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Variation of winter road surface temperature due to topography and application of Thermal Mapping

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It is known that topography is an important factor controlling the variation of road surface temperature (RST). In order to explore possible relationships between RST and topography, the authors used Thermal Mapping data obtained by a vehicle-mounted thermometer in a mountainous area in Nevada, USA, under different weather conditions in December 1994. The data were validated against the measurements of road surface sensors. After that, a step-wise regression technique is employed to find out possible statistic relationships between RST and altitude at different surveying routes. It was found that the relationships exhibited different characteristics in different climate domains and under different weather types. In most cases, the relationships were non-linear. In order to obtain more information about the cause of the residuals and the variation, the error of regression fitting is related to near-ground meteorological parameters (air temperature, dew point and wind, etc.). This study proved that Thermal Mapping is a reliable and effective method to display spatial variation of road surface temperature.

1. Introduction

Information on spatial variation of road surface temperature (RST) in a road network is important for highway engineers, highway authorities and road users alike to know where and when ice or frost is likely to occur on a stretch of a road in winter. Such information provides highway authorities with a valuable reference tool to decide where and when to salt or grit only if necessary. Additionally, it helps highway engineers and meteorologists to decide the optimum location and number of ice monitoring instruments in order to maximise effectiveness while minimising cost in winter road maintenance. In recent years, winter road maintenance has aimed at ensuring that the right treatment is given at the right time and in the right place at the right cost to ensure that the road network is kept safe and clear of obstruction to users. In order to achieve this it is vitally important to identify not only when but also which sections of road are likely to become icy or frosty.

The likelihood of frost or ice forming is determined by the energy receipt and loss at the road surface. This energy flow is controlled by a number of environmental and meteorological factors (such as exposure, altitude, road construction, traffic, cloud cover, wind speed, etc.). These factors cause significant variation in RST from time to time and from one location to another. It has been shown and experienced in both research and winter maintenance operations that winter night-time road surface temperatures can vary by over 10° C across a road network in a county. Such variation in RST means that on a particular night, some stretches of road may fall below freezing point while others may remain well above freezing. Therefore, a selective de-icing or anti-icing programme based on pre-determined spatial variation in road network RST enables highway managers to utilise valuable resources effectively while reducing environment impact.

There have been several numerical models for site-specific forecast of road surface temperature (e.g. Nysten, 1980; Thornes, 1984; Rayer, 1989; Shao, 1990; Voldborg, 1992; Shao & Lister, 1996) for a specific site or point of a road network. However, the effects of environmental and meteorological factors on controlling energy balance on road surface are non-linearly mixed and are rather complex. Therefore, it is neither realistic nor economical to make forecasts along a road stretch by a site-specific model. Although one may argue that a meso- or smaller-scale model is able to do the job, it is noticed that road surfaces which present only a very small portion of terrain differ largely from surrounding soil or grass surface in both thermal and dynamic characteristics, and significant difference of surface temperature exists between road surface and its nearby soil surface. These facts cast some doubts on the power of any meso- and smaller scale models to predict temporal and spatial variations of RST in a road network. In contrast to these numerical models, some researchers (Bogren *et al.*, 1992; Gustavsson & Bogren, 1993) used a local climatological and statistical model to describe and predict the variations. However, there are two major drawbacks of such local statistic models. First, huge numbers of observations are needed to obtain reliable statistic relationships. Second, any such model derived in one area can not be applied to another area without major modification.

In the 1980s, a technique called Thermal Mapping was developed in the United Kingdom and Sweden (Sugrue *et al.*, 1983; Gustavsson & Bogren, 1988). The technique uses a vehicle-mounted infrared thermometer to detect the underlying road surface temperature and displays the variation of RST along the survey route in a form of a 'fingerprint'. A fingerprint is a graphical diagram showing the departure of RSTs from their mean (y-axis) against distance (x-axis) for a particular survey route on a given night. The combination (called 'thermal maps') of different survey routes and thus fingerprints at the same night in a road network represents the spatial variation of RST in the network under different weather conditions which are generally categorised as extreme, intermediate and damped (Thornes, 1991). Based on both thermal maps and the numerical model forecast at reference sites, one is able to see the likelihood of ice or frost on different parts of a road network. This paper examines the spatial variation of RST along a road stretch in Toiyabe National Forest, Nevada, and attempts to find statistical relationships to describe the variation. Then the usefulness, applications and values of Thermal Mapping in winter road maintenance are discussed.

