Applied Research and Innovation Branch

CDOT THERMAL MAPPING REPORT

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16. Abstract
Thermal Mapping surveys were carried out on approximately 1000 miles of the Colorado Department of Transportation's (CDOT's) roads. The purpose of these surveys was to identify road surface variations across the network to determine whether forecast Thermal Maps or the data from the surveys would be useful to decision-makers in the CDOT regions. The distribution of road surface temperatures across the network and identifying Climatic Domains for the regions enabled Vaisala to look at current weather station locations and whether there were any gaps in coverage.

Implementation
The use of forecast Thermal Maps is one that will be determined by the Boulder maintenance area in winter 2014/15. The Thermal Maps will be tested using Vaisala RoadsDSS and the final decision on whether the Thermal Mapping could be valuable to CDOT operations will be made in conjunction with the decision-makers prior to any statewide implementation plan. Vaisala has advised on potential weather station locations based on the Thermal Map findings which would complement the current setup.

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Table of Contents

CHAPTER 1

General Information

About Vaisala

Vaisala is the world's leading supplier of meteorological instruments and services to meteorological organizations, transport authorities, research institutes, defence forces and industry.

A truly international company, Vaisala serves customers in more than 100 countries. Vaisala's Traffic Safety service incorporates a range of products from simple weather detecting devices to complete weather prediction and management services. Thermal Mapping plays a central role in many of the products within this range.

The thermal characteristics of any section of road or runway across a network are unique and can differ widely across a given area. These differences can be surveyed, quantified and categorized. Thermal Mapping is the only technique generally accepted as being able to confirm that the distribution of warm and cold areas across a network is consistent on each winter night under uniform weather conditions.

Thermal Mapping highlights potentially hazardous sections across a road or runway therefore providing the winter maintenance engineer with an enhanced information base from which to make crucial decisions. Vaisala has remained at the forefront of Thermal Mapping for over 25 years through continual investment in Research and Development, regular statistical testing for accuracy and repeatability, and has seen subsequent endorsement in many Scientific Journals.

To date Vaisala has completed contracts amounting to over 500,000kms of Thermal Mapping across a worldwide customer network.

CHAPTER 2

Introduction

Thermal Mapping

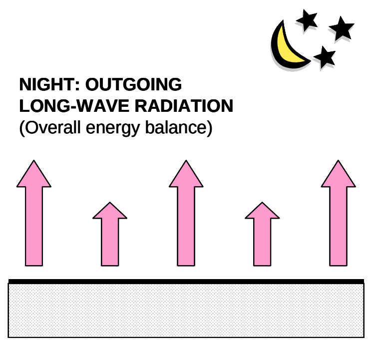
Thermal Mapping is a process by which the spatial variation of minimum night time road surface temperatures (RSTs) is measured using a high resolution infrared thermometer. The thermometer is mounted in a specially equipped vehicle and connected to an automatic data logger. Readings are taken along the road surface and recorded electronically at a rate of 10 readings per second. Thermal Maps are produced using collected data to provide a representation of the relative spatial variation of minimum RST under different weather conditions.

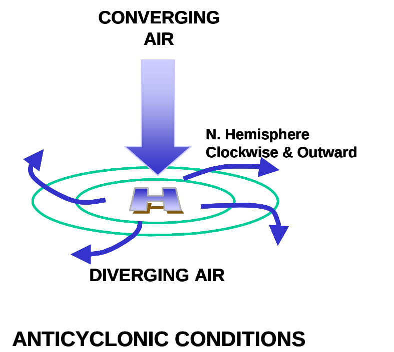
Meteorological Conditions

The prevailing weather conditions are the overriding large scale influence on RST. The scale of variation in RST is dependent on the weather. Cloud cover reflects, absorbs and emits heat in the form of radiation, and wind mixes air layers over the surface. Both these factors can effectively reduce variations in RST. Within Thermal Mapping, weather conditions are categorized into three scenarios: Extreme, Intermediate and Damped.

- Extreme

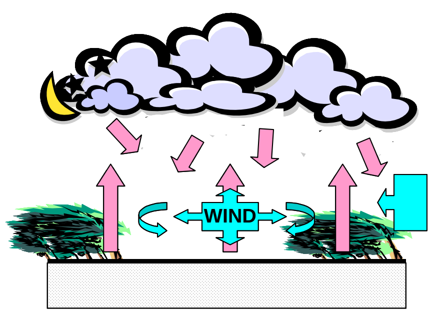
This scenario produces the greatest degree of variation in RSTs. It occurs when skies are clear and wind speeds are very low, or even calm. The absence of cloud and wind allow for maximum radiative cooling and thus heat loss from road surfaces. In addition, the lack of any significant mixing of air layers allows katabatic drainage (cold air pooling) to occur and the generation of temperature inversions as cooler ground surfaces chill the air immediately above them so that the usual decrease of temperature with height is reversed. This weather scenario is usually associated with anticyclonic (high pressure) systems, or high pressure ridges between cyclonic systems.

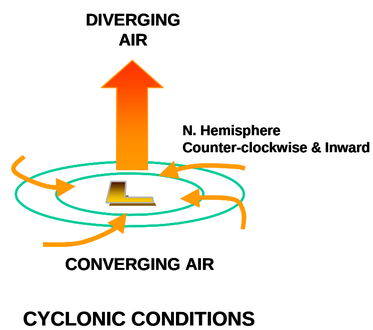




- Damped

This scenario represents the opposite end of the weather spectrum, consisting of total low level (below 13,000ft) cloud cover and moderate or stronger wind speeds. This produces a significantly reduced (or damped) variation in RST.





Similar results can also be obtained with lower wind speeds if conditions have remained cloudy throughout the preceding day. This kind of weather is commonly associated with cyclonic (low pressure) systems, which often bring associated bands of precipitation.

- Intermediate

Intermediate conditions are typically the result of either: a) medium to high level cloud cover with the absence of significant wind, or b) clearer skies with moderate wind speeds. These two situations produce similar results in that the degree of variation of RST is reduced from that found under Extreme conditions but is greater than that found under Damped conditions. This scenario can make up the bulk of winter weather and can be a result of various meteorological patterns, such as transient ridges and frontal approaches.

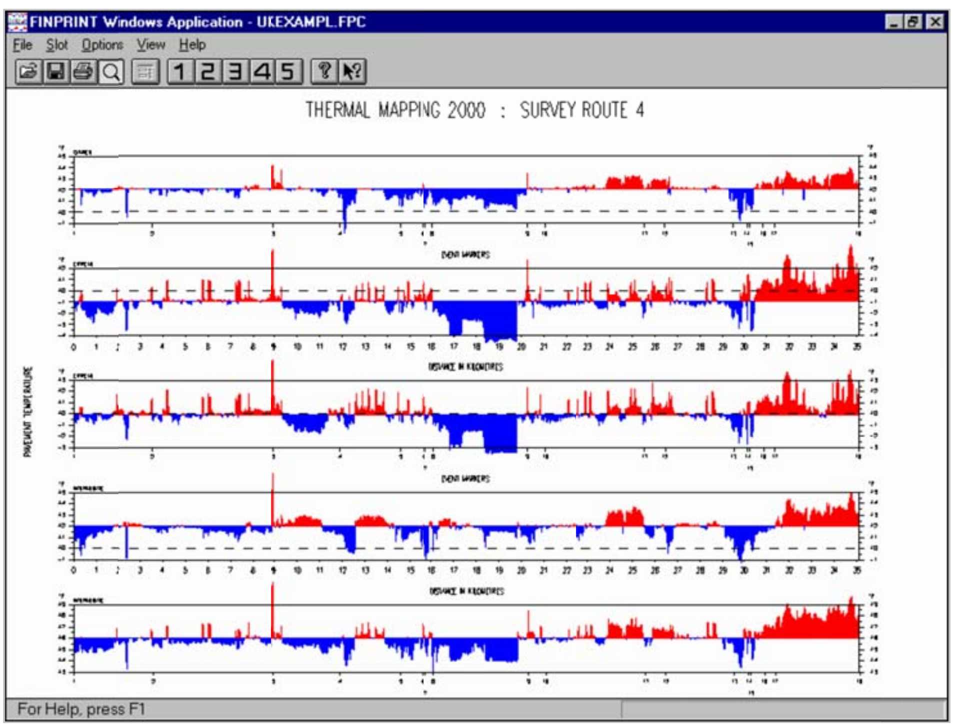
Thermal Mapping Results

The road/runway network is planned into Sectors, which are subdivisions of the overall network. Wherever possible Sectors are planned to operate within areas of climatic similarity and represent the network that can be surveyed by one vehicle on any one night.

Sectors are further split into a series of overlapping Routes, each being approximately 40 miles in length depending on the network. The purpose of splitting the Sectors into shorter routes is to reduce the chance of changes in weather conditions affecting the data.

