THERMAL MAPPING FOR A HIGHWAY GRITTING NETWORK

by

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VOLUME 1

ABSTRACT

Thermal mapping, the measurement of road surface temperatures (RSTs) with an infra-red thermometer (IRT) mounted in a moving vehicle, seeks to identify a 'characteristic and repeatable' thermal fingerprint (temperature profile) for any stretch of road. A number of uses have been suggested for the process, including ice detection sensor network design and identifying stretches of road for selective gritting, with potential financial and environmental benefits due to reduced salt usage.

The project `Thermal Mapping for a Highway Gritting Network' has resulted in the most extensive survey yet undertaken. The aims were to investigate the reliability/repeatability of fingerprints and establish confidence limits. Comprehensive mapping of Sheffield roads took place during winters 1988/89-1991/92. Significant errors (+/-3°C) in RST readings were identified after the first winter. Laboratory and road tests confirmed errors were produced due to warming/cooling of the IRT. Operating the IRT in a temperature control box eliminated these errors. Seven Sheffield routes were mapped during winters 89/90 and 90/91 with route 1 fingerprints (100) used for most of the analysis.

The main factors affecting the variation in RSTs were confirmed as altitude and land-use with localised peaks occurring under bridges and by trees and tall buildings. The occurrence of cold air drainage on clear/calm (`extreme') nights resulted in `low' RSTs at relatively low altitudes.

Differences were identified between what should have been identical extreme fingerprints. These were related to variations in the behaviour of cold air drainage from night to night and variations in wind direction/speed interacting with local relief.

Confidence limits for extreme fingerprints and maps, taking into account possible errors in mapping and differences between fingerprints, were +/-2°C and +/-2.5°C respectively. With important decisions concerning gritting made when RSTs are +/-5°C confidence limits of this magnitude have important implications for thermal mapping. Future use should be restricted to sensor network design and assessment/re-design of gritting networks.

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CHAPTER 1

INTRODUCTION

1.1. THESIS OUTLINE

This thesis presents the results and findings of the project `Thermal Mapping for a Highway Gritting Network'. Chapter 1 introduces thermal mapping and its role in winter road maintenance and also reviews thermal mapping literature. The study area - the City of Sheffield is looked at in detail in chapter 2 with particular emphasis on its climate. The first period of data collection (winter 1988/89) is discussed in chapter 3 with the identification of errors in road surface temperatures (RST) readings made by the infra-red thermometer (IRT) while mapping. The production of errors is looked at in detail in chapter 4, with laboratory and road tests described, along with an explanation of the process of error production. Chapters 5 and 6 present the results of mapping in Sheffield during winters 1989/90 and 1990/91 once the problem with the IRT had been eliminated. Chapter 5 describes the different types of thermal fingerprints observed and examines the relationship between a number of factors, such as altitude, topography and land-use, and the variation in RST. Chapter 6 looks specifically at the reliability/repeatability of fingerprints. Possible errors in vehicle-based thermal mapping are assessed in chapter 7 and confidence limits established for thermal fingerprints and maps. Thermal maps of the Sheffield area are also presented. Chapter 8 summarises the main conclusions of the project with recommendations for the future use of thermal mapping and areas of further research.

1.2. HIGHWAY WINTER MAINTENANCE

Highway Authorities throughout Britain have a responsibility to keep roads free from ice and snow under the Highways Act of 1959 (Section 129). The specific requirements may vary from one authority to another, but generally key routes must be kept clear for essential traffic. These would include motorways, trunk roads and other principal roads. Roads dealing with heavy commuter traffic and bus routes will also be kept clear as a priority. By far the most common method of 'snow and ice control' in Britain is to spread rock salt (sodium chloride), which occurs naturally in abundance in Britain, onto roads. Salt has the effect of lowering the freezing point of water thus melting any ice or snow which is already present, or preventing the formation of ice and accumulation of snow. Salt is effective down to -10°C, below which increasing quantities are required to obtain a reasonable rate of melting. However, in the temperature range 0 to -3°C, when it is most likely to be used in Britain, it is very effective. Also air temperatures are rarely below -3°C when snow falls in Britain. The spreading of rock salt is often termed 'gritting' and is preferably carried out in advance of ice forming or snow falling.

Precautionary gritting (before freezing occurs) is preferable for two reasons. Firstly, the amount of salt required to melt ice or snow which is already present on the roads is much greater than that needed for precautionary grits. Spreading rates for precautionary gritting are about $10g/m^2$ compared to $40g/m^2$ needed when ice and/or snow is already present (Thornes, 1991). Secondly, any amount of snow or ice on the roads, even for a short time, will cause disruption to traffic and possible accidents.

Consumption of rock salt in Britain exceeds two million tonnes per year (Parmenter and Thornes, 1986). As figure 1.1 shows, the highest nett users of salt (metric tonnes of salt per km of road) are generally in the North of Britain and particularly in areas of high altitude. However, the picture is not as clear as may be expected and will be complicated by factors such as road type (not all roads are gritted) and local winter maintenance procedures. The City of Sheffield uses an average of 22000 tonnes of salt each winter, although this varies considerably depending on the severity of the winter (see figure 1.2 and table 1.1).

With salt costing over £20 a tonne and taking into account the use of manpower and machinery, very large sums of money are involved in winter road maintenance. Figure 1.3 shows the total winter maintenance expenditure by Sheffield City Council Works Department for winters 1985/86 to 1990/91. In mild winters, such as 1988/89, expenditure can be limited to about £1million, but in severe winters this can rise to nearly £3million, eg. 1985/86. The severity of a winter can be assessed by studying a number of factors such as snowfall and nights of salting. Table 1.1 looks in detail at winters 1985/86 to 1990/91 and also includes 1962/63 and 1978/79, both cold and snowy winters, for comparison. If we compare total expenditure (fig. 1.3) with the data in table 1.1 it is clear that the most important factor (in determining total expenditure) is the number of nights with road surface temperatures (RST) at or below freezing. The total amount of snow that falls in a winter, although important, is not as crucial when considering total expenditure. In practical terms this means that a cold, dry winter with little snow will cost more than a generally mild winter with short spells of heavy snow.

It is important to note that the actual costs of spreading salt on British roads are even greater than these figures show. Other 'hidden' costs are involved. Extra costs to the local authority are caused by salt increasing the deterioration of roads (especially those of concrete construction) and steel bridges. The 'man-in-the-street' faces increased corrosion to vehicles and also potential environmental damage with salt entering water systems and high concentrations damaging roadside vegetation. Feick et al (1972) showed that highway salts can increase the relative amounts of toxic metals in equilibrium with the sediments of freshwater environments.

With such high financial and environmental costs it is vital that the gritting of roads is only carried out when necessary and as efficiently as possible. Gritting roads when it is not necessary will result in a costly waste of salt and unwarranted extra damage to motor vehicles and the environment. However, if roads are not gritted and ice forms, the possible consequences are accidents and death or injury, with possible expensive court action to follow. Clearly any maintenance engineer will 'err on the side of caution' when deciding whether to grit or not in order to avoid ice on untreated roads. To make an accurate decision a maintenance engineer needs to have as much information as possible about present and future road and weather conditions. The situation is further complicated by the maintenance engineer's lack of meteorological knowledge and sometimes inconsistent and confusing information. For example RSTs often differ from air temperatures (warmer or cooler) and technical terms used by meteorologists may confuse engineers and vice-versa.

1.2.1. Weather Forecasting and Winter Maintenance

Britain's climate is such that during the winter months air and RSTs often tend to fluctuate around freezing point. Unlike in countries such as Austria and Sweden, where snow and ice is an almost permanent feature during the winter, in Britain the variability of the occurrence of snow and ice (both spatially and temporally) makes both winter maintenance and forecasting road conditions for winter maintenance difficult. Also with ice at its most slippery at 0°C (fig. 1.4), due to a film of melted water, conditions are often hazardous and mistakes can be fatal and expensive.

The most important variable , in deciding whether to grit or not, is RST. Clearly, if the RST is at or below 0°C ice is a potential problem. The amount of moisture present is also important. If surface water is present on the roads and the RST is below freezing, ice will form and roads must be gritted. Even when roads are dry, if the air is cooled below its dew point temperature condensation occurs and hoar frost will form on the road if it is at 0°C or below, which can be compacted into ice by traffic. Deciding whether to grit or not is most difficult on so-called 'marginal' nights when RSTs are close to 0°C. When RSTs are well below or well above freezing the decision is easier to make.

1.2.2. Forecasting Road Surface Temperatures

The forecasting of RSTs is not easy. In the past forecasters worked on the assumption that as grass minimum temperatures were below air minimum temperatures then minimum RSTs would also be lower than the air minimum. RSTs do often differ significantly from air temperatures, but this difference is not consistent. The difference varies with time of day, time of year, type of road construction (depth and materials), and weather conditions. For example on a hot summer day with strong sunshine, RSTs may be up to 15°C higher than air temperatures. Conversely on a clear winter night, RSTs may be as much as 5°C cooler than air temperatures.

Hay (1969) carried out measurements using thermocouples on motorways near Newport Pagnall and Bray Wick and concluded that RSTs could best be forecast by simply equating the road surface minimum temperature forecast to the air minimum temperature forecast obtained by objective methods. The motorway was actually slightly warmer than the air temperature. Parrey (1969) related road surface minimum temperatures to both air minimum temperatures and the date. Ritchie (1969) found that the depression of RST below air temperature was primarily a function of the day of the year. In a paper (Thornes, 1977) discussing the salting decision-making process the author includes a cooling curve from a site on the A1 (concrete) showing that on a clear night with relatively light winds the RST was below the air temperature for all of the night. Thornes (1982) presents data on air and road surface temperatures from a site on the M4 motorway near Birmingham (asphalt). For most of the time the RST was warmer than the air temperature. On only four of the 30 nights was the road minimum lower than the air minimum temperature. The possible effect of traffic keeping the road warmer was noted. Rayer (1987) while conducting tests on the Met Office road surface temperature model on a tarmac test slab at Lyneham found that, over a four day period, RSTs were generally lower than air temperatures at night. Clearly there was no influence from traffic on this test slab. Roodenburg (1984) produced regression equations to forecast road surface minimum temperatures using data from a fully automated measuring network in the Central Netherlands. He incorporated seven variables in his equations including air and soil temperatures, sunshine and cloud amounts. A test on independent data proved the equations performed satisfactorily in predicting the lowest RST during a night.

Physical models of the heat exchanges at the road surface have also been developed (Thornes 1972, Rosema and Welleman 1977). These models required the input of a large number of variables such as net radiation; water vapour pressures; condensation and evaporation rates; conductivity of the road materials (wet and dry); and cloud amounts etc... With many of these variables either not known accurately or varying rapidly in both time and space, the models were of limited use. However, the last two decades have seen significant developments in the area of automated road weather sensors. These provide real-time point data enabling, amongst other things, better forecasting of RSTs.

1.2.3. Automated Road Weather Sensors

In the late 1960s there was increasing demand from local authorities for ice-warning systems which provide real-time data on road conditions (temperature, moisture and salinity) to aid winter maintenance staff in their decision-making process. Sensors embedded in the road surface measure RSTs, wetness and the amount of salt present. Atmospheric sensors are usually present at these sites providing data on air temperature, humidity, wind speed and precipitation. Data can be stored on site or sent (often by the general telephone network) to a central computer at gritting head quarters. Road surface conditions are continuously on display on a visual display unit (VDU) and any changes in conditions can be observed. Present manufacturers of ice-warning systems include Boschung (Switzerland), Surface Systems Incorporated (USA), Vaisala Ltd (Finland), and Findlay, Irvine Ltd in the UK. The City of Sheffield currently use the ICELERT Mark 5 system manufactured by Findlay, Irvine. This will be described in greater detail in section 1.5.1.

In the late 1970s and early 1980s a computer model of the heat and mass transfer at a road surface was developed by Thornes at Birmingham University in conjunction with the Transport and Road Research Laboratory (Parmenter and Thornes 1986). Trials in 1984/5 showed that using information from road sensors and meteorological data, RSTs could be forecast with considerable accuracy. By 1987 the Meteorological Office had developed its own RST model (Rayer 1987). Both models use actual observations obtained from road sensors, and a combination of observed and forecast values of atmospheric variables to produce site specific road temperature forecasts.

The forecasts are displayed on road temperature graphs on a VDU at gritting headquarters and decisions whether to grit or not can be made with a greater degree of confidence. The model can be run twice to produce a realistic and a pessimistic forecast if desired. The pessimistic forecast is often based on reduced cloud cover during the night. Actual RSTs are then plotted alongside the forecast graphs and if there is any significant deviation, the model can be re-run with up-to-date values and action taken if necessary. In recent winters (1990/91 and 1991/92) only a realistic forecast has been issued along with a measure of the confidence in the forecast.

Three ice prediction models are currently available in the UK - Thornes (Thornes, 1984), Met Office (Rayer, 1987; Thompson, 1988) and the Icebreak model (Shao, 1990). The performance of these three models is compared in an article by Thornes and Shao (1991a). A second paper by the same authors (Thornes and Shao, 1991b) analyses the meteorological input parameters and road thermal properties which are most important to the Icebreak model. The results show that the model is most sensitive to air temperature and cloud cover with little sensitivity to road thermal properties. The importance of sensor technology in affecting the accuracy of ice prediction models is discussed by Lister, McDonald and Pearson (1991). They show how errors in the sensor road temperature readings will be reproduced in forecasts and also affect subsequent statistical analysis on forecast performance. The importance of accurate, properly sited, exposed, well maintained and calibrated sensors is stressed.

With the development of road sensors local authorities and weather forecasters now have accurate and usually reliable real-time point data available. However, the condition of stretches of road between sensor sites is still not known with much accuracy. This is especially true in areas with large variations in relief and/or land-use. With sensors widely spaced, extrapolation from road sensors is likely to be very inaccurate. A very high density of sensors would be financially and practically impossible. The development of thermal mapping in the 1980s has gone some way to solving this problem.

1.2.4. Thermal Mapping

Thermal mapping is the process by which RSTs are measured by an infra-red thermometer. First used in Sweden and The Netherlands in the late 1970s it has been developed in Britain as a widely used tool for winter maintenance in the 1980s. Early research and development was carried out by the Atmosphere-Road Surface Interaction Study Group at Birmingham University (Sugrue, Thornes and Osborne, 1982; Working Paper No 10, 1983). As a result of this research Thermal Mapping International (TMI), a company specialising in the thermal mapping of roads for winter maintenance procedures, was formed (now Vaisala TMI). The theory behind thermal mapping and its use in practice will be looked at in detail in section 1.3. The result of carrying out thermal mapping on roads is to produce a map of the variation in road surface temperatures across a county/region. Temperature readings from sensors can then be extrapolated to the rest of the road network with greater accuracy. Thermal mapping has often been carried out in order to determine the best location for road sensors, i.e in cold or marginal locations. Thermal maps can also be helpful in re-designing gritting routes and assessing present gritting procedures.

1.2.5. The Development of the UK National Ice Prediction System

With the development of improved road sensors, thermal mapping and RST models, along with increasing co-operation between highway authorities and meteorological organisations (principally the Met Office), a national road ice prediction system has begun to develop. Many local authorities are making use of computer-generated forecasts of road temperatures to help in their winter maintenance operations.

As part of its 'Open Road' service, the Meteorological Office will provide forecasts for designated sensor locations using real-time data from the sensors and its own forecast data. TMI through its links with the Met Office provided software (forecast graphs, forecast texts, and tables of sensor data) for 'Open Road' services. Other software systems (eg. Findlay, Irvine's Icelert) can also be used.

The following services are available through 'Open Road':

1) 24 hour forecasts
2) 2-5 day forecasts
3) early morning summaries and preliminary advice
4) radar pictures
5) site specific ice prediction information
6) forecast thermal maps
7) dedicated sensor monitoring
8) updates as required

(taken from Meteorological Office 'Open Road' brochure)

The Meteorological Office has 14 Weather Centres around Britain and these provide ideal locations for regional systems to develop. Leeds Weather Centre is currently linked to sensors in the county of Humberside; the cities of Sheffield, Barnsley, Rotherham and Doncaster; and also the authorities responsible for gritting motorways in West and South Yorkshire. Manchester Weather Centre can serve all authorities responsible for gritting in the counties of Manchester and Merseyside. Birmingham Ice Prediction Centre (based at the University) provides forecasts for

Suffolk, West Midland motorways, Warwickshire motorways, Staffordshire and Berkshire (Thornes, 1989).

Savings can be made in a number of areas using these recent developments in winter maintenance. The number of unnecessary saltings can be significantly reduced and early warnings on adverse conditions mean early and efficient preparations can be made. Ice hazards on roads are less likely to be left untreated. Cheshire County Council installed their ice prediction system before winter 1986/87 and have predicted a reduction of 20% in salt usage (Thornes, 1989). Ponting (1984) estimated an average winter saving of £56000 on salt usage alone after the installation of an ice prediction system in Hereford and Worcester and in 1987/88 an estimated reduction in salt usage of 35.5% resulted in a saving of £88000 (Thornes and Fairmaner, 1989). Further savings would be made on labour and equipment. With these potential savings in costs the investment in new ice prediction systems could be repaid within a few years.

Winter maintenance procedures have benefited from three recent developments: automated road sensors, computer generated road temperature forecasts and thermal mapping. This research project concentrates on thermal mapping, looking, in particular, at its repeatability and reliability. The theory and practice of thermal mapping is discussed in considerable detail in section 1.3 while section 1.5 covers the research proposal and aims of the project.

1.3.THERMAL MAPPING THEORY AND PRACTICE

1.3.1. The Principles of Thermal Mapping

All bodies possessing energy (ie. above absolute zero, 0 Kelvin = -273.2^{o}C) emit radiation. A body, at a given temperature, if it emits the maximum possible amount of radiation per unit of its surface area, in unit time, is termed a black body or full radiator.

The relationship between energy emitted and the temperature of a body is shown by the Stefan-Boltzmann Law:

$$\text{Energy emitted} = \varepsilon \sigma T^4 \quad \text{(equation 1.1)}$$

where:

ε = surface emissivity

σ = Stefan-Boltzmann Constant ($5.67\times10^{-8}\mathrm{Wm^{-2}K^{-4}}$)

T = surface temperature (Kelvin)

Black bodies have a surface emissivity equal to one. All other objects have emissivities between zero and one (asphalt roads 0.95-0.99). It can be seen, from equation 1.1, that if the emissivity of a body is known and the amount of radiation it is emitting measured, then its temperature can be determined.

The wavelength composition of emitted radiation is dependent on the temperature of the body. Wien's Displacement Law states that:

> "A rise in the temperature of a body not only increases the total radiant output , but also increases the proportion of shorter wavelengths of which it is composed"

Figure 1.5 shows a Planck curve (spectral distribution of radiant energy from a full radiator) at a temperature of 300K - the average surface temperature of the Earth-Atmosphere system. The wavelength of peak emission occurs thus:

$$\lambda_{max} = \frac{2897}{T} \times 10^{-6}\mathrm{m} \quad \text{(equation 1.2)}$$

where:

λ_{max} = wavelength of peak emission

T = temperature of radiating body (Kelvin)

It can be seen that earthly bodies emit infra-red radiation mainly in the wavelength range 8-14μm (peaking at 9.6μm). The earth's atmosphere absorbs most long-wave radiation (3.0-100μm) due to the absorptivities of water vapour, carbon dioxide and ozone. However, an atmospheric window exists where the atmosphere is open to the transmission of long-wave radiation in the wavelengths 8-14μm. Most instruments used for infra-red thermography have a spectral bandpass in the range 8-14μm (or thereabouts), giving them a high temperature resolution at low target temperatures. They also benefit from the atmospheric window so there is virtually no attenuation of the measurement values by water vapour and gases.

The road surface can be viewed as an 'active' surface - a site of energy and mass exchange and conversion. It is where the majority of radiant energy is absorbed, reflected and emitted; where the main transformations of energy (eg. radiant to thermal, sensible to latent) and mass (change of state of water) occur; where drag is exerted on airflow; and where interception of precipitation occurs. The above is important when we consider the relationship between the (road) surface energy balance and the (road) surface temperature. Figure 1.6a illustrates the case showing the relationship between (road) surface energy exchange and the diurnal variation in (road) surface temperature. During the daytime energy is arriving faster than it can be dissipated, input exceeds output and the resulting energy surplus causes an increase in surface temperature. The maximum temperature occurs when inputs and outputs are in balance afterwhich outputs exceed inputs and the temperature falls. The surface is the site of net radiant absorption (storage) during the day but experiences net radiant emission at night (loss of long-wave radiation to the atmosphere) with an energy deficit and falling temperatures. Again the lowest temperature occurs with inputs and outputs in balance. The dynamic nature of this process must be emphasised with the balance between inputs and outputs in a state of flux for much of the time. It is affected by many factors varying both spatially and temporally, eg. weather conditions, road construction and site factors.

The diurnal variation in (road) surface temperature shown by figure 1.6a is the relatively simple case that occurs under constant weather conditions of cloud and wind. If factors such as cloud amount, precipitation, type of air mass, wind speed or humidity change, the nature of the heat exchanges at the surface will alter, the balance between inputs and outputs will be affected, and the nature of the diurnal variation in temperature become more complicated. For example: consider a day and early night of clear skies and light winds with a diurnal variation as shown in figure 1.6a. However, if after midnight cloud begins to increase, the net loss of long-wave radiation from the road surface will be reduced due to counter radiation from the clouds. The surface temperature would increase and the diurnal variation be as shown in figure 1.6b. Variable and broken cloud during the night would produce an even more complex picture.

The balance between inputs and outputs will vary temporally and spatially with changes to and differences between many of the factors mentioned above. It is therefore unlikely that all stretches along a road will have a similar balance at any one time particularly during the early part of the day and night when inputs and outputs are changing rapidly.

Thermal mapping is normally undertaken during the later hours of the night (midnight to 0600hrs) when temperatures are usually at their lowest. The rate of cooling is greatest in the early part of the night and falls towards dawn when temperatures may remain stable for a short time (see figure 1.6a). By mapping during the later part of the night and restricting runs to a maximum of an hour's duration, temperatures should not change much during a run.

Road surface temperatures will mostly depend upon the prevailing weather conditions. These will influence the time of the maximum and minimum RST and also the size of the diurnal range (difference between the maximum and minimum). The temporal variation of weather conditions will be large, particularly in a country such as Britain with its temperate climate. The spatial variation in weather conditions will be much less significant at the scale with which we are concerned (county/region at the most) and assuming there are no areas of high relief or coastlines.

There will be considerable spatial variation in RST caused by factors such as altitude, topography, shading, road construction, amount of housing/industry and traffic conditions. These factors affect RSTs to varying degrees depending on the prevailing weather conditions and will be discussed in detail in section 1.3.3. Because these factors will not vary over the short/medium term thermal mapping works on the principle that any route will have a standard, identifiable and repeatable road temperature profile under similar weather conditions (Sugrue, Thornes and Osborne, 1983; Sugrue, 1984; and Ponting, 1984). This is despite the complex and dynamic nature of the processes involved in determining road surface temperatures.

1.3.2. Thermal Mapping in Practice

Two main types of instrument have been used in recent years for the measurement of RSTs:

1) Infra-red thermometers

Infra-red thermometers (IRTs) have been used solely in vehicle-based thermal mapping. They are small, portable units, usually consisting of:

a) an optical system
b) a detector (often a pyroelectric cell)
c) a reference temperature unit
d) millivolt (signal) to temperature conversion
e) a display unit
f) an adjustable emissivity setting
g) a power supply

Three infra-red thermometers have been used: the Heimann KT-17, which is made up of three separate units (detector, display and power supply), the LAND Cyclops 33 and the Minolta/LAND Compac 3 (both one complete unit). The Compac 3 has been used in this research project and will be looked at in detail in section 2.2.

2) Infra-red scanners

Infra-red scanner units have been used for both airborne and vehicle-based thermal mapping. Research at Gothenburg University on measuring RSTs and local climate modelling (eg. Lindqvist, 1987; Gustavsson and Bogren, 1990) has involved the use of the Agema Thermovision 870 system consisting of:

a) a scanner unit

b) a display unit

c) a computer with software for thermal image analysis and correction functions.

Airborne mapping of the Lothian region, Scotland, was carried out in February 1986 (Stove, Kennie and Harrison , 1987; Beaumont, Harrison and Stove, 1987). A Barr and Stroud IR18 thermal video frame scanner (TVFS) was used providing data on surface temperature with a spatial resolution of $1m^2$. The TVFS is made up of four basic components:

a) a scanning system which views the scene and redirects the incoming infra-red radiation.

b) a detector (ferromagnetic or semiconductor) measuring the thermal variations.

c) a close circuit television display - the thermal variations modulate the intensity of an electron beam.

d) a video recorder for storing the thermal imagery.

Scanner systems require ground and air reference temperature data if absolute temperature measurements are required. Another factor that must be taken into account, when analysing a thermal image produced by a scanner, is the spatial variability of emissivity.

In order to describe how thermal mapping of roads is carried out a number of technical terms used must first be defined:

1) *Thermal mapping*: the measurement of surface temperatures along a road using an infra-red thermometer.

2) *Thermal fingerprint*: the graphical representation of road surface temperature (y-axis) against distance (x-axis) for a run along a particular route.

3) *The 'development' of a fingerprint*: a fingerprint is said to be well developed if there are large differences in temperature along the run. A well developed fingerprint has a large amplitude. The term amplitude will be used from now on.

4) *Thermal map*: the representation, on a road map, of the spatial variation of (minimum) road surface temperature (RST).

The IRT is mounted inside a vehicle above a hole in the floor. Temperature readings are recorded either on a pen chart recorder or directly into an on-board microcomputer.

At an early stage in the development of thermal mapping it became clear that it was necessary to standardise the distance travelled along a run for direct comparisons to be made between fingerprints. This is achieved through either the use of a pulse generator attached to the wheel of the mapping vehicle or a vascar unit fitted to the speedometer cable. Using the on-board computer, a pulse unit and associated electronics unit the IRT is triggered to take a temperature reading at pre-set distances (eg. 20m). The actual equipment used in this research project will be described in detail in section 2.2.

The temperature readings taken along a run are then processed to produce a thermal fingerprint (fig. 1.7). The datum used on a fingerprint is the average of all the temperatures recorded on that particular run. Locations along the route which are warmer than average (above the datum, normally plotted in red) and colder than average (below, normally blue) can easily be identified. By plotting temperatures relative to the average for a run, comparisons can be made between fingerprints taken on different nights even though absolute temperatures may be different.

When undertaking thermal mapping surveys TMI or Travers Morgan divide the area into a number of routes, which can be completed within an hour. Each route is usually mapped five times - twice each under extreme (clear skies and light winds) and intermediate (variable cloud and wind) conditions and once with damped weather conditions (windy and cloudy).

For each run a detailed description of the prevailing weather conditions is recorded. Measurements of cloud (amount and height); wind (speed and direction); air temperature; and dew point temperature are taken at the start and end of each run. Any significant changes in weather conditions during a run are also noted. The Department of Transport gives a detailed description of the parameters to which companies offering thermal mapping services must operate in its Thermal Mapping Specification (Department of Transport, 1988).

Using the thermal fingerprints, information on weather conditions, and topographic surveys of each route (altitude, vegetation, buildings etc) thermal maps of the area can be drawn. Three maps, showing the variation in RST under extreme, intermediate and damped conditions, are usually produced. Figure 1.8 shows a thermal map of the M5, M6 and M42 motorways near Birmingham.

1.3.3. Factors Affecting Road Surface Temperatures

As discussed in section 1.3.1 the spatial variation in road surface temperature at a local scale will be caused by factors such as altitude, topography, road construction, land-use (urban, industrial or rural) and traffic conditions.

ALTITUDE

Under normal conditions atmospheric temperatures decrease with height, the environmental lapse rate, at an average of 6.5°C per 1000m. Consequently air temperatures are lower at higher altitudes and so RSTs would also be expected to decrease with increases in altitude. Lapse rates can vary with air-mass type, weather conditions and time of year.

However, on some occasions the reverse may apply with the lowest temperatures occurring in low altitude sites. Under clear skies and with light winds night-time surface cooling is at a maximum and hence the air immediately above the surface cools. This results in an increase in temperature with height up to the inversion top where the normal lapse rate resumes. Just above the inversion layer is the 'thermal belt' where the warmest temperatures are often found. Also , because cold air is denser than warm air , katabatic or cold air drainage can occur where cold air flows downslope under the influence of gravity. This cold air 'collects' in cold air pools (frost hollows, valley bottoms) where the lowest temperatures often occur. Katabatic drainage is not easy to predict with onset times varying, possible surges of flow due to the release of trapped cold air (behind vegetation or in concave terrain) and possible overriding of previously trapped cold air in valley bottoms by even colder air.

TOPOGRAPHY

At night, roads cool by experiencing a long-wave radiation deficit with the atmosphere. This net loss of long-wave radiation can be reduced by buildings, trees and cuttings which reflect and absorb radiation from the road surface and then re-emit it back. The net loss of radiation is significantly reduced. Roads under bridges, through cuttings, and lined by trees or buildings usually stay warmer at night than roads 'open' to the atmosphere. The effect is particularly noticeable when skies are clear and large temperature differences develop.

These roads, which are warmer at night, will be shaded during the day and so daytime RSTs will probably be lower than at open sites exposed to the sun. Clearly, the daytime temperature of a road is a crucial factor in determining the night minimum temperature especially at the times of the year when daylight hours are still relatively long (early autumn and late spring).

Sky-view factor is a term used to indicate the degree to which a site is shaded/exposed. It relates the maximum incoming radiation that can theoretically occur to that which actually occurs and varies between 0.0 (no sky visible) to 1.0 (no obstructions visible). A road with a sky-view factor close to zero will lose little long-wave radiation at night and will be shaded for most of the day.

ROAD CONSTRUCTION

Heat is stored in the road structure during the day and is released at night. The rate of release of heat varies according to the thermal properties of the road. 'Thermal memory' is a term used to describe the length of time which a road retains its stored heat. It depends on the type of materials used in its construction (specific heat capacities), the depth of construction and the amount of solar radiation received during the day. Roads with a greater depth (eg. motorways) are usually warmer than those of shallower construction (especially roads over bridges). Concrete has a greater thermal memory than asphalt, due to its higher specific heat capacity, and so concrete roads are usually warmer than blacktop roads at night in winter (Thornes, 1987). However, Ponting (1984) and Croney and Croney (1991) find the opposite is true. Croney and Croney state that concrete roads reflect more heat during the day than tarmac roads resulting in a lower afternoon temperature and consequently lower night temperatures.

HOUSING/INDUSTRY

One of the effects of buildings, on RSTs, has already been mentioned - in reducing the sky-view factor. Urban areas can be several degrees warmer than adjacent rural areas (the urban heat island effect) and this will clearly influence the temperatures of roads within the urban area. The extra warmth is due to a number of factors such as domestic and industrial heat output and the greater thermal memory of materials used in construction as well as the effect of reduced sky-view factor mentioned above. The urban heat island effect is usually at a maximum in the autumn and spring under clear/calm weather conditions (Thornes, 1991). Oke (1978) points out that city centres are usually warmer than the outer suburbs.

Sheffield with a population of approximately 0.5 million should have a maximum urban heat island of 5°C (Oke, 1973). Work conducted by Colquhoun (1982), in 1977, identified a summer maximum to Sheffield's heat island with winter values (January-March, November and December) ranging from 0.2-3.5°C with an average of 1.18°C.

TRAFFIC CONDITIONS

Traffic can help to keep a road warm at night in a number of ways:

1) frictional heat generated by tyres.

2) radiant and sensible heat energy from engines and exhausts

3) traffic stirs the air above the road , mixing warmer air with the colder air layers near the road surface.

4) the shadow effect of traffic can reduce the loss of long-wave radiation by the road surface.

These combined effects mean that the heavily used inside lanes of motorways and dual carriageways can be warmer, at night, than other lanes (Thornes, 1982 and 1986).

1.3.4. Types of Thermal Fingerprint Observed

Although weather conditions will not vary spatially to any great extent the type of weather (in particular cloud and wind amounts) will influence the spatial variation of RST through the factors discussed in section 1.3.3.

Cloud reflects, absorbs and re-emits the long-wave radiation lost by road surfaces. Wind also reduces the cooling rate by mixing the warmer layers with the colder layers near the surface. Hence, under clear, calm conditions, typical of anticyclonic pressure systems, radiative cooling is at a maximum. Variations in RST will be large, because differences in radiative cooling will be greatest. Open/exposed stretches of road will cool rapidly while those sections of road sheltered by trees or buildings will cool relatively little. The type of fingerprint which occurs under these conditions is termed the 'extreme' fingerprint - it has a large amplitude (see figure 1.7a). The occurrence of low temperatures in valleys and hollows is likely to be due to cold air drainage.

The opposite of the extreme is the 'damped' fingerprint , when temperature variations along the run are limited (see figure 1.7c). This fingerprint occurs under cloudy, windy conditions, typical of cyclonic pressure systems , when net radiative cooling is at a minimum.

'Intermediate' fingerprints (fig. 1.7b) will occur under cloud and wind conditions between the two extremes discussed above. Particular interest is usually paid to the fingerprints produced when there is thick cloud and no wind or when there are clear skies with strong winds. Different fingerprints will probably occur on nights when there is extensive or localised fog.

1.4. THE DEVELOPMENT OF THERMAL MAPPING AND LITERATURE REVIEW

Thermal mapping is still a relatively new technique and consequently the amount of literature available for study is limited. This is compounded by the fact that thermal mapping in Britain was rapidly developed into a commercial process at Birmingham University. Because of this the number of publications with new research, original opinions, or a truly critical approach are limited. This review will look firstly at the development of thermal mapping as a process assisting winter maintenance operations. Later research (of a more critical nature), as the technique became a widely used tool, will then be described. Finally, the research project at Gothenburg University titled "Applied Climatology for Increased Traffic Safety and Road

Maintenance " will be discussed in the light of its use of thermal mapping and other infra-red thermography techniques.