2. Survey data

In December 1994, Thermal Mapping was carried out along a 250 km of highway network around the Lake Tahoe and Reno region of Nevada, USA, together with specific site measurements by five automatic road weather stations or Road Weather Information System (RWIS), located along State Route 431. The survey region is mountainous and has a dry climate. However, it shows a dramatic change of meteorological environment, mainly due to sharp changes in altitude over relatively short distances. The road network surveyed is subject to an altitude range of some 1100 m. The lowest altitude of about 1400 m is found along US395 around Reno and Carson City, and the highest is over 2500 m on SR431 where it passes over Mount Rose, on US50 at Spooner Summit and on SR207 over Daggett Pass.

In order to minimise the negative influence of altitude change on data analysis, the road network was divided

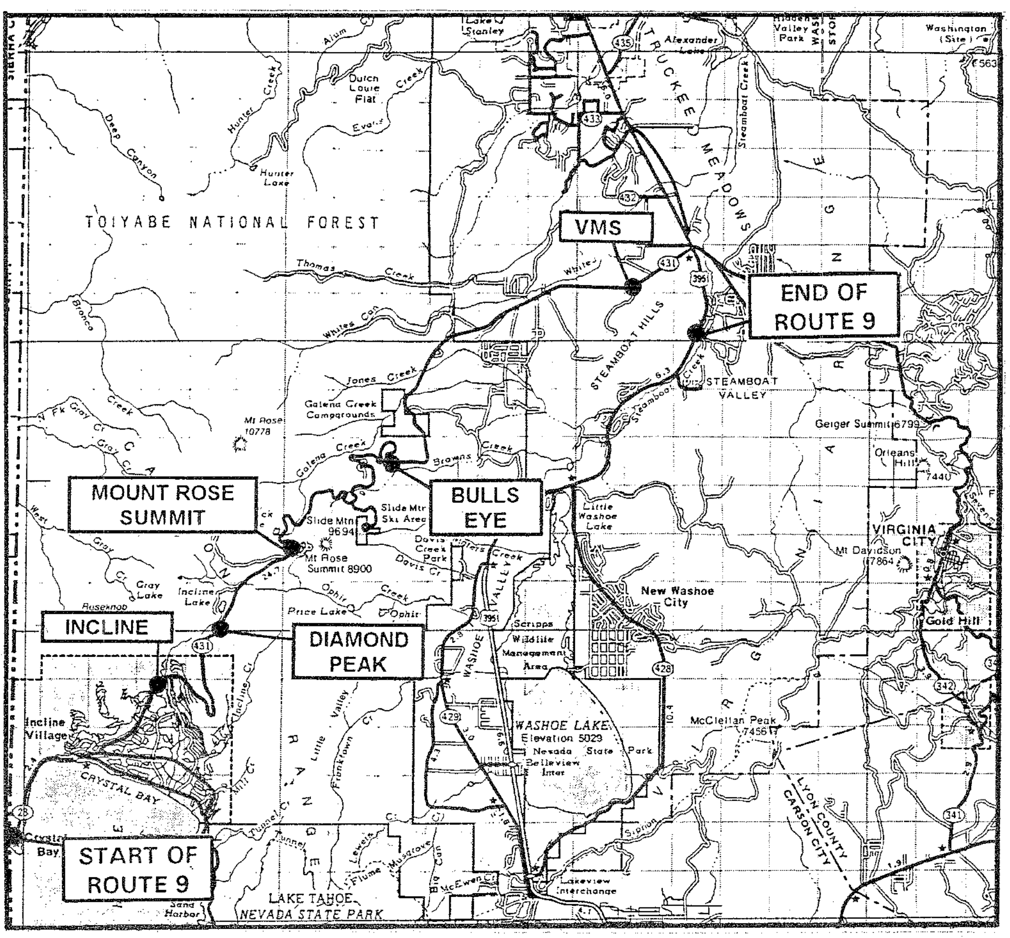

Figure 1. *Location of automatic road weather stations around Reno, Nevada.*

into nine Thermal Mapping survey routes, with each of the routes being approximately 30 km in length, in order to minimise any possible effects of non-linear temporal variation of weather conditions. The surveys took place under three weather conditions: extreme, intermediate and damped. Before, during and after each survey, automatic weather stations, located along survey route 9, monitored surface temperature, surface state, air temperature (T_a), relative humidity (RH), wind speed, etc. every 15 minutes. The five stations are: Incline, Diamond Peak, Mount Rose Summit, Bulls Eye and VMS. The location of these stations and survey route 9 are displayed in Figure 1.

The date and weather conditions under which Thermal Mapping surveys were done are summarised in Table 1. On the nights of 8/9 and 9/10 December 1994, the surveying region was covered by a high pressure resulting in dry, cold and stable weather conditions, and extreme thermal development or variation of RST over the whole road network. The nights of 10/11 and 13/14 December 1994 were generally dominated by a high pressure system but with high or medium and thin clouds developing. Therefore, the development of RST was intermediate. When a low pressure moved in on the night of 15/16 December 1994, the development of RST was largely 'suppressed', causing minimum spatial variation of RST. In order to identify the location of any significant change of local environment, a number of events are marked during Thermal Mapping surveys. These event marks provide a useful reference for data analysis.

