.90	—	—	—	—

underlying the samples obey a normal distribution function and all correlation coefficients which vary from 0.88 to as high as 0.98 are significant at the 1% level. The interpretation of the results is that each record in the second data series is highly predictable based on the first data series, or the variation of RST in the two series keeps the same pace and direction. In other words, the two series are highly associated and reliable.

On the other hand, the section similarity coefficient varies from 0.74 to 1.0 with a mean 0.89. The results show that it is easiest to recognise or divide different sections for damped fingerprints (SSC = 1.0), and most difficult for extreme fingerprints (SSC = 0.74 and 0.86). However, all SSC values are close or above 0.75, which is considered to be significant. The results demonstrate that the patterns of temperature distribution (in terms of sections with different temperature) of the series in comparison mostly remain the same or are repeatable for the same Thermal Mapping category. It is also noticed from Route 3 that the intermediate Fingerprint has the maximum number (40) of individual sections. This means that its temperature is the most variable in a small spatial scale. The division of sections of the intermediate survey is demonstrated in Figures 2 (for section length) and 3 (for mean section temperature). The figures show that its section length varies from 300 m to 2950 m and its mean section temperature changes within 4.4 and 11.7 °C.

It is clearly seen from Table 4 and Figures 2 and 3 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. All these results demonstrate that under strict quality control, Thermal Mapping is a reliable technique for representing spatial variation of road-surface temperature repeatedly.

6. Discussion and summary

It is critical that the statistical technique or methodology is used in its entirety and combined with the valuable experience of surveyors to assess levels of reliability and repeatability of Thermal Fingerprints. 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. Their LCC and SSC values are high (0.90) and moderate (0.74). Therefore, one might expect that both sets of data collected under the weather condition described as Extreme can be put into the same Thermal Fingerprint category of Extreme, although a moderate SSC value would have raised some question on it. A further 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 27 January 1995 (see Test 7) when weather conditions were clear and calm, the road surface itself was damp as a result of

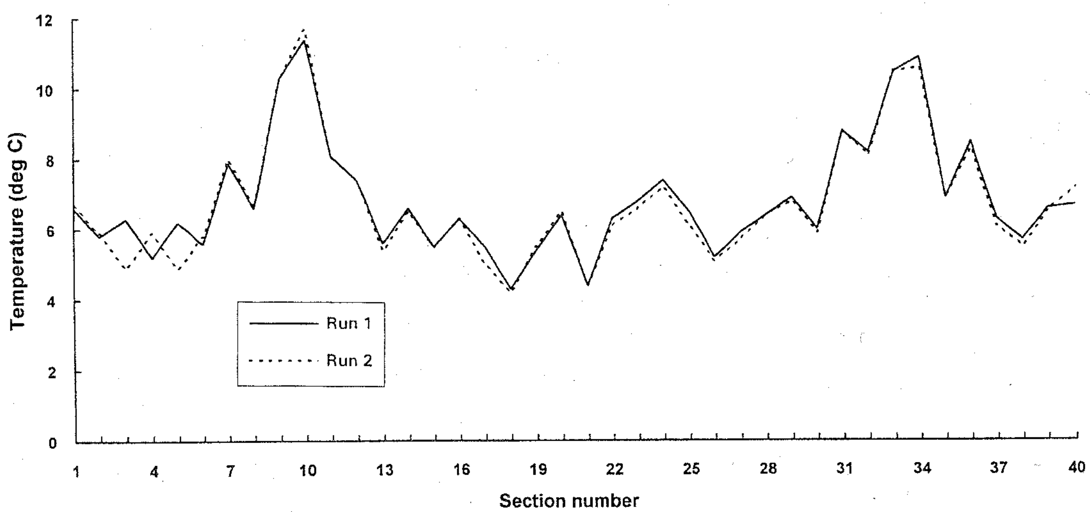

Figure 2. *Length of each section of intermediate survey (Route 3, 19 April 1995).*