The raw data collected during winter nights is downloaded and processed through computer software. A mathematical Gaussian Filter is applied to the survey data to eliminate any random noise and the data plotted as graphs known as Thermal Fingerprints. These Fingerprints are a graphical representation of the pattern of RST along the surveyed roads and illustrate the distribution of RST over the survey network.

Thermal Fingerprints are then combined to produce Thermal Maps. These maps represent the relative distribution of RST around the average for the road network surveyed in colour coded, 2.0ºF bands under each of the different survey conditions.



Thermal Mapping Applications

The Thermal Maps can then be used to locate the optimum position for the siting of RWIS stations (if not already in place), which use sensor technology to measure and monitor RSTs, surface conditions and a wide range of meteorological parameters. Combining the Thermal Maps, the road weather outstations and a meteorological forecast, a prediction of RST over the road network can also be produced for up to 24-hours ahead using a computer model and system. Finally, where anti-icing or deicing materials (usually salt) are used in winter maintenance practice, Thermal Maps can be used to optimize the winter maintenance routes. Route Optimization of this nature aims to maximize the efficiency of treatment routes to enhance safety for the road user by taking account of the Thermal characteristics of the road network under different meteorological conditions.

The Survey Network

Thermal Mapping was carried out along approximately 1000 miles of roads in Colorado. The survey network was divided into five Sectors of four Routes, making a total of 20 Routes. However, due to the recent floods to the west of the survey area, US 36 and US 34 were inaccessible for the Thermal Mapping surveys, leaving 4 Sectors. During the surveys checks were completed on the data by means of a series of overlaps between survey Routes to help in adjusting the data for ambient temperature change during the time of the surveys (known as *Drop-Off*). Data from existing CDOT RWIS stations was also used to cross-reference the rate of Drop-Off.

Figure 1 CDOT Thermal Mapping network

- The Surveys

Thermal Mapping surveys were conducted across the network between October 1013 and December 2013. The project specification was to collect data under Extreme conditions (calm and clear) and Damped conditions (cloudy and windy), to illustrate the degree of variation present across the region. As a result, Thermal Maps were produced displaying the variation of RST around the average for each of the three weather scenarios.

Meteorological conditions often vary across an area on the same night with associated effects on the distribution of RSTs. Therefore it is important to delineate relatively homogenous areas where conditions could be expected to be similar. This leads to the identification of *Climatic Domains*, which must also be considered when recommending or locating road weather stations.

Summary

Thermal Mapping is a technique that measures RST under key winter weather conditions, leading to the production of isothermally colour coded maps depicting the distribution of RST over a surveyed network.

The results provide invaluable information for highway engineers who deal with potentially dangerous winter driving conditions. The value of Thermal Mapping is then greatly enhanced when combined with road weather stations and meteorological forecasts under an ice prediction or Decision Support system.

Thermal Mapping was completed in Colorado along I-25, I-70, I-76, I-225, US 36, US 287, US 85, US 40 and US 6 between during the latter stages of 2013. This report discusses the results of those surveys, including the production of the Thermal Maps.

CHAPTER 3

Terminology

- Thermal Mapping

The measurement of the spatial variation of RST along a road using an infrared radiation pyrometer.

- Thermal Fingerprints

The graphical representation of RSTs plotted against distance, relative to the average RST for that particular survey Route on that particular night.

- Relative Average

Not an actual temperature but the relative average for the road network covered by Thermal Mapping surveys. All roads within the network are related to this average using different colour bands.

- Thermal Maps

Maps of the distribution of RST under different meteorological conditions by isothermally colour coded (2ºF) bands. These are related to the relative average RST for the region, which will change from one night to the next according to prevailing air mass and weather system.

- Climatic Domains

Regions within a survey area that may experience differing meteorological conditions on any one night.

- Marginal Night

Nights when the lowest RST for the region is forecast to be at or close to freezing.

- Extreme Conditions

Calm, clear nights typical of an anticyclone (high pressure system) producing the maximum RST development profile along a survey route.

- Intermediate Conditions

Clear and windy nights, or calm nights with total medium level cloud present. Such conditions will generally produce similar though less severe results than on an Extreme survey, with the exception of frost hollows which may be greatly reduced or even totally absent.

- Damped Conditions

Windy nights with total, low level cloud cover and possibly precipitation typical of cyclonic (low pressure) systems giving rise to a general flattening of the development of the RST profile.

- Frost Hollow

Under Extreme conditions cold air may descend under the effects of gravity (katabatic drainage) and gather in small valleys or dips in the road. This pooling of air may produce the coldest RSTs in the network.

- Katabatic Drainage

The "draining" of cold air down slopes under the force of gravity. Often causing Frost Hollows to occur as cold air gathers in dips or valleys.

- Mapping Sector

The highway network is divided into Sectors. These are smaller, sub-networks that can be surveyed by one vehicle within a typical operational window of between midnight and sunrise.

- Mapping Route

A Mapping Sector is divided into Mapping Routes that are approximately 20 miles in length (depending on the nature of the survey network) in order that the effects of changing weather conditions upon surveys are minimized.

- Road Surface Temperature (RST)

The actual temperature of the road surface of any given point of the network.

- Sky View Factor

"The ratio of the amount of the sky "seen" from a given point on a surface to that potentially available (i.e., the proportion of the sky hemisphere subtended by a horizontal surface)" OKE, Boundary Layer Climates (1987) Sky view thus describes and quantifies the amount of unobstructed sky/horizon that is visible at the surface.

- Thermal Memory

This is the term used to describe the length of time, which a highway structure, or any structure, retains the stored heat, which it gains due to day-time solar radiation. The Thermal Memory of a section of road depends on the depth of construction, the construction materials used and the amount of incident solar radiation received.

CHAPTER 4

The Spatial Variations of Road Surface Temperatures

RSTs vary in both space and time and this has to be taken into account when planning a Thermal Mapping project, as well as when interpreting the results. Thermal Mapping surveys are normally carried out when the average RST is within the range -4ºF to +50ºF.

Temporal Variations

Thermal Mapping must be conducted at night in order to capture the minimum RST distribution on any given night. The diurnal rhythm of RST is one in which the maximum temperature normally occurs in the early afternoon and the minimum temperature occurs around dawn. Immediately after sunset, RSTs fall very rapidly but this decline levels off so that during the latter part of the night RSTs change very little.

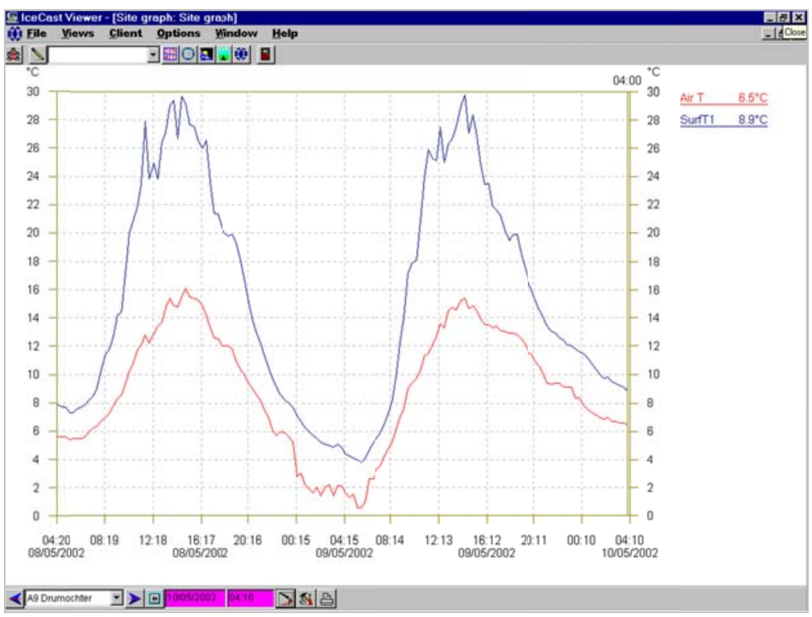


Figure 2 Diurnal variation at a weather station

It is therefore possible to directly compare temperatures measured on one section of road with those recorded on another. This comparison is facilitated by the use of short survey Routes (in both time and distance), which reduces the amount of surface temperature change between surveys.

- Solar Radiation

Incoming solar radiation varies throughout the winter in proportion with the total amount of daylight and the height of the sun in the sky. Minimum solar input occurs on the shortest day (December 21st) but the actual incident solar radiation at one place is also dependent on two variables: a) cloud cover and b) sky view factor.

- Cloud Cover

Clouds reflect and absorb solar radiation, thereby reducing the amount of direct solar radiation reaching the surface. They absorb heat not only from above but also from below due to re-radiation from the earth's surface. This absorbed heat is then re-radiated and at night this can significantly offset surface cooling.