Table 1. *General weather conditions for Thermal Mapping surveys of routes 1–9 (Nevada, December 1994)*

Date	Survey no.	Surface state	Cloud amount and height	Wind speed and direction
9 Dec. 1994	1	Dry	None	Calm
10 Dec. 1994	2	Dry	None	Calm
11 Dec. 1994	3	Dry	8/8, high	Calm
14 Dec. 1994	4	Dry	8/8, medium	Calm
16 Dec. 1994	5	Dry	8/8, medium	Light, westerly

3. Spatial variations

As mentioned in section 2, altitude plays an important role in controlling local climate. Significant variation is seen in five RWIS stations along survey route 9. The values of meteorological variables and RSTs shown in Table 2 are simultaneous sensor measurements of the RWISs shortly before dawn when Thermal Mapping surveys were carried out. In the table, Thermal Mapping measurements of temperature (RST_{TM}) are those extracted from data records at the distance where sensors are located. In order to remove possible inaccuracy in locating sensors in the Thermal Mapping records, RST_{TM} is an average over ten records (about 45 m) around estimated sensor locations. Then, RST_{TM} and sensor measurements (RST_S), which are interpolated to the time when the Thermal Mapping vehicle passed over the sensors, are averaged and maximum differences are extracted over five stations (see Table 2). It is seen from the table that Thermal Mapping measurements and sensor measurements have similar means and maximum differences (showing spatial amplitude of RST variation) among the five weather stations. However, it should be noted that at Incline RST_{TM} tends to be slightly colder than RST_S, while at VMS station RST_{TM} is warmer. This is because a depot located by the sensor at Incline caused a shading effect, which reduces longwave heat loss and temperature reduction at the sensor during the night. This is especially true when sky was clear and wind was calm (surveys 1 and 2). At the VMS station, which is located in a relatively open field, the sensor was on fast and yet colder lane while the survey was on slow and warmer lane.

Table 2 also shows that RST, air temperature and relative humidity vary significantly among these stations. Among these stations the maximum difference of RST can be as high as 5.2° C, air temperature 7.4° C, dew point temperature 11.4° C and wind speed 3.1 m s^{-1}. These differences occurred along State Route 431 in a horizontal distance of less than 19 km. Also, it is quite clear that RST of stations at higher altitudes, such as Mount Rose Summit and Diamond Peak, are generally colder than others. However, the relationship is neither linear nor simple and is not always true (especially when weather condition is damped, as on 16 December 1994).