1.4.1. The Development of Thermal Mapping as an Aid to Winter Maintenance Operations

The use, since 1967, of infra-red thermography in meso- and microclimatology has opened up many new areas of research, and also helped to overcome the long-term problem of measuring surface temperatures using sensors connected to the surface, ie. the possible effect of the sensor on the actual temperature measured. Infra-red imagery from aircraft and satellites have frequently been used in studies of urban climate (eg. Birnie et al, 1984; Barring, Mattsson and Lindqvist, 1985) and low temperatures (eg. Kalma et al, 1986; Collier, Runacres and McClatchey, 1988). It was in Sweden, in the mid 1970s, that infra-red thermography was first used in studies of road surface temperature (Lindqvist 1975, 1976; Lindqvist and Mattsson, 1975). These studies used stationary ground-based and airborne infra-red systems to detect early ice formation on roads. It was stated that:

> ".....infra-red thermography could be a
> useful tool in the future, when detecting
> road sections with high frequency of ice
> formation."

Rosema and Welleman (1977) report on the results of the research project conducted by NIWARS (Netherlands Interdepartmental Working Committee for the Application of Remote Sensing Techniques), October 1975 to October 1976, looking at the factors influencing road icing using thermal infrared observing techniques. Thermal images from an aircraft-mounted infrared line scanner, fixed measurement points and mobile measurements, using a Heimann radiation thermometer mounted in front of a car, are used. They state that the radiation thermometer did not function properly and that these instruments are not designed for the rough atmospheric conditions prevailing during the measurements (strong temperature changes and shaking).

Thermal mapping of roads in Britain using a portable radiation thermometer mounted in a vehicle is first referred to by Thornes (1977). It was used by the Atmosphere-Road Surface Interaction Study Group (ARSISG) at University College London, in an attempt to identify and quantify the systematic variation in RST due to local topography (altitude, aspect, bridges, heat islands, frost hollows etc). Many problems had arisen at this early stage in development.

Blackmore made considerable use of this new technique in his study on "Minimum Road Surface Temperatures in South-East England" in the winter of 1977/78. In his thesis (Blackmore, 1984) the theory behind thermal mapping, the instruments used and methods of measurement are explained. A number of problems with thermal mapping were also discussed including:

1) frequent calibration and correction for variations in ambient temperature were required due to using a relatively simple infrared thermometer.

2) the need for an emissivity map of the area to interpret the infrared thermometer readings.

In addition the author calculated the emissivity value of the road surface at 11 sites (all asphalt) and found that they varied between 0.98 to 0.99.

The research and development of thermal mapping continued in the late 1970s and early 1980s with the ARSISG (at Birmingham University since 1981) in conjunction with TRRL (Transport and Road Research Laboratory, now Transport Research Laboratory). Working Paper Number 7 (Sugrue, 1983) discusses, in some detail, the advantages and disadvantages of infra-red thermometry. The first major research project, solely on thermal mapping, was undertaken during the winters of 1982/83 and 1983/84. The M5 motorway, near Birmingham, was mapped using a Heimann KT-17 radiation thermometer. Sugrue, Thornes and Osborne (1983) describe the technique used and present some initial results including sharp peaks in RST beneath bridges and the warming effect of traffic. The results of this research project are discussed in much greater detail in Working Paper Number 10 (Sugrue, 1984). 'Low' RSTs were reported as occurring under conditions of low cloud cover (0-2 octas) and with winds of less than $3ms^{-1}$, while wet roads, in a westerly weather type and strong winds (greater than $5ms^{-1}$) produced 'warm' RSTs. Two types of road section were identified:

1) those that show little variation in temperature (relative to a datum) independent of the weather conditions.

2) those that show different deviations depending on the prevailing physical and meteorological situation.

Both papers identify a systematic and repeatable thermal fingerprint for much of the motorway.

Ponting (1984) discusses the thermal mapping of roads by Hereford and Worcester County Council during the winter of 1982/83. The mapping was carried out in order to evaluate and calibrate their existing highway sensors and identified a number of important features including:

1) heavily trafficked roads are warmer than lesser trafficked roads.

2) roads beneath bridges and concrete bridges over water tend to be warmer.

3) steel bridges tend to be colder especially when over steep/high valleys.

4) rivers looping alongside roads constructed on embankments were found to be persistent cold spots.

5) concrete roads and surfaces with white aggregates are generally 1-1.5°C colder than normal asphalt surfaces. (Nb. This may be due to the lower emissivity value of concrete. The author makes no mention of the emissivity value used or if it is changed for different road surfaces.)

An individual fingerprint, for each route, which would be of significant interest to the practising highway engineer was again identified with the following uses put forward for thermal mapping:

1) Assessing the gritting programme and priority order.

2) Calibrating existing sensors.

Thornes describes some of the results of the ARSISG thermal mapping project of the motorways near Birmingham in a number of papers (eg. Thornes, 1984 and 1985) and goes on to discuss the development (amplitude) of the fingerprint under varying weather conditions. The potential usefulness of thermal mapping as a tool for assisting winter maintenance operations is presented and Thermal Mapping International referred to.

Since the mid 1980s thermal mapping has become a widely used tool for winter maintenance operations, particularly in Britain. This is reflected in the number of references to the usefulness of thermal mapping in the winter maintenance literature. The County Surveyors' Society's 'Report on Ice Warning Systems' 1985 states that:

> " Prior to undertaking the installation of ice warning systems , the provision of a thermal map of selected routes is essential if the full benefit of the system is to be achieved."

The report also lists four reasons for carrying out thermal mapping:

1) To decide where to put permanent sensors.

2) To decide how many sensors are required to give adequate coverage.

3) To calibrate existing sensors.

4) Categorising routes into cold, warm and intermediate with selective salting of cold routes on marginal nights.

Harverson (1985b) discusses the human implications of new technology in winter maintenance. The author points out that although thermal mapping is a useful tool it should be used selectively and interpreted by the practical experts - the people whose job it is to decide whether to salt or not - who should also be involved in the siting of sensors.

Williams (1986) describes the thermal mapping procedure and equipment used by Travers Morgan and the theory behind thermal mapping. Three possible uses are suggested:

1) Identifying the locations for permanent sensors and the number required. Assessing current sensor networks.

2) Re-routing of gritting routes to ensure that cold stretches of road were treated first, or selective gritting of known cold spots..

3) Determining temperature differences between lanes on dual carriageways and motorways. This information is useful if road sensors only measure the temperature of one lane.

Parmenter and Thornes (1987) discuss the results of thermal mapping of the M6 and M42 motorways near Birmingham. The mapping procedure is described and three main uses for thermal mapping put forward:

1) Deciding where to locate permanent road sensors.

2) Providing a systematic profile of RSTs so that information is available about lengths of road between sensors.

3) Re-routing of gritting vehicles to carry out selective gritting.

The improvement in the efficiency of Cheshire's winter gritting operations, due to the use of their ice prediction system, is described by Faiz (1987). Thermal mapping, as an intricate part of this system, is discussed.

Thornes (1987) presents a comprehensive discussion of the main factors affecting RSTs. The effects of altitude, topography, road construction, the urban heat island, and traffic are explained. The three types of fingerprint (extreme, damped and intermediate) and the conditions in which they occur are described.

The plots of four fingerprints mapped in Central Scotland are featured in a paper by Smith (1988). The fingerprints, mapped on four different nights, are reproduced with their associated altitudinal profile and the variation in RST explained. The author concludes that even with short journeys, over moderate terrain, road weather conditions are unlikely to be uniform and that thermal mapping, as one of a number of new technologies, provides opportunities for more efficient salting programmes.

A performance and benefit analysis of the UK national road ice prediction system is given by Thornes (1989). The paper summarises the scale of operations in the UK at the time and introduces techniques for assessing the performance of winter maintenance operations. It reports that by the start of the 1988/89 winter 21500km of roads, in 45 UK highway authorities, have been thermally mapped. The author attempts to answer questions about the use of these new techniques in day to day operations and their practical implications. Analysis of minimum air and road temperatures identified the coldest and warmest sites under differing weather conditions. Results from Hereford and Worcester show that on 'extreme' nights air temperature increases with height by 2^{o}C per 1500ft (0.44^{o}C/100m). On damped nights temperatures decrease by 3^{o}C per 1500ft (0.66^{o}C/100m) while on intermediate nights the decrease is 2^{o}C per 1500ft (0.44^{o}C/100m). Because of these differences three thermal maps, corresponding to each weather type, are required for use in extrapolating between sensors.

Barisel (1990) reports on recent research in France, using a specially equipped van to measure a number of variables including RSTs with a radiation thermometer.

Thermal mapping has helped to identify zones of high risk and in the location of permanent weather stations.

Thermal mapping is accepted as a valuable component of the national ice prediction systems (McDonald and Lister ,1990) and to this effect the Department of Transport issued its "Thermal Mapping Specification" in 1988. It states that:

> " it is desirable for roads to be thermally
> mapped in order to identify their temperature
> profiles and the environmental characteristics
> which lead to variations in road surface
> temperature."

The Department will also pay for the mapping of the Secretary of State's roads.

1.4.2. Critical Research and Comments

Truly independent research projects, on thermal mapping, have been limited. This section will summarise the research which has been carried out and refer to examples in the literature where questions have been raised about the process of thermal mapping.

Harverson (1986b) discusses thermal mapping in some detail and raises some possible disadvantages of the process. It is pointed out that to cover a complete set of weather conditions (cloud amount, wind speed and direction) would be practically impossible due to the large number of permutations possible. The situation would be even more complicated if precipitation, traffic and time of year were included. Because the number of mapping runs is restricted for practical and financial reasons, certain thermal anomalies may not be shown on any of the maps because the conditions producing them did not occur while mapping. The author comments that thermal maps should be used in conjunction with local knowledge to help counteract this problem. The paper ends with the following paragraph:

> "If thermal mapping is to be used to limit the number of sensors in an ice warning system as well as to help determine their locations, then the calibration of the thermal mapping becomes as important as that of the sensors. At the moment, thermal mapping being the much younger technique, it has been allowed to operate under much looser constraints than those now applied to ice warning sensors. But if this technique is to be used to extrapolate sensor data to points at which no sensor has been installed, then the confidence limits of the process must be established."

An airborne thermal mapping technique for winter road maintenance is described in two papers - Beaumont, Harrison and Stove (1987) and Stove, Kennie and Harrison (1987). Both papers present the results of a survey and field investigations in the Lothian region of Scotland. The advantages of airborne mapping to that of vehicle-based mapping are discussed. The main disadvantages of vehicle mapping they refer to are:

1) the length of time required to complete thermal surveys, with the potential problem of changing ambient weather conditions.

2) the potential difficulty in relating a single longitudinal road temperature profile to its exact position on the ground and interpretation with respect to the local microclimate and environmental conditions.

The advantages of airborne mapping include speed of survey; breadth and detail of information; and ease of interpreting local environmental effects.

The Department of Geography, University College, Swansea, has an on-going involvement in the Welsh ice prediction system. The national network of 34 permanent sensors are all monitored by the master station at University College, Swansea. Recent research has included the comparison of the different ice detection systems and assessment of thermal mapping. Runacres, Colville-Symons and Symons (1989) review the state of the Welsh ice prediction system at the end of the 1987/88 winter. The assessment of thermal mapping during winter 1986/87 and comparison with a survey undertaken in spring 1986 by Travers Morgan is given in a comprehensive report by Symons, Williams and Colville-Symons (1987). The initial mapping (spring 1986) consisted of five runs along the length of the A470 and A44 in Powys and as far as Capel Bangor on the A44 in Dyfed. The later mapping was carried out independently with 12 runs being made along two separate routes. These routes covered the roads mapped by Travers Morgan in the spring of 1986 and were intended to provide a thorough checking of the first survey. The report discusses the value of thermal mapping in some detail and the most important points (and those most relevant to this project) are summarised below:

1) after analysis of both sets of mapping data it was found that the thermal fingerprint obtained in spring is not necessarily the same for winter, although differences were small. This seasonal variation was thought to be caused by differences in daylight hours and the potential solar receipt affecting possible accumulated temperatures.

2) a maritime influence on road surface temperatures was considered likely, when roads are located close to the coast, although this could not be reliably quantified.

3) several runs in one type of weather condition are needed to give an adequate picture of the thermal fingerprint. (No specific reason is given but {1} above is probably important).

4) it was concluded, from their findings, that thermal mapping was unnecessary where a route has a large altitude range as the effects of altitude can be interpolated from average lapse rates. Other factors do influence RSTs such as exposure, topography, weather conditions and maritime influences and although difficult to quantify thermal mapping indicates the combined effect of all these factors.

5) the results showed that an enhanced fingerprint is produced under clear, calm, anticyclonic conditions while mild, cloudy and wet conditions produce a fingerprint with a narrow temperature range.

6) the report stated that thermal mapping should only be undertaken under conditions which may pose an ice hazard (unless for research purposes). In these conditions the thermal footprint (fingerprint) will be enhanced and as thermal mapping is carried out to reduce ice hazards on roads it should be undertaken when actual conditions are most likely to produce this.

7) at least five runs should be made along each route under clear, calm, anticyclonic conditions in winter - see (2) and (5) above.

In addition, attitudes towards the process of thermal mapping were assessed with the following of particular interest:

1) The Department of Transport considered thermal mapping to be of benefit to all authorities primarily as part of ice prediction systems (presumably sensors), but also used on its own.

2) The authors of the report held a similar view to that of the Department of Transport within the specific context of Wales.

3) Welsh Highway Authorities:

a) Thermal mapping is considered to be useful to maximise the potential of ice detection equipment.

b) Although it was acknowledged that thermal mapping provides useful information, it was felt, by some, to draw attention to a pattern of cold spots already known to staff from operational experience.

c) With the difficulty of starting, stopping and re-starting gritting operations it was felt that little practical use could be made of thermal mapping on a day to day operational basis. (Nb. not applicable to all uses of thermal mapping).

d) Opinions varied as to whether it was advantageous to thermally map before installing ice sensors. There was little evidence of sensors being placed in the wrong location and there were limitations to sensor location due to the need to have services (telephone lines and electricity) available. However, if thermal mapping was carried out the sensor data would probably be of more value.

Harverson (1990) again expresses some concern about thermal mapping. She believes that general inaccuracies will result from the need to neatly classify weather into the three types and to simply demarcate 'night' and 'winter'. It is stated that there is some evidence showing that fingerprints mapped during the early part of the night differ from fingerprints taken under identical weather conditions at dawn. The author concludes by saying:

> " The Department of Transport's endorsement of thermal mapping in its very early and untried days gave the impression that here might be the key to safe, efficient winter maintenance. Now it is recognised that it is a useful but not essential addition to the ice warning system."

There has been limited thermal mapping carried out in the United States. Donahue and Associates carried out some thermal mapping for the State of Wisconsin in 1986 and although the results were interesting to the Highway Maintenance Department its usefulness was considered marginal. In addition New Jersey Department of Transport carried out some road temperature sampling along an interstate highway finding no great difference in temperature variations except on bridges. (Source: W. Overall, President Scan Systems and Services, pers. comm.).

A comprehensive and up-to-date review of thermal mapping is given by Thornes (Chapter 3 in Perry and Symons, 1991). Terminology is explained, those factors affecting RSTs discussed and the types of fingerprint produced are detailed. The author points out that thermal mapping is limited to providing relative temperature differences between stretches of road. It can only measure actual road surface temperatures to an accuracy of +/-2°C, because the emissivity of roads is not known accurately. Care must be taken, when interpreting results, if the emissivity of road surfaces varies in an area (also the emissivity of a dry road may differ from a wet or snow-covered road). The limitations of thermal mapping are summarised by a table of possible errors in vehicle-based mapping (see chapter 7 table 7.4). He also stresses the need to maintain the IRT within a constant temperature range during observations and for regular calibration. A possible future use for thermal mapping is suggested - controlling the rate of spread of de-icing chemical from a gritting lorry using a thermal map stored in an on-board computer.

1.4.3. Applied Climatology for Increased Traffic Safety and Road Maintenance.

Since the late 1970s the Highway Climatology Study Group, at the Department of Physical Geography, Gothenburg University, have been involved in research on RSTs and ice formation on roads. Work since the mid 1980s has been formalised in the project Applied Climatology for Increased Traffic Safety and Road Maintenance. This research has made frequent use of infra-red thermography and thermal mapping and the main papers of interest to this project are outlined below.

Lindqvist (1987) gives details of the theory of thermography and how it can be used to measure temperatures. The uses of airborne and ground based infra-red techniques for measuring RSTs are discussed and some initial results described.

The use of infra-red thermography to analyse variation in RST is the subject of a paper by Gustavsson and Bogren (1991). The authors describe how the infra-red equipment (an Agema 870, see section 1.3.2) is used from stationary, car and helicopter platforms. The advantages of each technique and the main factors affecting RSTs are discussed. The benefits of using an infra-red technique, for surface temperature measurement, as opposed to ordinary temperature probes are referred to.

Data obtained from thermal mapping are used in a number of applied climatological studies by the same authors (eg. Bogren and Gustavsson, 1989 and 1991). For example: temperature readings from mobile measurements and information from the Swedish Road Weather Information system (VVIS) are used to determine temperature variations associated with topography and weather. The influence of valleys on the variation in air and road surface temperatures has been determined (Bogren and Gustavsson, 1991). Temperature differences between valleys and surrounding areas increase with increasing depth and width of the valley with the prevailing windspeed being a major factor controlling the variation in temperature. If windspeed exceeds $3ms^{-1}$ there is no variation in temperature. The influence of cloud is also crucial with partly cloudy situations (3-5 octas) and no wind resulting in a temperature difference between the valleys and the surrounds 6^oC smaller than in clear and calm situations. In addition an increase in the cold air pool intensity of 1^oC lowers the road surface temperature by 0.4^oC. The risk of ice formation in a specific area can also be evaluated (Bogren and Gustavsson, 1989).

Other papers (Bogren, 1990; Gustavsson, 1990 and 1991) examine some of the factors (topography, wind and screening) affecting RSTs and the variation in the risk of ice formation on roads.

1.5. RESEARCH PROPOSAL AND PROJECT AIMS

1.5.1. Background to the Project

Sheffield City Council Works Department, like many authorities responsible for the winter maintenance of roads, continuously strives to improve the efficiency of their gritting operations. The use of new technology has played a crucial role in this.

From 1967 to 1987 an ice warning system was used in Sheffield which was connected, via dedicated telephone lines, to a large wall-mounted map of the city at gritting headquarters (Olive Grove Depot). For each of the 13 sensor locations there were three coloured lights: green denoting normal conditions; amber standby; and red indicated that conditions had become critical (ice likely to form or already formed). The system became increasingly outdated and difficult to maintain. During autumn 1987 it was replaced by the Icelert Mark 5 system (Findlay, Irvine Ltd) incorporating the benefits of past experience and the latest technological advances. The new system has nine surface sensor outstations located throughout the highway network of Sheffield (see fig. 2.3). Each sensor (see photos 1.1 and 1.2) continuously monitors (every two minutes) the temperature, moisture and salinity of the road surface. Air temperatures are also measured and five of the sites have a sensor which measures temperature at a depth of 30cm. The sensors are connected, by the general telephone network, to a monitor station at Olive Grove, where information is displayed on a VDU in the form of graphs and charts. Graphical displays showing temperature trends over the previous 24 hours are available with additional forecast text from Leeds Weather Centre. Figures 1.9-1.11 show some examples of the information available. Archive data are also stored both on hard and floppy disc.

Thermal mapping of the principal roads of Sheffield was carried out during February 1987, by Travers Morgan, to validate the location of the permanent sensors. Mapping runs were carried out on six nights (of which five were similarly cold and mostly clear). The fingerprints showed a common trend - decreasing temperatures from the City Centre to the Derbyshire boundary, as would be expected. However, the decrease in temperature between the city and Derbyshire boundary on some of the runs varied from 3-8°C despite the similar weather conditions. Comparisons were also made between the fingerprints and sensor data, during winter 1987/88, and these often showed little association.

Clearly, if five supposedly similar cold, clear nights could produce significant differences between the fingerprints, there must be considerable doubt about the reliability and repeatability of thermal mapping. As stated in section 1.4 there have been relatively few publications on thermal mapping with original research and opinions or a truly critical approach. Many publications suggest that high confidence can be placed in the process even if only a limited number of mapping runs are carried out. Other research and articles have called this into question and raised doubts about thermal mapping (see section 1.4.2) without providing the answers. Hence, the need for this research project. Sheffield City Council Works Department contacted the Department of Civil and Structural Engineering at Sheffield University with a view to setting up a joint research project. A SERC[1] CASE[2] award, 'Thermal Mapping for a Highway Gritting Network', was the result.

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[1] Science and Engineering Research Council

[2] Co-operative Awards in Science and Engineering

1.5.2. Detailed Proposals

Sheffield provides an ideal laboratory for studying the process of thermal mapping with considerable variation in relief and consequent climatic conditions. It was proposed that an extensive investigation, using thermal mapping techniques, should be undertaken. This study would aim to provide a better understanding of the factors affecting RSTs and in particular would be able to look at the repeatability and reliability of thermal mapping, ie. do two (or more) fingerprints mapped under the same weather conditions, along the same route, have the same shape and amplitude? It would also attempt to establish confidence limits for thermal maps and RST predictions using these maps.

One of the results of the project would be to produce 'appropriate, accurate, and reliable' thermal maps of the principal Sheffield road network. These maps could then be used to aid the authority's winter maintenance operations and improve the efficiency of gritting. Substantial savings in both manpower and materials could be made, as well as wider benefits to the community through the avoidance of unnecessary gritting and its detrimental effects on vehicles, highways and the environment. The results of this research project were likely to have wider general applications and would probably benefit other highway authorities.

CHAPTER 2

STUDY AREA, THE CITY OF SHEFFIELD

As pointed out in chapter 1 (section 1.5) Sheffield provides an ideal laboratory for examining the process of thermal mapping. There is considerable variation in all the main factors likely to affect road surface temperatures (altitude, land-use, topography and traffic conditions). Clearly, it is not just the physical environment of Sheffield which is important, but also its industrial and residential characteristics.

2.1. LOCATION AND DEMOGRAPHIC CHARACTERISTICS

Sheffield occupies a location in central England (latitude 53°25'N, longitude 1°29'W) as shown in figure 2.1. The city has grown up in a number of valleys on the eastern edge of the Pennines and is about 100km from both the east and west coasts. Sheffield is almost equidistant from the cities of Leeds, Manchester and Nottingham with the M1 motorway passing through the north-east of the city at Tinsley.

With Sheffield situated on the edge of the Pennines there is a distinct decrease in altitude from the west of the city to the east. The high ground to the west has caused some difficulties in terms of access to other parts of the country, particularly the north and west. The main roads over the Pennines (figs. 2.2 and 2.3) are the A57 (Snake Pass, 512m.asl), A628 (Woodhead Pass, 452m.asl) and A625. Tunnels have been constructed to the south (Bradway) and west (Totley) to overcome the problems for rail transport. The completion of the M1 in the 1960s has given Sheffield direct access to the UK's motorway network. The main roads of Sheffield tend to radiate out from the city centre and the outer ring-road is mostly restricted to the south and east of the city due to the physical constraints (fig. 2.3).

From Sheffield's original site on a spur of land overlooking the valley of the river Don it has expanded in all directions to its present day size as shown in figure 2.2. The City of Sheffield Metropolitan District has a population of 500500 (1991 Census of Population). Unlike many UK cities Sheffield does not have large areas of urban sprawl, but is instead very compact. Westward expansion is constrained by a Green Belt drawn against the Peak District National Park limits to the west and south of the city. Other distinctive features of Sheffield are its hilliness, particularly on the western side, and its residential polarisation.

The land-use of Sheffield reflects its historical development and this residential polarisation. Heavy industry tends to be concentrated along the Lower Don Valley (fig. 2.2) where most of Sheffield's steel industry has historically been located. In the last two decades the decline of the steel industry has meant that many sites have been demolished and some of these have recently been replaced by the development of leisure facilities (eg. Meadowhall shopping complex and Don Valley Athletics Stadium). Other manufacturing industry is concentrated along the Upper Don Valley, Sheaf Valley and in some out of centre locations (eg. Holbrook Industrial Estate and Ecclesfield). Sheffield's city centre, like most, has many high-rise buildings, shops and office blocks. The residential landscape reflects the city's social polarisation. Most of the south and west of the city consists of tree-lined suburbs while working-class districts and vast council housing estates (eg. Pitsmoor) are concentrated in the north and east. These areas are characterised by highly concentrated terraced housing or council houses (eg. Parson Cross) with little greenery. However, Sheffield does have numerous large open spaces throughout the city from Concord and Parson Cross parks in the north-east to Graves and Endcliffe parks in the south and west (figure 2.2).

As well as the city itself there are a number of smaller distinct settlements within the City of Sheffield boundary. These include the relatively large areas of Stocksbridge/Deepcar (to the north-west), Chapeltown/High Green (north) and Mosborough (south-east). In addition, principally on the western side, there are a number of villages within the Sheffield area such as Oughtibridge, Bradfield, Bolsterstone and Ringinglow. Recent new housing has been concentrated in the two peripheral areas of High Green and Mosborough. Mosborough became part of Sheffield in 1967 (along with Stocksbridge and High Green) and has developed in a similar way to a New Town. New housing development has been encouraged by Sheffield City Council's planning policy with a mixture of owner occupied and publicly rented housing. Many services have been allocated to the area, in particular Crystal Peaks shopping centre, along with new road access and extensive public transport services.

2.2. SHEFFIELD'S PHYSICAL ENVIRONMENT

2.2.1. Relief

Sheffield's built-up area mainly occupies the valleys of the river Don and its tributaries flowing down from the eastern side of the Pennines. The land between these valleys forms seven ridges often called the 'Seven Hills of Sheffield'. The built-up area on these ridges tends not to be as dense as in the valleys, especially on the western side, due to the problems of building on steep slopes. Within the

Sheffield District boundary the altitude varies from 30 to 550m (100 to 1800ft) above sea level. There is a steady decline from the high moorland in the west to the floor of the Lower Don Valley in the east. Generally the eastern parts of the city are hilly but less spectacular than the west. Figure 2.3 shows the detailed variation in relief in and around Sheffield. Not surprisingly there is a shortage of flat land within the city with the main areas along the floor of the Don Valley where industry concentrates. The tributaries have narrower areas of flat land. The tops of the ridges provide areas of gently undulating land such as Lodge Moor on the Hallam Ridge and Parson Cross on the Shirecliffe-Pitsmoor Ridge.

2.2.2. Climate

Sheffield's location is the main influence on its climate with considerable variation due to altitude and relief. Maritime influences are less than in much of Britain due to Sheffield being about 100km from either coast. The Pennines, to the west of the city, reduce the effects of the prevailing westerly winds by generally reducing wind speeds and producing a very marked 'rain-shadow' with decreasing rainfall east of the high ground. The city is also located on the boundary between the mostly high ground of Northern England and the lowland Midlands and south of England. Because of this Sheffield is often on the edge of distinctly different weather types on forecast maps.

As well as relief/altitude the influence of the city itself, on the climate, is important. Urban areas tend to reduce windspeeds due to increased friction from buildings and cities are often warmer due to extra heat inputs (eg. domestic and industrial) into the atmosphere (see section 1.3.3). Increasing altitude results in greater rainfall, higher windspeeds and decreases in sunshine and temperature. The lower temperatures of higher altitudes increase the occurrence of frozen precipitation and the higher suburbs of Sheffield can often be affected by snow while the city centre and eastern side are clear. The combined effect of decreasing altitude and moving closer to the city centre and main industrial areas results in considerable differences in the city's climate from west to east. The industrial/recreational Lower Don Valley has a relatively warm and dry microclimate which contrasts sharply with the cool and windy suburbs bordering on the Pennines. Along with the differences in land-use (open moorland to dense city centre high-rise buildings) the variations in altitude and relief result in Sheffield probably experiencing more climatic variation than any other British city.

Weston Park Museum, near the university (fig. 2.3), has a meteorological station (photo 2.1) with an observation record stretching back to 1882. Table 2.1 shows temperature, sunshine and precipitation records, for all months, for the period 1951-1980. Details of the meteorological station are:

Latitude: 53°23'N. Longitude: 1°29'W.
National Grid Reference: (43) 339873.
Height of rain-gauge above Mean Sea Level: 131m.
Height of barometer cistern above Mean Sea Level: 137m.
Height of anemometer above the ground: 24m.
Effective height of anemometer vane (above building): 14m.
Principal time of observation: 09.00 G.M.T.
Station Number: 4061.

TEMPERATURE

The location of this weather station at a relatively low altitude (131m.asl) and close to the city centre moderates extremes of temperature from occurring. The maximum temperature ever recorded is 34.3°C on August 3rd 1990, while the lowest, -

14.6°C, occurred on 10th February 1895. July is the warmest month and January and February are the equal coldest.

FROST

The average annual occurrence of air frost (minimum air temperature 0.0°C or below), for the period 1971-1990 is 35.2 days. Annual totals range from just seven frosts in 1974 to 60 in 1979 and 1985. These figures are for Weston Park and clearly there will be considerable variation with altitude and land-use. High altitude moorland areas will have a greater number of frosts and lowland areas, particularly in rural districts, may also have more frost due to cold air drainage.

PRECIPITATION

The 'rain-shadow' effect of the Pennines is demonstrated by the rapid fall-off in precipitation from west to east with 1066.8mm per annum at Redmires (3km from western edge of city, 338m.asl), 809.2mm at Weston Park and 645.2mm at Rotherham (86m.asl). Heavy falls of rain can occur if the wind is from the east or north-east when there is little interruption from high ground. The wettest month, on average, is November and the driest June.

SNOWFALL

Details of snowfall have only been recorded at Weston Park since 1937. On average snow lies (at 9.00am) on 20 days per year and falls on 25.6 days per year. The amount of snow increases considerably at higher altitudes on the west of the city and decreases to the east. Table 2.1 presents details of the occurrence of snow for the period 1951-80. February is the snowiest month.

WIND

Sheffield is not a particularly windy place with an average windspeed of 3.6m/s (8mph). The Pennines provide some shelter from the prevailing westerlies and the greater friction from buildings tends to reduce air-flow in the city. Windspeeds are greater at higher altitudes with the western suburbs generally windier than in the east. The highest windspeed ever recorded at Weston Park is 43m/s (96mph) which occurred on 16th February 1962. Figure 2.4 is the wind rose for Weston Park (1951-1980).

2.3. WEATHER CONDITIONS DURING THE RESEARCH PROJECT

The weather conditions during 'winters' 1988/89 , 1989/90 and 1990/91 will be described. For the purposes of this project the weather during the months of November through to April will be included. The national picture for each month is summarised below in sections 2.3.1-2.3.3 with table 2.2 showing the Lamb weather types for each day during the three winters. Details of weather conditions in Sheffield for the same periods are given in section 2.3.4.

2.3.1. Winter 1988/89

NOVEMBER

A mostly anticyclonic month with frequent frost and fogs. Mean temperatures were mostly below normal (except Scotland). It was very dry with less than 50% of normal precipitation in many places. Amounts of sun were mostly well above average.

DECEMBER

An exceptionally mild month dominated by south-west winds especially in the second half. It was very dry, but cloudy with considerable anticyclonic influence. Temperatures were well above normal everywhere. There was less than 50% of normal precipitation over most of England, Wales and eastern Scotland and less than 25% in a few places in the south. In parts of west Scotland and north-west England precipitation was close to average. Sunshine amounts were less than normal except in sheltered eastern areas where it was sunnier than normal.

JANUARY

An exceptionally mild and very dry month with no serious cold spells. It was dominated by westerly and south-westerly weather types with some anticyclonic influence at times. Temperatures were well above normal everywhere. Western Scotland was exceptionally wet (more than 200% of normal precipitation), but in parts of east Scotland and most of England and Wales only 50% of normal precipitation was reached. Sunshine amounts were above normal except in west Scotland.

FEBRUARY

A mild and unsettled month with gales in the north. Westerly and south-westerly weather types were dominant with little anticyclonic influence. Mean temperatures were well above normal everywhere. Except some eastern areas precipitation was above average with north-west Scotland very wet (200-400%). Normal amounts of sunshine were experienced except in north and west Scotland.

MARCH

A mild month, wet in places dominated by westerly and south-westerly weather types with considerable cyclonic influence. Mean temperatures were above normal everywhere. Precipitation was above average except in east Scotland and north-east England. West Scotland was again very wet with more than 200% normal precipitation. Sunshine was below normal everywhere except most of Scotland and northern England.

APRIL

A cold, cloudy and wet month dominated by cyclonic weather types and with considerable northerly influence between the 17th and 25th. April was colder than March in many places (including Sheffield) - a rare occurrence. Mean temperatures were below average everywhere and there was less sunshine than usual. England and Wales was very wet but most of Scotland drier than usual.

The official winter period (December to February) as a whole was exceptionally mild, very dry and quite sunny except for the north-west which was wet. March was also mild, but in contrast wet. The months of November and April were both cold, but in very different ways - November being dominated by dry anticyclonic weather conditions and April by wet cyclonic.

2.3.2. Winter 1989/90

NOVEMBER

An unsettled start was followed by dry anticyclonic conditions. Mean temperatures were near or above average in most places. Precipitation was well below average with northern and eastern Britain having less than 50% of normal. Sunshine amounts were well above average and places as far apart as northern Scotland and southern England had over 150% of average.

DECEMBER

A settled start dominated by anticyclonic influence was followed by a very unsettled mid-month with a cold spell in the north. Mean temperatures were below normal over much of Scotland, Northern Ireland, North Wales and parts of northern England and above average over most of southern and eastern England. Precipitation was well above average in the south with more than 200% in parts of the Midlands and southern England. Precipitation was below average from northern England northwards. It was very cloudy except in north and west Scotland which had more sun than normal.