Seasonal Variations

The variation of the height of the sun in the sky and the angle of incidence of incoming solar radiation means that the influence of sky view factor will change with the seasons. The sky view factor will also be influenced by the amount of foliage left on the trees in winter. The shedding of leaves by deciduous trees will allow more long wave radiation to escape at night, increasing the rate of cooling. For these reasons, the distribution of RST can show slight differences at the winter margins (e.g., April compared to December or January), when solar input is that much greater due to increasing hours of sunlight and the increased angle of the sun in the sky. This can cause some open road stretches with high sky view factors to absorb enough solar radiation during daylight hours to offset their normally rapid cooling regime after sunset.

- Latitude

Latitude affects the length of the days and the winter, as well as the height of sun in the sky. These are all important influences on the amount of solar radiation reaching the surface during daylight hours. For example, a stretch of road that has a high sky view factor will receive greater solar input. In higher latitudes, if all other factors are equal, such a stretch of road could be expected to display relatively low RSTs due to unrestricted cooling after dark. However, in lower latitudes where the angle of incidence of solar input is higher and days are longer, there may be sufficient heat absorbed during the day to offset the cooling after dark. This must be taken into account when examining the pattern and profile of RST distribution.

Systematic Spatial Variations

Although there are seasonal and diurnal variations to be considered, during the majority of the winter months, the combined effect of buildings, topography and tree cover is generally systematic at a single point. Each of these factors has a bearing on the distribution of RST but they rarely act in isolation and the RST at any given point is a complex interaction of a number of factors.

Sky View Factor

Sky view factor relates to the amount of "visible sky" and is used to determine the maximum incoming solar radiation that could theoretically occur, compared to that of the actual. It ranges from 0.0 when none of the sky is visible (e.g., inside a tunnel) to 1.0 when there are no obstructions visible (e.g., an open hilltop). Generally, the sky view factor depends upon tree and building cover, which reduce the incoming solar radiation to the surface via shading. Solar radiation input thus not only varies seasonally but also daily, depending on weather conditions, the amount of tree cover, topography and buildings.

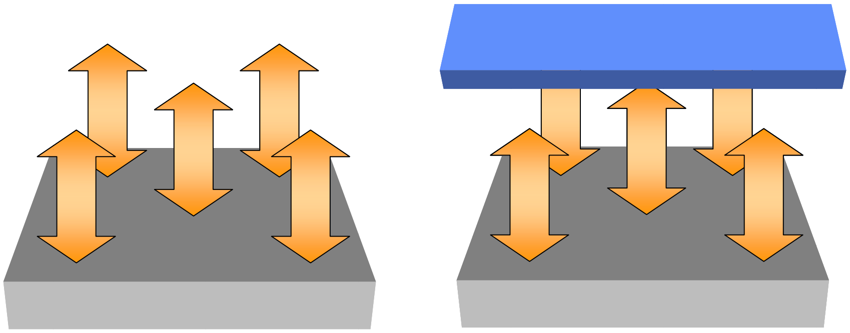


Figure 3 Effects of sky view factor

Altitude

Normally, the higher the altitude, the lower the road minimum temperature expected. This is the result of the decrease in air temperature with height that occurs in a normal, unstable atmosphere. The environmental lapse rate (the fall of air temperature with height above sea level) is usually about 10ºF per 1000m in altitude. RST could be expected to decline with altitude at a similar rate. However, *frost hollows* can cause the lowest temperatures to be recorded in valley bottoms, especially on clear and calm nights due to either the formation of inversions and/or the pooling of cold air. Cold air, being denser than warmer air, will tend to sink under the influence of gravity and this is called *katabatic drainage*. A frost hollow will occur where a slope is sufficiently steep for such drainage to take place, resulting in lower RSTs. The size of the cold air pool is related to the length and steepness of the slope. A cold

air pool at the bottom of a long, shallow slope will be greater in extent than one at the bottom of a short, steep slope as a result of the greater volume of cold air on the longer slope.

However, the air at the bottom of the short, steep slope may be colder due to the greater difference in height and therefore temperature between top and bottom of the slope. In some circumstances where there is sufficient relative relief, the normal environmental lapse rate will give cold temperatures at higher altitude and cold air drainage will also lead to low temperatures at lower altitudes. In these situations the warmest temperatures are obtained at middle altitudes, between the cold hilltops and the cold valley bottoms; this phenomenon is referred to as the *thermal belt.*

- ## Water Bodies

Water reacts more slowly than land surfaces to changes in solar input. While water bodies generally take longer to warm, their relatively poor thermal conductivity means that they retain heat for longer than road surfaces. As a consequence, during the winter months roads in close proximity to significant water bodies (e.g., coastal roads) can experience relatively warmer RSTs due to the ameliorating effect of warm air circulating off the water. This effect is usually most noticeable when wind speeds are greater than 4miles/h as air layers are more readily mixed. However, water bodies may freeze if ambient temperatures are sufficiently low to negate any warming effect.

- ## Topography

At night a road surface cools by radiation. Topography restricts radiative cooling from the surface by influencing the sky view factor and thus limiting the amount of long wave radiation that can escape. The effect of radiation loss to the environment is further reduced by buildings, trees, cloud cover, traffic and cuttings. Such features reflect, absorb and re-emit radiation from the road back to the surface, thereby offsetting radiation loss from the road surface and maintaining temperatures. As a result, at night roads lined by trees and/or buildings, roads running through cuttings, under bridges and in tunnels will tend to stay warmer than more exposed sections.

It must also be remembered that sheltered roads may warm more slowly than more exposed roads, since early morning solar radiation cannot reach the road surface. This can be an important factor if, for example overnight conditions lead to the formation of hoar frost on the road surface and surrounding fields. After sunrise, these hoar frost deposits are melted or sublimated by the incident solar radiation on exposed road sections. In shaded sections where solar radiation is unable to penetrate directly to the surface, RSTs may remain below freezing and early morning traffic can then compact the hoar frost into ice. Hence, areas with a low sky view factor can be more hazardous for a longer period of time than exposed sections if the RST falls below 32ºF.

Road Construction

Road construction is another important influence on RST patterns. Energy is absorbed / radiated from different construction materials at different rates according to their thermal properties. For example, concrete roads are generally warmer than blacktop roads.

The depth of construction is also important and typically the greater the depth of construction the warmer the road. As a result, main highways and arterial routes are normally warmer than other roads but this can also be additionally influenced by traffic flow volumes.

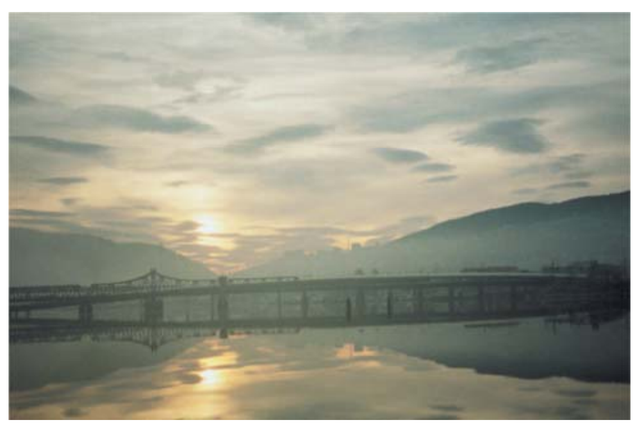
Finally, the seasonal variation in incident solar radiation must be considered. In late Autumn and Spring when frost formation is still a hazard, sufficient radiation may be stored in the road from the daytime input to offset the nighttime cooling.

Road construction, particularly that of highways and other major roads, tends to reduce the effects of minor topographical features. For example, embankments reduce the effects of cold air pooling by raising the road above the base of hollows and valleys. Cuttings reduce altitudinal variations and also restrict the sky view factor of the road.

Bridge Decks

Where a road crosses a bridge it is likely to be cooler due to its shallower construction and as a result it will possess a smaller thermal memory. This is the term used to describe the length of time that a road structure, or any structure, retains the stored heat that it gains due to daytime solar radiation.

The thermal memory depends on the depth of construction, the construction materials used and the amount of incident solar radiation received. Certain bridge decks, particularly those over water, may appear warmer as a result of re-radiation to the underside of the bridge from a relatively warmer water surface. In urban areas elevated viaduct sections can remain warm due to the effect of the urban heat island and traffic, despite their limited depth of construction.



Steel bridges normally cool much quicker than the road due to their high thermal conductivity and poor heat retention. This low thermal memory can create clear problems for winter maintenance as they can produce short icy sections on an otherwise safe road.

Urban Heat Island

The urban heat island effect is the name given to the phenomenon observed in towns and cities whereby the built-up area can be several ºF warmer than the suburbs or surrounding rural area. The actual magnitude of the heat island at any single location in the city will depend on the season and land use at that location.

The temperature difference between urban and rural areas is the result of industrial and domestic heat sources within the town or city, allied to the fact that the fabric of the urban environment, including roads, will retain heat to a greater degree than a rural area. This is the result not only of the construction materials but also the urban architecture and lower sky view factor.

