Fuzzy Categorization of Weather Conditions for Thermal Mapping

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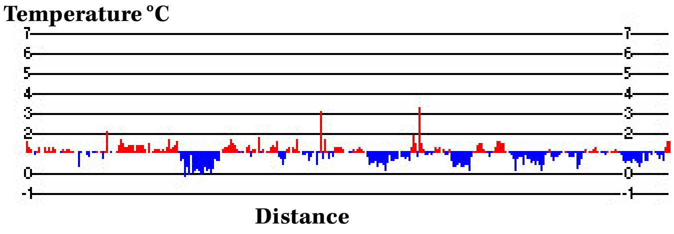
Thermal mapping is a technique using a vehicle-mounted infrared radiometer to measure the variation of road surface temperature (RST). Conventionally, the technique is conducted under three qualitatively categorized weather conditions: extreme, intermediate and damped. These three categories represent basic weather patterns and are widely used in thermal mapping. In real-time operation, however, determination of the weather category is hampered due to the lack of systematic classification. Furthermore, certain skills and knowledge of both thermal mapping and meteorology are required. As the thermal mapping technique is developing in the direction of providing a platform for automatic and dynamic forecasting of RST over an entire road network, it is necessary to have a sort of hands-off, quantitative, systematic, accurate and fast categorization of weather conditions for thermal mapping. For this purpose, the relationship between the change of weather conditions and variation of RST was analysed in order to define a time domain for application of a reliable categorization algorithm. Fuzzy membership functions were then established, based on cloud amount, cloud type, wind speed and relative humidity, to compose a fuzzy function of weather categorization for thermal mapping. The results of validation for the fuzzy categorization show that the algorithm can become a useful tool for thermal mapping.

1. Introduction

As a part of an integrated winter road-weather service system, the thermal mapping technique, which uses vehicle-mounted infrared radiometers to detect spatial variation of road surface temperature in a road network, plays an important role in revealing real-time spatial distribution of cold and warm road sections in a road network. Combined with a site-specific road ice prediction model, the technique assists meteorologists, as well as highway engineers, in the identification of where and when a stretch of road is likely to fall below freezing point.

In theory, a thermal mapping survey can be carried out at any time and under any weather condition. In practice, however, the survey is usually done at the time shortly before dawn when minimum surface temperature often occurs, and under a limited number of representative weather categories or patterns to avoid too many surveys and unnecessarily high costs. Such representative weather conditions and corresponding thermal mapping products (called thermal fingerprints) are categorized as extreme, intermediate and damped. While an extreme thermal fingerprint shows the largest spatial variation of RST, a damped fingerprint represents the smallest variation. An intermediate fingerprint is between the two. An example of an extreme thermal fingerprint in Birmingham, UK, is shown in Figure 1. It can be seen from the figure that details of the spatial variation of road surface temperature are revealed by the thermal mapping technique. It is obvious that the technique is a helpful tool not only in the study of road weather, but also in other micro-meteorological studies.

Fig 1. An example of a thermal mapping fingerprint



It has been widely recognized that an extreme weather pattern appears on calm, clear and relatively dry nights usually related to anticyclonic conditions. On the other hand, a damped pattern corresponds to cyclonic conditions with extensive cloud cover and humid air. Any weather conditions between these two extremes (e.g., moderate winds and some clouds) are usually classified into an intermediate category (e.g., Thornes 1991). In defining weather conditions in this way, there is inevitably vagueness concerning descriptive words such as 'moderate' winds and 'extensive' or 'some' clouds. Although such vague terms may be understandable to experts, they are not interpretable to amateurs or computers. This poses a problem to the further development of the technique in the context of an automatic, full-time operational application.

This paper deals with the vagueness or fuzziness problem by using fuzzy set theory to develop a practical algorithm for the categorization of weather conditions for application to thermal mapping. First, it investigates the relationship and response between road surface temperature (RST) and weather conditions. The investigation provides necessary information about the time domain (or period) during which weather conditions and thermal mapping products are likely to fall into the same category and the proposed fuzzy algorithm becomes effective. Second, a number of significant meteorological parameters are chosen and their membership functions are established. Thirdly for verification, fuzzy categorization based on these functions is carried out on examples collected in Birmingham. Finally, some conclusions are drawn together with a discussion on the usefulness, limitations and future development of the proposed fuzzy set algorithm in thermal mapping.