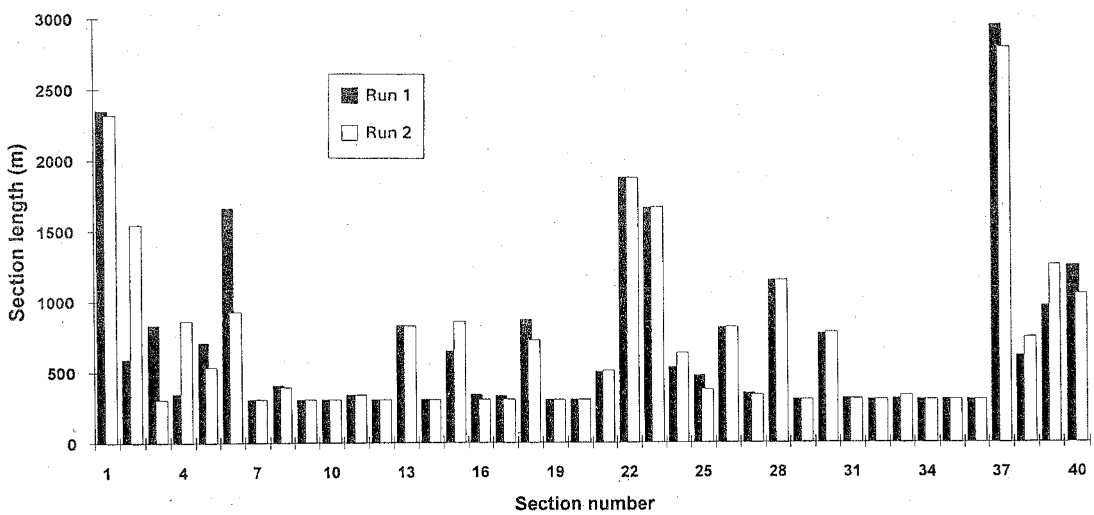

Figure 3. *Mean temperature for each section of intermediate survey (Route 3, 19 April 1995).*

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 are 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. The section similarity coefficient and linear correlation coefficient, together, are good indicators of the similarity of Thermal Fingerprints within a category. The data illustrate 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 around 0.9).

Acknowledgements

The authors wish to thank staff of Vaisala TMI for collecting and providing data needed in the study. Thanks also go to Dr. R. W. Riddaway and an anonymous referee for their helpful comments and suggestions.

References

Belk, D. G. (1992). Thermal Mapping for a highway gritting network. PhD Thesis, University of Sheffield, UK.

Bogren, J., Gustavsson, T. & Lindqvist, S. (1992). A description of a local climatological model used to predict temperature variations along stretches of road. *Meteorol. Mag.*, **121**: 157–164.

Gustavsson, T. & Bogren, J. (1988). Thermal mapping by use of infrared technique. In *Proceedings of the 4th International Conference on Weather and Road Safety*, Florence, Italy, 8–10 November 1988.

Gustavsson, T. & Bogren, J. (1993). Evaluation of a local climatological model – test carried out in the county of Halland, Sweden. *Meteorol. Mag.*, **122**: 257–267.

Oke, T. R. (1978). *Boundary layer climates*. Methuen & Co Ltd, London, 372 pp.

Sachs, L. (1982). *Applied statistics: a handbook of techniques*. (Translated by Z. Reynarowych). Springer-Verlag New York Inc., New York, 706 pp.

Shao, J. & Lister, P. J. (1995). Data filtering for Thermal Mapping of road surface temperatures. *Meteorol. Appl.*, **2**: 131–135.

Sugrue, J. G., Thornes, J. E. & Osborne, R. D. (1983). Thermal Mapping of road surface temperatures. *Phys. Technol.*, **14**: 212–213.

Thornes, J. E. (1991). Thermal Mapping and road-weather information systems for highway engineers. In *Highway Meteorology*, ed. by A. H. Perry & L. J. Symons, 39–67. E & FN Spon, London.