To see more differences of RST at the five stations, temperature time series of the night 9/10 December 1994 are plotted in Figure 2 as an example. The figure clearly shows that not only the temperature itself but also the pattern of temperature variation varies among the stations. The rate of temperature fall and the time when minimum temperature occurs largely differ from one station to another. Incline has the highest temperature and smallest cooling rate due to its low altitude and closeness to the moderating influence of Lake Tahoe. Under clear sky and calm winds, surface temperature at higher-altitude stations such as Diamond Peak and Mount Rose Summit is lower than that at other stations for most of the time. The amplitude of cooling, however, is the largest at VMS station, which sits on a east-facing slope not far away from the bottom of a basin. Its location means that on a cold night it is frequently subject to cold air drainage towards the bottom of the basin and a consequent large cooling effect. The results shown in Table 2 and Figure 2 illustrate clearly that topography, along with smaller-scale local factors (e.g. hills, buildings and trees on both sides of road), can make a significant contribution to both spatial and temporal variations in the thermal status of the road surface and produce a variety of

Table 2. *Comparison of road surface temperatures from Thermal Mapping (RST_{TM}, °C) and sensor measurements (RST_S, °C), air temperature (T_a, °C), dewpoint (T_d, °C), wind speed (m s^{-1}) and wind direction at five RIWSs on survey route 9 (Nevada, December 1994)*

Survey no.	Variable	Incline	Diamond Peak	M. R. Summit	Bulls Eye	VMS	Mean	Max. diff.
1	RST_{TM}	−10.2	−13.5	−13.2	−12.0	−9.8	−11.7	3.7
	RST_S	−8.3	−12.3	−13.5	−12.9	−10.3	−11.5	5.2
	T_a	−6.2	−9.7	−9.8	−5.3	−7.8	−7.8	4.5
	T_d	−8.8	−13.8	−14.8	−20.2	−11.1	−13.7	11.4
	Wind	0.4/NW	2.2/NNE	0	0	2.2/SSW	1.0/–	2.2/–
2	RST_{TM}	−8.0	−10.8	−10.2	−10.0	−9.1	−9.6	2.8
	RST_S	−7.2	−10.5	−10.4	−8.9	−9.7	−9.3	3.3
	T_a	−1.9	−2.8	−5.6	−4.1	−6.6	−4.2	4.7
	T_d	−10.3	−13.8	−15.6	−13.8	−11.1	−12.9	5.3
	Wind	0.9/NW	1.3/SW	2.7/S	0.4/WNW	1.8/SSW	1.4/–	2.3/–
3	RST_{TM}	−5.3	−8.2	−10.0	−7.0	−5.5	−7.2	4.7
	RST_S	−4.8	−7.3	−9.4	−5.4	−6.1	−6.6	4.6
	T_a	−3.7	−7.8	−9.7	−4.7	−2.3	−5.6	7.4
	T_d	−9.8	−10.0	−11.9	−11.9	−10.4	−11.0	2.1
	Wind	1.3/W	2.2/WSW	4.0/S	1.3/NNW	0.9.WSW	g1.9/–	3.1/–
4	RST_{TM}	−7.8	−7.9	−11.7	−8.5	−8.8	−8.9	3.9
	RST_S	−7.5	−8.3	−11.5	−8.8	−10.1	−9.2	4.0
	T_a	−5.4	−8.3	−10.6	−6.4	−6.9	−7.5	5.2
	T_d	−8.7	−9.3	−11.4	−9.3	−9.3	−9.6	2.7
	Wind	1.3/NW	0.9/WSW	2.2/S	0.9/SE	0.9/WSW	1.2/–	1.3/–
5	RST_{TM}	−1.1	−3.0	−3.5	−4.8	−3.8	−3.3	3.7
	RST_S	−0.9	−2.7	−3.8	−4.9	−5.8	−3.6	4.9
	T_a	1.1	−2.7	−1.7	−0.4	−1.8	−1.1	3.8
	T_d	−2.8	−3.2	−2.1	−3.6	−4.9	−3.3	2.8
	Wind	0.9/NW	0.9/SW	2.2/S	0.4/NNE	2.2/SSW	1.3/–	1.8/–