2. Thermal mapping and weather conditions

A lot of factors affect the energy balance of a road surface and thus its surface temperature. These factors can be briefly classified into permanent and non-permanent ones. Permanent factors include geographical location (e.g., latitude and altitude), topography (hills, valleys or slopes), road construction (structure and materials of road surface and sublayers), and localized features such as woods, lakes and urban heat island, which are sometimes also regarded as topographical features. These factors are called permanent because they change little or their influence on surface temperature is more or less at a certain level or 'fixed' during a winter season. In contrast, there are two non-permanent factors: traffic and weather. Compared with the factor of weather, traffic has a far less significant influence on RST and it changes little during weekdays. Therefore, the only important and changeable factor influencing RST is weather. Table 1 lists these factors and their possible effects on RST.

TABLE 1. Common factors controlling daily variation (mean and amplitude) of RST and their significance

Factors	**Significance**
Latitude	Important in determining average thermal status or temperature in winter.
Longitude	Little impact.
Urban	Minor to moderate.
Topography	Varying locally and depending on scale and pattern of the topographical features and weather conditions; The effect, however, is nearly constant.
Road construction	Minor influence for basic and common roads.
Traffic	Generally small but could be large under heavy traffic and in rush hours.
Weather	Most significant and important, especially under a clear sky and with a calm wind.

It has been shown that under a certain weather condition (i.e., if the non-permanent weather factor is "fixed"), the spatial variation of RST over a road network appears in a consistent pattern (Shao *et al* 1996). This consistency enables thermal mapping to be conducted under only a few selected weather conditions. In the UK, the terms of extreme, intermediate and damped have been widely used in thermal mapping survey and data analysis (Thornes 1991; Belk 1992; Shao *et al* 1996). Although extensive knowledge, experience and criteria have been used by experts in the practice of thermal mapping, there has been little published information, except Belk's research (1992), about classification of weather conditions, which are described by continuous variable, for thermal mapping. Belk (1992) used the following criteria for defining three types of weather conditions:

Extreme: cloud £ 1 octa and wind speed £ 2m/s.
Intermediate: either cloud = 8 octas, wind speed = 0;
or cloud = 0, wind speed ⌧3m/s.
Damped: cloud ⌧7 octas and wind speed ⌧3m/s.

All of the above conditions apply from the start to the end of a survey.

There are two problems with the above. First, the criteria do not completely cover all possible combinations of some important weather parameters. For example, cloud type which is critically important for influencing the variation of RST is missing. Also, some weather conditions (e.g., when cloud amount is 3 octas and wind speed is 2m/s) are not included. The second problem lies with the period (start to end of a survey as suggested by Belk) to which these criteria are applied. Physically, there should be a time lag for RST to follow the change of weather condition due to the thermal inertia of a road's sublayers. For example, if the sky clears just before the start of a thermal mapping survey, RST will not drop significantly, even in an open field, until some hours later. Thermal mapping data collected at that time will not show the sharp contrasts between colder road sections in open fields and warmer sections sheltered by trees, hills or buildings. In this case, weather conditions may be extreme according to the above criteria, but the thermal fingerprint may be intermediate. Therefore, this will inevitably cause inaccuracy and inconsistency of weather and thermal fingerprint classification in some circumstances.

3. Weather impact on RST

It is seen from the above discussion that a complete and quantitative set of criteria for weather conditions (and thus thermal fingerprints) is needed, and that a time domain for application of the criteria should be clearly defined. In order to decide the time domain, a road ice prediction model called Icebreak (Shao 1990) is used to simulate the response of RST to the change of weather condition. The simulation aims to find out how fast RST respond to any possible change of weather conditions.

Both research and experience suggest that in thermal mapping, the most important and variable factors are cloud amount (CA) and cloud type (CT; 0 for no cloud, 1 for low cloud, 2 for intermediate cloud and 3 for high cloud) (Thornes & Shao 1991). These two factors are largely responsible for the course of RST and air temperature changes at night. Therefore, the model-based numerical test of time domain concentrates on these two factors. First, the model was run based on all actual inputs without change on any of input parameters. This is called the original run. Then, the test was carried out by varying one of the two factors at a time and keeping other factors constant. It is called a perturbed run. By comparing the original and perturbed runs, the model simulation is able to reveal the possible impacts of change of weather condition on RST. Since weather impact on RST is strongest under extreme conditions, an extreme night (December 16-17, 1992) at Chapman's Hill (site code WN003) near Birmingham in England is selected for the test.