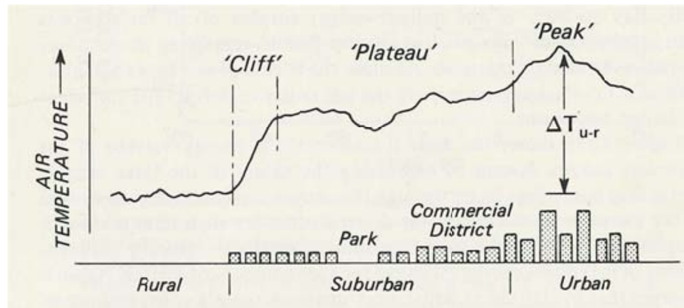
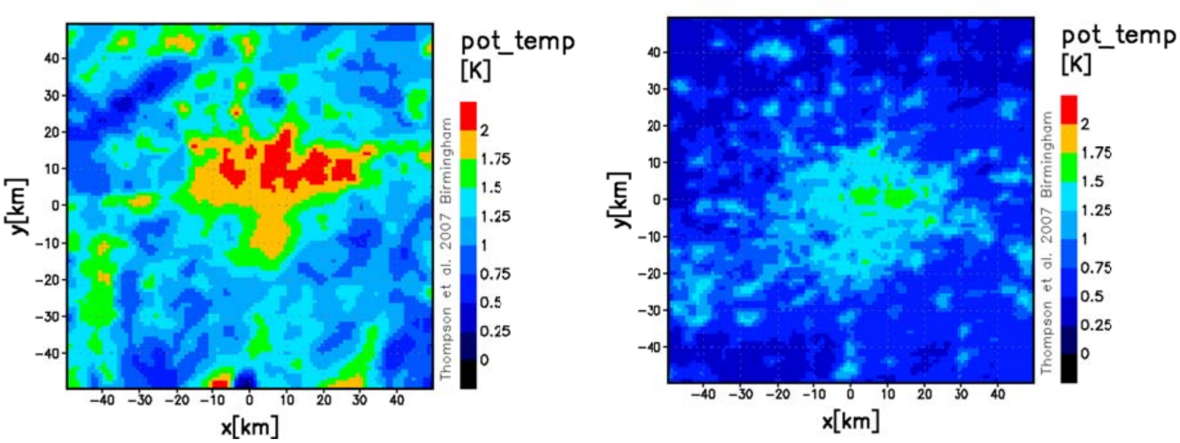


Figure 8.13 Generalized cross-section of a typical urban heat island (after Oke, 1976b).

The urban heat island effect is strongest in winter, at its weakest in summer and the effect is most noticeable when wind speeds are low. Higher wind speeds promote the mixing of colder, rural air with the warmer, urban air, thereby reducing the magnitude of the urban heat island. Within the city, the heat island effect means that topography, weather and traffic are usually less influential on RST than on other non-urban roads. The urban modification of the net radiation budget is strongly recognisable between the hours of 18:00 and 06:00, which is illustrated in the diagram below.



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- Traffic

Traffic tends to keep roads warm at night, acting like a shadow, offsetting the loss of heat by radiation. Traffic also stirs the air above the surface, promoting the mixing of warmer air with colder layers nearby and again can limit cooling on calmer nights. In addition, frictional heat generated by vehicle tyres and the gain of radiant energy by the road from engines and exhausts helps to keep roads with higher traffic flows warmer than less heavily trafficked roads.

Minimum RSTs can also vary across the lanes on Interstates and highway. Differences between lanes of up to 4ºF can occur due to the differences in the volume of traffic using each lane. Vehicles tend to concentrate in the nearside lane and as such at night these lanes are generally warmer than the outside lanes and slip roads. This phenomenon is most significant on roads with high traffic volumes at night.

Summary

RST is a function of a complex relationship between temporal variations (e.g., time of day) and systematic spatial variations (e.g., sky view factor and altitude). The amplitude of the variation will vary according to the prevailing weather conditions, with Extreme conditions leading to maximum variation and Damped conditions leading to minimum variation. The process of Thermal Mapping measures the spatial variation of RST and displays the results in map form for highway engineers to use as a tool to supplement local knowledge and experience for winter maintenance decision processes.

CHAPTER 5

Meteorological Conditions

Weather is a critical factor in deciding when to carry out a Thermal Mapping survey and knowledge of the actual conditions that prevailed during the survey period are also necessary when interpreting the results.

Thermal Mapping Surveys

The size and location of the Colorado network means that the surveys were carried out across a wide range of topography with diverse characteristics. The high altitude areas to the west coupled with the lower plain regions to the east frequently lead to varying meteorological conditions across the region.

This range of local geography gives the potential for varying weather conditions across the area, even on the same night. In order to ensure that the Thermal Maps are thus applicable it is necessary to divide the region into a number of climatically similar regions, known as Climatic Domains. As mentioned earlier in the report, surveys were carried out under Extreme and Damped weather conditions.

A summary of the readings taken for each night of the Thermal Mapping surveys can be found in the following table.

TABLE 1: Survey Meteorological Conditions

Date	Sector	Weather Scenario
10-15-2013	1	Extreme
10-16-2013	1,2 and 4	Damped
10-17-2013	3	Damped
10-18-2013	3	Extreme
10-21-2013	4	Extreme
10-22-2013	2,3	Damped
10-23-2013	2	Extreme

Summary

Weather conditions are critical when interpreting the results of Thermal Mapping data. Surveys were conducted under Extreme and Damped conditions to establish the different variations in RST for each meteorological scenario.

CHAPTER 6

The Thermal Maps

Introduction

Thermal Maps are a representation of the relative spatial variation of minimum RST of a surveyed highway network. Variations in RST from the overall survey average are denoted by differing colours for each 6.0°F variation:

The Extreme Thermal Map

The Extreme Thermal Map exhibits the maximum nighttime RST variation across the road network. This will occur under calm, clear conditions, typical of an anticyclonic (high pressure) system, allowing maximum radiative cooling of the road, cold air drainage and the likely development of a temperature inversion.

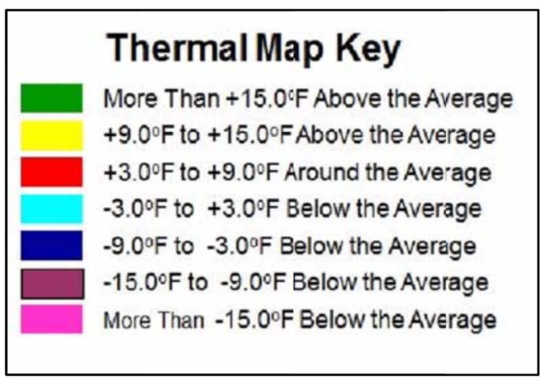

Figure 4 Thermal Mapping Key

- ### Temperature Range

Under Extreme conditions, the surveyed roads experience an approximate variation of 40ºF. However, this includes the particularly warm “spikes” of RST found where a bridge crosses over the road and RST cooling is offset by a low sky view factor. Without the influence of these “spikes”' the temperature range is approximately 25ºF. This is the range that can be expected on subsequent Extreme nights, providing the whole area surveyed experiences uniform Extreme conditions.

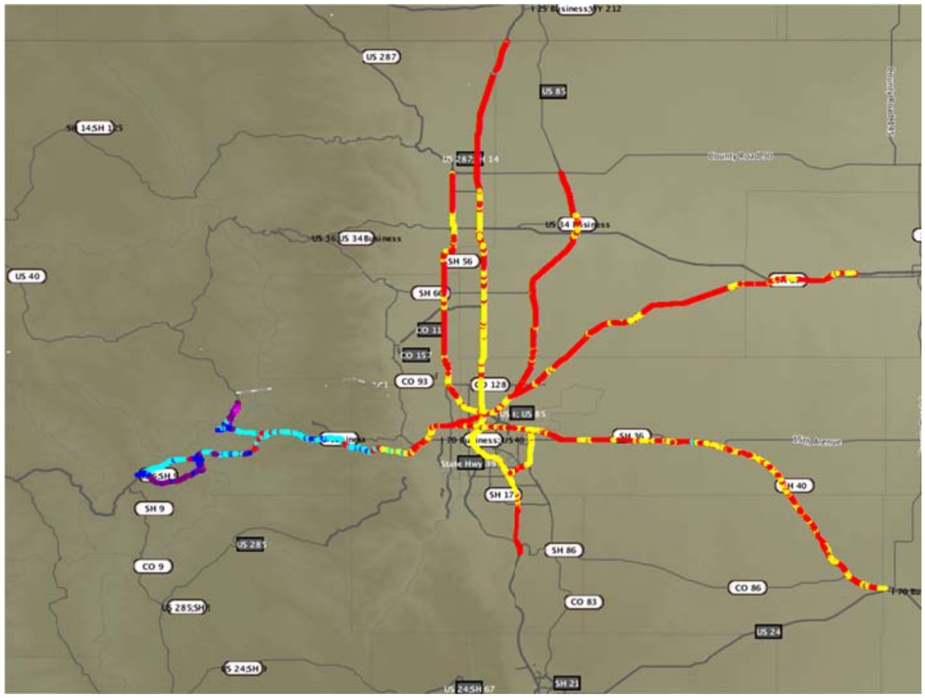

Figure 5 CDOT Extreme Thermal Map

General Patterns of RST Development

The wide range in altitude and topography across the survey region is reflected on the large variations of RSTs apparent in the Thermal Maps. It is possible to relate certain RSTs distributions to certain influencing factors. The coldest RSTs generally relate to the higher altitude areas to the west of the region. The distinction often associated between rural and urban areas is not as clear cut as may be expected but may be due to the nature of highways, which often bypass urban centers. This can be seen on I-25 as it passes through Denver. The RSTs in this area are amongst the highest on the network and can be directly attributed to volume of traffic and density of the surrounding street architecture.