JANUARY

A very mild, wet and windy month dominated by westerly and south-westerly weather types. Mean temperatures were well above normal everywhere.

Precipitation was also well above average (northern and central areas 150-200%) except on some eastern coasts.

FEBRUARY

Another very mild and wet month with severe gales at times. Westerly and south-westerly weather types were dominant with considerable cyclonic influence. Mean temperatures were above normal everywhere. It was very wet with over 200% of normal precipitation in many places. Sunshine amounts were also above normal except in some western areas.

MARCH

A very mild and dry month except in the north-west where it was wet. Predominant weather types were westerly and south-westerly with anticyclonic influence at times. Temperatures were well above average. West and north Scotland was very wet (more than 200%). In Eastern Scotland and much of England and Wales precipitation was very low with around 30% in many places. Sunshine was above average except in some western and northern areas.

APRIL

A very sunny month with damaging night frosts. Anticyclonic influence was strong for most of the month especially towards the end. The middle of the month was more unsettled. Mean temperatures were near to or a little above average in most places. Apart from western and northern Scotland precipitation was generally below average (parts of north-east England less than 25%). Parts of East Anglia and south-east England also had above average precipitation. Sunshine amounts were above normal almost everywhere.

The winter period as a whole was milder and wetter than average everywhere. November, March and April were all dry months with temperatures close to average except March which was mild.

2.3.3. Winter 1990/91

NOVEMBER

A generally dry month which was very sunny in the south and west. No particular weather type was dominant although there were periods with strong anticyclonic influence especially towards the end. The middle of the month was more unsettled. Mean temperatures were mostly a little above normal. Most places had below average precipitation. The south and west coasts had greater than normal sunshine amounts, but parts of north England were notably cloudy.

DECEMBER

A mixed month with strong anticyclonic influence in the first half, northerlies dominating the second week producing a wintry spell and westerly and south-westerly weather types predominating for most of the second half with a very stormy Christmas period. Temperatures generally were close to average. Amounts of rainfall varied considerably with southern areas generally below average. Most southern and western parts of England had above average sunshine amounts, but parts of north-west Scotland had only 30%.

JANUARY

Very unsettled until the 12th, dominated by westerly and south-westerly weather types, with snow in the north. The rest of the month was mainly anticyclonic. Mean temperatures were close to average everywhere. Sunshine amounts were well above average everywhere (east coast 150-200%). Most of Scotland had below normal precipitation while southern England was wetter than normal.

FEBRUARY

Cold during the first part of the month with easterly and south-easterly weather types dominant. The latter part of the month was much milder. Mean temperatures were below average everywhere. Precipitation amounts were particularly variable with areas near the English-Scottish border 150-190% of normal. The south coast and most western areas had above average sunshine while East Anglia was very cloudy.

MARCH

A cold start (easterly and south-easterly), mild mid-month (southerly and south-westerly with cyclonic influence) and then colder again with strong anticyclonic influence. Mean temperatures were above normal everywhere. Wales, Northern Ireland and most of south-west and western England had well above average precipitation with East Anglia and parts of the south-east drier than normal (40-60%). Sunshine amounts were below average almost everywhere especially in the north-west (55-65%).

APRIL

A unsettled start dominated by westerly and south-westerly weather types, with the second week very warm (southerly influence) , followed by a wintry third week with anticyclonic northerlies dominating. Mean temperatures were close to average everywhere. Sunshine amounts were greater than normal over eastern areas while in the west it was below average. Northern Ireland, western Scotland, Wales and the southern half of England were wetter than normal while eastern Scotland and north-west England were drier and parts of north-east England had less than 50% of average precipitation.

The winter as a whole was variable with temperatures close to or a little below average and precipitation generally slightly above normal. November was a mainly dry and mild month, March mainly wet and mild, while April had very variable rainfall with near average temperatures.

2.3.4. Sheffield

The weather conditions for Sheffield (Weston Park) for the three 'winters' are summarised below. Table 2.3 gives the monthly weather data (see table 2.1 for long-term averages for comparison).

1988/89

November was a sunny month with below average temperatures. The lowest temperature of 1988 (-2.3°C) was recorded and snow fell on the 20th and persisted until the 23rd. In addition there were 10 air frosts. In contrast December was the equal mildest on record (with 1934) with no air frosts or lying snow. It was a much drier and windier month than normal. January was a very dry month (the driest of

1989) and also very mild with only two air frosts. It was also the sunniest January for the decade. February was similar, being the mildest since 1967, with twice the average sunshine, only three air frosts and only very light snowfall. The winter period (December to February) was the mildest on record since records began in 1882. March was another mild and sunny month with the highest total sunshine for seven years and only two air frosts recorded. In contrast April's mean temperature was 2°C below average, four air frosts occurred and snow fell on six days. April is often the driest month of the year but was actually the second wettest in 1989 with more than twice the normal precipitation.

1989/90

November was a dry month with mean temperatures similar to normal. The first cold spell arrived towards the end of the month with three air frosts. The early part of December continued dry and settled but the weather then changed with very dull and wet weather for the rest of the month. It was the wettest month of the year (1989) with 34mm falling on the 13th and the unusual occurrence (for December) of a thunderstorm on the 16th. Some light snow fell. January was a very mild month (2.8°C above average) with only one air frost, little snow and the highest January overnight temperature (16th, 10.6°C) ever recorded. It was a very wet month with the second wettest day of 1990 occurring on the 27th (31.4mm) and the windiest January on record (since 1959) with gusts up to 34m/s (76mph). February was another very mild (mean temperatures 3.5°C above normal), windy and wet month. The highest ever February maximum (23rd, 17.5°C) and minimum (20th, 10.7°C) temperatures were recorded. There was only one air frost with very little snow. March continued the exceptionally mild spell with mean temperatures 3.4°C above normal although three air frosts were recorded. The highest mean and maximum temperatures since 1965 were achieved. In contrast to January and February it was very dry and sunny with a windy start to the month. April was very sunny and dry with temperatures just below normal and three air frosts.

1990/91

November's mean temperatures was just below normal with below average sunshine and precipitation. No air frosts were reported. December was a very unsettled month with strong winds, high precipitation and slightly below average temperatures. It was actually the coldest month of 1990 with four air frosts and three days of lying snow mid-month. The months of January and February 1991 were in marked contrast to the previous two winters. Both were colder than normal with 15 air frosts in January and 14 in February. In addition snow fell in both months with 15 days of lying snow in early February. Mild weather returned from mid-February and continued into March. Mean temperatures for March were 2.5^{o}C above average with only one air frost. It was also dull although just below average precipitation fell. April was a mixed month with mean temperatures and sunshine similar to normal. Precipitation was slightly above normal and two air frosts were recorded.

The mild winters of 1988/89 and 1989/90 had important implications for the progress of this project with few cold nights and in particular, few nights with extreme weather conditions. However, the frequent anticyclonic activity and cold spells during winter 1990/91 compensated for the previous two mild winters.

2.4. ROUTE SELECTED FOR DETAILED STUDY

As discussed in section 1.5 the main aims of this project were to assess the reliability/repeatability of thermal mapping; to identify the factors affecting road surface temperatures; and to produce thermal maps of the Sheffield area. In order to produce accurate thermal maps considerable work needed to be carried out on the first two of these aims. For this reason it was decided to concentrate on a single route initially, carrying out thermal mapping on a large number of nights under many different weather conditions.

The route was chosen to coincide with the location of as many Icelert sensors as possible to enable comparisons to be made between Icelert temperature readings and thermal fingerprints. While driving the route the sensors at Moscar Top, Hillfoot and Prince of Wales Road are directly driven over while the sensor at Tinsley is passed on the other side of the road.

The route chosen for the main study needed to be a representative cross-section of the city incorporating variations in as many of the main factors affecting road surface temperatures as possible. The route selected is shown in figure 2.5 and described in detail in Appendix 1. This route provides considerable variation in altitude from a height of 350m.asl at Moscar Top to only 30m.asl at Tinsley roundabout. All the major land-use types are represented along this route: open moorland at Moscar Top (see photo 2.2); tree-lined suburbs near Crosspool (photo 2.3); terraced housing at Hillsborough (photo 2.4); light manufacturing along the Upper Don Valley (photo 2.5); city centre buildings (photo 2.6); heavy industry in the Lower Don Valley and Shepcote Lane (photo 2.7); and relatively open country (at low altitude), with some industry, along Sheffield Parkway (photo 2.8). Different road types are also represented with single carriageway A-roads (eg. A57 and A6178), relatively minor B-roads (B6082) and heavily-trafficked dual carriageways (during the day) such as the Sheffield Parkway (A57/A630). All the roads along this route are surfaced with asphalt.

In later winters thermal mapping was to be extended to the rest of the principal highway network of Sheffield. Details of routes 2-7, mapped during winter 1990/91, are given in appendix 1.

CHAPTER 3

THERMAL MAPPING EQUIPMENT AND PROCEDURE AND MAPPING WINTER 1988/89

3.1. THERMAL MAPPING EQUIPMENT

3.1.1. Thermal Mapping Hardware

Following discussions with TMI and Travers-Morgan and Partners the equipment necessary for thermal mapping was obtained from Travers-Morgan (on the grounds of both cost and availability for use). Sheffield City Council Works Department supplied a Ford Escort van to be used for mapping. Various modifications to the van were carried out by Travers-Morgan and equipment installed during December 1988/January 1989.

EQUIPMENT PROVIDED

1) Minolta/LAND Cyclops Compac 3 Portable Infra-Red Thermometer (see photo 3.1)

The Compac 3 measures the road surface temperatures. It has a spectral response of 8-14μm and a measuring range of -50°C to +500°C with a resolution of 0.1°C. The temperature of a target can be measured at various distances up to 5m. The target is sighted through the view-finder and the greater the distance from the target the larger will be the measurement spot - the target must fill the sight in order that the temperature measured is accurate. The Compac 3 focuses and detects infra-red radiation emitted by the target and micro-processor based electronic circuits calculate the temperature of the target and produce both a digital display and serial digital output of this temperature. More details of the operation of the Compac 3 are given in chapter 4. The digital output provides data for a portable personal computer. The infra-red thermometer is powered by six AA batteries and the emissivity value can be adjusted using a push-button control in steps of 0.01 (0.01 to 1.00). The selected emissivity value is displayed next to the measured temperature. The detailed specification of the Compac 3 is given in appendix 2.

2) Bondwell 8 Portable Microcomputer (see photo 3.2)

The Bondwell 8 is used for data collection, storage and some processing. It is a lapsize portable microcomputer with 512kB dynamic user RAM and uses IBM compatible software. More details of the Bondwell 8 are given in appendix 2.

MODIFICATIONS TO THE VAN

1) A Vascar pulse unit was fitted to the van. The Vascar unit is designed to trigger the infra-red thermometer to take temperature readings at set distances. It is a speedometer pickoff device consisting of a slotted disc (6 slots), a lamp and a Darlington photo-transistor (fig. 3.1). The slotted disc is fitted to the speedometer cable and the device emits six 5 volt pulses per cable revolution. The speedometer cable was split and the Vascar unit fitted between the split ends (photo 3.3).

2) An electronic unit, fitted in the van's glove compartment (photo 3.4), was connected to the Vascar unit, infra-red thermometer and computer. This unit carries out two processes. Firstly, the number of pulses emitted by the vascar unit was too many to obtain pulsed temperature readings at the required intervals - the electronic unit reduces the number of pulses from the speedometer to the infra-red thermometer. The pulse frequency can be varied to suit the intervals at which temperature readings are taken and this is entered via the computer. When the van is travelling at 65kph (40mph) and the infra-red thermometer pulsed to take a reading every 20m the average surface temperature over a distance of 9m is measured. The second process carried out by the electronics box is to convert the signal from the infra-red thermometer into a format compatible with the Bondwell 8 computer.

3) A mounting for the Bondwell 8 was built and fitted to the dashboard in front of the passenger seat (photo 3.4). A small hole, 50mm in diameter, was cut in the floor of the van and a mounting for the infra-red thermometer fitted next to this hole (photo 3.5). The position of the road temperature measured lies between the wheels on the lateral axis of the vehicle (photo 3.5) and is approximately in the centre of the lane in the direction of travel. The layout of the equipment in the van is shown in figure 3.2.

3.1.2. Thermal Mapping Software

Savoy Computing (a branch of Travers-Morgan) wrote the IBM compatible software necessary for data collection, storage, processing and plotting of fingerprints. The program TEMPTHRM is used for data collection and is run on the Bondwell while mapping is in progress. It enables the distance between readings to be varied and accepts details of the route being mapped, atmospheric readings and road surface conditions. The program initiates the pulsing of the infra-red thermometer and the road temperatures measured are displayed alongside the count number on the computer screen. One count is equal to the pre-set distance for pulsed readings (usually 20m).

The route details, atmospheric readings and road temperatures are stored on a 3.5 inch floppy disc on completion of the program. TOPOTHRM is available for use in the Bondwell 8 to record details of vegetation, buildings, cuttings etc while travelling along a route.

Data processing and plotting of fingerprints is carried out by the program PLOTTHRM. This is run on a VIGLEN PC in the Department of Civil and Structural Engineering. The fingerprints are plotted using a ROLAND DXY plotter. The temperature data were transferred from the 3.5 inch discs to 5.25 inch discs for use on the VIGLEN. Fingerprints are plotted on A3 paper (three to each sheet) in lengths of up to 30km.

Due to slight differences in the PC and plotter used by Travers-Morgan and those used in the Civil Engineering Department there were some initial delays before PLOTTHRM could be used and fingerprints plotted. Savoy Computing provided a new DRIVERS program to be used with PLOTTHRM. A second version of PLOTTHRM was also provided so that fingerprints could be plotted up to both 25km and 30km lengths. These delays meant that fingerprints could not be plotted until March 1989 with implications for the progress of the project in its early stages (see sections 3.1.3 and 3.3).

3.1.3. Testing of Thermal Mapping Equipment

The van and equipment were tested by Travers-Morgan before delivery and found to be working correctly. As soon as the van was available for use in Sheffield (January 1989) a number of trial runs were carried out in order to confirm that the equipment was operating correctly and to get acquainted with the procedure for mapping.

TRIAL RUNS

The initial trial runs were made along a section of route 1 (fig. 2.5) on 10.1.89 and 13.1.89. The route was along the A57 from Moscar Top Icelert sensor to its junction with Rivelin Valley Road (A6101). The van was parked by the roadside and then driven (for approximately 20 minutes) prior to the start of the run. The run then commenced near the Moscar Top sensor heading towards Sheffield, the vehicle was turned round at the junction with the A6101 and then driven back to the sensor. This was carried out twice in succession (loops 1 and 2) on both nights and the run was completed within 30 minutes. Cloud and wind conditions were measured at the start and end of each run (see section 3.2 for equipment used). The weather on 10.1.89 was clear skies with light winds (extreme) and windy and cloudy on 13.1.89 (damped). Two further trial runs were made during the night of 23/24.2.89.

The initial trial runs confirmed that the thermal mapping equipment was set-up and working correctly. By relating the total distance travelled (mileometer) to the end count the Vascar pulse unit and associated electronic box were found to be working correctly, ie. pulsing the IRT every 20m. The repeated mapping of the same stretch of road, in a short period of time, would allow comparisons to be made between the temperatures measured. However, due to the software problems described in the previous section the fingerprints could not be displayed on a computer or plotted until March 1989. Examination of some of the temperatures measured during the trial runs (displayed on the Bondwell 8 in the van) suggested there were no major problems with the temperatures measured.

At this time the main concern with thermal mapping was the repeatability of fingerprints in different weather conditions, at different times of the year and at different times of the night. Because of this it was important to start mapping as soon as possible in order to produce a large number of fingerprints. With half of the first winter already passed mapping of route 1 commenced as soon as the trial runs were completed even though the fingerprints could not be plotted and therefore examined in detail.

3.2. THERMAL MAPPING PROCEDURE

The method for carrying out thermal mapping was broadly the same as that used by Travers-Morgan. The van was driven along the route to be mapped at speeds up to a maximum of 78kph(48mph). Speeds greater than this are too fast for the response time of the infra-red thermometer and the temperature of some stretches of road would not be measured. If this speed is exceeded the computer emits an audible warning. Each mapping run was completed within 45 minutes to ensure there was little or no change in the temperatures while mapping was being carried out. As far as it was possible exactly the same route was followed on every run although roadworks and slow-moving vehicles (eg. milkfloats) caused some deviation from the normal route.

Each mapping run commenced at the same time each night, 0425-0435hrs, as both air and road temperatures should be relatively stable if weather conditions do not change (see section 1.3.1). This is different to the timing of the thermal mapping companies who usually map through the night from midnight to dawn. The emissivity value, on the Compac 3, was set at 0.96 as used by Travers-Morgan. Unless otherwise stated all road surface temperatures have been measured using an assumed emissivity value of 0.96.

Weather observations and atmospheric readings were taken at the start and end of each run as follows:

1) wet and dry bulb air temperatures (^{o}C) using an Assman Hygrometer (photo 3.2).

2) windspeed (m/s) using an anemometer (photo 3.2).

2) cloud cover (octas) was estimated.

3.2.1. Methods of Data Collection Winter 1988/89

Route 1 was the only route mapped during the first winter (1988/89). Concentrating on a single route would enable a large number of runs to be made under varying weather conditions and differences in fingerprints would be easier to identify. The specific objectives and procedure are as follows:

1) to investigate the variation of thermal fingerprints:

  a) under different weather conditions
  b) under similar weather conditions

The thermal mapping equipment (Bondwell 8 and Compac 3) were stored inside a house while not in use. Before mapping commenced the computer and infra-red thermometer were taken to the van (parked by the roadside) and the equipment set-up for mapping. The van was then driven to the start of the run at the Sheffield/Derbyshire boundary on the A57 (about 20 minutes drive). The infra-red thermometer was switched on, atmospheric readings taken and mapping commenced at approximately 0430hrs. The run terminated near Park Square roundabout (Broad Street) some 45 minutes later. Route 1 was mapped once each night, in varying weather conditions.

2) to investigate if there is any variation in fingerprints mapped at different times of the same night in identical weather conditions.

Three runs were made along route 1 commencing at 2230 , 0130 and 0430hrs. The procedure was identical to above for the 2230hrs run, but the mapping equipment was then left in the parked van for the later runs. These runs were only to be made under extreme weather conditions (clear skies and light winds) when significant radiative cooling and cold air drainage was most likely and consequently changes in fingerprints most likely to occur.

3.3. MAPPING WINTER 1988/89

Thermal mapping of route 1 commenced mid January and was completed by the end of March. A total of 32 mapping runs were made during this period. Four of these were trial runs discussed in section 3.1.3. A total of 19 runs were made along the full route commencing at 0430hrs. Figure 3.3 shows extreme (3.3a), intermediate (3.3b) and damped (3.3c) fingerprints of route 1. Seven runs were also made along the full route, at varying times of the night, in order to examine possible changes in fingerprints during the night. Figure 3.4 shows the three fingerprints of the runs made during the night of 17/18.1.89.

Towards the end of April 1989 two runs, one under extreme conditions and one damped, were made along route 1 in the reverse direction (ie. Park Square roundabout to Moscar Top). The fingerprints from these reverse runs are shown in figure 3.5. The reasons for making the reverse runs and the implications of the results are discussed in section 3.4.2.

Table 3.1 gives a detailed summary of all the runs made during winter 1988/89 and includes details of cloud, wind and temperature measurements. The runs are also classified into categories (extreme, intermediate, damped and other) on the basis of the following criteria (determined by the author with reference to thermal mapping literature):

1) extreme: cloud < = 1 octa at start and end of the run
wind < = 2ms^{-1} at start and end.

2) intermediate: either 8 octas cloud and calm at start and end or
0 octas cloud and wind > = 3ms^{-1} at start and end.

3) damped: cloud > = 7 octas cloud at start and end
wind > = 3ms^{-1} at start and end.

4) all other runs classed as 'others'. Including those affected by localised or extensive fog.

3.4. PERFORMANCE OF THE INFRA-RED THERMOMETER WINTER 1988/89

During the early stages of the research project (December 1988-April 1989) increasing doubts arose about the performance of the Compac 3 infra-red thermometer. These doubts first came to light while assisting Travers-Morgan with thermal mapping in Rotherham during December 1988. Temperature readings of the road surface, made by the IRT, were much lower than would have be expected from the air temperatures recorded. Also, while testing the IRT successive temperature readings of the same object often showed some variability. On one occasion, after the IRT had been moved from a warm office at Olive Grove Depot to outside, successive temperature readings of the surface of the car park dropped markedly.

When the software problems (section 3.1.2) had been solved, and fingerprints plotted, visual inspection of the fingerprints from both the trial runs and complete runs reinforced the concern about the IRT's performance. Figure 3.6(a) shows the fingerprint from trial run CAL1 - sections (A) and (C), along the fingerprint, are the same stretch of road (van travelling in the same direction, towards Sheffield) mapped 15 minutes apart. Weather conditions were stable with clear skies and light winds. Under these conditions each section of road would be expected to be at very similar temperature; however, as the fingerprint clearly shows, section (A) is colder than section (C). Figure 3.3(a) is the temperature fingerprint from the complete run FULL12 mapped under extreme conditions. This fingerprint has a very distinct 'cold start' which is discussed in greater detail in section 3.4.2.

Clearly, from these observations of the IRT and early thermal fingerprints, there is some doubt about both the accuracy and consistency of temperature readings made by the Compac 3 infra-red thermometer under thermal mapping conditions used in the early stages of this research project.

3.4.1. Consistency of Temperature Readings

Successive temperature readings made by the Compac 3 of the same object often show some variability. Minolta/LAND's specification for the Compac 3 claims a repeatability of +/- (0.1% K + 1 digit), ie. if a temperature reading of 10.0^{o}C is made the next reading, of the same object, will be between 9.9 to 10.1^{o}C (J.Bamford, LAND Infrared ltd, pers. comm.).

Tests were carried out in order to identify and quantify the variability in successive temperature readings made by the infra-red thermometer. Before these tests commenced (summer 1989) the Compac 3 was calibrated by LAND at 0.0°C and room temperature (see appendix 3).

VAN TEST

Date: 11.4.89
Time: 0136-0210hrs
Location: in van, parked on Oakbrook Road, Sheffield

The IRT was positioned in the van as for mapping. The van was parked, with the engine off (and cold). Weather conditions were mostly cloudy with light-moderate winds (ie. little likelihood of air and RSTs changing over the test period). A series of temperature readings of the road surface were taken over a period of 34 minutes.

A total of 135 road temperature measurements were made and if we take the average of all readings (+0.95°C) as the true road surface temperature then:

1) 95% of all readings were within +/- 0.35°C of the true (average) temperature.

2) 81 of the readings (60%) differed from the next successive reading by 0.1°C or less.

3) only four (3%) of the readings differed from the next reading by 0.5°C and none by more than this.

LABORATORY TEST

Similar tests (to the above) were carried out in a constant temperature room in the Department of Civil and Structural Engineering. The IRT was mounted above a hole cut through a metal table and melting ice (at 0.0°C) used as the target (see photo 3.6). The IRT was left in the room for four hours to reach equilibrium with the room temperature. The emissivity of the melting ice was then determined by adjusting the emissivity value on the IRT until the average of a number of readings (three sets of ten) was 0.0°C. The emissivity value of the melting ice was found to be 0.99. The room temperature was maintained at 21.0°C for the duration of the test. A total of 160 temperature measurements of the ice were then made:

1) 97.5% of all the readings were within +/- 0.3°C of 0.0°C.

2) 65% of the readings differed from the next successive reading by 0.1°C or less.

3) only 5 (3%) of the readings differed from the next reading by 0.4°C and none by more than this.

The results of both laboratory tests and tests conducted in the van show that although the consistency of readings made by the IRT is not as good as claimed by the manufacturer they are acceptable for thermal mapping.

3.4.2. Accuracy of Temperature Readings

The visual inspection of a number of fingerprints mapped during winter 1988/89 suggested that there was a problem with the accuracy of the Compac 3 when used for thermal mapping. A number of lines of evidence, including comparison with Icelert temperature readings, supported the view that there were problems with the early temperature readings made during a run. These are outlined below:

VISUAL INSPECTION OF FINGERPRINTS

1) Trial runs (CAL1, 2 and 4)

Figure 3.6 shows the fingerprints of trial runs CAL1, 2 and 4. Sections (A) and (C) of the fingerprint, on loop 1 and loop 2 respectively, are the same section of road (Moscar Top sensor to Rivelin Valley Road on A57), travelling in the same direction (ie. the same side of the road), mapped about 15 minutes apart. With both CAL1 and CAL2 weather conditions were stable while mapping was undertaken (clear skies and light winds and cloudy, windy respectively). Section (A) is about 1°C colder than section (C) on both runs. This pattern is repeated with sections (B) and (D) although the actual difference in the temperatures measured is smaller tending to suggest that any errors in the IRT readings are worst at the start of a mapping run. CAL4 was mapped under variable weather conditions (windy with heavy showers) and the van had been driven for an hour before mapping commenced. In this situation the temperatures measured are colder during the later stages of the run.

2) Complete runs (FULL1-19, DEV1-3)

The fingerprints of most of the complete runs mapped during winter 1988/89 show a pronounced 'cold start'. The location of this 'cold start' does correspond with open moorland at high altitude (up to 350m.asl), but the road temperatures measured are lower than can be explained by the expected decrease in temperature with height and urban/rural differences. The cold start is most pronounced on clear, calm nights when temperature differences along the route would normally be at a maximum. Figure 3.3(a) shows the fingerprint of run FULL12, mapped under clear skies and light winds

0430-0515hrs on 2.3.89. The average temperature of the run is 5.6°C with temperatures reaching 8.5°C in the city centre and as low as -2.3°C for the first 5km of the run. Road temperature differences of over 10°C between urban and even high altitude rural areas are greater than would be expected. Temperature differences along a route mapped under damped conditions would expect to show little variation but examination of figure 3.3(c) shows that temperature differences of up to 6.0°C are experienced even on damped nights. Temperature differences as large as these have never been observed by Travers-Morgan since they began mapping in 1986 (Paul Williams, Travers-Morgan Maintenance, pers. comm.).

When more than one run was made during a night (DEV1-3) the cold start is present on all fingerprints although it is most pronounced on the earlier fingerprint. Figure 3.4 shows that there are a number of differences between the three runs mapped on the night of 17/18.1.89.

In late April 1989 two mapping runs were carried out in the opposite direction to usual (ie. Park Square roundabout to Moscar Top) in order to see whether similar road temperature profiles were repeated. The fingerprints for REV1 and 2 are shown in figure 3.5. REV1 (fig. 3.5a) was mapped under clear skies and light winds and REV2 (fig. 3.5b) in cloudy, windy and wet conditions. There are a number of differences between the fingerprints mapped in the reverse direction and those mapped in the normal way. On most of the runs starting at Moscar Top the temperature of the last section of the run (34-38km) along Sheffield Parkway (A57) and Park Square roundabout is slightly below average or up to 2°C above the average temperature for the run (eg. figs. 3.3a-c and 3.4a-c). However, with the reverse runs the same zone is colder with temperatures as much as 3°C below the average (fig. 3.5a). The end of the reverse runs (near Moscar Top) is not as cold as the start on most of the normal runs (also Moscar Top).

DIFFERENCES BETWEEN AIR AND ROAD TEMPERATURES

Air and road temperatures usually differ (see section 1.2.2) - the sign and magnitude of this difference depends mainly on the time of year and weather conditions. Generally, on clear, calm nights during the winter, with radiative cooling at a maximum, road surface temperatures are likely to be lower than air temperatures by 2-3°C especially if there is very little traffic which is the case on most roads in Sheffield at 0430hrs. This difference will be smaller in cloudier, windier weather and in some weather conditions road temperatures may be higher than air temperatures (eg. clearing skies after the passage of a cold front).

At the start and end of each mapping run air temperatures were measured, at a height of 1m, using the Assman Hygrometer. These air temperatures were compared to the road temperatures measured by the IRT at the start and end of each run. The second IRT temperature reading was used at the start of the run, because of the probable effects of the parked van on the first road temperature reading. Table 3.2 shows the differences between air and road temperatures for all the complete runs made during winter 1988/89. At the start of the run road temperatures were on average 3.5°C below air temperatures and only 1.2°C below at the end of the run. Although there are differences between the locations at the start and end of the run - in terms of degree of shelter, altitude, land-use, road type, they are not enough to explain the difference in the figures. Also, an average difference of 3.5°C at the start of the run is large when we consider that all weather conditions, as well as those when road temperatures may be higher than air temperatures, are included in the analysis.

RUNS AT DIFFERENT TIMES OF THE NIGHT

On three nights route 1 was mapped more than once during the night. On two of these nights weather conditions were mostly clear with light winds. Under these conditions, with radiative cooling unrestricted by cloud cover, both air and road temperatures would be expected to decrease during the night. However, the average road temperature of each successive mapping run increased. Air temperatures did decrease as expected. Details of the runs made on each night (17/18.1.89 and 7/8.3.89) are shown in table 3.3 and the fingerprints of the three runs made on the night of 17/18.1.89 are shown in figure 3.4.

COMPARISON OF IRT READINGS AND ICELERT DATA

The route taken for thermal mapping allowed comparisons to be made between temperature data from the Icelert sensors and road temperatures measured by the IRT while mapping.

For each sensor along the route (Moscar Top, Hillfoot, Tinsley and Prince of Wales Road) the road temperature as measured by the IRT was extracted from the thermal fingerprints. The location (in count numbers: 1 count = 20m) of each sensor had been noted while mapping so that the temperature data could be extracted as accurately as possible.

In order to extract the correct temperature from the Icelert graphs the time at which the sensor was passed had to be estimated. Again the time was noted while on a mapping run and minor adjustments made if the overall duration of the run was longer or shorter than on this run. The road temperatures were then extracted from the appropriate road temperature graphs from data which had been stored on the Icelert computer at Olive Grove Depot.

This procedure has a number of possible sources of error:

1) it is difficult to pin-point the exact reading from the fingerprint which corresponds to the location of the sensor.

2) the time at which the van passed each sensor could only be estimated to within 5 minutes on some runs. An incorrect Icelert temperature could then have been used.

3) a large proportion of the Icelert data from winter 1988/89 was missing from the computer at Olive Grove. This reduced the number of comparisons that could be made. Also, for some of the nights only the 24-hour temperature graph was available instead of the 1-hour graph. The 24-hour graph could only be read to an accuracy of +/-1°C instead of 0.2°C for the 1-hour graph.

4) the Icelert readings may not be accurate. On a number of nights during the winter the temperature of the road surface around each sensor was measured using a thermocouple and then compared to the Icelert reading recorded at the same time. Once again missing Icelert data reduced the number of comparisons that could be made. On the occasions that both temperature readings were available all Icelert readings were within +/- 0.5°C of the thermocouple readings, which is an acceptable level of accuracy. Also, calibration checks were carried out by Sheffield Works Department before the start of the winter.

5) the Tinsley sensor was not passed over by the van - it is on the opposite side of the road. Clearly, there could be a difference in temperature between the two carriageways . However, it was assumed that because there is very little difference between the two carriageways (photo 3.7) any differences in RST would be negligible.

After comparing the Icelert data and temperature readings from the thermal fingerprints no consistent relationship could be identified. Table 3.4 shows the Icelert and IRT readings and the differences between the two sets of data for the runs for which information was available. REV1 and 2 are also included. A few general comments about the data can be made:

1) only nine of the 39 comparisons between the Icelert and IRT readings were within +/-0.5°C. Three of these were at Tinsley and five at Prince of Wales Road, both in the latter half of the mapping run.

2) although the differences between the two sets of readings were inconsistent, the IRT temperature reading was always lower than the Icelert reading at Moscar Top (13/13) and generally either a little below or just above at Prince of Wales Road, excluding the REV runs.

3) the difference at Moscar Top was greater than at Prince of Wales Road on 8 of the 13 nights with both sets of data available. On four of the five occasions that Prince of Wales Road was greater the mapping procedure was different, ie. runs at different times of the night (DEV2C and DEV3C) or reverse runs (REV1 and REV2).

If we assume that the Icelert readings are accurate the above results again suggest that road surface temperatures are underestimated by the IRT at the start of runs (near Moscar Top). The differences between the IRT temperatures and Icelert readings are much smaller towards the end of the run except when a different mapping procedure was used.

3.4.3. Implications For Thermal Mapping

The evidence summarised in section 3.4.2 reinforced the concern over the accuracy of the temperature readings made by the Compac 3 infra-red thermometer while mapping during the first winter. All the evidence pointed to the fact that, using this method, road temperatures were underestimated by the IRT at the start of many of the mapping runs. However, this evidence does not come from tests specifically designed to identify this problem. Also the reliability/accuracy of some of the data used was not very high.

Further work was therefore felt to be necessary in order to identify the magnitude of the errors produced while mapping and hence the implications for thermal mapping. Because thermal mapping is concerned with relative temperature differences between stretches of road consistent errors in the temperature readings will cause few problems. However, if the errors vary during a run and are difficult to quantify the implications for the process of thermal mapping are very important.

Laboratory and road tests were designed and carried out in the second half of 1989 in order to confirm and quantify the errors produced by the Compac 3 while mapping and show how these errors were produced. These tests are described and the results presented in chapter 4.

CHAPTER 4

THE PRODUCTION OF ERRORS IN ROAD SURFACE TEMPERATURE READINGS WHILE THERMAL MAPPING.

As discussed in chapter 3, section 3.4, there was considerable concern about the performance of the IRT while carrying out thermal mapping. In order that mapping can be undertaken with any degree of confidence any errors produced by the IRT must be identified, quantified, explained and then, if possible, eliminated or corrected for.