During the daytime of December 16, 1992, the sky was overcast with low clouds at the Chapman's Hill site. Middle clouds replaced low clouds shortly before sunset at 1545. Around midnight, the sky cleared and remained clear until shortly after sunrise (0835). Roadside measurements of air temperature, dew point, wind speed and precipitation were collected at a roadside automatic weather station. Cloud data were provided by the nearby Birmingham Weather Centre of the UK Meteorological Office. A comparison between the model-based values and surface sensor measurements at the test site on an hourly basis showed that the model's 24 hour simulation error has a bias of -0.02°C and an RMS error of 0.71°C. A negligible bias and a small RMS error mean that the model can be regarded as a reliable tool to represent the change of RST during the night.

Four perturbed runs were designed with cloud amount and cloud type set at +/-2 octas and +/-1 level respectively. The perturbation was introduced at 1900 (about 3 hours after sunset) and maintained for 3 hours (since all inputs were in a 3-hourly interval). This means that the perturbation disappeared at 2200. The results of the original and perturbed runs are shown in Figure 2. It is seen from the figure that the difference of RST between the original and perturbed runs develops rapidly when a perturbation is imposed. The difference becomes highly significant at 2100 to 2200, and then decreases after disappearance of the perturbation. The figure shows that the impact of cloud perturbation on road surface temperature becomes negligible after 0300, or 5 hours after the perturbation was terminated.

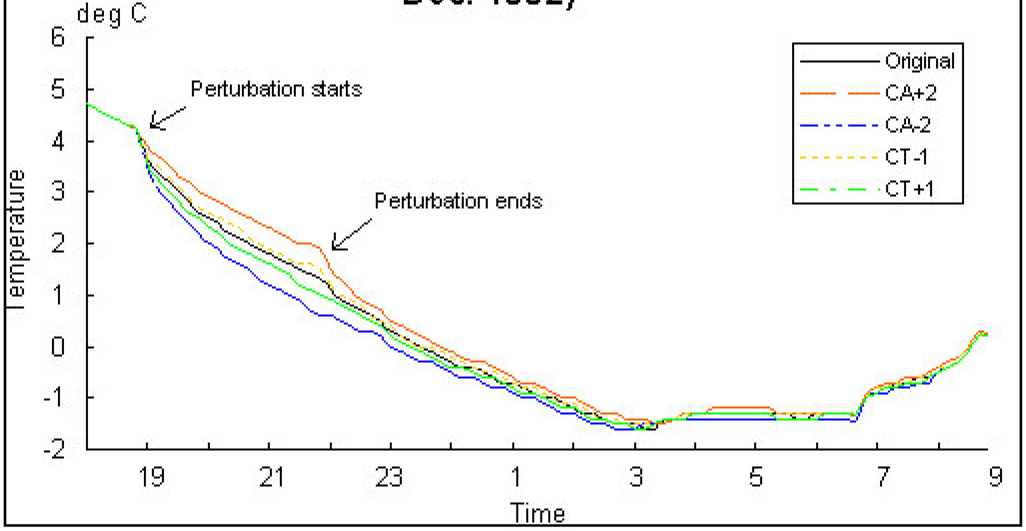
The magnitude of the perturbation introduced in this example is not great and can be reasonably expected to exist between any two similar nights. The example shown in Figure 2 indicates that the impact on RST at a night of a change of weather condition that can be expected in winter increases gradually and becomes most significant after 2-3 hours. The impact is likely to last about five hours.