Although the vast majority of the warmer RSTs are found within the densely populated areas, many of the more rural highways also display sections of above average RSTs. This is particularly true on I-70 in the south-east of the region, where localized changes in sky view factor and changes in road construction cause RSTs to remain warmer than average.

Influence of Altitude & Topography

The normal trend for RSTs is that the higher the altitude, the colder the road surface. This would appear true in the southwest of the Region, in particular along US 40 Berthoud Pass and US 6 Loveland Pass where temperatures along both these parts of the network are the lowest for the whole region.

Within this overall trend the distribution of RSTs at these higher altitudes can become more complicated by other factors such as slope aspect and cold air drainage. As a consequence, there is a wide range of RSTs even at these higher altitudes.

Figure 6 CDOT Extreme Thermal Map US 6

On the aforementioned roads the colder sections, more than 15.0ºF below the average, are not always found at the highest altitudes. The US6 as it passes the Loveland Ski Area displays some of the lowest RSTs of the network due to cold air drainage from adjacent high ground. Where the topography within these altitude areas also allows for cold air drainage this can result in some of the coldest sections of RSTs on the network.

Even away from the higher altitudes the topography of the landscape can create further areas of cold air drainage in the form of frost hollows. These are dips and depressions on the path of the road which allow cold air to pool, producing sections where RSTs appear over 6ºF colder than adjacent sections. There are various examples of this on I-70 between Denver and Idaho Springs where small pockets of cold air drainage lead to fluctuations in RSTs.

- ## Sky View Factor

Sky view factor is a crucial determinant in the development of RSTs, particularly under Extreme weather conditions. Roadside features, such as trees and buildings can significantly reduce the amount of sky visible at any one point.

The closer to the roadside and the taller the feature, the more radiation is reflected and re-emitted back to the road surface, thus offsetting cooling after dark. Where there are significant stands of trees along the roadside, RSTs are usually relatively warmer than those in the surrounding area.

Examples can be observed US287 S College Avenue to the south of Fort Collins. The high sky view factor along this stretch of the highway leads to RSTs being almost 6.0ºF colder than other roads in the vicinity.

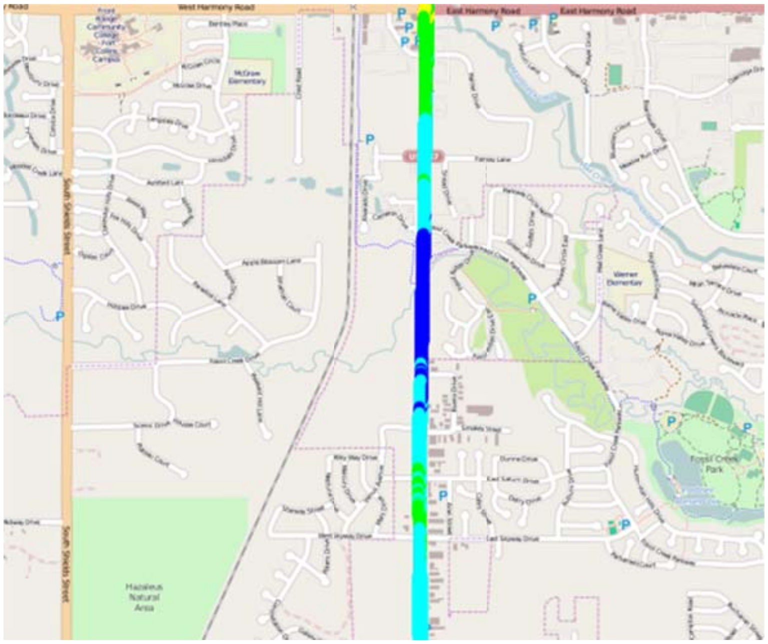

Figure 7 CDOT Extreme Thermal Map US 287

Buildings act in a similar but more exaggerated way to trees. As well as reducing the sky view factor, they can also act as heat sources, promoting RSTs in the immediate area. Examples of this effect are more common throughout the more urbanized parts of the survey network.

However, although trees and buildings reduce sky view factor and therefore offset cooling, when the sun rises these same areas may be the last to receive solar input. In a situation where the RSTs over the entire network fall below freezing, these areas may remain below freezing for longer, presenting potential problems for morning commuter traffic.

Influence of Urbanization

The main urban areas of Denver and Fort Collins both display a concentration of RSTs above average, particularly in the centers. Within the urban centers, buildings in close proximity to the road will offset heat loss from the road surface.

The general concentration of buildings will also emit radiation from industrial and domestic heat sources, and higher traffic volumes cause frictional heating from engines and exhausts and increases the shadowing effect to further offset radiative losses.

Within Denver in particular away from I-25 RSTs are closer to the average, often falling below. Away from the central areas the fall in RSTs generally corresponds with decreases in building densities and traffic volumes.

- Road Construction

Changes in road construction provide a significant contribution to the varying characteristics of RSTs. Different construction material, age and surface dressing type across lanes will result in differing relative RSTs, as is often the case where two roads of differing construction material and priority meet.

More localized influences of construction changes can be observed on bridge decks. Bridge decks and elevated sections of road are generally of a much shallower depth of construction than adjacent sections and accordingly have a reduced capacity to retain as much daytime solar radiation. This is supplemented by heat loss from both above and below the road surface.

Consequently, bridge decks and elevated sections usually exhibit relatively lower RSTs than surrounding roads and should be considered a potential ice hazard in adverse weather conditions.

Across the network there are many examples of bridge decks being colder than adjacent sections. Examples include I-25 as it traverses the South Platte River at Mile High.

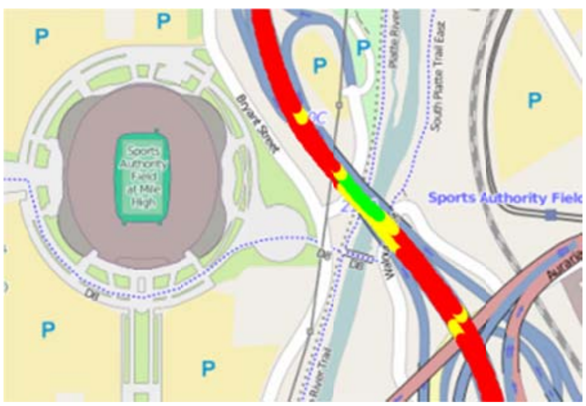

Figure 8 CDOT Extreme Thermal Map I-25

Extreme Map: Summary

Overall it may be seen that RSTs on the roads mapped within the region exhibit a wide range from well below to well above the relative survey average under Extreme conditions. Although the majority of the roads within the network possess a number of similar characteristics (such as construction depth and traffic flow), many localized factors combine to result in wide differences in RST. While there are some dominant influences on the RST distribution, most notably altitude, the relationship at any one point is very complex and involved, allowing RSTs to develop markedly away from the average, resulting in stretches of well above and well below average RST.

The Intermediate Thermal Map

The Intermediate Thermal Map depicts the relationship of RSTs that develop under clear, windy (>12km/h) or calmer, overcast conditions where cloud is medium to high level.

These result in a narrower temperature range due to increased mixing of air layers reducing cold air drainage and restricting frost hollow formation, or cloud cover reducing the effects of radiative cooling. The overall result of either of these scenarios is to reduce the amplitude of the Thermal Fingerprints and therefore the temperature range of the road surface.

Temperature Range

The Intermediate Map has an overall temperature range of approximately 15.0ºF, once any "spikes"' relating to features such as bridges are discounted. This reduction is a result of the change in weather conditions.