4.1. POSSIBLE SOURCES OF ERROR

Visits to the manufacturer of the Compac 3 infra-red thermometer (LAND Infrared, Dronfield, England) were made in an attempt to obtain an explanation for the problems with the instrument.

Following discussions with LAND personnel the production of errors was thought to be related to the workings of the IRT in relation to its own internal temperature and the temperature of the surrounds/background.

Total radiation detected by the IRT detector, producing an output voltage, is as shown below (equation 4.1) and in figure 4.1:

$$R = R_{(t)} + R_{(s)} + R_{(i)} - R_{(r)} \quad \text{(equation 4.1)}$$

where, R = total radiation detected by sensor

$R_{(t)}$ = radiation emitted by target

$R_{(s)}$ = radiation emitted by surrounds and reflected off target

$R_{(i)}$ = radiation emitted by instrument itself

$R_{(r)}$ = radiation re-emitted by detector

As can be seen from equation 4.1 the pyroelectric cell detects infra-red radiation from three sources, that emitted by the target, that emitted by the surrounds/background and reflected off the target, and radiation emitted by the instrument itself. The detector also re-emits some infra-red radiation and this must be corrected for. A thermosensitive resistor on the detector block measures the temperature of the block and then corrects for this re-emitted component.

Radiation from the surrounds and reflected off the target is termed 'glare'. To correct for glare the IRT assumes that the temperature of the surrounds/background is the same as its own internal temperature (as measured by the thermosensitive resistor) and makes a correction accordingly. However, if the background/surrounds are at a different temperature to the IRT the instrument will over/undercorrect for glare producing errors in the temperature reading. Table 4.1 shows errors of a 8-14µm IRT due to the surrounds being at a different temperature to the IRT (taken from LAND Technical Memo number 94). If the surrounds are warmer than the IRT the instrument will undercorrect for glare and temperature readings will be too high. If the IRT is warmer it will overcorrect and temperature readings will be too low. Temperature differences between the IRT and the surrounds are likely while carrying out thermal mapping, because the IRT is moved from a warm building into the back of a cold van. Also the temperature of the van air will differ from the background (the van floor - R.Barber, LAND, pers. comm.) and fluctuate during a mapping run. Radiation emitted by the exhaust pipe may produce significant errors due to its high temperature relative to that of the target.

Vaisala TMI use the Heimann KT-17 infrared thermometer in their thermal mapping operations. In communications with Micron Techniques (UK agents for Heimann until December 1990) it was stated that differences between the background temperature and the ambient temperature (equivalent to the IRT temperature) will only cause substantial errors due to glare with low emissivity targets (see equations 4.2 and 4.3 below).

Emissivity and reflectivity (ρ) are related (for most objects) thus:

$$\varepsilon + \rho = 1 \text{ (equation 4.2; Orlove, 1982)}$$

Equation 4.2 can then be re-written thus:

$$\rho = 1 - \varepsilon \text{ (equation 4.3)}$$

Taking into account the reflectivity of the target by incorporating equation 4.3, equation 4.1 can be re-written thus:

$$R = R_{(t)} + (1-\varepsilon)R_{(s)} + R_{(i)} - R_{(r)} \text{ (equation 4.4)}$$

With the high emissivity of roads (0.91-0.99) and the close proximity of the IRT to the road surface (approximately 60cm above) it was stated (by Micron) and it can be seen from equation 4.4 , that there was little likelihood of glare/reflection causing significant errors.

There was still considerable uncertainty about the cause of the errors produced by the Compac 3 IRT. Literature from specialist infra-red thermography sources was examined in an attempt to clarify the situation.

4.1.1. Infra-Red Thermography Literature

Firstly attention must again be drawn to the comments of Rosema and Welleman (1977) and Thornes (1991), referred to in chapter 1 section 1.4.1, with regard to the need to keep IRTs within a constant temperature range during observations.

Lowry and Gay (1970) describe the production of errors in infra-red thermometry and radiometry due to multiple reflections between the target environment viewed by a thermometer/radiometer and the background environment. They point out that the error increases as either the target or background departs from the blackbody condition (emissivity = 1.00) and as the background becomes warmer relative to the target.

The problem of glare (reflection off the target) is discussed by Ohman (1981). He emphasises the complicated nature of the problem by stating:

> " all bodies within the hemisphere that
> the object surface is facing contribute to
> the radiation that is reflected into the
> scanner, the amount depending on their
> respective temperature, size, distance and
> angle to the object plane."

Stigter, Makonda and Jiwaji (1982) report that out of doors measurements, using an IRT, yielded consistently low values in full sunshine and that results generally fluctuated. The conclusion from the paper states that changes in the outer surface temperature of the IRT create heat flows at the reference side of the sensitive thermopile which produces errors in the temperature readings. The importance of minimising these temperature gradients is also stressed.

Errors produced due to temperature variations within the instrument are also discussed by Huband (1985) and Wright (1990). The need to insulate an infrared radiometer to minimise internal gradients is reported by Stigter, Jiwaji and Makonda (1982).

Combining the information from the suppliers of the IRTs with the observations and advice to be found in the literature the source of errors is likely to be due to a combination of two causes. Firstly temperature differences between the IRT and its surrounds and secondly variations in the temperature of the instrument itself. Laboratory and road tests were carried out in order to quantify any error produced and, if possible, identify its exact source.

4.2. LABORATORY TESTS ON THE COMPAC 3 INFRA-RED THERMOMETER.

The tests were designed to simulate conditions in the van while thermal mapping was being carried out. Any errors in the IRT readings should then be reproduced. Reproducing the exact temperature regime of the van was not attempted due to its complexity (see section 4.4.2). The main aim was to set up temperature differences between the IRT and its surrounds and also to warm and cool the IRT. The results would hopefully confirm the production of errors and help to identify the main cause(s).

4.2.1. Equipment Design

The equipment used in the lab tests is shown in figures 4.2 and 4.3 and photos 4.1 and 4.2. It consists of a temperature control box placed on top of a metal table. The box is constructed from wood with a layer of insulating material on the inside (2.5 cm thick). The metal table is approximately 60 cm above floor level, corresponding to the distance between the IRT and road surface during thermal mapping. A hole was cut in the table base and the IRT mounting (from the van) fixed next to the hole. In order that the IRT's temperature display could be read a hole was cut in the top of the box. This hole was mostly filled with a piece of polystyrene. The box was heated by a 55 watt halogen bulb attached to one side of the box and the temperature controlled by a thermo-stat fixed to the opposite side. Two fans, fixed to the metal table, circulated the air preventing temperature gradients being set up across the box. The temperature control box and table were placed in a constant temperature room (at approximately 20°C) in the Department of Civil and Structural Engineering where most of the tests were conducted.

4.2.2. Test Procedures

Melting ice was used as the target source for all the tests, remaining at a constant temperature of 0°C. The emissivity of the ice was determined using the IRT (see section 3.4.1) and found to be 0.99. Any deviation from 0°C in the temperature reading would show the sign and magnitude of any errors produced.

A total of 10 tests were carried out in the constant temperature room each lasting 150 minutes. Initially the thermo-stat was set at 30°C and the bulb turned on. The bulb was then controlled (on/off) by the thermo-stat until it was turned off permanently with 40 minutes of the test remaining.

IRT temperature readings (the average of ten), box air temperature, the internal temperature of the IRT and ice temperature were recorded every ten minutes. The box air and internal IRT temperatures were measured using thermocouples (calibrated before and after the tests, see appendix 3) and the ice temperature measured with a BSI standard test thermometer used for the calibration (see photo 4.3). The IRT was calibrated by LAND and the author before the tests commenced (see appendix 3).

Two slightly different types of tests were carried out in the constant temperature room (five of each). In type A tests the IRT was fixed to the mounting with a gap of approximately 2.5 cm between the table base and IRT lens. In type B tests the IRT was placed flush with the table base.

In addition one subsidiary test (55 minutes, IRT in position as type A) was carried out - the IRT was warmed to well above the room temperature, kept at this temperature for 30 minutes and then the temperature control box removed. The internal IRT temperature and temperature readings were then recorded every five minutes.

A further set of five tests (type C) were conducted in a room at a steady 12-14°C. The test procedure was slightly different to that of types A and B in that the box and IRT were initially warmed to 20°C to ensure that their starting temperatures were similar to those at the start of the other tests. This was to demonstrate any possible differences in the errors produced due to different background temperatures and the resulting different warming/cooling rates. The box air temperature was maintained at 20°C for 30 minutes and then the thermo-stat turned up to 30°C and the test conducted as in types A and B (IRT in position as type A).

4.2.3. Results

TYPE A

All type A tests produced similar results (see table 4.2). The results of test 1A are shown in detail in figure 4.4. As the box temperature increased rapidly during the early stages of the test positive errors were produced reaching a maximum of +3°C about 30 minutes into the test. As the bulb was turned on/off by the thermo-stat errors remained positive but became smaller and tended to fluctuate. Approximately 5 minutes after the bulb was turned off permanently and the box cooled rapidly errors became negative reaching a minimum of -2°C approximately 130 minutes after the start of the test.

TYPE B

Type B tests produced similar results to type A (see table 4.3 and figure 4.5). However, box temperatures rose slightly quicker (with the gap closed) and positive errors were generally larger. The box cooled at a slower rate and negative errors were smaller.

SUBSIDIARY TEST

The result of the subsidiary test is shown in figure 4.6. The IRT was maintained at a temperature of around 28°C and then allowed to cool by removing the temperature control box. As the IRT cooled negative errors were produced throughout the whole test period (55 minutes) reaching a minimum of -2.5°C ten minutes after the box was removed. Errors then became smaller and were around -1°C by the end of the test.

TYPE C

The results of type C tests , see table 4.4 and figure 4.7, were broadly similar to those of types A and B in that positive errors were produced when the box warmed and negative errors when it cooled. However, due to the cooler air around the box it warmed at a slower rate and cooled faster. Positive errors were smaller (maximum +1°C) and negative errors larger (down to -3°C).

4.2.4. Discussion

The laboratory tests demonstrated that operating the IRT in an environment where temperatures fluctuate considerably produces significant errors in the IRT temperature readings.

If errors were caused solely by reflection of infra-red radiation from the backgrounds/surrounds off the target (glare) the sign of the error would be easy to determine. When the IRT is at a higher temperature than the surrounds it would overestimate the amount of background radiation reflected off the target, overcorrect and produce negative errors. In type A, B and C tests despite the IRT always remaining warmer than the surrounds positive errors are produced for most of the test. With the subsidiary test negative errors are produced with the IRT warmer than the surrounds. The largest negative error occurs when the IRT is 5.2°C warmer than the room. If glare was responsible for most of the error the largest error would be expected to occur when there is the greatest difference between the temperatures of the IRT and the room (7.3°C at start of test).

The clearest relationship to emerge from all the laboratory tests is that as the IRT warms positive errors are produced and as it cools negative errors. The greater the rate of warming/cooling the greater is the magnitude of the errors produced although with a time-lag of between 10-35 minutes. Errors are likely to be mainly the result of variations in the temperature of the IRT itself rather than differences between the IRT temperature and temperature of the surrounds. Furthermore with the emissivity of ice 0.99 and no 'hot object' (such as the exhaust) near the target any errors due to reflection off the target will be virtually zero in the laboratory tests.

4.2.5. Relationship Between Warming/Cooling Rates and Magnitude of Error Produced

Average warming/cooling rates and the corresponding average error produced were determined for all the laboratory tests. The warming/cooling rates and error were calculated over the period of time when warming/cooling was uninterrupted. For example: test A1 (see table 4.2) - the warming rate was calculated over the period 0-60 minutes and average error determined from the readings made at 10, 20, 30, 40, 50, and 60 minutes. Separate warming/cooling rates were determined for both the box air temperature and internal IRT temperature and are shown with their associated error in tables 4.5 and 4.6.

The relationship between box air warming rate (WRa) and error (E) is shown in figure 4.8. The greater the rate of warming the larger is the error produced. The regression equation is:

$$E = 0.624 + 0.129WRa \quad \text{(equation 4.5)}$$

The R^2 value for this relationship is 96.6%, which is very high and significant at the 0.5% level. A warming rate of $0^{\circ}C\ hr^{-1}$ (constant temperature) would produce an error of $0.6^{\circ}C$ according to these results.

The relationship between box air cooling rate and error is much less clear (fig. 4.9) with an R^2 value of only 4.3%.

Figures 4.10 and 4.11 show the corresponding plots of warming and cooling rates of the internal IRT temperature against error. There is a strong relationship in both cases. The regression equation for IRT warming rate (WRi) against error is:

$$E = 0.198 + 0.255WRi \quad \text{(equation 4.5)}$$

with an R^2 value of 98.4% (significant at 0.5% level). The regression equation for IRT cooling rate (CRi) is:

$$E = 2.76 + 0.521CRi \quad \text{(equation 4.6)}$$

with an R^2 of 76.3% (significant at 0.5% level).

Figure 4.12 shows both warming and cooling rates (of the IRT) with corresponding errors. Three regression lines are plotted on the graph - one for warming rates only (equation 4.5 above), one for cooling rates (equation 4.6 above) and one combining both warming and cooling rates ($E = 0.451 + 0.224W/CRi$). It is interesting to note that the cooling rate and associated error from the subsidiary test (marked S on graph) lies closest to the regression line of the warming rates (IRT). This suggests that the relationship between warming/cooling rates and error is best shown by the warming rates in tests A, B and C and the cooling rate from the subsidiary test. These warming/cooling rates were unaffected by previous warming/cooling during testing which has the effect of complicating the relationship as shown by those between cooling rate (air) and error and to a lesser extent between cooling rate (IRT) and error. Once temperatures begin to fluctuate during the tests and warming/cooling is complicated the errors produced by the IRT vary considerably and the relationship is not as clear (eg. fig. 4.9).

4.3. LABORATORY TESTS ON THE HEIMANN KT-17 INFRA-RED THERMOMETER

Vaisala TMI (formerly Thermal Mapping International) use the Heimann KT-17 infra-red thermometer for measuring road surface temperatures. Having already established that the Compac 3 infra-red thermometer produces errors, when operating in an environment where temperatures fluctuate, it was felt necessary to assess the performance of the KT-17 under similar conditions.

The Heimann KT-17 is a portable infra-red thermometer, with spectral sensitivity range 8-14μm, consisting of three separate units - the detector unit with pyroelectric cell; a display unit; and the power supply (see photo 4.3). The display unit provides a continuous measure of the target temperature (in degrees Celsius, readable to 0.1°C). The emissivity value is adjustable from 0.01 to 1.00 in steps of 0.01 by means of two switches located in a compartment on the backside of the instrument.

4.3.1. Test Procedure

The tests on the KT-17 were similar to those carried out on the Compac 3 (see section 4.2.3). The temperature control box used is shown in photo 4.4. The test procedure was modified to some extent and the details are as follows:

1) The KT-17 was warmed/cooled in the temperature control box placed in a constant temperature room (at 19-20°C).

2) The height of the box was increased by 10cm because the KT-17 detector unit is bigger than the Compac 3 IRT.

3) Melting ice was used as the constant target temperature at 0°C. The emissivity value was set at 1.00 (as determined in tests similar to those described in chapter 3 section 3.4.1).

4) The KT-17 was turned on 30 minutes before the start of the test (following the manufacturer's instructions).

5) The heating source was turned on and the box warmed at a decreasing rate for 70 minutes. The bulb was then turned off and the box cooled for the remainder of the test (50 minutes). The duration of the tests was restricted by the warming-up time required by the KT-17 and the power supply (rechargeable) only lasting 150 minutes.

6) The following temperatures were measured every 10 minutes with thermocouples:

a) Box air temperature
b) KT-17 internal temperature (inside the emissivity compartment).

7) The KT-17 temperature reading was taken every 10 minutes - the range of values over a 15 second period were noted and the mid-value taken as representative.

4.3.2. Results

Five tests were completed and the results are summarised in table 4.7. Figure 4.13 shows the detailed results of test 1. Initially as the box temperature rose rapidly small positive errors were produced (up to 0.5°C). Errors soon became negative (40 minutes into the test) and remained so for the rest of the test. The negative errors reached a maximum just after the bulb had been turned off (down to -1.7°C). Errors then became smaller as the box cooled and ranged from -0.3 to -0.6°C at the end of the test.

4.3.3. Discussion

The laboratory tests on the Heimann KT-17 demonstrate that operating it in an environment where temperatures fluctuate considerably produces errors in the temperature reading. The errors are not as large as with the Compac 3 and follow a very different pattern. The KT-17 produces negative errors for all but the first 30 minutes of the test irrespective of whether the box is warming or cooling. The largest error occurred when there was the greatest difference between the box/IRT temperature and the room temperature. The warming/cooling rates in the KT-17 tests were less than in the tests on the Compac 3 due to the same heating source warming a larger volume and this might have reduced the magnitude of the errors.

The errors may be caused by glare - a warmer IRT (than the background) would overestimate the amount of glare, overcorrect and produce negative errors. Also the largest error occurred at the same time as there was the largest temperature difference between the IRT and surrounds, which would be expected if glare was the cause of the error.

However, using an emissivity value of 1.00 the KT-17 will assume there is no glare (no reflection - see equations 4.2 and 4.3) and therefore not correct for any. If there was some reflection off the target (true emissivity less than 1.00) any errors would be positive.

The UK agents for Heimann (Micron Techniques until 31.12.90 , Palm Microsystems Ltd since 1.1.91) were contacted seeking an explanation for the production of errors by the KT-17, but none has been forthcoming.

4.4. ROAD TESTS (DECEMBER 1989)

The laboratory tests confirmed that significant errors were produced by the IRT when it is operated in an environment where temperatures fluctuate. The next stage was to quantify the errors actually produced while carrying out thermal mapping. This was necessary in order to determine the magnitude and therefore the significance of errors produced while mapping and whether it was possible to correct for these errors.

Quantifying the errors produced while mapping presented one major problem - that is the temperature of the target (the road surface) must be known. The accurate measurement of the surface temperature of more than 30km of road is practically impossible (hence the need for thermal mapping). This problem was solved by 'replacing' the road with a tray of melting ice beneath the IRT (see photo 4.5) ensuring a constant target temperature of 0°C.

4.4.1. Procedure

The nature of the temperature environment in the van during the first winter's mapping must be reproduced in order to quantify any errors that are produced. To do this the identical mapping procedure was adopted, the only difference being the emissivity value used, 0.99 instead of 0.96. The IRT was left in the same room inside the house , the van parked on the road and , while driving , the van heating operated as before. Mapping runs were carried out when air temperatures were in the range +2 to +8°C to ensure the ice in the tray was melting. The fingerprints produced would be a measure of the ice temperature and should be 0°C. Any deviation from 0°C would show the sign and magnitude of any errors produced while mapping.

The temperature of the van floor and air were recorded using two thermistors connected to a Grant Recorder (providing a continuous measure of the temperature variation). The internal temperature of the IRT was measured using a thermocouple. Any errors produced by the IRT could then be related to temperature conditions in the van.

4.4.2. Results

THERMAL FINGERPRINTS

Four runs were made using melting ice as the target temperature (ICER 1-4). The fingerprints from these runs are shown in figure 4.14 and 4.15. All the fingerprints show a similar trend in the temperature readings. Negative errors (down to -3°C, ICER 4) were greatest at the start of the run, becoming smaller and then positive 10-13km along the route. Errors then remained positive (0.5 to 1.5°C) for the remainder of the run. During ICER 3 most of the ice melted and the temperature recorded was sometimes that of the tray bottom (eg. 32 - 33km).

TEMPERATURE VARIATIONS IN THE VAN

The Grant Recorder only functioned correctly for ICER 1 and 2. The temperature variation for run ICER 1 is shown in figure 4.16. Similar temperature measurements were made during one mapping run towards the end of winter 1988/89 producing similar results.

The temperature of the IRT was, as expected, much higher than the van air temperature when first placed in the back of the van. The van air temperature initially rises slowly, while driving to the start of the mapping run, then drops slightly as the van is parked, and the engine switched off, to take atmospheric readings before the run commences. Once the mapping run is underway the van air temperature rises rapidly and reaches its maximum approximately ten minutes into the run. Temperatures then remain high, fluctuating slightly, for the remainder of the run. The van floor temperature follows a similar trend to van air temperature although warming at a slower rate and is 6 to 10°C cooler than the van air for most of the run.

The IRT cools initially, at a rate of 6-8°C hr^{-1}, and then begins to warm just after the mapping run has commenced (1.5 to 2.5°C hr^{-1}) and this continues until the end of the run. The results of the laboratory tests (section 4.2.5) show that an IRT warming rate of 1.5 to 2.5°C hr^{-1} will produce an error of 0.4 to 1.0°C, which is similar to the errors produced on the ICER runs. Cooling rates of 6 to 8°C produced errors of -0.4 to -1.6°C in the laboratory which are lower than the errors produced while mapping. This can be explained by the fact that prior to cooling in the lab the IRT had warmed and with the lagged effect of this warming the cooling errors were reduced. For the same reason the positive errors produced by warming during a mapping run would have been reduced to some extent by the previous cooling.

4.4.3. Discussion

Placing a warm IRT into the back of a colder van causes the IRT to cool, producing negative errors during the early stages of a mapping run. The time-lag effect, as observed in the laboratory tests, means that negative errors are produced at the same time as the van air was warming rapidly and the temperature of the IRT was just beginning to rise. The increasing van air temperature warms the IRT producing positive errors for approximately two thirds of the run.

The implications of these results are important for thermal mapping. The ICER runs show that firstly, errors vary considerably during a run (eg. ICER 4, -3°C to +2°C) and secondly, the errors vary from night to night depending on the starting temperatures of the IRT, van and air. The corollary of the above is that it is impossible to correct for the errors produced while thermal mapping during winter 1988/89 because:

1) the temperature conditions during the actual mapping runs were not known and

2) even if they had been it would be impossible to calculate the magnitude of the errors produced during a run.

It is important to note that the procedure adopted for mapping in winter 1988/89 was likely to have emphasised and enhanced the significance of the error in that:

1) the IRT was left in a warm house and then moved into a cold van maximising the temperature difference. In other situations when mapping is carried out by Travers-Morgan and TMI the initial temperature difference between the IRT and van may be less.

2) the time difference between placing the IRT in the van and commencing a mapping run was only 20-25 minutes. A longer time period would give the IRT more time to reach equilibrium with the van temperature.

3) all the mapping carried out during the first winter was completed within 75 minutes of placing the IRT in the van. When mapping for most of the night the majority of runs will be carried out when the IRT has reached the van's temperature.

Having made the above observations, however, it should be noted that the temperature of the van fluctuates even with steady heating (fig. 4.16) and if windows are opened or stops are made the van will cool rapidly, affecting the performance of the IRT. From the authors own experience of commercial thermal mapping frequent stops are made, while mapping through the night, both to take atmospheric readings and for rest periods. In addition, during runs, the heating may be altered or windows opened to refresh the driver.

4.5. HOW ERRORS ARE PRODUCED

After discussing the results of the laboratory and road tests with LAND an explanation was obtained for the production of errors in the IRT reading while thermal mapping.

There are two possible sources of error both related to the workings of the IRT - one caused purely by a physical phenomenon and the other is an instrument error. In order to understand how errors in the temperature reading are produced we must first understand, in greater detail, how the IRT determines the temperature of an object.

Infra-red radiation enters the instrument via the lens system. At the front of the detector block is a chopper wheel with alternate missing segments (fig. 4.17). This chopper wheel rotates allowing the sensor to view the target and chopper blade alternatively. The chopper blade is of known emissivity and temperature (measured by the thermosensitive resistor) and the detector responds to the difference in irradiance between the target and chopper blade (reference) and produces an output voltage. The total radiation received by the detector when viewing the target (see figure 4.1 and equation 4.3) is the sum of the radiation emitted by the target; radiation emitted by the background/surrounds and reflected off the target; that re-emitted by the detector itself; and radiation emitted by the casing of the instrument (internal reflection).

The IRT can easily correct for radiation re-emitted by the detector because its temperature is known accurately with the thermosensitive resistor located on the detector block itself (fig. 4.17). The IRT corrects for reflected radiation off the target and internal radiation from the instrument casing by assuming that its own temperature and the temperature of the surrounds and casing are equal. This is where errors can be produced.

4.5.1. Internal Reflection

Errors in the temperature reading will be produced when the IRT is moved into an environment where the temperature is different from its own. This is termed 'bounce' (R.Barber, LAND, pers. comm.) and is primarily caused by internal reflection of infra-red radiation emitted by the body of the IRT. In a constant temperature environment the IRT can correct for internal reflection because its body is at the same temperature as the thermosensitive resistor on the detector block. However, when the IRT is moved into an environment at a different temperature errors will be produced in the temperature reading. For example, if the IRT is moved from a room at 20°C to one at 10°C negative errors will be produced until the IRT has reached equilibrium with the new room temperature taking 20-30 minutes as shown in figure 4.18 (R.Barber, pers. comm.).

As the IRT warms/cools thermal fronts move from the outside in. This will result in the thermosensitive resistor, located on the detector block in the centre of the instrument and away from the sides of the body, being at a different temperature to the outer casing of the IRT. The amount of internal reflection detected by the pyroelectric cell will be under/overestimated and errors produced. When the IRT cools there is less infra-red radiation emitted by the instrument casing than is estimated by the instrument (using the temperature of the thermosensitive resistor), it therefore overcorrects and produces negative errors in the temperature reading. The opposite occurs as the IRT warms. The results of the laboratory and road tests confirm this explanation. However, the situation is more complicated than described above - in both the laboratory tests and the van the IRT was exposed to cycles of warming and cooling.

4.5.2. Glare (reflection from surrounds/background)

The results of the laboratory and road tests suggest that glare does not contribute significantly to the errors in the road temperature readings (see sections 4.1 and 4.3.4). However, there is likely to be an element of the error caused by glare and so it must be discussed in more detail.

As stated by Ohman (see section 4.2) the amount of glare depends on the object's temperature, size, distance from the target and angle to the target plane. The emissivity of the target is also crucial (see equations 4.2 and 4.3). The emissivity value used (0.96) is high and so there will be relatively little reflection off the target (assuming this is the true emissivity). When thermal mapping, most of the background is made up of the base of the van (R.Barber, pers. comm.). From the tests carried out (see section 4.4.2) the temperature difference between the IRT and van floor is 3 to 5°C (IRT warmer) while mapping is being carried out. Any error, due to glare, caused by this relatively small temperature difference and considering the high emissivity value will be negligible and furthermore will not vary much during a run .

Although most of the van floor will be at this low temperature the exhaust system will be considerably hotter (say 100°C).

To determine the total radiation entering the IRT and therefore calculate any errors due to 'glare' equation 4.4 can be re-written incorporating equation 1.1:

$$R = \varepsilon_t \sigma T_t^4 + P_1(1-\varepsilon_t)\varepsilon_1 \sigma T_1^4 + \ldots\ldots P_n(1-\varepsilon_t)\varepsilon_n \sigma T_n^4 + \varepsilon_i \sigma T_i^4 - \varepsilon_r \sigma T_r^4$$

(equation 4.8)

where, R = total radiation received by detector (producing associated output voltage)

t = target

i = IRT

r = detector

and suffices 1.....n refer to the emissivities and temperatures of 1.....n objects which are 'seen' by the road by the proportions, P.

To calculate likely errors due to glare it is assumed that the IRT casing and detector block are at the same and stable temperature and so internal reflection and the radiation re-emitted by the detector block (both assumed to be black) can be corrected for. The surrounds/background (objects 'seen' by the road) will be assumed to consist of the van floor and exhaust only. The proportions 'seen' by the road are estimated to be 0.95 for the floor and 0.05 for the exhaust. The emissivity of the van floor (dirty metal) will be approximately 0.90 and for the exhaust (oxidised steel) 0.85 (R.Barber, pers. comm.). The road emissivity is assumed to be 0.96.

From tests carried out (section 4.4.2) the IRT is usually approximately 4°C warmer than the van floor. The road temperature is likely to be a few degrees below the floor temperature. Temperatures to be used in the calculated example are:

IRT = 8°C (281K)

Floor = 4°C (277K)

Road = 0°C (273K)

Exhaust = 100°C (373K)

Then (ignoring internal reflection and the re-emitted component):

$$R = (0.96 \times \sigma \times 273^4) + (0.95 \times 0.04 \times 0.9 \times \sigma \times 277^4) + (0.05 \times 0.04 \times 0.85 \times \sigma \times 373^4)$$

$$= 315.62863$$

IRT determines temperature using:

$$R = \varepsilon_t \sigma T_t^4 + (1-\varepsilon_t)\, \varepsilon_s \sigma T_s^4 \qquad \text{(equation 4.9)}$$

IRT assumes surrounds/background (s) temperature equal to IRT's temperature and emissivity of background/surrounds is 1.00, thus:

$$R = (0.96 \times \sigma \times T_t^4) + (0.04 \times 1 \times \sigma \times 281^4)$$

and,

$$315.62863 = (0.96 \times \sigma \times T^4) + (0.04 \times 1 \times \sigma \times 281^4)$$

re-arranging and calculating,

$$T = 272.8$$

$$\text{error} = 273 - 272.8 = -0.2\text{K}$$

$$\underline{= -0.2^{\circ}\text{C}}$$

Further calculations have shown that different absolute temperatures (ie. maintaining differentials between IRT, road and background) produce very similar errors. These errors are very small and furthermore are unlikely to vary much during a run and can, therefore, be ignored.

Errors due to glare during the laboratory tests will also be negligible for the same reasons as above. In addition, the temperature difference between the IRT and background will be relatively small (particularly for the table base nearest the target) and there will be no contribution from an exhaust. Finally the higher emissivity value used (0.99 with the Compac 3 and 1.00 with the KT-17) will reduce any element of error due to glare to virtually zero.

4.6. EXPLANATION OF ERRORS/INCONSISTENCIES IN THERMAL FINGERPRINTS AND TEMPERATURE DATA WINTER 1988/89 (CHAPTER 3, SECTION 3.4.2)

The errors and inconsistencies identified in the thermal fingerprints mapped during the winter of 1988/89 and between data on road surface temperature (IRT and Icelert) and air temperatures can be explained in the light of the results and conclusions from the laboratory and road tests carried out on the Compac 3 IRT.

4.6.1. Thermal Fingerprints

TRIAL RUNS

During the early stages of the trial runs CAL1 and 2 the IRT, having been placed in a cold van, was producing negative errors in the road temperature reading. This resulted in the identical stretch of road mapped on the first loop being approximately 1°C colder than on the second loop. In the later stages of the runs the IRT would have been producing smaller negative errors or even small positive errors as the van and IRT warmed up (see figures 4.14 and 4.15). CAL4 was mapped after the van had been driven around Sheffield for one hour. In this case the later stages of the mapping run are colder. This is probably due to the lower air temperatures in this mostly high altitude rural area causing the van to cool and produce negative errors later in the run.

COMPLETE RUNS

The exaggerated 'cold start' found on most of the complete runs, starting at 0430hrs, is easily explained with reference to the fingerprints from the ICER runs (figs 4.14 and 4.15). Large negative errors during the early stages of the mapping run and smaller positive errors later on distort the true shape of the fingerprint enhancing the low temperatures which would normally be expected to occur at the start (high altitude rural area) and affecting the mean temperature for the mapping run.

When more than one run was made during the night the cold start was most pronounced on the first run (see fig 3.4). The mapping procedure for the first run is identical to that of the complete runs commencing at 0430hrs (above) in that the IRT is moved from a warm house and put into the back of a cold van. This results in the errors described above. However, with the subsequent runs the IRT was left in the van (drivers compartment) and would therefore be at the same temperature as the van when driven to the start of the run. Consequently there would be little/no cooling, and only small negative errors or more likely small positive errors (van warming) would be produced. In this situation the true low RSTs at the start of the run would not be exaggerated and may even have been restricted, producing the observed differences in the shape of the fingerprints.

4.6.2. Differences Between Air and Road Temperatures

Large negative errors at the start of the mapping runs meant that measured RSTs were much lower than true RSTs. If we correct for the probable errors in RST at the start (-2 to -3°C) and end (+1°C) of the runs the discrepancy in the difference between air and road surface temperatures at the start and end of the runs is not as large.

4.6.3. Runs at Different Times of The Night

When more than one run was mapped during an extreme night average RSTs increased from one run to the next despite air temperatures falling as would be expected. This is caused by the different procedures used between the first and subsequent runs as explained in section 4.6.1. The large negative errors produced during the early stages of the run mean that RSTs are underestimated for some of the run. With smaller positive errors being produced for the majority of the run the overall effect is that the measured average RST is close to or just above the true average. The average for ICER1 was 0.4°C, for ICER2 0.0°C and for ICER4 0.9°C when it should have been 0°C in all cases (ICER 3 average was 1.6°C with the temperature of the ice tray measured at times due to most of the ice melting). However, with the second and third runs the IRT starts at the same temperature as the (cold) van, therefore warms for most if not all of the run and the measured average RST will be significantly higher than the true average. Hence the increase in average RSTs during the night.

4.6.4. Comparison Between IRT Readings and Icelert Data

There had been very little association between IRT road temperature readings and Icelert readings during the first winter's mapping. This is not surprising considering the magnitude and variation in the errors produced while mapping. The approximate locations of the four Icelert sensors along route 1 are marked on figures 4.14 and 4.15 and shows that the error in RST reading at Moscar Top was -2 to -3°C, +0.5°C at Hillfoot and Tinsley and +0.5 to +0.8°C at Prince of Wales Road. It is clear why the IRT reading was consistently lower than the Icelert data at Moscar Top and much closer at Tinsley and Prince of Wales Road. Changing the mapping procedure (runs DEV2C and 3C) would produce a different pattern of errors (see section 4.6.3) and carrying out mapping in the reverse direction (REV1 and 2) also altered the pattern of errors in relation to the location of the Icelerts (see chapter 3, section 3.4.2). In these circumstances the relationship described above broke down with the IRT reading at Moscar Top generally being closer to the Icelert reading than at Prince of Wales Road.