Further evidence supporting the results shown in Figure 2 is obtained by an autocorrelation analysis of RST series. In the analysis, an autocorrelation coefficient (ACC) is defined by

$$ACC(\tau) = \frac{1}{n-\tau}\sum_{i=1}^{n-\tau}\left(\frac{T_i-\overline{T}}{s}\right)\left(\frac{T_{i+\tau}-\overline{T}}{s}\right) \qquad t=1, 2, ..., m. \qquad (1)$$

where, *n* is number of temperature records (T), $\overline{T}$ and *s* are estimates of mean and standard deviation of the temperature respectively, t is a time lag in hours and *m* is the maximum lag (=24 hours). A high value of ACC(t) means that the temperature at time *i* has a significant influence on the temperature at *i*+t. The analysis was carried out at five automatic roadside weather stations with hourly measurements of RST. The five stations are: Chapman's Hill (WN003, 13/12-30/12/1988) and Leeming airfield (LM001, 02/03-23/04/1993) in the UK, San Pietro (SM001, 19/01-16/03/1994) in Italy, Kvassheim (RL002, 10/02-18/02/1994) in Norway and Beekbergen (GN001, 13/02-21/02/1994) in the Netherlands. Results of the analysis are displayed in Figure 3 for t=1, ..., 12. Generally, ACC falls towards zero fairly rapidly at the first several time lags. If an ACC below 0.4 is regarded as insignificant, it can be generally said to "cut off" at t=5 to 6 hours in the figure. This indicates that RST has a good "memory" of up to five or six hours, or in other words, road

FIG. 2. Variation of RST due to perturbation in cloud amount and type (Chapman's Hill, 16-17 Dec. 1992)



surface thermal status at time *i* has a much reduced or insignificant impact after *i*+5 hours. As RST is largely controlled by weather conditions, this result implies that the influence on road surface temperature of a change in dominant weather condition becomes insignificant after 5-6 hours.

Both numerical simulation and statistical analysis demonstrate that

- the influence of a change in dominant weather condition on RST is most significant after 2-3 hours and negligible after 5-6 hours of the beginning of the influence;
- accurate weather information is essential for delivering reliable thermal mapping results. Therefore, a representative weather category for thermal mapping should consider not only the weather condition when a survey is being undertaking, but also the conditions several hours before the survey.
- weather conditions under which thermal mapping is being conducted should be consistent and stable for several hours (including the time for the survey), in order for the road surface to reach thermal equilibrium and to allow RST to respond fully and truly to the governing weather conditions;
- thermal mapping should be carried out once a certain weather condition has persisted for 2 to 3 hours;
- a proper algorithm or method to classify weather conditions and thus thermal fingerprints should have a time domain of 2-3 hours plus the duration of the survey.

4. Fuzzy categorization

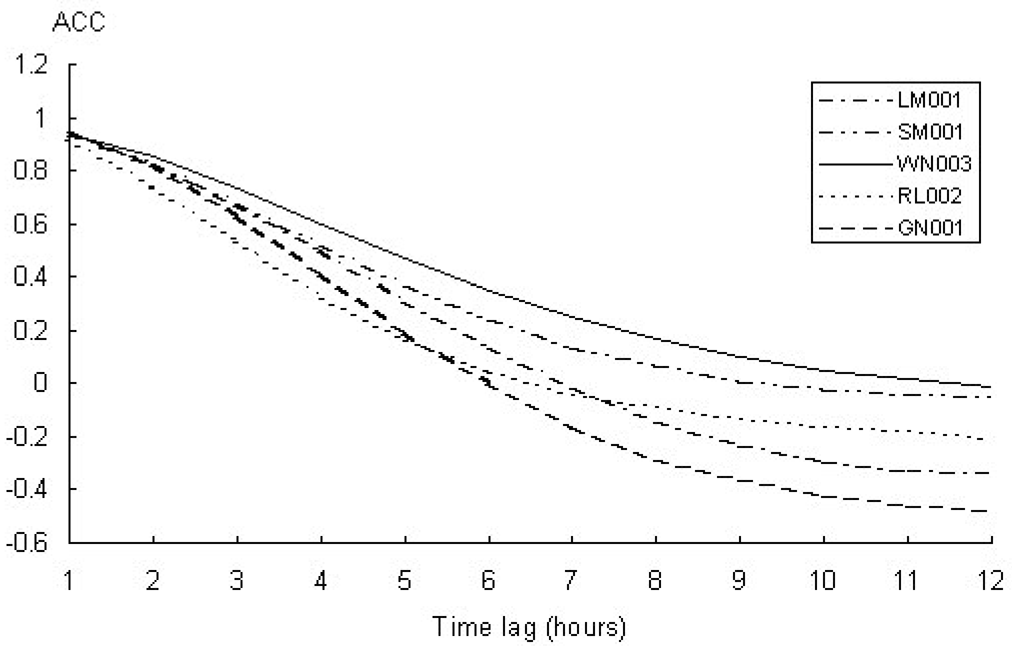
While most traditional tools for classification are crisp (i.e. yes-or-no type), fuzzy set theory is able to deal with phenomena with vague criteria or "borders" (i.e. more-or-less type) of classes. In thermal mapping, it is neither practical nor reasonable to draw a crisp, deterministic and precise border between extreme, intermediate and damped categories. For example, it is not certain if a weather condition with 2 octas of high cloud and wind speed 2m/s (a non-extreme category according to Belk) will result in a significant difference in RST, compared to that with 1 octa of medium cloud and wind speed 2m/s (an extreme condition). As the borders of classification of weather conditions in thermal mapping are non-crisp, the problem should be dealt with by fuzzy set theory (Zadeh 1965; Zimmermann 1991). Research has shown that fuzzy set theory can be a valuable tool for meteorologists (e.g. Cao & Chen 1983; Boreux 1994; Kuciauskas *et al.* 1998; Maner & Joyce 1997; McBratney *et al.* 1985; Murtha 1995).