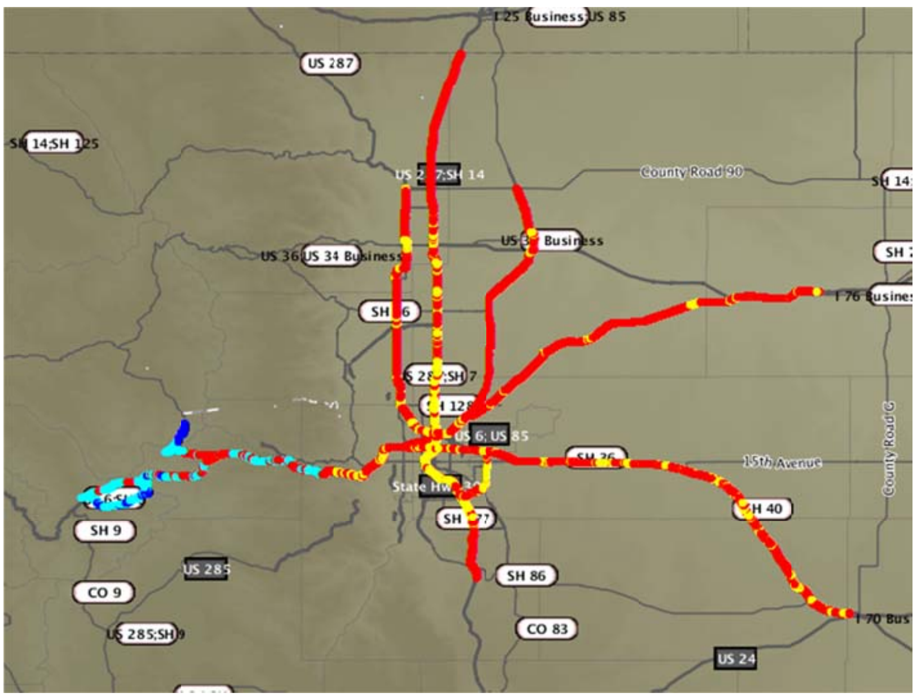

Figure 9 CDOT Intermediate Thermal Map

Patterns of RST Development

Although many of the general trends of the Extreme Map are borne out on the Intermediate Map, there is less overall development around the average RST. As a consequence a far greater distance of road falls into the Light Blue (below average) and Red (average) categories.

Under Intermediate conditions there is a greater mixing of air layers and as a result there is a reduction in the effects of cold air drainage. This is evident along I-70 between Denver and

Silverthorne. Under Extreme conditions these valley roads displayed RSTs well below the average. However, with the reduction in cold air drainage RSTs on these roads appear up to 6ºF closer to the average than they appear on the Extreme.

Other, smaller frost hollows often become less apparent or even non-existent under Intermediate conditions, depending on their particular location and exposure to the mixing of air layers.

The importance of some features show under both Extreme and Intermediate conditions. Bridge decks for example tend still to display lower RSTs than surrounding roads as can again be seen by on I-25 bridges particularly to the south of Denver.

Areas of concentrated low sky view factor also tend to retain their temperature profile and often remain above average and this is once again demonstrated in the central areas of Denver and Fort Collins.

Altitude also remains crucial and the coldest stretches of road on the survey network remain the higher relief areas. For example, Berthoud Pass and Loveland pass still display RSTs of over 9.0ºF below the average, reaching into 12.0ºF on some sections.

Intermediate Thermal Map: Summary

The distribution of colour bands on the Intermediate Thermal Map is generally consistent with those on the Extreme Map. However, the influence on RST development of many localized factors are not as marked as under Extreme conditions, with an apparent shift toward the relative average as a result. The prime factor in the relative reduction of RST development is the influence of wind, which mixes the air layers above the road surface and dampens out extremes of temperature.

The Damped Thermal Map

The Damped Thermal Map demonstrates the pattern of RSTs that develop with increased cloud cover (especially under 2000m) that offsets radiative cooling of the road surface, and higher wind speeds that mix the air layers and reduce temperature inversions.

Consequently the importance of localized features is reduced while larger effects such as proximity to the sea and changes in altitude are dominant. As a result, the Damped Thermal Map displays a greatly reduced variation in RST from the overall average. The majority of the road network falls within 4.0ºF either side of the network average.

- ## Temperature Range

Under Damped Mapping conditions very few spikes occur in the data where bridges pass over the road, or at any similar locations. Overall, the variation in RST is approximately 15ºF.

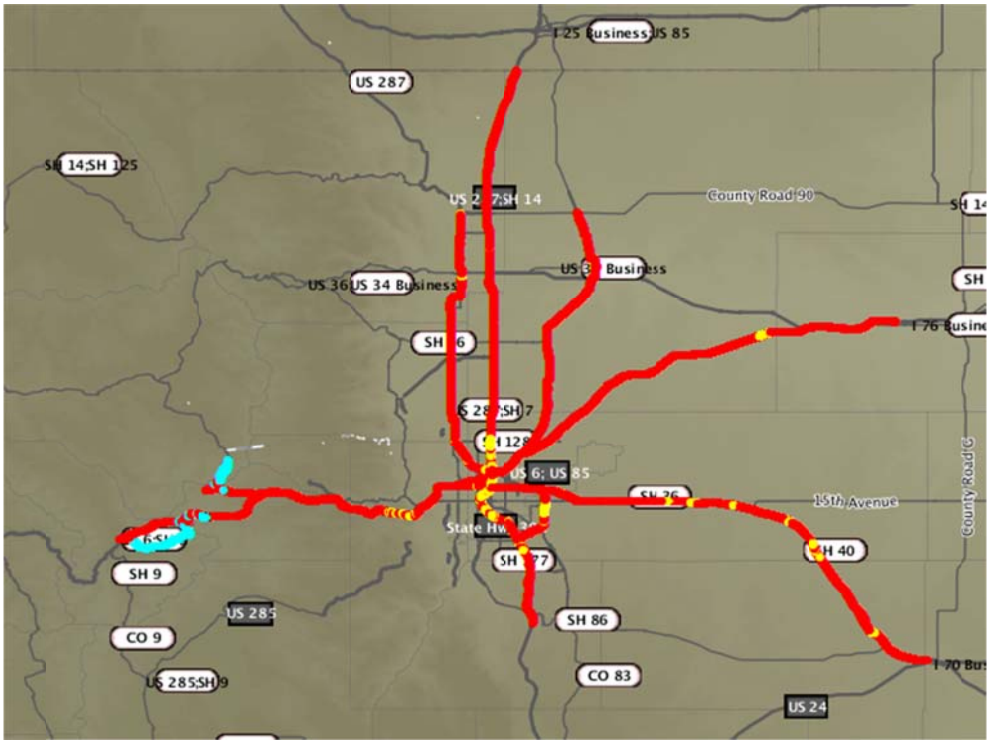

Figure 10 CDOT Damped Thermal Map

- Patterns of RST Development

The overall trend under Damped conditions is for RST to fall into the Red (average) category. In a few instances factors aside from the weather, will influence the development of above or below average RST. The most dominant of these is altitude, as there continues to be a fall of temperature with height.

As a result the colder areas of the region are once again found at the higher altitudes. This is again illustrated on the western sections of the network, in particular on the US 40 and US 6 which continue to display the coldest RSTs under Damped conditions. The main urban areas also continue to display the major concentrations of above average RSTs.

Damped Thermal Map: Summary

Under Damped conditions RSTs fall into either the Green (average) or Light Blue (just below average) range, with the majority of the road surveyed falls into the average category. This is a consequence of cloud cover affecting the radiative cooling of the road surface, combined with higher wind speeds mixing the air layers to inhibit temperature inversions. These meteorological factors reduce the importance of localized features and promote the significance of other affects such as changes in altitude.

The Thermal Maps: Summary

There is an extremely complex relationship between many factors that affect the distribution of RSTs. This relationship is at its most complex when there is no cloud to offset radiative cooling and no wind to mix air layers (i.e., under Extreme meteorological conditions).

However, the temperature relationship between sections of road under different constant weather scenarios is generally consistent, although the magnitude of variation in RST differs depending on the prevailing meteorological conditions.

Thermal Maps are representative of the relationship between RSTs, assuming constant meteorological conditions across the whole of the area surveyed. However, this is not always the case in practice so it is important to identify any required Climatic Domains prior to using the Thermal Maps operationally.

CHAPTER 7

Climatic Domains

Introduction

The Thermal Maps constructed from the data collected during the winter of 2013 relate to the various weather scenarios previously outlined. This assumes that the meteorological conditions are constant across the region. This is likely to be true of a number of winter nights, particularly when anticyclonic conditions prevail, but there are many nights on which the weather will vary from one part of the region to another, allowing some roads to cool more rapidly than others where skies are clear, and offset cooling where cloud persists.

It is therefore possible that while one part of the region may be experiencing Extreme conditions, another may be experiencing Intermediate, or even Damped conditions, due to a changing meteorological situation. This variability in weather depends on a number of factors, not least the size of the area in question and its position with regard to major upland areas and coastline.

Defining Climatic Domains

In order to represent this variation it is necessary to subdivide the road network into smaller, discrete areas referred to as Climatic Domains. The boundary of a Climatic Domain and the number of climatic areas covering a particular network is dependent upon the proximity of geographical features likely to influence the weather over the network. These influences are generally threefold:

1. Proximity to large water bodies such as oceans, large lakes and rivers, which provide a ready source of moisture and therefore have a tendency to produce cloud in the air mass passing over them.
2. Proximity of high ground, which forces air to rise over it making the air unstable and often producing cloud in the process.
3. Prevailing and dominant wind directions during the winter months - which dictate the extent of the influence of water bodies and high ground on any particular night.