4.7. ELIMINATION OF ERRORS WHILE THERMAL MAPPING

Errors in the IRT temperature reading, caused by internal reflection, would be eliminated if the IRT is operated in a constant temperature environment. The temperature control box, used in the laboratory tests, was fitted in the back of the van so that the IRT could be operated in an environment where the temperature could be controlled. A number of modifications to both the van and box had to be carried out before a successful procedure for operating the IRT in the control box was obtained.

4.7.1. Modifications to the Temperature Control Box and Van

1) The thermo-stat used to control heating of the box during the laboratory tests was replaced by a more sophisticated CAL 900 temperature controller, with temperature range 0-55°C (see photo 4.6). After some initial problems with the controller due to incorrect calibration (solved by visits to the supplier) the temperature variation of the box air was restricted to approximately 2°C, ie. if the controller was set at 12°C temperatures varied from 11 to 13°C.

2) With the heating source (halogen bulb) turned on and off by the temperature controller, a cycle of warming and cooling was produced. This resulted in sufficient warming/cooling of the IRT to produce a cycle of significant positive

and negative errors (+2.0 to -0.5^{o}C) in the temperature reading (see figure 4.19). The errors were measured using melting ice in the tray as the target temperature.

3) The IRT was insulated using domestic pipe lagging in an attempt to reduce the effect of the warming and cooling on the IRT. However, despite the magnitude of the errors being reduced, due to the lower rates of warming/cooling, a cycle of positive and negative errors was still produced and the errors were still significant.

4) Further tests on the box and its heating system showed that the box would remain at a relatively steady temperature if left to reach its equilibrium temperature, ie. the bulb was left on permanently and eventually the heat input from the bulb equalled the heat loses from the box . However, when the van was driven the heating system was used and the van warmed. This extra heat entering the system caused the box air to rise to a higher equilibrium temperature (fig. 4.20).

5) To eliminate the effect of the additional heat entering the box the amount of insulation around the box and on the van floor was increased. In addition, the front section of the van was partitioned off from the back of the van, using loft insulation, to ensure operating the heating system would not affect the temperature control box (see photo 4.6).

6) The halogen bulb was reduced in power using resistors to ensure that the equilibrium temperature was relatively low (4 to 15^{o}C depending on the air temperature). This meant that the equilibrium temperature could be reached quickly (within 40 minutes) and was close to the background temperature (van floor) maintaining errors due to glare to a negligible level.

7) Trial runs showed the box would reach the equilibrium temperature relatively quickly and during the run temperatures varied very little (figs. 4.21 and 4.22). Any variations were restricted to a maximum warming/cooling rate of 3°Chr^{-1}. Test runs with melting ice showed that virtually all readings (>95%) were within 0.5°C of the true ice temperature with no obvious cycle/pattern to the errors (fig. 4.23a and b).

4.7.2. Mapping Procedure Winter 1989/90

The following procedure for carrying out thermal mapping was then adopted and used during winter 1989/90:

1) The IRT was mounted in the back of the van at 0300 hours and the halogen bulb turned on.

2) At 0400 hours the IRT was turned on by quickly lifting up and replacing the temperature control box. This did not significantly affect the box temperature.

3) The van was driven to the start of the mapping run (Derbyshire boundary Moscar Top) and each run commenced at approximately 0430 hours.

4) The temperature of the temperature control box was noted at 0400 hrs and the start and end of each run. If the change in temperature during a run resulted in a warming/cooling rate significantly greater than 3°C hr^{-1} the data was excluded/ignored (see table 4.8).

4.7.3. New Temperature Control Box Winter, 1990/91

The temperature control box used during winter 1989/90 was replaced by an improved design box which was easier to operate. The new box was designed, built and tested late summer and early autumn 1990 in readiness for mapping winter 1990/91. The main features of the new box were:

1) It was made of metal, insulated, fixed to the van floor and had a hinged lid.

2) Two bulbs were used as the heating source. The larger bulb (40 watts) is left permanently on, whilst the smaller bulb (10 watts) is controlled by the CAL 900 temperature controller.

Photo 4.7 show details of the box.

After considerable testing of the new box the following procedure was adopted for operating the box while mapping:

1) At least 20 minutes before driving to the start of a run the IRT was placed in the box and the bulbs and fans turned on.

2) After this initial period the box temperature was noted and the lid lifted up slightly. The IRT was turned on and the CAL 900 controller adjusted so the smaller bulb was turned off. The lid was closed as quickly as possible in order not to significantly alter the box temperature.

3) The van was driven to the start of the run (taking a minimum of 20 minutes).

4) Before the mapping run commenced, the box temperature was noted to ensure there had been no significant change in temperature since the IRT had been turned on. If the box temperature had changed more than 1°C mapping did not commence until the box temperature had remained stable for at least 10 minutes.

5) The box temperature at the end of the run was noted to ensure any changes in temperature during the run were not large enough to produce significant errors.

6) Temperatures usually warmed during a run. The maximum rate was approximately 3°C hr^{-1} and will not produce significant errors in the IRT reading (see section 4.7.4).

7) The rear van doors were only opened once during a night's mapping, to change the battery powering the box. Opening of the van doors caused the box temperature to drop relatively rapidly especially on windy nights.

8) The Compac 3 IRT must operate in temperatures above 0°C. The temperature of the temperature control box depends mainly on the outside air temperature. To ensure the box temperature remained above 0°C the power of the larger bulb was adjusted using resistors. Normally two 2.2 ohm resistors in series were used, but on very cold nights these were replaced by a single 3.3 ohm resistor.

9) Test runs, using melting ice as the target temperature,showed that errors were restricted to +/- 0.5°C during a run with no significant cycle to the errors (fig. 4.24a and b).

4.7.4. Warming/Cooling of the IRT While in the Temperature Control Box

As mentioned above (sections 4.7.2 and 4.7.3) warming/cooling rates of the box air , during mapping, were restricted to a maximum of 3°C hr^{-1}. From the results of the laboratory tests (fig. 4.8) we can see that a box (air) warming rate of 3°C hr^{-1} should produce errors in the temperature reading of 1.1°C. However, during test runs using a tray of melting ice as the target temperature , errors were restricted to +/- 0.5°C using the temperature control box (figs. 4.23 and 4.24). The IRT does not perform any better in a constant temperature room (see chapter 3 section 3.4.1).

There are a number of reasons to explain this:

1) Any element of glare in the errors (although small) will be less (probably zero) with the ice tray runs than in the laboratory tests. This is because the ice is only 5cm below the IRT during the runs while it is approximately 60cm below the IRT during the laboratory tests.

2) The relationship between box (air) warming/cooling rate and IRT warming/cooling rate, from the laboratory tests, is shown in figure 4.25. A box warming rate of 3.0°Chr^{-1} will produce a IRT warming rate of 2.2°Chr^{-1}. This will result in an error of only +0.7°C (figure 4.10).

3) The errors from the laboratory tests were the result of a combination of varying warming/cooling rates. Some of these were very high particularly during the early stages of the tests. However, during the mapping runs the IRT warms at a slower rate initially and then remains at a relatively constant temperature for at least 30 minutes. Then relatively low and steady air warming rates are experienced (maximum 3.0°C hr^{-1}). Particularly remembering the lag effect it is not surprising

that errors during the laboratory tests appear to be higher than during the mapping runs for the same average warming rate.

4.8. CONCLUSIONS AND SUMMARY OF MAPPING UNDERTAKEN DURING WINTERS 1989/90 AND 1990/91

A laboratory investigation of the errors produced while thermal mapping winter 1988/89 allowed temperature control boxes and associated procedures to be developed which restricted these errors to +/-0.5^{o}C during mapping runs. This allowed mapping to be undertaken with much greater confidence during winters 1989/90 and 1990/91.

The objectives were as outlined in chapter 3 section 3.2.1. An additional objective was to extend mapping to most of the principal highway network of Sheffield in order to produce thermal maps of Sheffield.

Thirty-four runs were made along route 1 in varying weather conditions, commencing at 0430hrs during winter 1989/90. In addition on 7 of these nights when weather conditions were mostly clear skies and light winds an earlier run commencing around 0000hrs was made.

During winter 1990/91 mapping was extended to the rest of the principal highway network of Sheffield. A further 66 runs were made along route 1 commencing at 0430hrs and a total of 145 runs along routes 2-7 (see appendix 1) commencing between 0000 and 0330hrs. Table 4.8 summarises the runs made during both winters allocating them to extreme, intermediate, damped and other categories (see chapter 3, section 3.3). The analysis of thermal fingerprints can be found in chapters 5 and 6.

CHAPTER 5

TYPES OF THERMAL FINGERPRINTS OBSERVED AND FACTORS AFFECTING ROAD SURFACE TEMPERATURES

The different types of fingerprint recorded along route 1 will be presented and described with particular emphasis on the fingerprints mapped under extreme, intermediate and damped weather conditions. The overall shape and amplitude of each fingerprint will be described with the main factors influencing this shape and amplitude discussed. The second part of this chapter will examine, in greater detail, and at a much smaller scale, the factors affecting RSTs under the different weather conditions of extreme and damped. This will be based principally on the fingerprints of route 1, but examples from other routes will be included where appropriate.

Unless otherwise stated the fingerprints are classified according to weather conditions recorded at the start and end of each run and using the classification outlined in chapter 3 section 3.3. A fingerprint could be included in a category (extreme, intermediate or damped) even if the observed weather conditions (cloud and wind at start and end) were not strictly appropriate to a category if the differences were considered to be negligible.

5.1. TYPES OF FINGERPRINT MAPPED ALONG ROUTE 1

With 100 fingerprints of route 1 commencing at 0430hrs, under a wide range of weather conditions (table 5.1), all the potentially different types of thermal fingerprint observed during data collection in Sheffield should be represented by route 1 fingerprints. In addition, because the 100 fingerprints of route 1 have been used for statistical analysis (see chapter 6 section 6.1) only route 1 fingerprints will be used in this section.

During data collection mapping runs were undertaken in as many different weather conditions as possible. However, greater emphasis was placed on obtaining fingerprints during extreme; clear/windy and cloudy/calm intermediate; and damped conditions. With the greatest temperature differences and lowest temperatures recorded under extreme conditions particular emphasis was placed on mapping under these weather conditions. In the following sections a number of representative fingerprints for each weather condition will be described.

5.1.1. The Extreme Fingerprint(s)

Fingerprints of route 1 mapped under extreme weather conditions showed some variation in shape and amplitude. This variation and the reasons for this variation will be discussed in greater detail in chapter 6. Figures 5.1 to 5.3 show three examples representing the range of extreme fingerprints mapped along route 1. Figure 5.1 is the fingerprint of run MS9 (29.11.90), figure 5.2 shows run MS62 (28.3.91) and figure 5.3, MS37 (14.2.91). The altitudinal profile of route 1 along with variations in land-use and location details are shown in figure 5.4.

The overall shape of all the extreme fingerprints is similar with most of the first 9km of the run in the higher altitude rural areas to the west of Sheffield below average (down to 4°C below). Warmer (less cold) stretches of road in this section of the fingerprint are usually associated with trees by the side of the road (eg. at 4km). There is no consistent significant decrease in RST with altitude as the route descends from Moscar Top to the Rivelin Valley which might have been expected under conditions favouring katabatic drainage. This may have been due to there being a large number of trees in the area preventing cold air draining off the higher ground or, if by the roadside, keeping RSTs higher by reducing the sky-view factor. The influence of the urban heat island and low altitude can be seen with most of the urban area and in particular the city centre above average (up to 2.5°C above excluding localised peaks). The amplitude of the extreme fingerprints is large, as expected, with temperature differences of 6 to 7°C (excluding localised peaks). The fingerprints are characterised by large temperature fluctuations over short distances with distinct peaks and troughs (see around 28km fig. 5.3).

Differences in the shape of the extreme fingerprints are mainly to be found in the second half of the run in the low altitude eastern side of Sheffield (Attercliffe, Tinsley and Darnall). There are a number of locations (eg. 25-26km) which are above average on some fingerprints (eg. MS9 fig. 5.1) but are below average on others (eg. MS62 fig. 5.2 and MS37 fig. 5.3). Also some cold spots are more pronounced on some runs than others (compare 17.5km fig 5.1 to fig 5.3). Clearly with all RSTs being related to the average for that run any differences in one section will alter the shape of the rest of the fingerprint as can be seen by the smaller but still noticeable differences in the low RSTs recorded in the first 9km of runs MS9, MS62 and MS37 (figs. 5.1-5.3 respectively).

Under clear skies with light/calm winds cold air drainage is likely with the accumulation of this cold air in low altitude areas and valleys/hollows. Many of the cold spots within the urban area, referred to above, are in low altitude areas and or valleys/hollows. At 13km and 17.4km the route follows the Upper Don Valley (altitude 50m.asl) with higher ground in the vicinity to the west and east at 13km and west, east and north at 17.4km. The cold spots in section 25-28km are located in the level plain of the Lower Don Valley at an altitude of 40-50m.asl.

To summarise, the main factors affecting the overall shape and amplitude of the extreme fingerprints are the variation in altitude, local relief (eg. valley/hollow) and the urban heat island effect. The relationship between altitude and RSTs is, however, complicated with low altitude areas both in rural (eg. 6.5km Rivelin Valley) and in particular urban areas experiencing low temperatures due to cold air drainage on extreme nights.

5.1.2. The Damped Fingerprint.

Figure 5.5 shows the thermal fingerprint of run MOS5 mapped 19.2.90 under damped weather conditions. The amplitude of the fingerprint is much smaller than the extreme with a temperature variation along the run restricted to about 4^{o}C. Local temperature variations are much smaller than on the extreme fingerprint (compare 28km fig. 5.5 with fig. 5.3). Mixing of the air by wind and reduced net radiative cooling due to counter radiation from clouds prevent large temperature differences from developing. The high altitude areas at the start of the run (0-12km) are below average while most of the city, at low altitude, is above average. With a mean lapse rate of 0.65^{o}C/100m and an altitude difference of 320m along the run the expected difference in air temperatures and hence RSTs would be approximately 2^{o}C. The actual difference of 4^{o}C is likely to be caused by the urban heat island effect keeping air and RSTs higher in the low altitude urban areas. The RST difference between Moscar Top and Crosspool is approximately 1^{o}C on run MOS5 which is very similar to that which would be expected due to the altitude difference between the two sites (160m). The effect of changes in altitude can be easily picked out - note the increasing temperature as the route drops into the Rivelin Valley (3-6km) and the decrease in RSTs as it climbs again towards Crosspool (8km). Even the relatively small increase in altitude as Prince of Wales Road climbs towards its junction with Sheffield Parkway (32-33.5km) results in a small but detectable decrease in temperature.

Although altitude is clearly the dominant factor in shaping the damped fingerprint, the urban heat island effect is also likely to influence RSTs. With the high altitude areas being mostly rural and low altitude areas mostly urban, the urban heat island effect is likely to increase the temperature difference between these high and low altitude areas. The urban heat island effect is smaller in the outer suburbs. Not surprisingly with limited cooling and effective mixing of air there is no evidence of cold air drainage on damped fingerprints.

5.1.3. The Intermediate Fingerprint

Intermediate fingerprints will be mapped under any weather conditions between those of extreme and damped, although particular attention is usually paid to fingerprints mapped under either cloudy and calm or clear and windy conditions. Figure 5.6 shows the fingerprint of run MOS9, mapped 28.2.90 under virtually clear skies with moderate to fresh winds. The effect of the wind is to restrict the development of temperature differences along the run by mixing the lower air layers. In addition, this mixing prevents cold air drainage from occurring. Consequently the temperature variation of about 4.5°C is less than with the extreme fingerprint, but greater than the damped fingerprint because radiative cooling is not reduced as much by counter radiation from cloud cover. Figure 5.7 shows the fingerprint of MS10, mapped 2.12.90 under cloudy and calm conditions. The net loss of long-wave radiation from the road surface is restricted due to counter radiation from the cloud cover, but with no wind temperature differences of 4.5°C developed along the run. This is identical to the magnitude of the temperature differences along the clear/windy intermediate fingerprint.

With both types of intermediate fingerprint the dominant factor affecting the overall shape and amplitude is altitude with the high altitude areas to the west of Sheffield and higher suburbs below the average temperature of the run. The lower altitude city centre and eastern suburbs are mostly above average with the increase in altitude at 32-33.5km again associated with a decrease in RSTs. As with the damped fingerprint the urban heat island effect is likely to have increased the difference in RSTs between the high altitude rural areas and low altitude city by more than would have been expected under normal environmental lapse rates (2.5°C for the intermediate nights compared to 2°C on the damped night). The influence of the urban area is again less in the outer suburbs (Crosspool) with temperature differences between there and Moscar Top only 0.3-0.6°C greater than would be expected from the altitude difference.

The shape of the intermediate and damped fingerprints are very similar with only the amplitude of the examples shown the distinguishing feature although the difference is often small. Again altitude is the dominant factor influencing the shape of intermediate fingerprints with the urban heat island effect also important. The intermediate and damped fingerprints have a very different shape to extreme fingerprints mainly due to the accumulation of cold air at low altitudes on extreme nights.

5.1.4. Other Fingerprints

Many of the mapping runs along route 1 were undertaken in weather conditions with varying amounts of cloud and wind. The shape of most of these fingerprints is similar to those of the damped and intermediate fingerprints shown in figures 5.5 - 5.7 with variations in amplitude broadly corresponding to the amount of cloud and wind during a run. The relationship between cloud and wind during a run and the amplitude of the resulting fingerprint is analysed in detail in chapter 6 section 6.1. However, on a number of occasions the fingerprints had distinctly different shapes or are of particular interest and these are described below.

THE EFFECT OF FOG ON FINGERPRINT SHAPE/AMPLITUDE

On a few nights mist/fog was present for all or some of the mapping run. Figure 5.8 shows the fingerprint of run MS46, mapped 27.2.91 under clear skies and calm winds. These weather conditions are ideal for the formation of fog with unrestricted radiative cooling allowing air temperatures to fall below the dew point temperature resulting in condensation and the formation of fog. On this night localised fog had developed in the Lower Don Valley approximately corresponding to 25-30km on the fingerprint. The effect of this localised fog is seen in the higher than usual RSTs (relative to average) in this area (compare to figs. 5.1-5.3). This is caused by fog reducing radiative cooling (counter radiation from fog itself) and the release of latent heat of condensation as the fog forms. The shape of the rest of the fingerprint will be altered as shown by the cold section 31-35km which is not observed to the same extent on other extreme fingerprints (figs. 5.1-5.3).

Figure 5.9 is the fingerprint of run MS53, mapped 11.3.91, when a mild southwesterly air-stream brought low cloud and very moist air across the Sheffield area. There was mist/fog in places along the route especially at the start which was affected by low cloud. The resulting fingerprint has a very low amplitude with a temperature variation of only 2°C despite there being little/no wind (and therefore intermediate weather conditions). Note that the section with the highest altitude did not have the lowest road surface temperature due to the effect of fog/low cloud in this area.

THE EFFECT OF SNOW/SLUSH/WATER PRESENT ON THE ROAD SURFACE ON FINGERPRINT SHAPE/AMPLITUDE

On five nights (see table 5.1) snow and/or slush (melting snow) was present on some stretches of road along the mapping route. The effect of this snow/slush varies depending on the amount present (was all the road covered?), how long it had been there (enough time to be affected by the temperature of the road or vice-versa) and its condition (dry snow, melting slush or frozen). For example figure 5.10 shows the fingerprint of run MOS3, mapped 15.2.90 with a recent, light (less than 10mm) and patchy snow cover for the first 2.5km with RSTs seemingly unaffected - note the normal increase in RST as the route decreases in altitude. However, on the night of 27.2.90 (run MOS8) there were heavy sleet/snow showers before and during the mapping run producing a very different fingerprint shape (see fig. 5.11). At a number of places along the route snow or slush had settled on the roads to a depth of approximately 20mm. The effect of this on the shape of the fingerprint is, not surprisingly, significant with all of the cold sections of the fingerprint (below average) corresponding to where snow/slush had settled on the road (0-13km, 17-18km, 23-26.5km and 29-33.5km).

It is important to point out that the emissivity of snow/slush is likely to be different from that of the road surface and so the different temperatures measured by the IRT may partly be due to these differences in emissivity. The potential problem of variations in emissivity due to differences in condition of the road is discussed in greater detail in chapter 7 with particular reference to the fingerprint of MOS8.

Figure 5.12 is the fingerprint of run MS42, mapped 20.2.91 in cloudy and windy weather conditions. During the previous few days (7.2.91 to 12.2.91) there had been periods of snow with heavy accumulations particularly at high altitude. By the night of 19/20.2.91 most of the lying snow had melted but piles of snow remained at the roadside, in the high altitude areas, where snow-ploughing had taken place (0-4km and 7-10km in particular). With air temperatures during the run +2 to +4°C this snow continued to melt with water accumulating on/running across the road surface. As a result the measured RST in these areas is around 0°C, the temperature of melting ice/snow. This could have been caused by the road surface being maintained close to 0°C by the water or by the temperature of the water itself being measured. Again possible differences in the emissivity of water and the road surface may be important (see chapter 7).

5.2. FACTORS AFFECTING ROAD SURFACE TEMPERATURES IN SHEFFIELD

The main factors affecting the variation in RSTs in the Sheffield area will be discussed in the light of the results of the thermal mapping undertaken during winters 1989/90 and 1990/91. The varying effect of these factors, on RSTs, will be described by considering the contrasting weather conditions of extreme and damped. Intermediate fingerprints were not considered because the factors effecting RSTs act in very similar ways under damped and intermediate weather conditions with the only difference being the generally greater amplitude of intermediate fingerprints due to greater cooling (see section 5.1.3). Fingerprints from route 1 will provide most of the data and examples, but fingerprints from other routes will also be used where appropriate. It is important to bear in mind that the RSTs recorded while thermal mapping represent the combined effect of all the differing factors and because of this it is often difficult to isolate the individual effect of any single factor.

5.2.1. Altitude

As discussed in section 5.1, altitude has probably the greatest single effect on the variation in RST on both extreme and damped nights. However, the influence of altitude on air temperatures and consequently RSTs varies considerably with these two types of weather conditions. In addition, the relationship between altitude and RSTs is complicated by other factors and in particular the influence of the urban area. In Sheffield most of the high altitude areas are to the west of the city in rural areas while the urban area is predominantly at low altitude, particularly the eastern suburbs. In order to facilitate the study of the relationship between altitude and RSTs the thermal fingerprints of route 1 will be considered in two parts - namely rural (1 - 7km) and urban (9km to the end of the run). The section 7 - 9 km is not considered as it represents the transition between rural and urban areas although on many nights (but not all) there is a distinct rise in RST at 8.4km approximately corresponding to the edge of the built-up area. The brief analysis in sections 5.1.2 and 5.1.3 showed that the urban heat island effect is smaller here than close to the city centre with no apparent effect on fingerprint MOS5 (fig. 5.5). The effect of altitude on RST will initially be considered separately for each section (rural and urban) under both extreme and damped conditions.

THE EFFECT OF ALTITUDE IN THE RURAL AREA UNDER EXTREME WEATHER CONDITIONS

The relationship between altitude and RSTs during extreme nights in the rural area is complicated (see figs. 5.1-5.3 and 5.8). The normal lapse rate (a decrease in temperature with increasing altitude) is not consistently observed. In extreme conditions cold air drainage is likely with the lowest temperatures recorded in low altitude valley bottom sites (eg. start of Rivelin Valley 5-7km on route 1). However, although low temperatures do occur in this area they are rarely lower than at the highest altitude (0-1km). The relationship is likely to be complicated by interaction with other factors such as vegetation (see section 5.1.1) and local relief.

As discussed in chapter 1, section 1.3.3, it is possible that in an area of varying altitude/relief the lowest air and road temperatures can occur both at high and low altitude sites with a warmer zone (the thermal belt) at intermediate altitudes. In the rural area of route 1 there is no clear thermal belt and on occasions the lowest temperatures occur at these intermediate altitudes (eg. run MS37, fig. 5.3, 3.1km, 270m.asl).

Lapse rates between the high altitude rural area (0.5km, 360m.asl) and low altitude rural area (6.3km, 170m.asl) were determined and are shown in table 5.2. On four of the 17 extreme nights there was a temperature inversion with lower temperatures at the low altitude site (lapse rates +0.05 to +0.74°C/100m). On four occasions there were relatively steep negative lapse rates (>0.5°C/100m) with the lowest temperatures at the high altitude site. On the remaining nine nights there was little difference between the RSTs at the two sites. It is important to note that on a number of these nights lower RSTs were recorded between these two sites (eg. run MS7, fig. 5.13, 3.5km) and that the lapse rates shown in table 5.2 only represent the temperature difference between two specific sites. Likely reasons for the occurrence of low RSTs at these intermediate altitudes are discussed in detail in chapter 6, section 6.3.2.

To summarise, the effect of altitude on RSTs in the rural area is very varied. Lowest temperatures are often recorded at the highest altitudes under normal lapse conditions, but inversions also occur with low RSTs at low altitudes due to the accumulation of cold air draining off the higher ground. There is no thermal belt at intermediate altitudes, as may be expected, and the influence of other factors such as local relief, wind direction and vegetation may be important (see chapter 6 section 6.3.2).

THE EFFECT OF ALTITUDE IN THE URBAN AREA UNDER EXTREME WEATHER CONDITIONS

The relationship between altitude and RSTs in the urban section of route 1, on extreme nights, is more complicated than in the rural area (see figs. 5.1-5.3). This is due to the additional influence of the urban area on RSTs. The initial 4km of this section (9-13km on fingerprints) show a steady decline in altitude from 200m.asl to 60m.asl. On runs MS9 (fig. 5.1) and MS62 (fig. 5.2) this drop in altitude is initially associated with a steady rise in RST (especially 9-10km). For run MS37 (fig. 5.3) and from 10km on the other two runs the relationship is not as clear. From 13km to the end of the run there is little variation in altitude (40-60m.asl) except for the rise to 110m.asl at the junction of Prince of Wales Road (A6102) with the Parkway (32-33.5km). This rise in altitude is not associated with any clear decrease in RSTs and on occasions temperatures increase (MS9, fig. 5.1). Despite the minimal altitudinal variation in most of the urban area RSTs fluctuate considerably - as well as the likelihood of cold air accumulating in these low altitude areas other factors such as the proximity and density of buildings/industry complicate the relationship between RSTs and altitude.

The influence of cold air drainage on RSTs can be seen in the urban area on many extreme nights, especially runs MS62 and MS37 (figs. 5.2 and 5.3 respectively). Low RSTs (more than 2°C below average) are recorded in low altitude sites at a number of locations. There is a persistent cold spot at 17.4 km, along Penistone Road (A61) from the roundabout with the A6102 to Herries Road, altitude 60m.asl. The magnitude of this cold spot varies from run to run: 0.5°C below average run MS9, 0.8°C below average MS62 and as much as 2.2°C below on MS37. This site is located in the Upper Don Valley with higher ground to the north, west and east - an ideal location for the accumulation of cold air draining off the higher ground. This stretch of the A61 is also relatively open with (only) terraced housing and open spaces by the side of the road (see photo 5.1). The differences in the magnitude of this cold spot at 17.4km are likely to be caused by differences in the intensity of cold air drainage. The level plain of the Lower Don Valley experiences areas of low RST especially in the section 25-26km (see figs 5.2 and 5.3). On run MS37 there are numerous other cold spots in the Lower Don Valley and Darnall areas (27.5 to 33km) indicating extensive cold air drainage that night. These cold spots are as much as 2.2°C below average and are nearly as low as the RSTs recorded at the high and low altitudes in the rural area. On one run (MS36, fig 5.14) the RST temperature recorded at 17.4 km is the equal lowest temperature recorded for the whole of the run.

The cold spots in the Lower Don Valley occur in relatively open areas where any buildings are set back from the road, eg. at 24.7km Don Valley Stadium (see photo 5.2). Although most of the road is at a similar altitude the influence of buildings/industry is crucial with higher RSTs recorded where large buildings are situated close to the road such as at 26.5km (see section 5.2.2 for greater detail). The cold section in the Darnall area occurs in a relatively open area with buildings set back from the road and the higher ground to the south is likely to be a local source of cold air drainage.

Lapse rates between the high altitude urban area (9km, 200m.asl) and the lowest altitude urban area (26km, 40m.asl) were determined and are shown in table 5.2. Inversions occurred on two nights (DV7B and MS37), but on most nights lower RSTs were recorded at the high altitude site. The steepest lapse rate (RST) of -1.56°C/100m occurred on the night of 27.2.91, run MS46 (see fig. 5.8) when fog had formed in the Lower Don Valley. This raised the RSTs relative to areas where fog had not formed (see section 5.1.4) producing a large RST difference between the two sites. These lapse rates are not representative for all locations because only one site is used. If the low altitude site had been at 25.5km more inversions would have been observed.

THE EFFECT OF ALTITUDE IN THE RURAL AREA UNDER DAMPED WEATHER CONDITIONS

The relationship between altitude and RSTs in the rural area on damped nights is much clearer than on extreme nights. Cloud cover and greater windspeeds restrict cooling and prevent cold air drainage from occurring. RSTs decrease with increasing altitude as expected. Examples of runs along route 1 in damped weather conditions are shown in figure 5.5 (MOS5), figure 5.15 (MOS7) and 5.16 (MS14).

On all three runs there is a similar trend in RSTs with rising temperatures as the route descends from Moscar Top (360m.asl) to the Rivelin Valley (170m.asl) and then a decrease in RSTs as it climbs again towards the urban boundary (6-7km) at Crosspool. On all three runs the lowest RSTs (1.5-2.8°C below average) are recorded at the highest altitudes (0-1km) although on run MS14 (fig. 5.16) RSTs almost as low occur at 4.3km (230m.asl). On this night water from melting snow by the roadside for the first 3km of the run may have prevented RSTs from dropping as low as might have been expected.

Lapse rates between the high altitude rural area and low altitude rural area were determined for damped weather conditions (see table 5.3). The average lapse rate is -0.40°C/100m. This is similar to the figure quoted for Hereford and Worcester of -0.44°C/100m (Thornes, 1989), a mainly rural county.

THE EFFECT OF ALTITUDE IN THE URBAN AREA UNDER DAMPED WEATHER CONDITIONS

The relationship between altitude and RSTs in the urban area on damped nights is clear with the lowest RSTs (1-2°C below average) recorded in the high altitude areas on the western side of the city (eg. Crosspool 9-10km). The low altitude city centre and eastern suburbs experience the highest RSTs (1-2°C above average excluding local peaks). The steady descent from 9km (Crosspool) to 13km (junction of Hoyle Street and Infirmary Road) is reflected in a rise in RSTs. The ascent from 50m.asl to 110m.asl at 32 to 33.5km (A6102 climbing from Darnall to its junction with the Parkway) is associated with falling RSTs.

The variations in RSTs in the section of the route where altitudes vary little (13.5-31.5km) is caused by factors such as housing/industry which are discussed in sections 5.2.2 to 5.2.4.

Lapse rates between the high altitude urban area (Crosspool, 9km, 200m.asl) and low altitude urban area (Attercliffe, 26km, 40m.asl) were determined and are shown in table 5.3. The average is -1.01°C/100m with a range of -0.77 to -1.65°C/100m. These lapse rates are considerably steeper than in the rural area. This is probably due to there being a larger urban heat island effect at the low altitude site in

Attercliffe (near city centre and industry) than at the high altitude site in Crosspool (outer suburbs) as discussed in section 5.1.2.

5.2.2. Housing/Industry

As discussed in chapter 1, section 1.3.3, housing/industry will effect RSTs in two different ways. Firstly by reducing the sky-view factor and, secondly, by the release of additional heat energy from buildings, industrial processes and traffic. The combined effect is to produce higher air temperatures and hence higher RSTs in the urban area. The urban heat island effect will be discussed here. Reductions in sky-view factor can also have a very dramatic and localised effect on RSTs and this is discussed in section 5.2.3.

The magnitude of the urban heat island effect on RSTs is not easy to determine in the Sheffield area, because of the large variations in altitude that are encountered. If there was little variation in altitude the effect of the urban area on RSTs could be relatively easily determined by comparing similar sites (in terms of exposure/openness) in the urban and rural areas. However, with most of the rural areas at high altitudes and most of the urban area at much lower altitudes the effect of the urban area on RSTs cannot easily be isolated.

In order to determine the magnitude of the urban heat island effect the influence of altitude must be removed. Table 5.4 shows the overall lapse rate of RSTs (Moscar Top to Attercliffe) and rural lapse rate (Moscar Top to Rivelin Valley) for all runs along route 1. The first point to note is that there are no inversions between the high altitude rural area and low altitude urban area (overall lapse rate) despite seven inversions occurring in the rural area (rural lapse rate). The average overall lapse rate is -0.71°C/100m while the average rural lapse rate is -0.41°C. If we assume that the average rural lapse rate represents the true average lapse rate for the area then the additional effect of the urban area can be determined:

-0.71(overall) - -0.41(rural) = -0.3°C/100m
altitude difference = 320m
average urban effect = 3.2x0.30 = 0.96°C

This is very similar to the average winter urban heat island magnitude (air temperature) determined by Colquhoun (1981) for Sheffield of 1.18°C.

There are some problems with this method in that it assumes that the Rivelin and Attercliffe sites are similarly exposed and affected by cold air drainage to the same extent. However, it does clearly show that RSTs in the urban area are higher than in the rural area when the influence of altitude is removed.