In fuzzy set theory, if X is a collection of weather conditions denoted by x, a fuzzy set (A) of certain weather conditions in X is a set of ordered pairs:

$$A = \{(x, \mu_A(x) | x \in X\}$$
(2)

where, $\mu_A(x)$ is called the membership function or grade of membership of x in which maps X to the membership space M. Here, fuzzy set is called normal as the value of its membership function is limited to the values between 0 (lowest grade of membership) and 1 (highest grade of membership). In

FIG. 3. Autocorrelation coefficients (ACC) of RST



the fuzzy set theory, the membership function is a crucial component and is usually defined or determined by knowledge and experience.

For thermal mapping, cloud amount (x1; octas), cloud type (x2; 0-3), wind speed (x3; m/s) and relative humidity (x4; %) are the four most important weather factors governing the variation of RST. For the convenience of expression of its membership function, cloud type takes the value of 0 for no cloud, 1 for high cloud, 2 for intermediate cloud and 3 for low cloud in this paper. Research (Thornes & Shao 1991) and operational experience indicate that less cloud amount, higher cloud type, weaker winds and a drier atmosphere are likely to result in an extreme thermal fingerprints. Therefore, the membership functions of each of the factors are defined as

(x1) = 0 for x1=0 octa
= 0.92*exp(x1/10)-1 for x1⊠1
octa. (3)

(x_2) = 0 for x2 = 0
= for x2 >
0. (4)

(x_3) = 0 for x3 £ 2m/s
= $\ln[1 + 0.22(x_3-2)]$ for 2 < x3 < 10m/s
= 1 for x3 ⊠
10m/s. (5)
and

(x_4) = 0 for x4 £ 70%
= for x4 > 70%. (6)

The four membership functions are displayed in Figures 4(a-d). The figures show grade of membership of each individual factor. The combined effect of these factors on weather categorization in thermal mapping is expressed in the function

$$\mu_A(x) = [\mu_A(x_1) \cap \mu_A(x_2)] \cup [\mu_A(x_3) \cup \mu_A(x_4)] \quad (7)$$

where fuzzy intersection operator () and union operator () are defined as "min" and "max" operations respectively. Weather categories () are determined by specified values of the combined membership function [Eq.(7)] as

(x) = 0 for extreme;
= 0.5 for intermediate;
= 1 for damped.