Example Climatic Domains

Figure 11 illustrates a typical example of how changes in topography can lead to variations in localized weather conditions. Air that is forced to rise can become unstable and lead to cloud formation, particularly if it has passed over a water body and become moist.

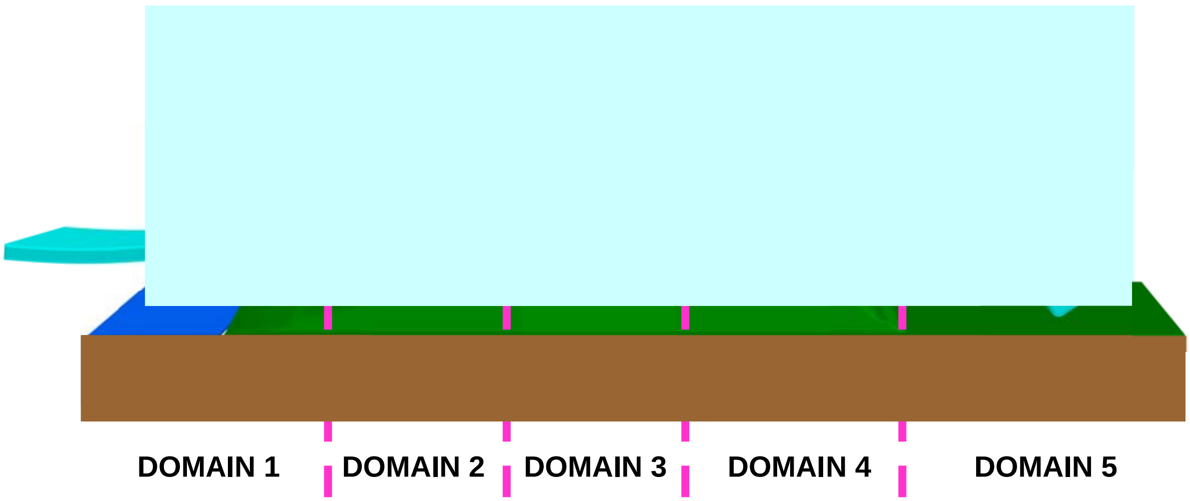

Figure 11 Example Climatic Domains

Domain 1 might typically experience warm, moist onshore winds during the day with offshore breezes at night. During the Winter months, there may be sufficient stored energy in the water body to provide an ameliorating effect to offset nighttime radiative cooling on the land.

Domains 1 and 2 have the potential for thick cloud and the possibility of precipitation as the moisture laden air is forced to rise over the land mass. Domain 3, if at sufficient altitude may experience precipitation in the form of snow and in extreme situations have perpetual snow or ice coverage.

In Domain 4, as the air descends from the high ground it becomes more stable and makes precipitation less likely. In addition, the moisture in the air may have been exhausted on the higher ground, leading to a rain shadow effect. Overall, this allows cloud cover to break, leading to less restricted radiative cooling of the road surface.

Finally, in Domain 5 the air has become considerably more stable and cloud cover may be non-existent. This allows unrestricted cooling of the road surface but may also leave this Domain susceptible to fog if there is localized sources of moisture.

From this, it can be seen how weather conditions can vary within the same region. As weather is a crucial determinant of minimum RSTs, it is clearly important for these variables to be taken into account.

- ### CDOT Climatic Domains

The CDOT network incorporates a wide range of altitude, topography and land use, all of which will have an important influence on the meteorological conditions.

The Domains have also been delineated with the current number and location of Forecast Stations already installed in Colorado in mind. Historical weather information has also been utilized to develop the Domain boundaries.

Climatic Domain I: Mountain
This Domain covers the division of the continental divide from the far west of the network to the east of Idaho Springs. Due to the high altitudes in this Domain, significant snowfall can be expected during the winter months.

Climatic Domain II: Foothills
This Domain stretches from the far south of the network to the state-line. It incorporates all the front-range roads which can be susceptible to snowfall because of the higher altitudes.

Climatic Domain III: West and South Metro
This Domain again stretches all the way from the north to the south of the network it extends eastwards from the Foothills to east of the I-25 corridor. From historical data, this Domain experiences snowfall and weather fronts which differs from the Foothills in intensity but is significantly more than further east of the I-25 corridor.

Climatic Domain IV: Eastern Plains
This is the largest Domain in the region and is defined by all roads to the east of the I-25 corridor and as far south as the higher altitudes of Palmer Ridge.

Climatic Domain V: Palmer Ridge
Located in the south of the region, the higher altitudes here warrant a separate Domain to both the Eastern Plains and Metro Domains. Dependent on the prevailing weather front, temperatures here could be much colder than surrounding Domains and it will not be affected as much from the mountainous relief to the west of the region

Summary

The survey network may experience differing weather conditions in different areas on the same night, but the Thermal Maps have been produced for constant meteorological conditions.

To account for the possibility of changing weather conditions, the current survey network has been divided into five regions, or *Climatic Domains*. While these Domains have been identified from experience during surveys and topographical maps, they may not encompass the full range of climatic areas in the region. They are intended for use as a general guide and are open to change with the benefit of the knowledge of local highway engineers or meteorologists.

It is possible that the boundaries of the Domains may migrate slightly from night to night, depending on local conditions (such as wind speed and direction) but their overall position is representative of the major climatological influences.

CHAPTER 8

Weather Station Recommendations

Sensors can provide information about RSTs at selected points within an area. Related to the Thermal Maps, this allows the maintenance engineer to know precisely what is happening at any location in the Thermally Mapped network.

Locating Sensors

To obtain maximum use by the maintenance engineer, sensors should be sited in order to represent a cross-section of temperature regimes and a good geographical spread across the area, highlighting some of the following:

1. Climatic differences across the road network
2. The range of temperature encountered from the Thermal Mapping
3. The geographical extent of the road network
4. Large temperature anomalies (e.g., large bridge decks or overhanging vegetation)
5. Areas of porous road surface

Depending on the focus of winter maintenance operations it is generally not advisable to locate all stations in the coldest spots since this can lead to over-treatment of those areas that remain above 0°C on marginal nights. Locating sensors in a variety of temperature regimes will provide a representative picture of the total temperature range over the road network on a particular night. The larger the geographical area covered by the road network, the greater the possibility for weather change on the same night and the greater the need to divide the region into smaller Climatic Domains.

Sensor Designation

If there is an ice prediction system planned or in use, there are two possible designations for weather stations: Forecast Stations, and Non-Forecast Stations. For an ice prediction system, there should be one Forecast Station per Climatic Domain and ideally one Non-Forecast Station to act as a back-up and to give supplementary information.

Forecast Stations are used to drive the forecast model with the ice prediction system. They should be sited on stretches of road that are representative of their Climatic Domain and also in areas that demonstrate stable RSTs across all the weather scenarios (Extreme, Intermediate & Damped).

Non-Forecast Stations can be sited in areas of potential variability, i.e., those areas which show significant shifts in relative RST between Thermal Map type (e.g., frost hollows) and/or in known problem areas or accident blackspots. Ideally, there should be two Non-Forecast Stations per Climatic Domain. Ideally, all weather stations should be located away from roadside obstructions such as trees or buildings. This will allow for an accurate forecast of RSTs to be produced for the complete road network on any particular night, including nights on which the weather will vary from one part of the network to another.

Ice Prediction / Ice Detection

The advantage of completing Thermal Mapping and installing an ice prediction system is that it will give the highway engineer a fuller picture of what is occurring over the highway network and allow him/her to take precautionary measures such as applying anti-icing materials.

The technique of Thermal Mapping means that fewer road sensors are required to give a picture of minimum RST distribution across the network, as the ice prediction model calculates the temperature for each section of highway using information gathered from weather stations and meteorological inputs. If stations are for detection/warning only, then different criteria may well apply to their location. For example, it may be that weather stations will be better placed in existing problem areas, where accidents due to ice formation have been a feature in the past. It may also be advisable to locate stations where the lowest RSTs are found and/or where there are moisture sources, to give warning of potential hazards.

In addition, there may be more human or subjective considerations related to issues such as traffic flows. Site specific Forecast Graphs show the forecast progress of RST at single points as distinct from Forecast Thermal Maps, which show the minimum RST across the Thermally Mapped highway network. There will be some sections of highway surface which cool more rapidly than others (such as bridge decks) and in some instances it can be helpful to monitor these sections in real time in order to contribute to the information used in deciding on the timing of treatment. Regardless of whether Stations will be used in a prediction or detection capacity, Thermal Mapping provides vital information on the specific thermal characteristics of a location on the network.

Stations can be sited used Thermal Mapping in order to provide both the optimum number of stations but also ensure that they are positioned in areas with stable Fingerprint profiles (e.g., avoiding “spiky” or noisy Fingerprint area that may skew sensor interpretation).