Table 5.2 shows the lapse rates (rural, urban and overall) for the specific weather conditions of extreme. The average overall lapse rate for the 17 extreme runs is -0.69°C/100m which is higher than would be expected considering the likelihood of cold air drainage producing inversions (positive lapse rates). The effect of the urban area on extreme nights can then be determined by subtracting the average rural (extreme) from average overall (extreme):

-0.69(overall extreme) - -0.15(rural extreme) = -0.54°C/100m
altitude difference = 320m
urban effect = 3.2x0.54 = 1.73°C

If we carry out the same procedure for all other runs along route 1 the average overall lapse rate is -0.72°C/100m and average rural lapse rate is -0.46°C/100m. The average urban effect on RSTs in all other weather conditions:

-0.72 (overall)- -0.46(rural) = -0.26°C/100m

altitude difference = 320m

urban effect = 3.2x0.26 = 0.83°C

The urban heat island effect is therefore greater in extreme weather conditions as would be expected (chapter 1 section 1.3.3) In addition, the analysis of some fingerprints in sections 5.1.2 and 5.1.3 indicated that the urban heat island effect is greater near the city centre (Attercliffe) than in the outer suburbs (Crosspool) as would be expected.

The influence of urban areas on RSTs can be detected from fingerprints of other routes. Figures 5.17-5.19 show thermal fingerprints of route 2 mapped under extreme weather conditions. Note the sudden drop in RST at 19km corresponds to the approximate western edge of the built-up area. There is no variation in altitude across this boundary and although there is a reduction in the amount of trees by the roadside at this location some of this drop in RST is likely to be caused by the change in land-use from urban to rural. This effect is not as clear with damped (fig. 5.20) and intermediate (fig. 5.21) weather conditions when the urban heat island effect is expected to be smaller and greater windspeeds will even out temperature differences across the rural/urban boundary.

Route 4 passes through the village of Oughtibridge on the A6102 to the north-west of the city. Even small urban areas such as Oughtibridge (population approximately 3500) have a visible effect on thermal fingerprints. Figure 5.22 shows the run ST24 in damped weather conditions. There is a noticeable rise in RSTs as the route passes through Oughtibridge at 9-10km with no significant change in altitude and a marked drop in the amount of trees which might be expected to cause temperatures to drop.

Other small urban areas can be picked out by their association with higher RSTs. Run CB21 under extreme weather conditions (see fig. 5.23) shows the effect on RSTs of the small conurbation of Hoyland Common on the A6135 (25-26km). Note the much lower RSTs at similar altitudes out of the urban area (24-25km and 26.5-27km).

The end of route 6 (from 26km) is a low altitude area (35-45m.asl) on the eastern edge of Sheffield. Figure 5.24 shows a thermal fingerprint of route 6 (RNG4) mapped under extreme weather conditions. RSTs are lower at the end of the run (0-1°C below average) than in the city centre (1-2.5°C above average excluding local peaks) which is at a slightly higher altitude (55-65m.asl). The same is true for the damped fingerprint (fig. 5.25) when cold air drainage (another possible cause for the difference) would not have occurred. The large urban heat island effect in the city centre is clearly responsible for the higher RSTs.

On all the different routes the highest RSTs in all weather conditions are recorded in the city centre. Although other factors such as altitude, traffic and variations in sky-view factor will be partly responsible, the urban heat island effect due to additional heat inputs from housing/industry is clearly important.

5.2.3. Topography

The factors discussed above, namely altitude and the urban heat island effect, tend to influence RSTs at a relatively large scale, ie. they effect the overall shape of the fingerprint. Differences in topography can have dramatic effects on localised variations in RST. With the IRT measuring the average emittance over a stretch of road for each measurement point, differences in speed of the mapping vehicle and slight differences in distance travelled per run and hence location of each temperature measurement means that very localised variations in RST may not be detected on every mapping run. This must be borne in mind when comparing different fingerprints.

Open stretches of road with a high sky-view factor lose more long-wave radiation to the atmosphere than those sheltered by trees or buildings (low sky-view factor). With radiative cooling at a maximum under clear skies and light winds these differences in sky-view factor will produce temperature differences which are most pronounced in extreme weather conditions. This can be seen by comparing an extreme fingerprint of route 1 (eg. fig. 5.1) with a damped fingerprint (eg. fig. 5.5). Local variations in RST are much larger on the extreme fingerprint with differences of more than 6°C over very short distances (see around 28km fig. 5.1). Trees, buildings and bridges over the road are the three main factors producing these local variations in RST. There are numerous instances where these factors affect RSTs on all routes and a number of representative examples are given below.

TREES (extreme nights)

The effect of trees on RSTs can be seen by examining extreme fingerprints of route 1 (figs. 5.1-5.3). There are a large number of trees by the roadside at 2.8km (northern side of road) and 3.6 and 4.4km on both sides. These reduce the sky-view factor and hence the net loss of radiation from the road surface resulting in temperatures 1.5-2°C warmer than adjacent open stretches of road at similar altitudes. The rapidly fluctuating temperatures in the first 1km of route 1 (with little/no variation in altitude) can be related to small groups of trees by the road (eg. at 0.6km).

The influence of a large wooded area on both sides of the road can be seen in the shape of extreme fingerprints of route 5 (fig. 5.23 run CB21). The section 17.4-20km (A61 north of Sheffield) has dense woodland on both sides of the road.

Despite this section of the route being at a relatively high altitude (150-200m.asl) and in a rural area RSTs are as much as 2°C above the average for the run and significantly warmer than nearby open stretches of road at similar altitudes (eg. 24-25km near junction 36 of M1).

BRIDGES (extreme nights)

The largest and most localised variations in RST occur when the route passes under a bridge. Examples of locations when route 1 passes under bridges are at 22.1, 23, 29, 31.8 and 36.6km - note the large peaks at these sites with RSTs as much as 3°C above adjacent open stretches of road (figs. 5.1-5.3). The largest peaks are found between 27-28.5km. The four peaks in this section, up to 6°C above adjacent stretches (fig. 5.3), are recorded where the route passes under the M1 motorway at Tinsley roundabout (the roundabout is driven round twice producing four peaks).

Route 7 (fig. 5.26, run AB14, extreme) passes under the railway bridge of the now disused Victoria Station at 14.3km (Furnival Road). The bridge is approximately 55m wide, constructed of stone (see photo 5.3) and RSTs up to 6°C above adjacent stretches of road are recorded near the centre of the bridge.

It is clear that the wider the bridge the warmer will be the RSTs beneath it. In the centre of bridges such as Victoria Station or the M1 the sky-view factor will be virtually zero with little net loss of radiation. Other narrower bridges, such as the railway bridge at 31.8km of route 1 (approximately 10m wide), will have a sky-view factor greater than zero even in the centre and so RSTs can fall further than under the wider bridges. As well as reducing the loss of long-wave radiation by re-emitting/reflecting back radiation emitted by the road below, the bridges themselves will emit radiation some of which will be absorbed by the road below. Bridges with a large depth of construction, such as at Victoria Station, will store a lot of heat through the day which will be emitted at night keeping the roads below even warmer.

BUILDINGS (extreme nights)

Buildings by the side of roads will reduce the sky-view factor, reduce the net loss of long-wave radiation and prevent RSTs from falling as low as adjacent open stretches of road. This effect can clearly be seen in the urban area and, in particular, the city centre where tall buildings, often very close to the road, produce relatively high RSTs. For example at 21.6km of route 1 (figs. 5.1-5.3) there are large buildings (South Yorkshire Police Headquarters and Whitbread Exchange Brewery) situated very close to the road (see photo 5.4). In this area RSTs 3-3.5°C above the average for the run were recorded.

The effect of large factories is particularly noticeable on route 7 (fig. 5.26). In the section 21.5-22.1km the route passes by the site of Sheffield Forgemasters Steelworks at Brightside Lane (A6109) with large buildings on both sides of the road (photo 5.5). In this area RSTs are up to 4°C above the average for the route (up to 5°C above nearby open stretches 22.5-23km) with some of the highest RSTs in the whole of the Sheffield area being recorded.

DAMPED NIGHTS

Trees, bridges and buildings do not produce as large peaks in RST on damped nights when there is less cooling. Figure 5.5 shows the damped run along route 1 on 19.2.90. There is much less variation in RSTs in the first 6km even where there are trees by the side of the road. At 4.4km, where there are trees on both sides of the road, RSTs do increase slightly but this may be caused by a decrease in altitude as much as by the trees. Bridges over the route still produce peaks in RST (at 22.1, 23, 29, 27-28.5, 31.8 and 36.6km) although they are smaller than on extreme nights, being only up to 1.5°C above adjacent stretches of road (up to 2°C above for the M1 bridges). The emittance of heat by the bridges towards the roads below will produce these higher temperatures even on nights with limited cooling. The warm RSTs caused by buildings are smaller on damped nights, eg. 21.6km is only 1.5°C above average compared to 3.5°C above on extreme nights. Figure 5.27 is the damped run AB23 (route 7) - Brightside Lane between Forgemasters Steelworks is only 1.5°C above the average for the run and only 1°C above nearby open stretches of road.

5.2.4 Other Features

ROAD CONSTRUCTION

Information on depth/type of road construction is very difficult to obtain (J.Charlton, Sheffield City Council Works Department, pers. comm.). In any case, variations in RSTs caused by variations in road construction are likely to be masked by other factors affecting RSTs.

Sheffield has only a few roads with concrete surfaces and none of these were mapped during the project. Possible differences in the emissivity of concrete and blacktop roads mean that care must be taken when comparing measured RSTs of both surfaces (see chapter 7 for further details).

TRAFFIC CONDITIONS

The amount of traffic on most roads in Sheffield at night is negligible, particularly after midnight when most of the mapping runs were carried out. Any influence on RSTs is likely to be small and therefore probably masked by variations in the factors discussed in sections 5.2.1-5.2.3. In addition RSTs were only recorded on the inside lane of dual carriageways and so comparisons between lanes carrying different traffic amounts are not possible.

Some of the highest RSTs (over 3.5°C above average, route 6, RNG4, extreme, fig. 5.24) were recorded in Commercial Street (10.5-10.9km) where the heaviest night traffic tends to concentrate (taxis and buses). However, the heat island effect and reduced sky-view factor due to large offices/shops (photo 5.6) are likely to be the main reason for these high RSTs.

CROSSING BRIDGES OVER ROADS/RAILWAY LINES

There are a number of locations where routes cross bridges over roads or railway lines below. The effect of this on RSTs is not clear. At 32.8-33.2km route 1 crosses the Parkway on the A6102. On run MS37 (fig. 5.3) this is associated with low RSTs particularly at 32.8 and 33.2km where the route crosses the bridges over the Parkway. The shallower depth of road construction of these road bridges may be responsible for the lower RSTs but it is complicated by being in an open area where cooling is likely to be greater anyway. In addition, bridges will lose long-wave radiation to the atmosphere both above and below the bridge, although this will be countered to some extent by receiving radiation emitted by the road below. The low RSTs are not as clear on other runs in extreme conditions (figs. 5.1 and 5.2) although small localised troughs are still present.

On route 2, at 0.1-0.2km the route (A6135) crosses over the M1 motorway. There is no clear effect on RSTs with the bridge warmer than average on some extreme nights and colder on others. There is little difference between RSTs on the bridge and on adjacent stretches of road either side. This is true in all weather conditions (figs. 5.17-5.21).

Although bridges crossing over roads are likely to be of a relatively shallow construction with low heat storage capabilities they will also receive radiation emitted by the road below. This may be significant if the road below is heavily trafficked and/or of deep construction such as the M1 (above). The effect on RSTs of crossing a bridge over a road is likely to be complicated by factors such as the type of road below and its distance from the bridge above. In addition, they may be used by services such as power cables or water pipes which may act as an additional source of heat.

Route 1, at 36.75km, on the Parkway crosses over the railway line from Sheffield central station (photo 5.7). This is associated with lower RSTs on extreme runs (figs. 5.1-5.3) - note the lower RSTs just after the peak of Bernard Road bridge (36.6km). The lower heat storage of this relatively shallow bridge and little heat input from the railway line below (as opposed to heavily trafficked roads) combine to produce these lower RSTs.

BRIDGES OVER WATER

Route 1 crosses the river Don at 21.7km (Lady's Bridge) and route 4 crosses at both Lady's Bridge (18.3km) and Blonk Street (18.5km). Although they are difficult to pick out there are peaks at these locations (fig. 5.1 route 1 and fig. 5.28 route 4) with relatively high RSTs despite the shallow construction of the bridges (photos 5.8 and 5.9). The water flowing below the bridges acts as a heat store providing a source of heat for the road above and preventing RSTs from dropping as low as might be expected.

However, the effect of crossing over water on RSTs is not consistent. Route 3 crosses over the river Loxley at 4.8km and the river Don at 13.2km. At these locations RSTs are actually lower than adjacent stretches of road under extreme weather conditions (fig. 5.29, RIV5). The effect on RSTs of bridges crossing over water is likely to be complicated by the fact that they are usually in more open locations when in urban areas (you don't build factories on bridges) and are of shallow construction. These two factors are likely to produce lower RSTs counteracting the warming effect of the water under the bridge. In addition, the depth of the river may be crucial with the rivers Loxley and Don much shallower at 4.8 and 13.2km respectively of route 3 than at the locations along routes 1 and 4 referred to in the paragraph above. Clearly the shallower the depth of water the smaller will be the heat source.

SHEFFIELD HEAT AND POWER PIPES

Sheffield Heat And Power is a company providing heating to many city centre buildings by piping hot water heated by burning industrial and domestic waste. The possible effect, on RSTs, of pipes containing water at over 100°C was investigated particularly as it was known that there was a pipe near the start of the Parkway where high RSTs were recorded on route 6 (figs. 5.24 and 5.25, 11.6-11.8km). Information provided by Sheffield Heat And Power on the location of their pipes showed that there was little/no correlation between the location of the pipes and high RSTs. The pipe near the Parkway only passed under the road for a very short section near Park Square Roundabout (11.5km). In addition, since the pipes are extremely well insulated with only 2% heat loss and buried at a minimum depth of 600mm, any effect on RSTs is likely to be negligible.

5.3. Conclusions

Thermal mapping in Sheffield has identified extreme, intermediate and damped thermal fingerprints. There is some variability in the shape of extreme fingerprints of route 1 and this is discussed in greater detail in chapter 6 which examines the repeatability and reliability of thermal mapping. The majority of the other fingerprints of route 1, including damped and intermediate (cloudy/calm and windy/clear), have a very similar shape with only the amplitude the distinguishing feature. Chapter 6 will also examine the relationship between the amplitude of thermal fingerprints and cloud and wind during a run and other factors. The occurrence of fog or snow can produce very different fingerprints (shape and amplitude).

Altitude and the urban heat island effect are crucial in determining the overall shape of fingerprints with low RSTs in low-lying areas due to the accumulation of cold air on extreme nights a feature. The effect of trees and buildings by the roadside and bridges over the road in producing local peaks in RSTs, identified by previous thermal mapping research (see chapter 1 section 1.4.1) has been confirmed. However, roads crossing over water are not consistently warmer and bridges over other roads not consistently colder as identified by other thermal mapping research (eg. Ponting 1984).

The key point to emerge has been the complex nature of the factors affecting RSTs. The effect of any individual factor is difficult to isolate, particularly at the local scale in urban areas where rapid fluctuations in sky-view factor, road construction, anthropogenic heat inputs and traffic conditions are likely.

CHAPTER 6

THE RELIABILITY AND REPEATABILITY OF THERMAL FINGERPRINTS

Most of the uses put forward for thermal mapping rely on the principle that there is an identifiable and repeatable thermal fingerprint (shape and amplitude) for any single stretch of road under identical weather conditions (see chapter 1 section 1.4.1). However, as discussed in section 1.4.2 of chapter 1, questions have been raised about the repeatability of thermal fingerprints - in particular the suggestion that fingerprints may vary with the time of year and the time of night that mapping was undertaken.

This chapter will initially look at the variation in the amplitude of thermal fingerprints of route 1 in relation to the amount of cloud and wind during a run. Other factors likely to influence the amplitude of fingerprints will also be examined.

Variations in fingerprint shape will be examined by focussing on extreme fingerprints providing the greatest variation in RSTs and ideal conditions for microclimatic differences to develop (eg. cold air drainage). Under these conditions, any differences in thermal fingerprints are likely to be most visible. In addition, differences in extreme fingerprints of route 1, which were touched upon in section 5.1 of Chapter 5, were related to variations in cold air drainage.

6.1. THE VARIATION IN THE AMPLITUDE OF THERMAL FINGERPRINTS

The amplitude ('development') of thermal fingerprints of route 1 varies considerably (compare fig. 5.1 to fig. 5.5). It can be seen that when cooling is unrestricted under extreme weather conditions, road temperature differences along a stretch of road are at their greatest and the amplitude is large (fig. 5.1). Conversely, with restricted cooling under damped weather conditions, large temperature differences cannot develop and the fingerprint has a small amplitude (fig. 5.5). Thermal mapping theory and literature (see chapter 1 sections 1.3 and 1.4.1) state that the greater the amount of cloud and wind during a run the smaller will be the amplitude of the resulting fingerprint. This relationship was examined using the thermal fingerprints of route 1 (mapping commencing at 0430hrs).

6.1.1. The Measurement of the Amplitude of Thermal Fingerprints

The amplitude of thermal fingerprints is usually described, in the literature, in qualitative terms such as 'large', 'small', 'restricted' or 'literally damped'. However, in order to investigate the relationship between cloud and wind during a run (and other factors) and amplitude it is necessary to have a quantitative measurement of the temperature variation/amplitude of a thermal fingerprint.

A statistical project was undertaken by a post-graduate student in the Department of Probability and Statistics, Sheffield University, using the thermal fingerprints mapped during winter 1989/90 (Mokube, 1990). Following discussions with the author of this thesis, the standard deviation, the variability about the mean, was used as a measure of the amplitude of thermal fingerprints. For the temperature values $x_1, \ldots\ldots x_n$ with mean $\bar{x}$,:

$$\text{standard deviation (SD)} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}}$$

Fingerprints with a large amplitude should have a high SD representing a large variation in RSTs and those with a small amplitude should have a low SD.

Table 6.1 gives details of all runs made along route 1 commencing at 0430hrs including weather conditions and SD for the resulting fingerprint. The highest SD, of 1.6664 (MS9), occurred on a clear and calm night. Lower SDs are associated with runs in windy and cloudy weather conditions, eg. run MOS7, with a SD of 0.6701.

Although it is generally true that high SDs are associated with extreme weather conditions and low SDs with damped weather conditions the relationship is not as clear as expected. The fingerprint with the lowest SD (0.5319 MS53) was mapped on a cloudy but calm (intermediate) night. Also some runs in cloudy and windy conditions (eg. MOS4, SD 1.0235) had higher SDs than some runs mapped in mostly clear skies and light winds (eg. MS48, SD 1.0092).

One problem of using SD as a measure of the amplitude of thermal fingerprints can be shown by looking at extreme fingerprints of route 1 (figs. 5.1-5.3). The fingerprint of run MS9 (fig. 5.1) has the highest SD (1.6664), with MS37 (fig. 5.3) 1.0827 and MS62 (fig. 5.2) 1.1133. However, the actual local variation in RST is greater on runs MS37 and MS62 than on MS9 (see 24-33km). It is apparent that the occurrence of cold spots in low altitude urban areas under extreme conditions, due to cold air drainage, reduces the overall variability (SD) of fingerprints by increasing the number of observations close to the mean, although local fluctuations in RST are greater and the 'development' of the fingerprint would be considered larger.

A second measure of the amplitude of thermal fingerprints, which should be more representative of the amplitude of the fingerprint in most weather conditions, was also used in analysis. The measure used is the difference between the maximum and minimum RSTs recorded during a run (termed D). Clearly with only two RSTs being used and with the maximum always occurring at the same location (under the M1 motorway bridges at Tinsley roundabout) it may not be representative of the whole fingerprint. This was investigated by determining the relationship between D and SD. Figure 6.1 shows the plot of SD against D for route 1 fingerprints. The correlation coefficient is 0.754 with R^2 56.8% and the regression equation:

$$D = 1.08 + 5.21SD$$

There is a clear relationship between D and SD and it is interesting to note that three of the four outliers (marked on fig. 6.1) are extreme runs - MS9 whose x value gives it a large influence and MS29 and DV1B which have large standard residuals, when the problem of cold air drainage reducing SD will occur. D is therefore considered to be a reliable indicator of the amplitude of fingerprints and both SD and D will be used to investigate the relationship between amplitude and weather conditions during a run.

6.1.2. Variation of Amplitude with Cloud and Wind During a Run

Cloud amount (octas) and wind speed (ms^{-1}) were recorded at the start and end of each mapping run and details are shown in table 6.1. The four variables (cloud at start and end, wind at start and end) were regressed individually against SD and D for the 100 fingerprints of route 1 (start 0430hrs). The resulting regression equations are shown in table 6.2 for SD and 6.3 for D along with the linear correlation coefficient, R^2 value (percentage of variation in SD/D explained by each variable) and the significance of the coefficient.

Although the coefficients are significant for the four factors with both SD and D, the R^2 values are small except with cloud at the start (SD, $R^2 = 31.4\%$ and D, $R^2 = 58.3\%$) and cloud at the end with D (32.2%). The plots of SD against cloud start and D against cloud start are shown in figures 6.2 and 6.3 respectively. The positions of the runs referred to in section 6.1.1 are shown on both figures. Note the difference in the position of the extreme runs (MS9, 29, 37, 62 and DV1B) with SD and D relative to the drawn regression lines. All coefficients are negative, confirming that greater cloud and wind reduce the variation in RSTs (amplitude). Cloud amount is more important than windspeed in influencing the amplitude of fingerprints. Weather conditions at the start are more important than at the end.

It is not surprising that better results are generally achieved with cloud and wind values at the start of the run as opposed to those at the end. On a number of occasions changes in weather conditions during the later stages of a mapping run were recorded at the end even though they were unlikely to have affected RSTs. For example: run MS7 on the night of 22.11.90 - the weather had been clear and calm all night until cloud cover increased approximately 15 minutes before the end of the run.

Overall cloud is more important in influencing the amplitude of thermal fingerprints than wind speed. This may be partly due to the different behaviour of these two variables and the methods of measuring. Wind tends to fluctuate much more than cloud in the short term and in addition will be influenced by local relief and topography. Measured cloud amounts are likely to be more representative of the general weather conditions than the measured wind speeds which are only determined over a short period of time (1-2 minutes).

6.1.3. The Effect of Weather Conditions During the Earlier Part of the Night (ie. before 0430hrs)

The dynamic nature of RSTs is discussed in chapter 1 section 1.3.1. RSTs are not purely a function of weather conditions and heat fluxes at the time of measurement, but are the result of both past and present weather conditions and heat fluxes. Clearly the further away, in time, from the moment of measurement the less significant will be the weather conditions/heat fluxes. It is likely that weather conditions during the night prior to 0430hrs will have had some influence on RSTs measured during a run. For example: consider the extreme scenario of a night with complete cloud cover and strong winds until skies cleared and wind speed decreased at 0420hrs - the thermal fingerprint recorded will have a relatively small amplitude due to the damped weather conditions prevailing for most of the night despite clear skies during the actual run.

During winter 1989/90 no observations on cloud amount and wind speed were made before 0330hrs. Twenty-four hour wind data are available for Sheffield (at High Bradfield, the Department of Geography and Weston Park Museum), but night-time cloud amount is not recorded. In winter 1990/91 mapping of routes 2-7 took place between 0000 and 0400hrs prior to mapping of route 1 at 0430hrs. Weather conditions (cloud and wind) were recorded at the start and end of mapping runs during these hours, providing observations on the general weather conditions in the Sheffield area. This allowed the relationship between amplitude (SD and D) and weather conditions during the earlier part of the night to be examined for runs along route 1 in winter 1990/91 (66 runs MS1-MS66). In addition qualitative observations, such as clear and calm, were made between dusk and midnight. The following DM values (dusk to midnight) were assigned to these observations so they could be regressed against amplitude (SD and D):

	DM value
clear and calm all night (extreme)	1
mostly clear and calm	2
clear and windy/cloudy and calm all night/variable cloud and wind	3
mostly cloudy and windy	4
windy and cloudy(8/8) all night	5

The values of cloud and wind recorded at 0000 and 0300hrs and DM values for all MS runs are shown in table 6.1.

These factors were regressed against SD and D and the results are shown in table 6.2 and 6.3 respectively. The results of regressing SD and D against cloud and wind during a run (start and end) for the same 66 MS runs are shown for comparison. The results are generally as expected with cloud more important than wind. For SD the influence of weather conditions declines the further away from the start of the mapping run - cloud at start R^2 = 28.2%, at 0300hrs 24.1%, at 0000 20.5%, and for DM 12.6%. For D cloud at 0000hrs has more influence on amplitude (R^2 51.5%) than cloud at 0300hrs (45.0%) although the difference is small. For both SD and D cloud at 0000 and 0300hrs and DM have a greater influence on the variation in amplitude than wind even at the start of the run.

The amplitude of thermal fingerprints is influenced by weather conditions earlier in the night. The closer to the start of the mapping run the greater is the influence. Recorded cloud is confirmed as being of greater importance than measured wind in affecting the variation in RSTs.

6.1.4. Other Factors Affecting the Variation in Amplitude of Thermal Fingerprints.

ROAD CONDITIONS

The effect of snow, slush and large amounts of surface water on the shape of thermal fingerprints is discussed in chapter 5 section 5.1.4. Because of the uncertainty regarding what temperature is actually being measured in these conditions (road, snow or water) the 14 nights with snow, slush or large amounts of surface water (see table 6.1) were removed from the data set for analysis. The SD and D of the remaining 86 runs were regressed against cloud at the start. For SD against cloud start the R^2 value actually decreased slightly from 31.4% (100 runs) to 30.4% (86 runs). For D against cloud start the R^2 value barely changed (58.3% for 100 runs compared to 58.2% for 86 runs).

A probable explanation for this small decrease in R^2 with SD after removing the runs with snow, slush or water on the roads is that the snow/water acts in a similar way to cloud and wind in reducing the variation in RSTs. Incorporating these runs in the analysis increases the explanation of variation in SD by reinforcing/emphasising the effect of cloud and wind in 'damping' the fingerprint. This effect can be seen with figure 5.11 (MOS8) where snow on the roads reduces the temperature variation especially in the urban area - compare the lack of variation in RST 24-26km and 29-33km where there was snow on the road with the temperature fluctuations 19-23km where the roads were clear.

The effect is even smaller with D. This is likely to be due to the fact that the maximum RST is always recorded under the M1 motorway at Tinsley roundabout. This location will be sheltered and largely unaffected by snow/water and so the effect described above will not occur to the same extent. SD is a measure of the overall variation (all RSTs) and so with snow/water affecting large sections of the fingerprint it will be affected more by these weather conditions.

The following RD values were assigned to each of the 100 mapping runs along route 1 representing the road conditions during the run:

	RD value
dry	1
dry/damp	2
damp	3
damp/wet	4
wet	5
very wet	6
snow/slush	7

Road conditions were then regressed against SD and D and the results are shown in tables 6.2 and 6.3 respectively with R^2 18.2% for SD and 5.8% for D. The negative relationship will be caused by the fact that wetter roads are generally associated with cloudier and windier weather conditions producing fingerprints with smaller amplitudes. The higher R^2 value for SD is likely to be for the same reasons discussed above (ie.location of maximum RST).

WEATHER CONDITIONS DURING THE PREVIOUS DAY

What happens to RSTs during the previous day is likely to have some influence on night RSTs although with the large time difference involved for winter studies this effect is probably small. On sunny and calm days with relatively strong heating of open stretches of road large temperature differences are likely to develop along roads. On cloudy and windy days RSTs will vary little except at the larger scale due to altitude and land-use differences. These two very different day-time temperature profiles may influence the night-time thermal fingerprint.

Sunshine (hours) during the previous day (see table 6.1) was regressed against SD and D for the 100 runs along route 1. The regression equations are shown in tables 6.2 and 6.3 respectively. With SD the correlation coefficient is +0.2608 with R^2 6.8% and with D +0.2828 and R^2 8.0%. This positive correlation is probably caused by the fact that sunny days are more often than not are followed by clear nights which will produce fingerprints with a larger amplitude.

Wind speed during the previous day (see table 6.1) was regressed against SD and D (see tables 6.2 and 6.3 respectively). With an R^2 value of only 0.4% for SD and 0.0% for D there is no relationship between wind speed during the previous day and the amplitude of the thermal fingerprint.

6.1.5. Combined Effect on Amplitude

The combined effect of the factors discussed above, on the variation in amplitude (SD and D), was examined. Multiple regressions using cloud and wind during the run, road conditions, weather during the earlier part of the night and sun and wind during the previous day were carried out. Initially all variables will be included in the multiple regression analysis. The t values for each variable are given indicating the relative importance of each variable. The adjusted R^2 value is also given which takes into account the degrees of freedom. If a variable is added to an equation R^2 will get larger even if the added variable is of no real value. This is compensated for by using R^2 (adjusted) and is an approximately unbiased estimate of the population R^2.

Having calculated the multiple regression equations variables which are not significant at the 10% level are removed and the regression equation recalculated using the significant variables. This is repeated until all the variables in the resulting equation are significant. The deletion of variables does not imply that the variable(s) in question is(are) unrelated to SD/D and so the full equations are included for completeness.

For the full data set (100 runs) weather conditions during the earlier part of the night were not available. The multiple regression consisted of 7 predictors : cloud at start and end, wind at start and end, sunshine and windspeed previous day and road conditions. The regression equations are :

$$SD(100) = 1.40 - 0.0455Cs - 0.0044Ws + 0.0035Ce + 0.0084We + 0.0152SUN - 0.0123Wp - 0.0512RD \quad (MR1)$$

with R^2 (adj.) = 44.8%

variable	t-value	significant (10%)
Cs	4.50	+
Ws	0.33	-
Ce	0.36	-
We	0.48	-
SUN	2.02	+
Wp	1.26	-
RD	3.99	+

$$D(100) = 9.25 - 0.344Cs - 0.0026Ws - 0.1120Ce - 0.0299We + 0.1310SUN - 0.0156RD - 0.1050Wp \quad (MR2)$$

with R^2 (adj.) = 64.5%

variable	t-value	significant (10%)
Cs	6.18	+
Ws	0.04	-
Ce	2.14	+
We	0.31	-
SUN	3.16	+
RD	2.21	+
Wp	1.95	+

Note the positive coefficients for cloud and wind at the end with SD, which is contrary to what is expected. However, both are insignificant even at the 10% level with the low t-values showing that they are relatively unimportant in explaining the variation in SD. Sun (SD and D) and wind (D) during the previous day along with road condition (SD and D) are all significant. This is likely to be due to their association with certain weather conditions.

The regression equations were recalculated excluding the insignificant variables:

$$SD(100) = 1.35 - 0.0422Cs - 0.0549RD + 0.0131SUN \quad (MR3)$$

with R^2 (adj.) = 45.6%

variable	t value	significant (10%)
Cs	6.75	+
RD	4.77	+
SUN	1.82	+

$$D(100) = 9.27 - 0.3490Cs - 0.1100Ce + 0.1330SUN - 0.1650RD - 0.1130Wp$$

(MR4)

with R^2 (adj.) = 65.2%

variable	t-value	significant (10%)
Cs	6.99	+
Ce	2.18	+
SUN	3.25	+
RD	2.46	+
Wp	2.42	+

The same 7 predictors were regressed against SD and D for the 66 runs during winter 1990/91. The regression equations are:

$$SD(66) = 1.45 - 0.0415Cs - 0.0174Ws - 0.0011Ce + 0.0281We + 0.0134SUN - 0.0577RD - 0.0210Wp \quad (MR5)$$

with R^2 (adj) = 41.4%

variable	t-value	significant (10%)
Cs	3.32	+
Ws	1.04	-
Ce	0.09	-
We	1.01	-
SUN	1.23	-
RD	3.03	+
Wp	1.68	+

$$D(66) = 9.93 - 0.323Cs - 0.0022Ws - 0.165Ce + 0.011We + 0.118SUN - 0.316RD - 0.132Wp \quad (MR6)$$

with R^2 (adj.) = 65.5%

variable	t-value	significant (10%)
Cs	4.74	+
Ws	0.02	-
Ce	2.55	+
We	0.07	-
SUN	1.98	+
RD	3.04	+
Wp	1.94	+

The regression equations were recalculated excluding the insignificant variables:

$$SD(66) = 1.49 - 0.0457Cs - 0.0615RD - 0.0186Wp \quad (MR7)$$

with R^2 (adj.) = 41.8%

variable	t-value	significant (10%)
Cs	5.86	+
RD	3.69	+
Wp	1.67	-

$$SD(66) = 1.40 - 0.044Cs - 0.065RD \quad (MR8)$$

with R^2 (adj.) = 40.2%

variable	t-value	significant (10%)
Cs	5.61	+
RD	3.87	+

$$D(66) = 9.93 - 0.323Cs - 0.165Ce + 0.118SUN - 0.319RD - 0.132Wp \quad (MR9)$$

with R^2 (adj.) = 66.6%

variable	t-value	significant (10%)
Cs	5.32	+
Ce	2.66	+
SUN	2.03	+
RD	3.39	+
Wp	2.15	+

Five additional factors, cloud and wind at 0000 and 0300hrs and DM were incorporated into the multiple regression for the 66 MS runs. The regression equations are:

$$SD(66) = 1.43 - 0.0336Cs - 0.0195Ws + 0.0019Ce + 0.0192We - 0.0159C0 + 0.0194W0 - 0.0061C3 - 0.0064W3 + 0.0089SUN - 0.0573RD + 0.0318DM - 0.0242Wp \quad (MR10)$$

with R^2 (adj.) = 38.7%

variable	t-value	significant
Cs	2.17	+
Ws	0.98	-
Ce	0.14	-
We	0.51	-
C0	1.12	-
W0	0.55	-
C3	0.44	-
W3	0.15	-
SUN	0.71	-
RD	2.88	+
DM	0.66	-
Wp	1.87	+

$$D(66) = 10.4 - 0.197Cs + 0.009Ws - 0.122Ce + 0.110We - 0.168C0 + 0.214W0 - 0.0304C3 - 0.240W3 + 0.0603SUN - 0.269RD - 0.160DM - 0.150Wp \quad (MR11)$$

with R^2 (adj.) = 70.6%

variable	t-value	significant (10%)
Cs	2.59	+
Ws	0.09	-
Ce	1.93	+
We	0.59	-
C0	2.42	+
W0	1.23	-
C3	0.45	-
W3	1.15	-
SUN	0.98	-
RD	2.75	+
DM	0.67	-
Wp	2.35	+

Incorporating weather conditions during the earlier part of the night in the full multiple regressions has no consistent effect, decreasing the percentage of variation explained for SD from 41.4% (MR5) to 38.7% (MR10) and increasing the variation explained for D from 65.5 (MR6) to 70.6% (MR11).