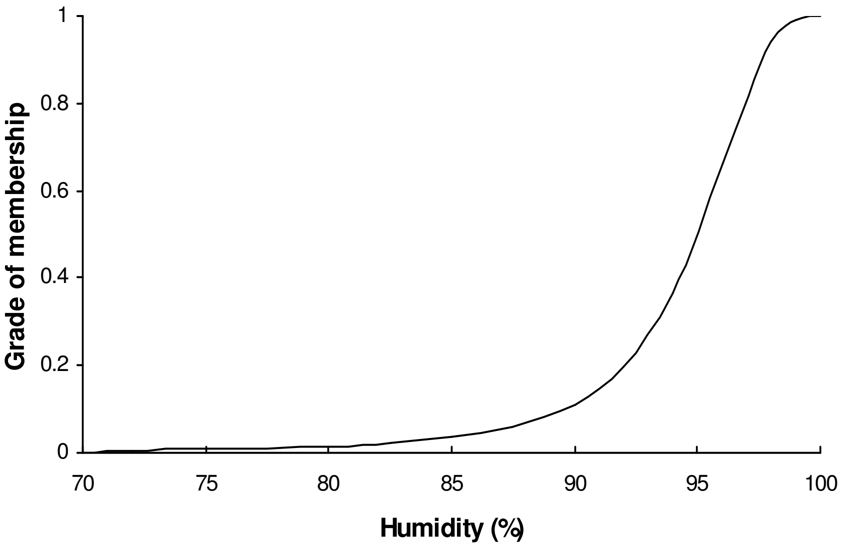
Equation (7) and the above criteria mean that

- cloud is largely responsible for creating an extreme condition (hence the minimum operation between x_1 and x_2);
- high wind speed or high humidity tends to produce a damped or intermediate condition (hence the maximum operation between x_3 and x_4).

For a given night, *y*, its categorization is determined by the closeness of the value of (*y*) to either 0 (extreme), 0.5 (intermediate) or 1 (damped). For the reasons discussed in Section 3, cloud amount, cloud type, wind speed and relative humidity should be the average values of 2 to 3 hours before the thermal mapping survey starts.

There are quite a few measures of fuzziness to indicate the degree of fuzziness of a fuzzy set. A simple measure is to regard an index of fuzziness as a normalized distance (Kaufmann

FIG. 4(d). Display of membership function of relative humidity



1975). In this paper, the degree of fuzziness of a real set [] belonging to one of the three pre-defined extreme, intermediate and damped sets [] is defined by the 'distance' between them:

$$f(A) = \frac{|\mu_A(y) - \mu_A(x')|}{\|\sup(x')\|} \quad (8)$$

where, = 0.25. The value of the index varies from 0 to 1. The index of fuzziness indicates confidence or certainty of the categorization. The higher its value (>0.75), the more uncertainty there is in the categorization.

5. Validation

To verify the algorithm expressed in Section 4, a number of representative thermal mapping surveys were studied. These sample surveys were based on a research route (#3) in southeast Birmingham. The route (together with others) has been used and is still used for the purposes of research, testing of new equipment and training. The route takes about 25 minutes to complete a single run from start to finish in order to minimize the unpredictable impacts of weather condition change on RST during the survey. In the study, hourly cloud data was again provided by the Birmingham Weather Centre of the UK Meteorological Office. Hourly wind speed and relative humidity (except the night of 19 April 1995 for which the data were from the Centre) were recorded by sensors at Chapman's Hill which is about 7 miles away from the starting point of the research route.

The date and observations of the variables required in the algorithm are shown in Table 2. In the table, the values of meteorological variables were averaged over a 5-hour period prior to the end of each survey. These averages represent the prevailing weather conditions before and during the surveys. The results of each survey have been categorized into damped, intermediate or extreme according to weather conditions by Vaisala's staff using their own criteria similar to Belk's and their personal experience after in-office data analysis. Standard deviation (SD) of RST is also shown in the table. The reason for using SD as an index of degree of RST development (or degree of spatial variation) can be found in Shao *et al* (1996). In general, a higher value of SD is related to extreme thermal fingerprints and a lower SD to damped fingerprints.

The category of thermal fingerprints derived by the fuzzy algorithm and its fuzziness [$f(A)$] are given in Table 2, together with the category by the staff without taking account of SD. The three categories are labelled as: E for extreme, I for intermediate and D for damped. It is seen from the table that the fuzzy method based on basic meteorological parameters produces the same categories as the conventional method that requires intensive before- and after-survey analysis, calculation and personal experience. It is noticed in the table, however, that the fuzziness of the survey on 27 January 1995 is so large (0.8) that some doubts can be cast regarding the categorization of this case. More detailed investigation (for instance, analysis of SD and road surface state) through the night reveals that the fingerprint should be recategorized more appropriately as a sub-category between extreme and intermediate.