Weather stations combined with Thermal Mapping then give an overview of the entire network RSTs rather than just receiving site specific information from individual sensor locations.

TABLE 2: Existing CDOT Weather Stations on the Thermal Mapping Network

SITE NAME	HWY	DIRECTIO	MP	Latitude	Longitude	Altitude (r
025N190 SURREY RIDGE	025	N	189.45	39.486560	-104.871990	1946
025S185 FOUNDERS POINT	025	S	185.1	39.424830	-104.876720	1895
025S191 S. of Ridgegate	025	S	191	39.510482	-104.871270	1861
070E216.6 Loveland Pass Exit	070	E	216.7	39.687858	-105.882933	3238
070W205 Silverthorne	070	W	205.7	39.630650	-106.062820	2706
070W210 Lower Runaway Truck Ramp	070	W	209.79	39.656640	-105.996013	3038
070W213 EJT West Portal	070	W	213.3	39.676389	-105.943231	3380
070W218 Hermans Gulch Exit	070	W	218.1	39.701779	-105.861435	3157
070W221 Bakerville Exit	070	W	221.1	39.692206	-105.808015	2993
070W246 Floyd Hill	070	W	246.5	39.720928	-105.410115	2394
070W253 Genesse	070	W	253.60	39.710530	-105.294340	2370
070W304 BENNETT	070	W	304	39.738670	-104.433270	1689
070W348 CEDAR POINT	070	W	348.3	39.356990	-103.870130	1768
025N242 St Vrain	025	N	241.2	40.175571	-104.979362	1475
025N259 Crossroads Blvd	025	N	259.3	40.433370	-104.991810	1542
025N276 Wellington	025	N	276.4	40.682936	-105.000127	1573
025S251 Berthoud	025	S	251.1	40.321120	-104.980640	1514
025S298 Natural Fort	025	S	298.1	40.987810	-104.911760	1837
034W070 Cedar Mont	034	W	69.7	40.392191	-105.427581	2171
036W038 Baseline Road	036	W	38	40.001375	-105.259267	1637
076E037 Keenesburg	076	E	36.5	40.110230	-104.565763	1525
076W067 Wiggins/Bijou Creek	076	W	67.1	40.248500	-104.037560	1381
287 @ SE 19th St	287	N	331	40.369243	-105.072462	1543
025N194 C-470 EAST	025	N	194	39.556465	-104.870033	1798
025S194 C-470 WEST	025	S	194	39.556206	-104.871830	1810
025N213 I-70 EB/WB	025	N	213	39.779698	-104.988916	1560
025S213 I-70 West	025	S	213	39.779868	-104.990864	1580
025S229 SH-7	025	S	229	40.000169	-104.981524	1581
070W260 Rooney Rd	070	W	260	39.712470	-105.194760	1885
070W276 Colorado Blvd	070	W	276	39.780235	-104.943331	1603
070W283 Chambers	070	W	283	39.771518	-104.810140	1644
225N004 Parker Road	225	N	4	39.658749	-104.842258	1717
225N007 Mississippi Ave	225	N	7	39.697122	-104.828713	1702

Weather Station Recommendations

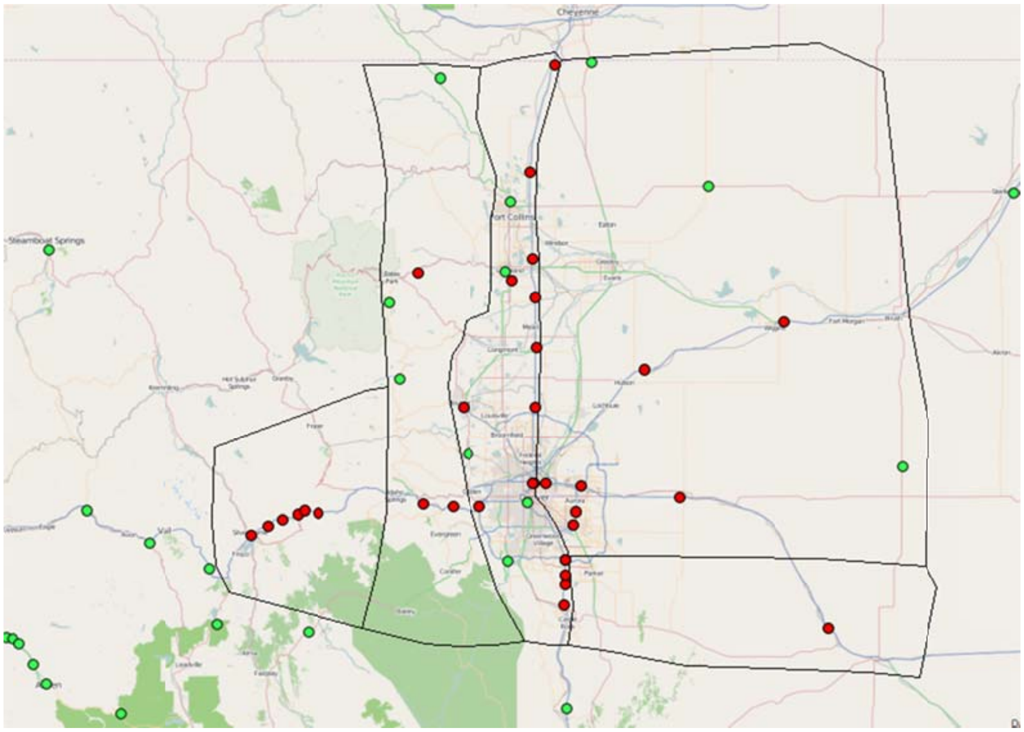

Figure 12 Current CDOT stations (stations actually on the Thermal Mapping network in red)

CDOT has comprehensive weather station coverage and this report will investigate any potential gaps in that coverage. Table 2 above lists the existing weather stations that are specific to the Thermal Mapping network. Due to the size of the Thermal Mapped region and the extent of the Thermal Mapping carried out across the region there may be scope for further stations to be installed. With regard to Forecast stations there is enough potential coverage in all Domains apart from Palmer Ridge Domain. Recommendations for station locations from Thermal Mapping surveys should be supplemented by closer site inspections to validate the availability of communications and power.

Climatic Domain I: Mountain

Figure 13 Recommended Non-Forecast Station 1

Located on US 40 in the area of milepost 236, this section is one of the coldest on the entire network and would benefit from a monitoring station.

Figure 14 Recommended Non-Forecast Station 2

Located on US 6 to the east of the Loveland Ski Area entrance, this section is again one of the coldest of the whole network

Climatic Domain II: Foothills

The only section currently on the Thermal Map for this Domain is the section of I-70. This section of road is adequately covered by stations at the moment but we may revisit this once we have completed the data collection on US 36 and US 34

Climatic Domain III: West and South Metro

Figure 15 Recommended Non-Forecast Station 1

Located on I-25 at Mile High as it traverses the South Platte River. This section is relatively colder than other sections in the vicinity and would benefit from a monitoring station due to the high level of traffic in this area.

Climatic Domain IV: Eastern Plains

Figure 16 Recommended Non-Forecast Station 1

Located on US 85 north of La Salle as it crosses the South Platte River. This section of road is up to 5°F colder than surrounding sections.

Figure 17 Recommended Non-Forecast Station 2

Located on US 85 to the east of Greeley as it crosses the Cache La Poudre river. Again this section of road is up to 5°F colder than surrounding sections.

Climatic Domain V: Palmer Ridge

The size of the current network that is part of this Domain does not warrant another station. However, it may be beneficial to have another forecast station in place in case there are any issues with the current station at Cedar Point.

Figure 18 Recommended Forecast Station 1

Located on the eastbound highway approx. 2.3 miles east the Limon off ramp, this location displays stable RSTs about 300 yards either side of the exact location. The RSTs here are also representative of the Domain.

Summary

The Thermally Mapped network has been split into five Climatic Domains to take account of any variation in weather conditions on winter nights that could affect the temperature profiles and any forecasts within an ice prediction system.   Six weather stations have subsequently been recommended (one Forecast sites within each Climatic Domain, along with a back up Non-Forecast weather station) to provide a comprehensive coverage and full picture of RSTs across the Thermally Mapped network during the winter months.

CHAPTER 9

Next Steps

- Obtain forecasts for each CDOT Domain
- Identify maintenance area to trial Forecast Thermal maps and report back - this will involve support and training from Vaisala
- Identifying potential improvements to aid with winter treatment decisions
- Following trial period, assessing the benefits of Thermal Mapping and how it can be implemented statewide
- Utilizing the Thermal map data in the forthcoming route optimization research project.
- Utilizing the Thermal Map data in the upcoming performance measurement research project.

One of the major benefits of Thermal Mapping is that it can be used in a Road Forecasting system to extrapolate site specific information to the entire network. For that reason, CDOT will have access to the Thermal Maps in Vaisala's Navigator system to assess the benefits for winter treatment operations.