The regression equations were recalculated excluding the insignificant variables:

For SD see equations MR7 and MR8.

$$D(66) = 10.3 - 0.249Cs - 0.276RD - 0.135Wp - 0.209C0 - 0.096Ce \quad (MR12)$$

with R^2 (adj.) = 72.1%

variable	t-value	significant (10%)
Cs	4.19	+
RD	3.19	+
Wp	2.43	+
C0	4.08	+
Ce	1.69	+

There are a number of other factors which might influence the variation in amplitude of thermal fingerprints which have not been/cannot be included in this analysis. This could explain why there is still quite a large element (particularly for SD) of the variation in amplitude of fingerprints which has not been accounted for (particularly for SD). These are:

1) Variations in cold air drainage

2) Traffic conditions

3) Variations in urban heat island intensity (time of year/day or day of week)

4) Wind direction

5) Air mass type (may affect lapse rates)

6) Other atmospheric variables such as humidity

7) Accumulated temperatures (heat store)

8) Fog, which is known to reduce temperature variations.

The analysis so far has considered all mapping runs as one data set. This assumes that the factors discussed above affect the amplitude of thermal fingerprints in the same way under all weather conditions. This may not be the case and it was therefore investigated by considering extreme and damped runs separately.

6.1.6. Factors Influencing the Variation in the Amplitude of Extreme Fingerprints

Thirteen of the 17 extreme fingerprints considered in chapter 5 section 5.2.1 were recorded in winter 1990/91. The SD and D of these 13 runs were regressed individually against the 12 factors cloud and wind at start, end, 0000hrs, 0300hrs, sun and wind during the previous day, road conditions and DM. The regression equations and R^2 values are shown in table 6.4.

The picture is complicated with differences between SD and D. This is not surprising with most of the discrepancies in the relationship between SD and D occurring on extreme nights (see section 6.1.1).

Any relationship involving cloud at the start and end will be ignored because there is very little variation in the value of cloud recorded for the 13 extreme runs (see table 6.1).

There is some evidence to suggest that weather during the earlier part of the night is important in affecting the amplitude of extreme fingerprints, with wind being more important than cloud (D against CO, W3, and SD against W3). This is not surprising because on extreme nights with little/no difference in cloud amounts slight variations in windspeed are likely to have a significant influence on amplitude. The greater importance of cloud at 0000hrs than 0300hrs may reflect the fact that with steep cooling rates in the early part of extreme nights any cloud at this time may have a significant effect on amplitude. On only three of the 13 nights (MS36, MS38 and MS62) was recorded wind speed, at 0300hrs, greater than $0ms^{-1}$ corresponding to the three smallest D values (see table 6.1).

The influence of sunshine amount during the previous day is interesting. With SD the R^2 value is 32.4%, but with D it is only 2.7%. Greater amounts of sun during the day is associated with extreme fingerprints with lower SDs. This can be explained by considering the role of shade/shelter on warming during the day and cooling at night. On a sunny day open stretches of road will warm quicker than those stretches shaded by trees/buildings. If skies remain clear during the evening and night these open areas, with a high sky-view factor, will cool quicker than the shaded areas and the temperature differences will initially even out and then the open areas become cooler with differences remaining small (lower SD). On cloudy days temperature differences will not be as large, if at all, and if a clear night follows the open areas will cool quickly producing large night-time temperature differences (higher SD). The low R^2 value with D is probably due to the unique nature of the site where the maximum temperature occurs.

6.1.7. Factors Influencing the Variation in Amplitude of Damped Fingerprints

The damped runs analysed were those referred to in chapter 5 section 5.2.1 and in addition six other runs, virtually damped, were included (MS18, 42, MOS4, 8, 14 and 20). Only 4 of these runs were made during winter 1990/91, which is too small a data set for statistical analysis and so weather conditions during the earlier part of the night were not considered.

The only significant relationships (table 6.5) were found with wind at end for both SD (62%) and D (31.8%). Again with complete cloud cover on all these nights, variations in wind speed were crucial in determining the amplitude of damped fingerprints. On damped nights most local fluctuations in RSTs occur in the urban area (bridges and buildings) and with wind at end being measured in an urban area it may be more important in influencing RST variations than wind at the start which is measured in a high altitude rural area, where RST variations are normally less.

The amount of sun during the day is not important as any temperature differences established during the day will be smoothed out due to high wind speeds at night.

6.1.8. Conclusions

Statistical analysis of the thermal fingerprints of route 1 has shown that although cloud and wind during a run are important in determining the amplitude of fingerprints, other factors also have an influence. Overall, cloud is more important than wind, although problems with reliably measuring wind speed may be responsible. Despite this slight differences in measured wind speed seem to be important in influencing the amplitude of extreme and damped fingerprints.

The main additional factor to affect the variation in the amplitude of fingerprints is cloud during the earlier part of the night. The effect of snow/water on the roads and fog in damping the development of fingerprints is also apparent.

Weather conditions during the previous day generally have little influence on amplitude because of the length of time before mapping commenced. However, there is some evidence that on extreme nights greater sun during the day can reduce overall temperature variations at night.

6.2. COOLING RATES OF AIR AND ROAD SURFACE TEMPERATURES

Differences between what should be identical fingerprints will occur because of differences in relative cooling rates between stretches of road from night to night or different starting points between nights (see section 6.1.6). The nature of cooling rates will be examined using data from air and road surface temperatures in Sheffield. Possible factors producing differences in cooling rates will then be discussed using examples from extreme fingerprints of Sheffield routes 1 to 7 and additional runs in Derbyshire where large variations in altitude and relief (deep valleys and high altitude moorland) provide an ideal location for the occurrence of cold air drainage on extreme nights.

The nature of the cooling of RSTs at night is discussed in Chapter 1 section 1.3.1 with the dynamic nature emphasised. Thermal mapping principles state that temperature differences will develop along a stretch of road, especially under clear skies and light winds, because of differences in the rates of cooling; open stretches of road with high sky-view factors cool rapidly, while sheltered stretches with low sky-view factors cool at a slower rate. If we consider the simplified situation with RSTs, at sunset, the same along a stretch of road then differences in cooling rates will produce differences in fingerprint shape with time. If say point A, an open site, cools at $2^{o}C$/hour and point B, a sheltered site, cools at $1^{o}C$/hour then after 1 hour the difference will be 1°C and after 2 hours 2°C - any thermal fingerprints recorded at these two times will differ accordingly.

The above scenario assumes that cooling rates remain the same through the night which is not the case. Thermal mapping takes place in the later hours of the night (usually after midnight and especially towards dawn) when with non-linear cooling (see chapter 1 section 1.3.1), the magnitude of the cooling rates is not as great. Hence, at this time of night absolute differences in cooling rates between different stretches of road would be relatively small and therefore any differences in fingerprints that are likely to develop should be small.

However, if skies clear later on in the night (say 2am) rapid cooling rates will be experienced at the time of mapping is being carried out and with large relative differences between cooling rates significant differences may be recorded between what should be identical fingerprints.

The picture is further complicated when cold air drainage is considered. Katabatic flows will alter cooling rates with rapid drops in temperature where cold air accumulates. The behaviour of katabatic flows will vary from night to night with respect to onset times, type of flow (continuous, surging or overriding) and intensity (Mahrt, 1986). Clearly this variability can affect the shape of thermal fingerprints even if mapped at the same time each night.

6.2.1. Observed Cooling Rates

To confirm the predicted variation in cooling rates during a night, thermograph traces from King Edward VII Hospital (Rivelin Valley Road) and High Bradfield and data from Icelert sensors for 3 clear nights with light winds in January 1992 (13/14th, 16/17th and 21/22nd) were examined.

Tables 6.6 to 6.8 show the RSTs at eight of the Sheffield Icelert sensors (Morehall out of action) relative to the Moscar Top sensor for each of the three extreme nights of 13/14.1.92, 16/17.1.92 and 21/22.1.92 . Cooling rates ($^{o}Chr^{-1}$) are also shown for the three-hour periods 2100-0000 hours, 0000-0300 hours , 0300-0600 hours and overall (2100 to 0600 hours).

As expected overall cooling rates (2100 - 0600 hours) vary from site to site with a range of 0.10 to $0.37^{o}Chr^{-1}$. Cooling rates also vary through the night at each site with a general decrease towards dawn, although this is not always the case (eg. Elliott Lane 16/17.1.92). The highest overall cooling rates on each of the three nights occurred at the Prince of Wales Road and Tinsley sensors with Moscar Top and Ringinglow generally experiencing the lowest cooling rates. With the high altitude sites of Moscar Top and Ringinglow likely to start off with the lowest RST at sunset, these differences in cooling rates meant that RSTs at most of the Icelerts were closer to that of Moscar Top later in the night. Clearly this would produce differences in fingerprints if mapping was carried out. Figure 6.4 shows plots (equivalent to a thermal fingerprint) of the relative RST (to Moscar = $0^{o}C$) of the Icelert sensors for the night of 13/14.1.92 at 0000hrs (fig. 6.4a) and 0600hrs (fig. 6.4b) - note the changes in the plots between 0000 and 0600hrs.

The thermograph traces, showing air temperature, for King Edward's Hospital and High Bradfield for the nights of 13/14.1.92 and 16/17.1.92 (no data for High Bradfield 21/22.1.92) are shown in figures 6.5 and 6.6 respectively. Overall night cooling rates (2100-0600) and cooling rates for the three-hour periods 2100-0000, 0000-0300 and 0300-0600 hours are also shown. Overall cooling rates are much greater at King Edward VII Hospital than High Bradfield.

The cooling rates for both the thermograph and Icelert sensor sites can be related to the relief (fig. 2.3) and topography for each location. The location of the Icelerts and thermograph sites are shown on figure 2.3. The two thermograph sites are very different, with High Bradfield an exposed moorland site at high altitude (395m.asl) on the western edge of the Pennines while King Edwards is in the Rivelin Valley at an altitude of 160m.asl. Cold air draining off the Pennines is likely to accumulate in the Rivelin Valley maintaining the steeper cooling rates at King Edwards. Greater windspeeds are likely at High Bradfield producing smaller cooling rates.

The variation in the cooling rates of RSTs at the Icelert sensors can also be explained by considering the locations and topographies of each of the sites. Tinsley, Prince of Wales Road and Hillfoot, which experience much steeper cooling rates than Moscar Top, are at low altitude and relatively open locations (see fig 2.3 and photos 6.1 to 6.3 respectively) where accumulation of cold air is likely and cooling is not restricted due to obstructions such as large buildings or trees. Ringinglow is a very similar site to Moscar Top, both in terms of altitude (330m.asl and 350m.asl respectively) and topography, with shelter from trees at Moscar Top (see photo 6.4) and some trees and houses at Ringinglow (see photo 6.5). The similarity between these two sites results in similar cooling rates (see tables 6.6 to 6.8). Elliott Lane, Birley Moor and Bradway Road are at intermediate altitudes (see fig 2.3) and are more open than Moscar Top (compare photos 6.6-6.8 to photo 6.4 of Moscar Top). RSTs at these sites generally get closer to Moscar Top through the night and with cooling rates generally not as large as at Prince of Wales, Tinsley and Hillfoot.

Data on air and road surface temperatures confirm that different sites cool at different rates and highlight the dynamic nature of this cooling process. These differences, particularly on extreme nights, are likely to be caused by variations in sky-view factor and the occurrence of cold air drainage. Although under ideal conditions of clear skies and light winds all night cooling rates should tail-off in the latter part of the night, in practice they actually fluctuate (see tables 6.6-6.8). These fluctuations may be caused by surges in cold air drainage or slight variations in wind speed/direction or cloud cover. However, it is possible that variations will occur even in constant and supposedly ideal conditions of clear skies and light winds.

6.3. FACTORS PRODUCING DIFFERENCES IN THERMAL FINGERPRINTS

Possible reasons for differences in what should be identical fingerprints include mapping at different times of the year (for example: December and March) and at different times of the night. However, these are not likely to be the actual factors producing differences in fingerprint but may act through such things as length of night (affecting length of cooling period), hours of sun during the previous day and angle of sun during the day. These factors will be considered along with the effect of differences in wind direction and slight variations in windspeed during extreme nights.

6.3.1. Length of Cooling Period

For standardisation purposes and ease of measurement, if we consider the cooling period, for a night with clear skies and light winds, to begin at sunset (in reality it begins earlier) then the length of the cooling period will vary both with time of year and the time at which mapping is carried out. Clearly for the mapping runs along route 1, which all commenced at 0430 hours, the cooling period will be longest for any run during the night of 21/22 December. Also for routes 2-7 for two successive nights a run made at 0100 hours will experience approximately two hours less cooling than a run made at 0300 hours the next night.

The possibility of differences in fingerprints due to mapping at different times of the night was specifically investigated during winter 1989/90 and January 1992 by mapping the same route on more than one occasion during the same night.

On seven mostly clear nights with light winds in winter 1989/90 two runs were made along route 1- the first (DV1-7A) commencing at approximately 2345 hours and the second (DV1-7B) at 0430 hours. Details of these runs are shown in table 6.9. On four of the nights (DV2, 3, 5 and 6) weather conditions changed significantly before the second run commenced and so are not considered further. On the nights 15/16.2.90 (DV1 A +B) and 4/5.4.90 (DV7 A+B) clear skies and light winds remained for all of the night and on the night of 17/18.3.90 (DV4 A+B) slight increases in cloud and wind just before the start of the mapping run were considered unlikely to have affected the fingerprint.

Figs 6.7 to 6.9 show the fingerprints for runs DV1 A+B, DV4 A+B and DV7 A+B respectively. Although the fingerprints show the same general shape, there are some noticeable differences between the earlier and later runs. With runs DV1 A+B (fig. 6.7) the first 4km of the run are as much as 3.5°C below average on run A but generally only 2 to 3°C below average on run B. Cold spots in the low altitude areas are colder on run B than run A - at 17.5 km, 0.5°C below average run A, more than 1°C below on run B (see also 13km and 18.5-20 km). Similar differences can be seen between runs A and B during the nights of 4/5.4.90 (fig 6.9) and, in particular, 17/18.3.90 (fig 6.8). These changes in fingerprints during the night are likely to be related to cold air drainage with open low altitude areas (see 25-30km DV4 A/B fig. 6.8) becoming colder relative to open high altitude areas. It is interesting to note that the standard deviation of the fingerprints are less for the later B runs, confirming that the effect of cold air drainage on fingerprints is to lower the overall variation (see section 6.1.1).

Further investigations were made into the effect of cold air drainage on fingerprint shape through the night. Mapping runs were made in the Hope and Edale valleys of Derbyshire where there is considerable variation in relief (160-410m.asl) over short distances with very little urban influence (see fig. 6.10). Two mapping runs were made on each of the nights 16/17, 21/22, 26/27 and 27/28 January 1992 with run A (DB1-4A) commencing at around 2345 and run B (DB1-4B) at 0500 - 0530 hours. Details of these runs are shown in table 6.10. The second runs on the nights of 16/17 and 27/28 were affected by fog and so these nights are not considered further. On all of the DB runs, the air temperature was measured in the valley bottom near Hope station (see fig 6.10 for location) as well as at the start and end of the runs. This enabled the intensity of the cold air pool to be measured (between start of run and Hope station) and the relationship between changes in the intensity of the cold air pool and its effect on RSTs to be investigated.

Figure 6.11 shows runs DB2A and B on the night of 21/22.1.92 . Note that the high altitude area at the start of the run (0-0.5km) is warmer on run B (0.5°C below average to 1°C above) than run A (around 1°C below average) and the low altitude area slightly colder (note the more extensive cold area 3-7 km). Runs DB3A and B are shown in fig 6.12 and the differences between the two runs are particularly noticeable. The first 0.5 km of run A is as low as 1°C below average, while on run

B it is up to 1.5°C above average with absolute temperatures actually higher on run B at this location. The valley bottom area (3-7 km) is noticeably colder on run B with relative (to average) temperatures 0.5 to 1°C colder and absolute temperatures over 1°C colder generally.

The cold air pool intensity was determined using the air temperatures measured at the start (410m.asl) and in the valley bottom (near Hope station 160m.asl). Table 6.10 includes details of the air temperatures measured at these two locations and RSTs recorded at the valley bottom site. An intensification of the cold air pool of only 0.1°C on the night of 21/22.1.92 (runs DB3A and B) produced no change in the absolute RSTs measured in the valley bottom. On the night of 26/27.1.92 an intensification of the cold air pool by 1.7°C reduced RSTs by 1.3°C in the valley bottom. Although only based on two nights data these results confirm the findings of Bogren and Gustavsson (1991) that an intensification of the cold air pool reduces RSTs, but by a lesser amount.

Routes 2-7 (Sheffield) were mapped at different times of the night between 0000 hours and 0330 hours. This meant that even on nights with constant clear skies and light winds the length of cooling period prior to a run varied. Also seasonal differences in daylength would produce differences in cooling periods even if runs were mapped at the same time. Variations in cooling period prior to a run may produce differences in what should be identical fingerprints due to variations in relative cooling rates and cold air drainage.

Five extreme thermal fingerprints of route 2 are shown in figures 5.17-5.19 (ECC4, 7 and 14) and 6.13-6.14 (ECC19 and 22). All five nights had been clear with light winds since sunset. Differences in the fingerprints are particularly noticeable in the first 7km and last 2km of the run. Any changes in fingerprints due to mapping later in the night (longer cooling period assuming daylength the same) are most likely to show up in locations where cold air drainage occurs producing steep cooling rates. Road temperature differences (relative to average) between a site of cold air drainage (3.3 km route 2, 65-70m.asl) and a nearby higher altitude site (2.6 km route 2, 100m.asl) were determined as an indication of the cold air (RST) pool intensity at this site (3.3km) for each of the five nights. The two sites were similarly open with any buildings set back from the road and the location is shown in figure 6.15.

Table 6.11 shows details of the 5 extreme runs along route 2 with the magnitude of the cold air (RST) pool, time of start of run, date of run, length of cooling period (sunset to start of run), wind speed and direction. Wind data were obtained for High Bradfield, which is the best site in the Sheffield area to indicate the general airflow across the area, and for the Department of Geography. The average wind speed for the 2 hours before the run, the hour during the run and hour after the run was used. Because of the high altitude and exposed nature of the High Bradfield site, windspeeds are relatively high.

For route 2, on these five nights, the intensity of the cold air pool at 3.3 km varied between 0.8 and 1.9°C with the length of cooling period ranging from 550 to 600 minutes with clear skies and light winds all night. The largest cold air pool would be expected to occur with the largest cooling period, but this is not the case. The run with the longest cooling period (ECC19) has a cold air pool of only 1.1°C.

Variations in cold air pool intensities were also determined for sites on routes 6 and 7 (see figure 6.15 for locations and altitudes). Table 6.12 shows the results for route 6 and table 6.13 for route 7. Cold air pools vary considerably (1.3 to 3.2 °C for route 6 and 0.6 to 2.0°C for route 7). The relationship between length of cooling and cold air pool intensity is again not clear.

All mapping runs along route 1 commenced at 0430 hours (except DVxA runs). Despite this, significant differences were found between extreme fingerprints (chapter 5 figs 5.1 to 5.3) which were related to differences in cold air drainage. Table 6.14 shows the extreme runs along route 1. The nights with continuous clear skies and light winds since sunset are indicated and date of run, start time, length of cooling period and cold air pool intensity (site 17.4 km, see fig 6.15) are shown. Runs MS26 and MS27 mapped only two days apart with virtually identical cooling periods have identical cold air pool intensities at 17.4 km. However runs MS37 and DV1B which were mapped on similar dates (different winters) have very different cold air pool intensities (1.9 and 0.0°C respectively). Cold air pool intensity was regressed against length of cooling period for the 17 extreme runs along route 1. This resulted in a R^2 value of only 0.5%. There is no clear relationship between the intensity of the cold air pool and length of cooling period prior to the mapping run.

Clearly these differences in fingerprints cannot be related directly to mapping at different times of the night or year resulting in varying lengths of cooling prior to mapping runs. The occurrence of cold air drainage and its variability both in terms of duration, extent and form is a probable cause of most of the differences in extreme fingerprints. Factors other than length of cooling period will now be considered.

6.3.2. Wind Speed and Direction

On clear nights with light winds when cooling of roads is considerable and cold air drainage possible, slight variations in wind speed and direction may be crucial in affecting cooling rates on some stretches of road. Gustavsson (1990) in an investigation into the effect of topography and wind on RSTs states that :

> " Even a slight wind can disturb
> developed cold air pools and
> drainage of cold air"

As part of the same research project, Bogren and Gustavsson (1991) found that variations in RSTs between valleys and exposed areas were evened out when winds exceeded $3ms^{-1}$. McDonald (1984) in a study on lapse rates in Langdale Valley (Cumbria, England) found that inversions did not form if the regional wind speed exceeded $3ms^{-1}$.

Cold air pool intensity at 17.4km of route 1 for the 17 extreme runs was regressed against wind speed recorded at the Department of Geography (see figure 6.16). This resulted in a R^2 value of only 5.0% showing that wind speed alone has little/no influence of the development of the cold air pool on extreme nights.

Section 5.2.1 of chapter 5 mentions the possibility of differences in wind direction affecting the shape of extreme fingerprints of route 1. Table 6.15 shows the location of the three lowest RSTs recorded for each of the extreme runs along route 1. There is considerable variation with the lowest or equal lowest RST recorded at the highest altitudes (355 - 360m.asl 0-1 km) on 13 occasions, at intermediate altitudes (250-320m.asl, 2.0-3.7 km) on 6 occasions and at the lowest altitudes (185-200m.asl, 5-7 km) on 1 occasion. On one run (MS36) the equal lowest temperature was also recorded at 17.5 km (60m.asl).

The general pattern of RST for the first 8 km of the route was examined and related to the wind direction and speed for each night bearing in mind the local relief of the area (see fig 6.17). Seven different patterns of RST were identified for the 17 extreme nights. These were :

1) High and intermediate altitudes coldest, low altitudes less cold; 5 occasions, eg. MS17 (fig 6.18).

2) High, intermediate and low altitudes at similar temperatures; 5 occasions, eg. MS27 (fig 6.19).

3) Intermediate and low altitudes at similar temperatures, high altitudes less cold; 2 occasions, eg, MS26 (fig 6.20).

4) intermediate altitudes coldest, then lowest altitudes, high altitudes least cold; 2 occasions, eg. MS7 (fig. 5.13).

5) high and low altitudes coldest, intermediate least cold; DV1B (fig. 6.7a).

6) intermediate altitudes coldest, then high altitudes, low altitudes least cold; MS37 (fig. 5.3).

7) high altitudes coldest, then intermediate, low altitudes least cold; MS11 (fig. 6.21)

Table 6.16 gives details of the runs associated with these patterns including windspeed and direction for each night. The following points can be made:

1) With winds at their lightest (MS7 and MS41) both low and intermediate altitude sites are colder than high altitude sites. This is to be expected with extensive cold air drainage and accumulation of cold air at low altitudes with no interruption/impedance by even light winds.

2) Intermediate altitude sites are lower or as low as the high altitude sites on all but two nights. This is probably due to the local relief (see fig. 6.17) with the road at intermediate altitudes sheltered from wind in most directions by higher ground to all sides. In contrast the high altitude sites are exposed to the wind from most directions and are therefore likely to experience slightly greater windspeeds even on nights with generally low windspeeds.

3) On the nights that the highest altitudes are coldest or equal coldest, the winds are usually blowing from the northerly sector (NW-NE) - the direction from which the high altitude sites are partly sheltered by higher ground to the north (fig. 6.17).

4) The lowest altitude sites are only colder than intermediate altitudes on one night (DV1B). This is likely to be due to the nature of cold air drainage in this area. Cold air draining off the higher ground to the north at intermediate altitudes may override less cold air already trapped in the valley bottom (Mahrt, 1986). More likely, however, is that cold air may be trapped at this location by concave terrain and/or vegetation - note the location of a wooded area close to the road at the intermediate altitudes (fig. 6.17).

The cold air pool sites examined in section 6.2.1 in relation to the variation in intensity of the cold air pool with length of cooling period prior to mapping will now be analysed with respect to wind direction and windspeed. Do variations in wind direction and/or speed affect the intensity of cold air pools on extreme nights.

Table 6.14 shows the cold air pool intensity at 17.4km of route 1 (relative to 9.5km) for the 17 extreme runs, along with details of wind direction and speed. As stated there is no clear relationship between intensity and the general wind speed (see fig. 6.16). However, there are some indications that wind direction is important. On four nights (runs MS9, MS38, MOS11 and MS62) there was no cold air pool at 17.4km with the normal decrease in RST with increasing altitude. On all of these nights the wind had a distinct northerly component. With the extensive high ground of the Pennines to the west, Sheffield will be sheltered more when winds are blowing from the west/south-west than when winds are blowing from the north where the high ground is less extensive (see fig. 2.1). In addition, the site at 17.4km is situated in the Upper Don Valley which flows broadly north-north-west to south-south-east (see fig. 6.15). Winds from the north are likely to be funnelled down the valley limiting the development of the cold air pool.

The cold air pool sites on routes 2 and 6 are located on the eastern side of the city (see fig. 6.15). The intensity of the cold air pool is greatest with winds in the west (see tables 6.6 and 6.7) when the city is sheltered by the Pennines.

The cold air pool site on route 7 is located on the western side of the city (fig. 6.15) and the relationship between intensity and wind direction is not as clear (table 6.8). The largest intensity occurs with a east/south-easterly wind when the site is sheltered by higher ground to the south (see fig. 6.15).

If we look again at the differences of the extreme thermal fingerprints of route 2 in the last two kilometres (see figures 5.17-5.19 and 6.13-6.14) we can see that ECC4, 7 and 19 are broadly similar while ECC22 and especially ECC14 are different. There were no differences in road surface conditions and no fog or low cloud on any of the nights. This stretch of route 2 is the A625 at high altitude on moorland to the west of Sheffield (see fig 2.3). Figure 6.22 shows the detailed variation in relief for the last few kms of the run (route marked with distance along fingerprint shown). It shows that the last 1 to 1.5 km of the route is in the Burbage Valley with higher ground to the east, north-east and north and ground falling off to the west/south west. The low RSTs recorded at the end of the route (25.8 km) on runs ECC 4,7 and 19 are likely to be caused by cold air draining off the higher ground and down the Burbage Valley which may also be trapped in this area by concave terrain and/or vegetation. On these nights winds were blowing from the WNW to NW sector (see table 6.11) with the Burbage Valley sheltered. This would allow both greater cooling of RSTs due to less mixing and also cold air to drain unimpeded. However, on the nights of runs ECC14 and 22 the wind was blowing from the WSW, straight up the valley. Although wind speeds were generally light, cold air was probably prevented from draining down the valley by the general airflow and combined with less shelter and greater mixing, RSTs did not fall as low as on the other three runs.

6.3.3. Potential Solar Receipt

Seasonal differences in thermal fingerprints due to variations in daylength and therefore potential solar receipt and accumulated temperatures have been identified. In particular the report by University College, Swansea (Symons, Williams and Colville-Symons, 1987) identified differences in fingerprints mapped in April 1986 and March 1987, close to the spring equinox (12 hours daylength), and those mapped in December 1986, close to the winter solstice (8 hours daylength).

Three thermal fingerprints of route 1 mapped close to the winter solstice (MS9, MS11 and MS17, figs. 6.23a, b and c respectively) were compared to three fingerprints mapped close to the spring equinox (DV7B, MOS24 and MS62, figs. 6.24a, b and c respectively). The most important point to make is that there are significant differences between the three fingerprints within each group. These differences and the likely causes have been discussed above. No consistent difference could be identified between the spring and winter fingerprints. For example: if we look at the location of the lowest RSTs recorded. On two of the spring runs the coldest site was at 0.8km (DV7B and MS62), on the other night (MOS24) it was at 0.4km. Although the coldest site was in a different location for two of the winter fingerprints (MS9 and MS11, 0.1km) on the other run (MS17) it was at 0.8km.

6.4 CONCLUSIONS

Differences in fingerprints mapped under supposedly identical extreme weather conditions have been identified. The main causes of these differences are likely to be variations in the extent and behaviour of cold air drainage and differences in wind direction interacting with local relief. Differences due to relief (wind speed and direction) and cold air drainage are likely to be less in areas where there is limited variation in relief and altitude. Much of the research into thermal mapping was undertaken in the West Midlands where variations in altitude and relief are limited. This may explain why differences in fingerprints were not identified. Mapping at different times of the night and year will produce differences in thermal fingerprints, but these differences are not consistent and cannot be related to length of cooling period or daylength. There is a general variability in extreme thermal fingerprints which is caused by a number of interacting factors which are difficult to predict and/or explain. This is not surprising, considering the dynamic nature of the process of cooling at road surfaces, and has important implications for thermal mapping (see chapter 8).

CHAPTER 7

THERMAL MAPS OF SHEFFIELD, POSSIBLE ERRORS IN VEHICLE-BASED THERMAL MAPPING AND CONFIDENCE LIMITS FOR THERMAL FINGERPRINTS AND MAPS

Thermal maps showing the variation in road surface temperature in the Sheffield area, under extreme and damped weather conditions, have been prepared using thermal fingerprints of routes 1-7. The extreme thermal map is compared to three fingerprints of an eighth (combined) route, consisting of sections of routes 1, 3, 4, 5 and 6, mapped under extreme conditions during January 1992 and data on RSTs from Icelert sensors. Possible errors in vehicle-based thermal mapping are assessed with particular emphasis on the effect of variations in the emissivity of road surfaces. Finally, confidence limits for thermal fingerprints and thermal maps derived from these fingerprints are determined in the light of the assessment of errors and comparison of the extreme thermal map with Icelert data and the 1992 fingerprints.

7.1 THERMAL MAPS OF SHEFFIELD'S PRINCIPAL HIGHWAY NETWORK

The thermal fingerprints mapped along routes 1-7 provided a very large amount of data on RSTs in Sheffield. Some of these fingerprints were used to produce extreme and damped thermal maps of Sheffield's principal highway network showing the relative RST during the later hours of the night in 'winter' (November to early April). An intermediate thermal map was not produced due to the similarity of many intermediate and damped fingerprints (see chapter 5 sections 5.1.2 and 5.1.3).

7.1.1. Preparation of the Thermal Maps

Clearly not all fingerprints mapped along routes 1-7 could be used or, indeed, were relevant to the preparation of extreme and damped thermal maps. The fingerprints selected for the preparation of the thermal maps are shown in table 7.1. They were selected on the basis of shape and amplitude with particular emphasis on the weather conditions during and prior to the mapping run.

Generally a fingerprint was used for the extreme thermal map if weather conditions (clear skies and light winds) were the same for the whole of the night up to the completion of the mapping run in question. Some fingerprints were excluded because their shape was influenced by localised fog patches or if they differed significantly from the majority of the plots. Others were excluded because their standard deviation was low for an extreme fingerprint, compared to the whole set for that particular route, although allowances were made for the effect of cold air drainage on the SD of some fingerprints (see chapter 6 section 6.1.1). The criteria for selecting the damped fingerprints were similar except weather conditions were cloudy and windy and SDs low. If there were two or more fingerprints for each route they were combined using MINITAB (a simple statistics package for use with PCs) to produce average fingerprints (table 7.1).

Five of the seven routes passed through Park Square Roundabout and so its temperature was determined and used as a basis for comparing the fingerprints of different routes against one another. The RSTs (relative to Park Square = average

= 0°C) were then plotted on two maps showing the principal highway network of Sheffield. Routes 2 and 3 did not pass through Park Square Roundabout although sections did coincide with parts of other routes allowing the RSTs of these routes to be plotted relative to Park Square Roundabout. Figure 7.1 shows the completed extreme thermal map and figure 7.2 the damped thermal map.

7.1.2. The Thermal Maps

Both the extreme (fig. 7.1) and damped (fig. 7.2) thermal maps are plotted on identical road maps showing the principal highway network of Sheffield. The variation in temperature is shown by different colour shading on the maps (see maps for key). All RSTs are relative to the RST of Park Square roundabout - eg. sections of road shaded purple are between 2.5 and 1.5°C below the RST of Park Square Roundabout. The choice of Park Square roundabout, a warm location, as the base point meant that most stretches of road were below 'average'.

THE EXTREME THERMAL MAP

The temperature variation across Sheffield, shown by the extreme thermal map, is generally as expected. The lowest RSTs occur at the highest altitudes, more than 4.5°C below average at:

Sheffield/Derbyshire boundary on Ringinglow Road, 400m.asl.
A625 near Fox House Inn, 380m.asl.
A57 near Moscar Top, 360m.asl.

There is also clear evidence of cold air drainage with low temperatures occurring at a number of low altitude sites:

A6102 near junction with Morehall Lane, 120m.asl, end of a valley.

A6102 (Low Road through Oughtibridge), bottom of a hill and in a small dip.

Junction of B6087 and A6135, Ecclesfield, 65m.asl, low point with high ground around.

A57 near junction with Rivelin Valley Road, valley bottom site, 180m.asl.

Rivelin Valley Road (A6101) at Under Tofts, 130m.asl, near valley bottom, base of sloping ground.