The results show that the fuzzy method is not only able to categorize weather conditions and thermal fingerprints correctly, but also able to provide more information on the certainty of the categories by using a fuzziness index. The results also show that the current three (extreme, intermediate and damped) weather/fingerprint categories in thermal mapping are not enough to represent all possible situations.

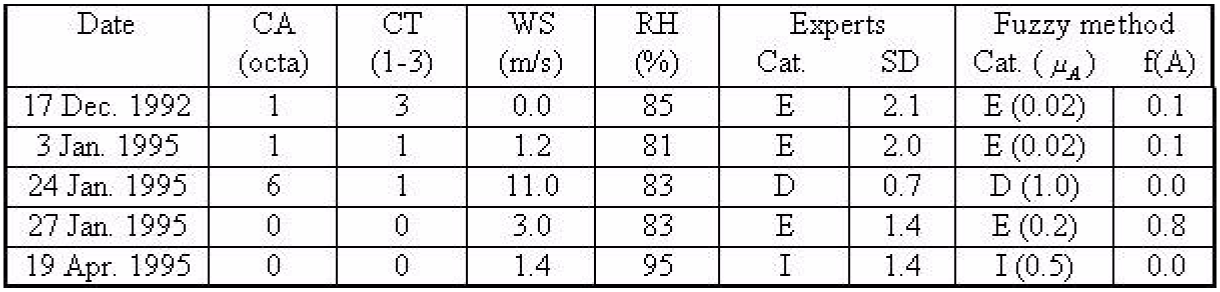
6. Discussion and summary

It has been shown that

- a proper time domain, during which weather conditions should remain relatively stable, is important for correct classification of weather conditions for thermal mapping; and
- the fuzzy categorization algorithm is able to emulate effectively experts in the task of classifying weather conditions affecting RST evolution.

It should be pointed out, however, that when weather conditions are subject to a rapid or significant change, it is difficult and impractical to identify accurately a dominant and representative weather category by the algorithm (or any other

TABLE 2. Examples of thermal mapping survey and their categorization (Cat.) by thermal mapping experts and the fuzzy method



Date	CA (octa)	CT (1-3)	WS (m/s)	RH (%)	Experts		Fuzzy method	
					Cat.	SD	Cat. (μ_A)	f(A)
17 Dec. 1992	1	3	0.0	85	E	2.1	E (0.02)	0.1
3 Jan. 1995	1	1	1.2	81	E	2.0	E (0.02)	0.1
24 Jan. 1995	6	1	11.0	83	D	0.7	D (1.0)	0.0
27 Jan. 1995	0	0	3.0	83	E	1.4	E (0.2)	0.8
19 Apr. 1995	0	0	1.4	95	I	1.4	I (0.5)	0.0

algorithm). Apart from this limitation, it can be seen that more detailed categories (e.g., sub-classes of each of the extreme, intermediate and damped categories) can be readily made by assigning different grade values of combined membership functions, using Eq.(7), to the sub-classes. For example, a value of 0.25 of Eq.(7) can be regarded as a border weather type between extreme and intermediate, and 0.75 as another border between intermediate and damped. These two borders can be used to derive two subcategories: extreme-intermediate and intermediate-damped. Adding the two extra categories will make the overall categorization more accurate and realistic.

In summary, it is demonstrated in this paper that a reasonable change of weather condition (e.g., cloud amount increases or decreases by 2 octas) in thermal mapping triggers a significant road surface temperature response. The impact (called "lagging effect") of weather condition on the temperature becomes significant after 2 to 3 hours and remains effective for about 5 hours. This means that a representative thermal mapping survey should take account of weather conditions 2 to 3 hours before the survey. Because of the lagging effect, a correct weather categorization of thermal mapping becomes possible when and only when weather conditions are relatively stable for a period of 2-3 hours preceding the survey, and during the survey.

This paper also shows that correct categorization of weather conditions can be achieved by using fuzzy set theory. The algorithm represented in this paper is quantitative, more practical and applicable than existing qualitative measures. It will help the current site-specific road weather warning system to provide automatic, full-time and accurate weather warnings in two dimensions across a road network in near future.

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