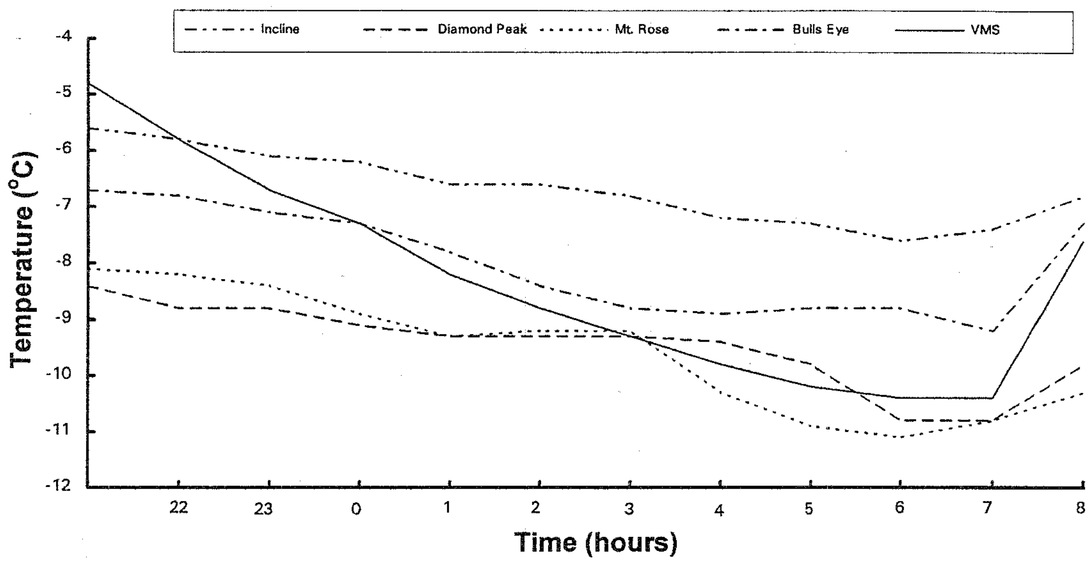

Figure 2. *Road surface temperature variation during the night of 9–10 December 1994 at five roadside weather stations in Nevada.*

spatial patterns of RST under different weather conditions.

To investigate possible relationships between RST and altitude, a multiple step-wise regression analysis was applied to survey data for all nine routes. Where an event number was marked in a Thermal Mapping data series, its location is identified and its altitude is derived by reading from a detailed road and topography map. The temperature (RST_{TM}) recorded at the events in Thermal Mapping is abstracted from the data series. Therefore, a number of pairs of RST and altitude are available on each Thermal Mapping route at different nights. In the regression analysis, the predictor is the departure (or difference) of RST at each recorded event from route mean RST, and the regression variables are linear and non-linear terms of normalised altitude (A), i.e., A, A^2, $A^{1/2}$, A^{-1} and A^{-2}. The significance level of rejection in the regression is 5%. The results are summarised in Table 3. In this table, '–' or '+' stands for the sign of coefficient of the term, and D or I for the trend of decrease (D) or increase (I) of variation of RST with these variables. For example, D–I means that RST decreases with altitude first and then increases.

Table 3. *Relationships of RST difference (from its route mean) and linear and non-linear variables of altitude (A). (D or I for the trend of decrease or increase of variation of RST with these variables; '–' or '+' stands for the sign of coefficient of the variables in regression equations)*

Route	Date	A	A^2	$A^{1/2}$	A^{-1}	A^{-2}	Trend
1	09/12/94		–				D
	10/12/94	–	+				D–I
	11/12/94					+	D
	14/12/94	+				+	D–I
2	09/12/94	–					D
	10/12/94		–				D
	11/12/94	–		+			I–D
	14/12/94	+		–			D–I
	16/12/94	+	–				I–D
3	09/12/94	–					D
	10/12/94		–				D
	11/12/94	–					D
	14/12/94	–					D
	16/12/94	–					D
4	09/12/94		–				D
	10/12/94		–				D
	11/12/94		–				D
	14/12/94	–					D
5	09/12/94		–				D
	10/12/94		–				D
	11/12/94		–			–	I–D
	14/12/94		–				D
	16/12/94		–				D
6	09/12/94		–				D
	10/12/94		–				D
	11/12/94		–				D
	14/12/94		–				D
	16/12/94		–				D
7	09/12/94		–				D
	10/12/94		–		–		I–D
	11/12/94				–		I
	14/12/94		–				D
	16/12/94		–		–	+	D–I–D
8	09/12/94			–			D
	10/12/94		–				D
	11/12/94		–				D
	14/12/94		–				D
	16/12/94	–				–	I–D
9	09/12/94		–				D
	10/12/94		–				D
	11/12/94		–				D
	14/12/94		–				D