Abbeydale Road (A621), 110m.asl, near valley bottom.

The outer suburbs of Sheffield are generally up to 1.5°C below average with colder sections at the higher altitudes (eg. Bradway, Lodge Moor and Bents Green) and where cold air draining off higher ground has accumulated (see above). Much of the city is around average with the city centre up to 1.5°C above average in places. A few locations are warmer than this:

1.5 to 2.5°C above -

Commercial Street, tall buildings close to the road with relatively heavy night traffic.

Lady's Bridge over the River Don (the effect of passing over water).

Brightside Lane (A6109) near junction with A6102, large industrial buildings.

Sheffield Parkway - under Bernard Road; under A6102 roundabout; and first 250m of the Parkway after exiting from Park Square (possibly relatively heavy traffic, concrete banking or considerable depth of construction).

more than 3.5°C above -

Under the large railway bridge (Furnival Road, B6073) at the now disused Victoria Station.

A large section of the A61 north of Sheffield (from B6087 for approximately 2km) is relatively warm (up to 1.5°C above average) considering its altitude and distance from the city centre. This section of road passes through the village of Grenoside and dense deciduous woodland.

THE DAMPED THERMAL MAP

The temperature variation shown by the damped thermal map is influenced mainly by altitude and to a lesser extent by the urban heat island effect. The temperature range is not as great as with the extreme thermal map.

The lowest RSTs (up to 3.5°C below average) coincide with the high altitude ares around Sheffield especially in the west (A57, 360m.asl; A625, 380m.asl; Ringinglow Road, 400m.asl; and A621, 285m.asl). The cold section of road at the junction of the B6054 and A616 is located at the highest point along that route (Quarry Hill, 160m.asl).

The difference in RST, of 3 to 4°C, between the highest altitude sites (400m.asl) and the lowest (40m.asl) is greater than would be expected from the normal environmental lapse rate in damped weather conditions (0.65°C/100m). The additional heat due to the urban heat island effect increases the temperature difference between the rural high altitude sites and the urban/industrial low altitude sites by approximately 1.5°C. However, low lying rural areas, such as Sheffield Parkway (A630) near the M1, are generally at a similar temperature to the city, although this may be due to the relatively heavy traffic on this route.

Most of the city and low-lying eastern suburbs are around average. The warmest temperatures (up to 1.5^{o}C above) occur at Commercial Street, where there is probably considerable heat input from office sources and relatively heavy night traffic, and along the first 200m of the Parkway (heading east) again possibly due to heavy traffic or the greater depth of construction.

Important areas to note are the relatively low temperatures (up to 2.5^{o}C below) along the A6102 through Stocksbridge, despite the relatively low altitude (150-175m.asl) and urban influence with some heavy industry. The coldest section on the A57 (south-east of Sheffield) is at the Sheffield/Rotherham boundary despite it being the lowest altitude along the route (35m.asl). At this location the road crosses over a railway line with the road raised on an embankment. The low temperatures may be due to a small 'thermal memory' with shallow construction of the road as it crosses the rail line and limited contact with any ground around.

7.1.3. Comparison of the Extreme Thermal Map with 1992 Fingerprints and Icelert Data

SCH RUNS

On three nights in January 1992 (13/14, 16/17 and 21/22), under extreme weather conditions, an eighth Sheffield route was mapped (SCH1-3). This route was made up of sections of some of the original Sheffield routes (see appendix 1 for details) so that the resulting fingerprints could be compared to the temperature variation shown by the thermal map. The three fingerprints are shown in figure 7.3 (a-c).

Firstly, despite weather conditions being identical and the three runs all being made within in an eight day period there are some notable differences between the fingerprints:

0-3km - SCH1 warmer.

8-10km - SCH3 warmer.

17-18.4km - SCH2 colder.

30km-end - SCH3 colder.

Sections of the SCH runs were compared to the completed extreme thermal map. Table 7.2 shows the relationship between the temperature pattern shown by the thermal map and that shown by each of the SCH runs (nb. a qualitative comparison). The general pattern ties in well - ie. cold start (A57 and A6101), warm city centre and cool end (Bradway, A6102). However, there are a number of differences in the actual magnitude of the temperature variations shown.

The SCH runs are warmer than the thermal map during the early stages of the run (A57, A6101, 0-6km) - in particular SCH1. The association between the thermal maps and SCH runs is quite good in the urban area (10-21km) and very good along the outer ring-road (A6102, 23-28.5km). However, from its junction with the A61 (30-35km) there are again some differences particularly with SCH3 which is much colder than the thermal map in places.

ICELERT DATA

The temperature variation shown by the extreme thermal map was compared to the differences between the Icelert sensors on the same three nights that the SCH runs were mapped.

The Moscar Top sensor was assumed to be at $0^{o}C$ and the temperatures of the other Icelerts adjusted accordingly to maintain the temperature differential. The thermal map allows a range of temperatures for any location - ie. Moscar Top is between

3.5 and 2.5°C below average. This means that a range of temperature values for each of the Icelert sensors would be accommodated by the thermal map. However, even with this possible margin of error there is little association between the temperature pattern shown by the Icelert sensors and that shown by the extreme thermal map (see table 7.3). The tie-in was very good at Ringinglow and quite good at Elliott Lane and Tinsley. However, there was little tie-in with the other sensors particularly Birley Moor and Prince of Wales Road. The Icelerts were generally colder than predicted by the thermal map - ie. they were closer to the temperature of Moscar Top than the thermal map indicated.

7.1.4. Conclusions

With the relatively poor degree of association between parts of the SCH runs and much of the Icelert data and the completed extreme thermal map there is some doubt about the accuracy of the temperature variations shown by the thermal maps. However, they probably represent a good picture of the general variation in RST in the Sheffield area (ie. the trends) and this is confirmed by the fact that the relationship between RST and factors such as altitude, relief, topography and land-use is generally as expected.

7.2. POSSIBLE ERRORS IN VEHICLE-BASED THERMAL MAPPING

Table 7.4 is a list of possible errors in vehicle-based thermal mapping (Thornes, 1991). This list excludes possible errors due to warming/cooling of the IRT during operation (see chapter 4) although in the accompanying text the author states that:

> "Again care must be taken to maintain

> the infra-red camera within a constant
> temperature range during observations..."

However, this advice is a bit vague with no indication of how large the temperature range can be. The possible errors listed in table 7.4 (except emissivity) and warming/cooling of the IRT will be assessed below in section 7.2.1 with respect to the Sheffield project and the likely magnitude of any error determined. The problem of variations in the emissivity of road surfaces is discussed separately in section 7.2.3 because of the greater uncertainty concerning its likely effect on RST readings.

7.2.1. Assessment of Errors

WARMING/COOLING OF THE IRT

The production of errors due to warming/cooling of the IRT is discussed in detail in chapter 4 and so there is little need for further discussion.

In summary, potential errors of +/-3°C have been identified while thermal mapping due to fluctuations in the temperature of the environment in which it operates. Carrying out thermal mapping with the IRT in a temperature control box reduces errors to +/-0.5°C which is as good as the best performance of the IRT in a constant temperature room.

TEMPERATURE OF THE INSTRUMENT

Infra-red thermometers are normally calibrated to operate within a specific temperature range. The manufacturer's specification for the Compac 3 (see appendix 2) states the operating temperature range as 0 to 50°C. While mapping in

Sheffield the heating of the temperature control box was adjusted to ensure that the IRT operated in a temperature above 0°C (chapter 4, section 4.7.3). Clearly, there is no problem with the upper limit of this temperature range.

For commercial mapping heating of the mapping vehicle will ensure that the IRT(s) would be operated within the temperature range. The Heimann KT-17 has a similar operating temperature range of 0 to 60°C.

DETECTOR SENSITIVITY; MILLIVOLT TO TEMPERATURE CONVERSION; ATMOSPHERIC ABSORPTION; AND LENS WAVEBAND

The Compac 3 and Heimann KT-17 are both high-technology instruments specifically chosen for the purpose they are used for. With extensive testing and calibration, any errors for these reasons will be negligible and will be accounted for by the +/-0.5°C accuracy of the IRT operating in a constant temperature room.

DIRTY LENS/CONDENSATION

During mapping in Sheffield regular inspections were made of the IRT lens. The position of the IRT in the van while mapping ensured that little/no water/dirt splashed onto the lens. No condensation was ever observed on the lens. Regular cleaning of the lens, according to the manufacturer's instructions, was carried out.

VEHICLE RADIATION

The problem of radiation from the vehicle exhaust and/or floor entering the instrument is discussed in chapter 4 sections 4.1 and 4.5.2. Any possible errors were considered to be negligible and are incorporated in the likely errors calculated in section 7.2.3.

TYRE PRESSURE

Regular checks were made on the tyre pressure of the vehicle as part of the regular maintenance procedures. Any variations in distances between observations due to differences in tyre pressure will be small. Furthermore, the IRT does not measure the infra-red radiation emitted at a single point of the road surface, but determines the average RST over a stretch of road as the vehicle moves. The length of the stretch of road sampled will vary with the response time of the IRT used and the speed of the vehicle. This means that the process of thermal mapping has an averaging and sampling procedure in-built. Any variations in the location of the start of measurement and variations in the speed of the vehicle will ensure that over a period of time more of the road will have its temperature measured than if measurement points and speed of vehicle were identical every night. Clearly this also means that some points may be missed on some nights and this must be borne in mind when analysing fingerprints. However, this 'problem' will not produce any errors in the actual RST recorded, but only differences in the exact location of measurement points, or the distance which measurements are averaged over, from run to run.

LANE CHANGES

Mapping vehicles may have to move to different lanes, at a different temperature, due to roadworks, parked vehicles or slow-moving vehicles. Any differences in measured temperature are likely to be small and usually over short distances. If, say, due to roadworks a large section of a route is affected then the fact should be noted and taken into account when analysing the resulting fingerprint (as it was during this project).

Lane changes may also slightly alter the distance of the run and hence the location of temperature measurements. However, this is not considered a problem as discussed above.

WARM-UP OF INSTRUMENT

According to the manufacturer's operating instructions the Compac 3 IRT does not require a warm-up period. Tests in a constant temperature room showed that the Compac 3 accurately measured temperatures immediately after being turned on provided it had been in that environment for some time previous. In addition, for all the mapping runs during winters 1989/90 and 1990/91, the IRT had been turned on for a minimum of 20 minutes before mapping commenced.

The Heimann KT-17 requires a warm-up period of 30 minutes according to the manufacturer's operating instructions. The KT-17 was only used in a small number of laboratory tests and the warm-up period was adhered to. It is assumed that companies carrying out thermal mapping using the KT-17 follow the operating instructions.

7.2.2 Magnitude of the Errors Discussed Above (7.1.1)

Using a high-technology instrument such as the Compac 3, which is properly tested, calibrated and used according to the manufacturer's instructions the possible errors discussed above will not produce significant errors in RST readings made by the IRT.

All the errors discussed above, except tyre pressure, lane changes and vehicle radiation are applicable to the IRT operating in the constant temperature room. Tests showed that, in this environment, errors in the temperature reading were +/-

0.5°C. As stated, any errors due to vehicle radiation will be incorporated in the calculated errors in section 7.2.3. Differences in the location of observations due to variations in tyre pressures and/or lane changes are likely to be insignificant when considering the averaging and sampling process of thermal mapping. In addition, these are not likely to produce errors in the actual RST measured but only some uncertainty about the exact point the measured temperature relates to - no practical decisions or uses are/have been based on individual measurements requiring pin-point locations but are based on stretches of road.

Any errors in relative and absolute RST readings will, therefore, be restricted to +/-0.5°C.

7.2.3. Possible Errors Due to Variations in the Emissivity of Road Surfaces

To determine absolute RSTs using infra-red thermometers such as the Compac 3 and Heimann KT-17 the emissivity of the road surface must be accurately known (see chapter 1 section 1.3.1). If we are concerned only with relative RSTs, a consistent difference between the emissivity value used on the IRT and that of the road surface, the true emissivity value, would cause few problems because it will produce a constant error. (Nb. the actual magnitude of the error will vary slightly depending on the target temperature, although with the small range of temperatures likely to be experienced while mapping this variation will be negligible).

The two main thermal mapping companies use different emissivity values when carrying out thermal mapping - 0.96 by Travers-Morgan and 0.99 by Vaisala TMI. This suggests some uncertainty regarding the true emissivity value of road surfaces. Thermal mapping, meteorological and infra-red thermography literature was examined in order to ascertain the emissivity value of road surfaces.

Table 7.5 shows the emissivity values of blacktop (asphalt) and concrete roads, along with other emissivity values relevant to this project, to be found in the literature and other sources. As can be seen the emissivity values for blacktop roads vary considerably from 0.86 to 0.99. Most references quote a single value suggesting little/no variation in the emissivity of blacktop roads. However, tests conducted by LAND on ten samples of blacktop road (from Sheffield), provided by the author of this thesis, and three samples provided by the Department of Transport showed that emissivity values varied between 0.86-0.92 with most (11/13) in the range 0.90-0.92. Note that there is a large difference between the values determined by LAND and those determined by Blackmore (1982).

Gustavsson and Bogren (1990) state that:

> "To ascertain the (emissivity) value of
> an object, it is possible to use emissivities
> given by tables and lists in infrared
> handbooks. However, the values may be of
> varying quality......."

They also point out that field tests identified little variation in the emissivity value due to homogenous asphalt layers, although this contradicts the findings from the LAND tests.

In addition, it is likely that the emissivity of the road surface will vary depending on its condition. Sugrue, Thornes and Osborne state that:

> "For motorway blacktop a value of emissivity
> = 0.99 has been found to be representative,
> though obviously this will fluctuate

> depending on whether the road is wet or dry and, for example, where oil or rubber deposits are present on the surface. Observed errors in absolute temperatures are generally in the range 0.2-0.5°C, which is acceptable for comparative purposes."

Quoted emissivity values for water range from 0.95-0.99, clear ice 0.91 and 0.96, rime frost 0.98-0.99 and snow 0.82-0.99. The emissivity of the road surface will be affected if significant quantities of snow, ice or water are present on the surface. Recent work by the Meteorological Office (A.Astbury, pers. comm.) has suggested that dry blacktop roads have an emissivity close to 0.90 and this increases to 1.00 when roads are wet or damp.

Errors in relative RST readings are, therefore, possible due to variations in the dry emissivity of roads and also due to variations in the condition of the road surface. Likely errors due to variations in emissivity will first be calculated and then examples from mapping in Sheffield used to help evaluate these calculated errors.

LIKELY ERRORS DUE TO VARIATIONS IN THE EMISSIVITY OF BLACKTOP ROADS

Likely errors in RST readings, due to using the incorrect emissivity value, can be calculated using equations 4.8 and 4.9 (see chapter 4 section 4.5.2 for details). If we assume the true emissivity values to be 0.90 and 0.99, representing both the range of most of the quoted values for dry asphalt and the likely range if road surface conditions vary, then calculated errors, with the Compac 3 emissivity set at 0.96, are shown in table 7.6 for three different temperature regimes. These temperature regimes are realistic examples based on IRT, van floor and target temperatures measured in the field.

As can be seen the calculated errors range from -0.22 to +0.14°C. These errors represent the worst case scenario with road emissivity values varying from 0.90 to 0.99 and also include errors due to 'glare' (reflection of radiation emitted by surrounds off target). The errors are very similar to those produced when the true emissivity is 0.96 (see chapter 4 section 4.5.2). In practice it seems that using an incorrect emissivity setting and/or variations in true emissivity will not produce large errors in RST readings. In conclusion, combining these results with the errors discussed in sections 7.2.1 and 7.2.2 likely errors in both absolute and relative road temperature readings will be at worst +/-0.7°C.

To summarise, with the emissivity of the Compac 3 set at 0.96, likely variations in the true emissivity value have little effect on the accuracy of RST readings made by the IRT.

MEASURED RSTS WHILE THERMAL MAPPING IN SHEFFIELD

The relatively small errors calculated above suggest that both relative and absolute RSTs have been measured with an accuracy of (at worst) +/-0.7°C while mapping in Sheffield. This can be confirmed by briefly examining some of the temperatures recorded.

Table 7.7 shows the average RST for the 100 route 1 fingerprints with the average of the measured air temperatures recorded at the start and end of each run also shown. The difference between these two values is also shown (negative = road cooler). The average of these differences is -1.01°C. On 77 of the runs the average RST was lower than the average of the two air temperatures, on 21 nights the road was warmer and on two nights temperatures were the same. With data collection taking place during the period late autumn to early spring, when daylength is short with limited solar receipt and long night cooling periods, these values would be expected. If we look at the differences in greater detail we can see that most of the occasions when RSTs were warmer than air temperatures occurred in early Spring when solar receipt will be greater and cooling periods shorter. In addition, the nine occasions when RSTs were cooler than air temperatures by more than 2.5°C occurred in the period late December to mid February with most in extreme weather conditions when cooling is at a maximum.

The occurrence of snow/slush on roads can be used to check the accuracy of the IRT readings. Route 7 crosses the central reservation between Attercliffe Road and Savile Street at 24.65km. On run AB5 (10.12.90, fig. 7.4) melting snow/slush (depth approximately 50mm) was present on the road surface at this location. As can be seen by examining the fingerprint the measured RST at this point was -0.2°C which is very close to the temperature of melting ice/snow at 0.0°C.

The effect of snow/slush on thermal fingerprints is discussed in chapter 5 section 5.1.4. If we again examine the fingerprint of MOS8 (fig. 5.11) we can see that in the area where slush (melting snow) was present on the road, at 13.5-14.4km, temperatures measured were between -0.6 to +0.2°C, again close to the temperature of melting ice/snow. In the areas where the snow had not begun to melt recorded temperatures were below 0.0°C, especially at the higher altitudes and in rural areas (0-7km) where the temperature of the road below the snow was likely to be below freezing with air temperatures around 0.0°C.

Measured RSTs close to 0.0°C were recorded for much of the first half of fingerprint MS42 (see chapter 5 section 5.1.4 and fig. 5.12). These were related to the occurrence of melt-water from piles of snow by the roadside flowing across the road. With emissivity variations producing insignificant errors in temperature readings these could have been caused by either or both of the following:

1) the temperature of the water, at approximately 0.0°C, being measured.

2) the road temperature itself, at approximately 0.0°C with air temperatures 2°C and the melt-water flowing across, being measured.

The above observations confirm that temperatures measured by the IRT during thermal mapping in winters 1989/90 and 1990/91 were accurate with errors at most +/-0.7°C, but probably less.

These errors, in relative RST readings, are considerably less than those suggested by Thornes (1991) of +/-2.0°C. However, the complex nature of the situation must be emphasised and also the fact that in order to calculate errors (section 7.2.3) some assumptions and interpretations have had to be made.

7.3. CONFIDENCE LIMITS FOR THERMAL FINGERPRINTS AND THERMAL MAPS

One of the aims of the research project (chapter 1 section 1.5.2) was to establish confidence limits for thermal fingerprints and thermal maps. Having assessed and quantified the possible sources of error in vehicle-based thermal mapping (section 7.2 above) confidence limits, specific to this project but with wider implications, can be determined.

The accuracy of the RST readings has been determined as +/-0.7°C - both for absolute and relative temperatures. This takes into account both instrument accuracy and possible variations in road emissivity of between 0.90 and 0.99 while using a value of 0.96 with the Compac 3. Differences in what should be identical fingerprints have been identified (see chapter 6) and these must be taken into account when establishing confidence limits for fingerprints. Differences of up to 1.5°C often occur between extreme fingerprints of route 1 (eg. figs. 5.1-5.3). Therefore, confidence limits for any individual extreme fingerprint are likely to be in the order of +/-2°C, ie. if an individual extreme fingerprint was used to forecast RSTs on an extreme night,possible errors, at any location, will be +/-2°C. With damped and intermediate fingerprints temperature variations are less and so likely (and observed) differences less. Confidence limits for damped/intermediate fingerprints are, therefore, likely to be in the order of +/-1 to 1.5°C.

Additional errors must be taken into account when assessing confidence limits for the thermal maps. Any errors due to averaging of fingerprints is taken into account in the paragraph above. However, because the thermal maps are plotted manually additional (estimated) errors of 0.5°C are possible (nb. thermal maps are plotted manually in commercial operations). Confidence limits for the extreme thermal map are, therefore, +/-2.5°C and for damped/intermediate +/-1.5 to 2.0°C. These confidence limits are larger than the magnitude of the difference between temperature zones on the thermal map.

Both the calculated errors in relative and absolute RST readings and confidence limits are based on the mapping method used during most of this project - using the temperature control box. Other mapping operations may, therefore, experience different and possibly larger errors due to warming/cooling of the IRT while mapping is being carried out. The implications of this and the confidence limits, for thermal mapping, are clearly important and are discussed in chapter 8.

CHAPTER 8

OVERALL CONCLUSIONS AND RECOMMENDATIONS

The concluding chapter of this thesis summarises the principal findings of the project 'Thermal Mapping for a Highway Gritting Network'. The implications of these findings for the process of thermal mapping and, in particular, the various uses that have been put forward for thermal mapping/thermal maps will then be discussed. Finally, recommendations concerning the process of carrying out thermal mapping and its future use will be discussed and possible areas of further research outlined.

8.1. PRINCIPAL FINDINGS OF THE PROJECT

8.1.1 Accuracy of the IRT

IRTs are sensitive instruments which need to be thermostatically insulated when operated in 'harsh' environments where temperatures fluctuate. Ideally IRTs should be operated in an environment at a constant temperature. Laboratory and road tests have shown that the Compac 3 IRT, used for thermal mapping during this project, will produce errors in IRT readings in the order of -3 to +2°C while carrying out thermal mapping in the 'normal' way - i.e without precautions/modifications. These errors are caused by warming/cooling of the IRT and are discussed in detail in chapter 4.

Operating the IRT in a temperature control box and maintaining temperature fluctuations to a minimum reduced errors while mapping to +/- 0.5°C. This is as good as the best performance of the IRT in a constant temperature room and is an acceptable level of accuracy which allowed intensive thermal mapping of Sheffield's road network.

8.1.2. Factors Affecting RSTs

With 242 mapping runs completed along seven routes in Sheffield and additional calibration runs, combined runs and runs in Derbyshire, this project represents the most comprehensive thermal mapping of an area and the most intensive research project ever undertaken into the process. This has provided, amongst other things, considerable information on the factors affecting RSTs.

Altitude and land-use (urban versus rural principally) are the two main factors affecting RSTs at the large scale (county/region at most) and hence the overall shape and amplitude of thermal fingerprints. The effect of these two factors on RSTs in the Sheffield area has generally been as expected, although interaction with other factors such as vegetation and relief have been shown to complicate the relationship, especially with altitude (see Chapter 5 and 6).

At a much smaller scale (less than 1km) the importance of bridges over roads, trees and buildings in producing localised peaks in RSTs, especially under extreme weather conditions, has been confirmed. However the project has not found any consistent relationship between 'cold' RSTs on bridges over roads/rail lines and 'warm' RSTs on bridges over water identified in other research (see Chapter 5).

The variation in RSTs is the result of many interacting factors including the constant or relatively constant altitude, land-use, vegetation, sky-view factor and road construction and those varying, namely traffic and weather conditions. The thermal fingerprint shows the combined effect of all these factors on RST with the individual effect difficult to quantify. This project has been able to determine the effect of altitude , land-use (urban verses rural), vegetation and sky-view factor in RSTs in the differing weather conditions of extreme and damped. However, the nature of the research project and practical difficulties have meant that the relationship between road construction and traffic conditions and RSTs could not be investigated further. Overall, the picture is very complex, particularly in urban areas where rapid fluctuations in sky-view factor, anthropogenic heat inputs and traffic conditions produce very rapid and often dramatic fluctuations in RSTs. Although for research purposes it would be desirable to be able to isolate and quantify the effect of each of these factors at all locations the highway engineer is only concerned with the actual resulting RSTs shown by thermal fingerprints and maps.

8.1.3 The Reliability and Repeatability of Thermal Mapping

Many of the uses suggested for thermal mapping rely on the principle that there is an identifiable and repeatable thermal fingerprint for any stretch of road under identical weather conditions. However, the results of this research project have called this into question.

Although extreme fingerprints do show similar trends in RSTs there are frequent differences at the more local scale. These differences are not insignificant (see Chapters 5 and 6) and have not been explained by mapping at different times of the night or year as previously suggested.

Differences in what should be identical extreme fingerprints have been related to the complex behaviour of cold air drainage and its likely variation from one night to the next and variations in wind speed and particularly wind direction and their interaction with local relief. Clearly this finding has important implications for the use of thermal mapping, although differences are likely to be less significant in areas where there is less variation in altitude and relief than Sheffield/Derbyshire.

8.1.4 Errors in Vehicle-Based Thermal Mapping and Confidence Limits

A number of possible sources of error in vehicle-based thermal mapping have been identified (Thornes, 1991) and they have been assessed and quantified in relation to this project in Chapter 7 of this thesis.

Errors in RST readings whilst mapping have been calculated as within +/-0.7^{o}C when using the temperature control box. These errors are due to instrument accuracy (+/-0.5^{o}C) and possible variations in road emissivity (+/-0.2^{o}C).

Confidence limits for thermal fingerprints, taking into account the errors outlined above (and in Chapter 7) and differences between fingerprints (8.1.3), have been estimated at +/-2^{o}C (extreme) and +/-1-1.5^{o}C (damped). Confidence limits for thermal maps are greater due to possible errors in the plotting of RST data on to road maps- +/-2.5^{o}C (extreme) and +/- 1.5-2.0^{o}C (damped). These confidence limits are large considering RSTs are in the range +/- 5^{o}C at most when important decisions regarding gritting are made. The implications for the process of thermal mapping are again important.

In areas with limited variations in relief these confidence limits are likely to be smaller due to the likelihood of less variation in thermal fingerprints.

8.2 THE IMPLICATIONS OF THE FINDINGS FOR THERMAL MAPPING

The implications of the findings for thermal mapping will be analysed by discussing each of the areas of thermal mapping that have been put forward (Chapter 1 section 1.4.)

8.2.1 Assisting the Design of Sensor Networks (location/number)

Thermal fingerprints and thermal maps can be used to assist the design of sensor networks. This use only requires information on cold, warm or marginal locations and an indication of the variability of RSTs across an area rather than actual RSTs to a high level of accuracy. This project has shown that thermal fingerprints and maps do indicate the general variability in RSTs across an area and so can be used to assist the location of sensors and provide an indication of the number required to give adequate coverage.

8.2.2 Assessing Current Gritting Practices with Prioritising of Routes and/or Re-design of Gritting Networks

Current gritting practices can be assessed using thermal fingerprints/maps as this only requires an indication of the variability in RSTs across an area. In areas such as Sheffield, where there is considerable variation in altitude, half-grits are often carried out on marginal nights with only high altitude routes gritted. The thermal map may be able to help to fine-tune the half-grit indicating how far it should extend (with allowances for the confidence limits).

8.2.3 Extrapolating RSTs from Sensors to the Rest of the Road Network Providing Real-Time Information for all Stretches of Road

Given the magnitude of the confidence limits for both thermal fingerprints and maps, forecasting RSTs by extrapolating from sensors will be of limited accuracy, hence basing any gritting decisions on the information is not advisable. The poor tie-up between Icelert sensors and the 1992 thermal mapping with the extreme thermal map reinforce this point.

8.2.4. Classification of Routes into Cold, Warm or Intermediate with Selective Gritting on Marginal Nights. Identification of Locations for Priority Gritting.

These uses are similar to 8.2.2 although taking the process one step further - in carrying out actual gritting on the basis of information provided by thermal mapping.

The magnitude of the confidence limits means that selective treatment would either be too risky or not selective - ie. to take into account the confidence limits most of the network would probably have to be gritted. If there are very large differences in RST across an area then it might be possible to exclude warm routes on marginal nights, say in city centres.

However, both these uses suffer from practical limitations - it is often not practical or cost effective to grit short stretches of roads or even different routes on different nights. Consider the scenario of a marginal night followed by a very cold night. The 'gaps' in the network, which were not treated on the marginal night, would have to be treated on the second, cold, night. If the whole network had been gritted on the first night there may have been enough residual salt left on the roads to preclude the need for salting on the second night. The costs of gritting include manpower and machinery and not just the cost of the salt.

8.2.5. Calibration of Existing Sensors

The calibration of permanent ice detection sensors using thermal mapping is not currently possible. Considering the possible errors in measuring absolute RSTs and the difficulty in pin-pointing the exact location of sensors on a thermal fingerprint calibrating sensors with thermal mapping data is a potentially dangerous practice. Furthermore, thermal mapping, as a form of remote sensing, should be calibrated using ground truth (sensor) data and not vice-versa.

8.2.6. Determining Temperature Differences Between Lanes on Dual Carriageways

Thermal mapping can provide information on RST differences between lanes although the confidence limits must be considered. The likelihood is that any measured difference would be of a similar magnitude to these confidence limits. In any case, practical benefits for this information would be limited as it is currently not possible to grit a single lane on a dual carriageway.

8.2.7. Controlling the Rate of Spread of De-Icing Chemical Using a Thermal Map Stored in an On-Board Computer

This has been suggested as a possible future use and clearly depends on the development of the process in the future. Currently with the large confidence limits involved this use could lead to untreated roads or, if the confidence limits are allowed for, little reduction in the amount of de-icing chemical used. In addition, attention must again be drawn to the practical difficulties of selective salting discussed in 8.2.4.

8.2.8. Controlling the Rate of Spread of De-Icing Chemical Using an IRT Mounted in Front of the Gritting Vehicle

This use was suggested to the author at a recent conference (20th PTRC Summer Annual Meeting, 13-18th September 1992, UMIST). Considerable work would be required, in terms of equipment design and elimination of errors in the use of IRTs, before any degree of confidence could be placed in the RSTs measured. Currently it is emphasised that thermal mapping is concerned with relative RSTs whereas this use requires accurate absolute temperatures. Attention is again drawn to the practical problems of selective salting.

8.3. RECOMMENDATIONS AND FURTHER WORK

8.3.1. The Use of Thermal Maps

Thermal maps should only be regarded as indicating the general variation in RSTs across an area. Accordingly they should be restricted in their usage to the assessment of both current gritting practices and sensor networks. Potential savings (both financial and environmental) could still be available with these uses.

It is interesting to note that after the initial enthusiasm regarding thermal mapping, with many potential uses put forward, the suggested uses are currently limited to identifying those parts of the road network that require treatment first and designing sensor networks with 'in an ideal world' treating only cold routes on marginal nights (Thornes, 1991).

During the course of this project the author has had frequent contact with the people who have to make the gritting decisions from many parts of the UK. There has been little confidence shown in thermal maps and the suggested uses for the maps. The author is not aware of any gritting decisions having been based on information provided by thermal maps.

8.3.2. Undertaking Thermal Mapping

Firstly, considerable care must be taken when using IRTs to measure RSTs. The IRT should be operated in an environment where temperatures, ideally, remain stable, or at least fluctuations are kept to a minimum. Frequent calibration checks should be made, ensuring these are conducted in a way similar to the actual mapping process. The simple method used in this project, of 'replacing' the road with a tray of melting ice to provide a constant target temperature of 0.0°C, could be used. However, variations in road emissivity and their effect on errors must also be considered.

The concern over the reliability and repeatability of thermal fingerprints, particularly in areas of variable relief, suggest that more thermal mapping runs should be made than is currently the case in most commercial operations. However, due to time and financial constraints, this is unlikely to be possible and so due consideration should be given, when analysing and presenting the results, to the possible variation in fingerprints under identical weather conditions.

8.3.3. Further Work

There are a number of areas of further research which would have been investigated if time and/or practical considerations had allowed.

EMISSIVITY

Although variations in the emissivity of road surfaces have been shown to have little effect on the accuracy of measured RSTs, further work in this area is desirable. There is little information available on the actual emissivity value of road surfaces and its variability. In addition, the effect of snow, water, rock salt, rubber and oil on the road surface is not completely understood.

FACTORS AFFECTING RSTS

Although this project has confirmed many of the relationships previously identified between factors such as altitude, sky-view factor and the urban heat island and RSTs there is still a need for further research in some areas. An investigation into the effect of road construction and traffic conditions was not within the scope of this project and would warrant further work. In addition, the effect, on RSTs, of crossing over water/other roads on bridges was found to be more complicated than suggested by previous research and confirmation of this project's findings would be desirable.

THERMAL FINGERPRINTS IN COASTAL AREAS

Maritime influences on thermal fingerprints are likely to be significant. In particular, wind direction, which was found to be important in producing differences in extreme fingerprints in the Sheffield area, could have an even greater effect in coastal areas. For example, consider two clear nights, one with the wind blowing off the sea and the other with the wind blowing from the land. This could produce significant differences in the thermal fingerprints recorded. An investigation into the effect of wind direction on the shape/amplitude of extreme fingerprints of a coastal road (eg. A171/A165 in North Yorkshire) is therefore desirable.

8.4. APPLICATIONS AND BENEFITS

The initial research proposal of this project (chapter 1 section 1.5.2) stated that:

> "The results of this research project were
> likely to have wider general applications
> and would probably benefit other highway authorities."

The results of this project do certainly have wider applications with most major roads in Britain now thermally mapped. However, with some doubts raised about the accuracy and reliability/repeatability of mapping any applications are generally restrictive. The potential uses have been narrowed down to the assessment/re-design of gritting and sensor networks and the need for care when undertaking thermal mapping and interpreting the results has been emphasised.

The reduction in salt usage with consequent savings in financial and environmental costs was, perhaps, the primary benefit hoped for from this project. Significant reductions in salt usage are unlikely, other than those which may be available by improved sensor/gritting network design. The principal benefits relate to the increase in knowledge about the process of thermal mapping, highlighting the need for further development work, and possibly preventing the misuse of thermal fingerprints/maps with the potential problems that may arise from this.