It is seen from the table that of five different altitude variables, A^2 is the most frequent and the linear term (A) is the next. In general, the results show a decrease of RST with increase of altitude. However, it should be noted that the relationship becomes complicated in some routes and on some nights. As would be expected from inspection of low-level radiosonde ascents, these data confirm that there is no simple or generalised relationship between temperature and altitude. In some circumstances, temperature increases (or decreases) first and then decreases (or increases) with altitude after a critical level of altitude. At a different route and under different weather conditions, the relationship appears differently and the rate of decrement of RST with altitude is not the same at all. The regression results demonstrate that statistical relationships between RST and altitude are too complicated and unreliable to be of realistic value in describing or predicting RST from altitude alone.

One example showing the complex nature of spatial variation of surface temperature is given in Figure 3, which shows the variation of RST along with topographical changes. From the figure, it is hard to imagine that a statistical method or model is able to capture fully the characteristics of temperature variation along a stretch of road with sufficient accuracy. Although a lot of research has been carried out to develop a local climatic model and many interesting results have been shown to describe and predict variation of RST along road stretches (Bogren *et al.*, 1992; Gustavsson & Bogren, 1993), there are still some doubts on the accuracy and general applicability of such a statistics-based climatic model.

It is this difficulty that Thermal Mapping overcomes in an easy and effective way, being an accurate tool to describe and display the variations of RST as shown in Figure 3.

4. Application of Thermal Mapping

Thermal Mapping is a technique that involves a series of sub-processes (such as signal collection, data logging, data analysis and data display) to measure and represent the variation of road surface temperature across a road network. Its data collection and logging are usually carried out during the night, before dawn. The analysis and display of the data are done in the office by trained and experienced staff. In recent years, the accuracy, reliability and repeatability of Thermal Mapping have been studied by Shao & Lister (1995) and Shao *et al.* (1996). The results of the research demonstrate that under strict quality control, Thermal Mapping is an effective tool for providing reliable and

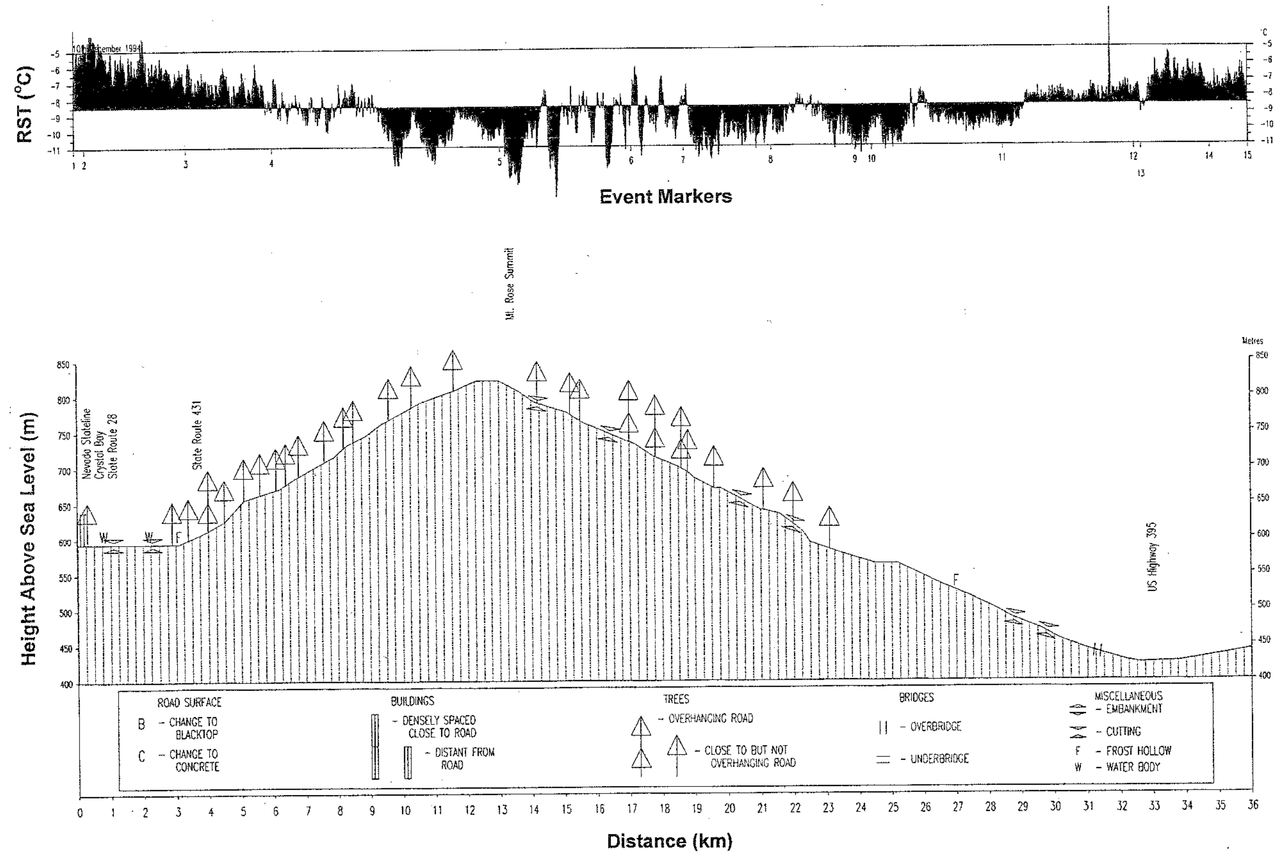

Figure 3. *Cross-section of RST variation along with topographical changes (Route 9, December 10, 1994).*

repeatable description of spatial variation of RST in a road network.

It can be seen from Figure 3 that RST responds significantly to many topographical features such as tunnels, elevation, trees, buildings and water bodies. While elevation of a highway and openness of the sky cause a 'cooling effect' on surface temperature, sky closure by roadside trees and/or buildings or the existence of a large water body nearby result in a 'warming effect'. In Figure 3, several cold spots or 'ice hollows' have been detected and represented in the fingerprint.

This example shows that Thermal Mapping provides four major operational benefits:

(a) Providing an objective method of optimising the location and number of road weather (RWIS) stations required to cover a particular road network by precisely representing spatial variation of road surface temperatures;
(b) Providing a complete picture of road surface minimum temperature, identifying those sections of a road network likely to freeze first, or 'ice hollows';
(c) Providing a dynamic picture of spatial and temporal variations of road surface temperature (e.g. where and when frost or ice is to occur in a road network), in combination with a numerical and site-specific road ice-prediction model;
(d) Providing the necessary database from which to re-prioritise treatment routes allowing treatment to be concentrated on only those roads likely to freeze, in order to minimise salt usage, operation cost and the damage to environment.

It is believed that all these benefits can be realised by integrating RWISs, ice forecast, Thermal Mapping and salting route optimisation with a small investment.

5. Summary

The study presented in this paper shows that on either a small scale, such as might be found in a county or city network, or a large network, such as in a state, the road surface temperature and other meteorological parameters vary significantly in a complex terrain like a mountainous area. Although there appears a general trend toward a decrease of surface temperature with increase of altitude, the trend is too complicated to be described by a statistical and quantitative method. To overcome this difficulty, Thermal Mapping is able to provide an economic, easy, effective and accurate way to describe and re-display the actual spatial variations of road surface temperature in a road network. In application, however, when the Thermal Mapping survey is carried out in a hilly or forested area attention needs to be drawn to Thermal Mapping data validation and comparison against sensor measurements, for the shading effect due to nearby hills or/and trees will cause significant difference between Thermal Mapping records and sensor measurements when the survey is on one lane of the road while the surface sensor is on another.

The values of Thermal Mapping can be maximised through the integration of roadside automatic weather stations, numerical prediction models and salting route optimisation, to largely cut down winter road maintenance costs and reduce damage to our environment.

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