Urban design and city analysis due to transportation network: The role of green and grey infrastructure on thermal properties of roadways in the city of Sheffield, UK

By:

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Declaration

I confirm that this s my own work and the use of all materials from other source has been properly and fully acknowledged.

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Abstract

Climate change driven by anthropogenic activities is leading to atmospheric warming. In tandem rapid urbanization and densification of cities is exacerbating the urban heat island effect. A phenomenon where surface and air temperatures in urban areas is higher than that of adjacent rural areas, despite these locations experienced the same weather conditions. Urban heat islands are driven by 1. an inability to dissipate solar energy through the absorbance of incoming radiation, and the slow re-radiation of infra-red energy from hard surfaces (brick, concrete, tarmac etc.) and 2. the release of heat energy from anthropogenic activities (machinery, building heating or cooling systems, computers, vehicle engines and emissions). Although urban heat islands are understood at a city and neighbourhood level, information is still limited at a more local scale. This research aimed to partially address this by providing a better understanding of thermal behaviour around roadways, in a northern temperate-climate city, i.e. Sheffield. Specifically, the research aimed to understand how roadside structure and features influenced the local thermal properties of the roadways. Empirical experiments using high replication rates were employed to determine the influence of road location, the presence of infrastructure (buildings, trees etc.), sunlight angle and vehicle flow on local microclimates. The data confirmed previous findings that green infrastructure especially trees, but also hedges and grass provided a significant local surface cooling effect (up to 4-5^{o}C). In contrast, hard surfaces such as offices and houses promoted higher temperatures. Temperature gradients between green and grey infrastructure were noted at an intimate scale (e.g. across roadways), but also across neighbourhoods (e.g. moving from a park towards highly dense build housing). The local cooling effect of trees on pavements and roadways was clearly demonstrated using the transactional road profile methodology.

Trees at either side of the road providing a more uniform cooling affect across a roadway, than trees just at one side or the other. Higher numbers of vehicles significantly enhanced road surface temperatures (roads were warmer at rush hour, compared to equivalent quieter periods). Road temperatures were influenced strongly by the amount of incoming solar radiation and sunlight angle (time of day), but in general, the middle of the road was often warmer than other parts of the road transactional profile. This may be due to it experiencing more sunlight for longer during the day, but may also be influenced by colour of material (black tarmac) and indeed, vehicle movements. Other key factors influencing road temperatures could include the 'openness' of the site and degree of shading from adjacent objects (as measured by the 'sky view factor'). These results are discussed within the context of roadway design within a changing climate.

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Last but not least, dedicated to the memory of my grandmother, ''Fadelah'', and my grandfathers, '' Salih and Mohammed'' my uncles '' HamdAllah'' who always believed in my ability to be successful in the academic arena. You are gone but your belief in me has made this journey possible.

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List of abbreviation

IPCC	Intergovernmental Panel on Climate Change.
RST	Road Surface Temperature.
AR	Aspect Ratio.
COP	Coefficient of Performance.
LCA	Life-cycle assessment.
UHI	Urban Heat Island.
USHI	Urban Surface Heat Island.
AUHI	Atmospheric Urban Heat Island.
UCL	Urban Canopy Layer.
UBL	Urban Boundary Layer.
SVF	Sky View Factor.
(H/W)	Height / Width Ratio.
Fig	Figure.
ANOVA	Analysis of variance.
ST	Surface Temperature.
AT	Air Temperature.
AV	Air Velocity.
RH	Humidity.
RF	Reference point.
NW_SE	North West-South East

Chapter 1 Objective, Introduction and Literature review

1.1. Objective of the Dissertation

Climate change and urbanization are making our cities warmer places. This research aims to understand better the morphology and activity of streetscapes and how that influences thermal aspects at a local scale. In summary the research investigates the impact of roadside morphology (Green v Grey such as buildings trees, hedges etc.), the orientation of roads and roadside features and traffic movement through roads on the local micro-climatic conditions. It aims to identify ways to mitigate the effects high temperatures associated with urban road ways, through more effective urban design.

The specific objectives of the research project are described below:

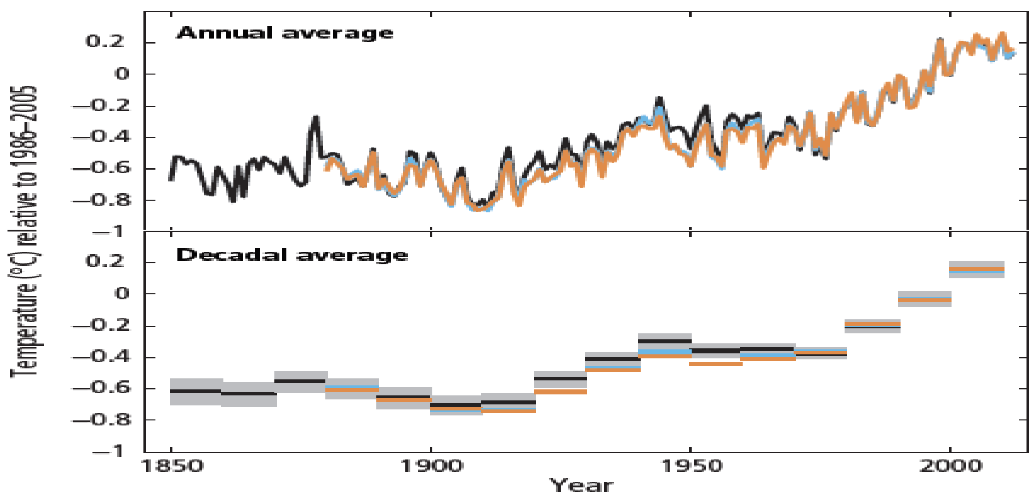
- To determine how Grey vs green structures influences the micro-climatic effects around roads.
- To identify how orientation of roads, the relationships between roadside features and traffic movements contribute to urban heat island effects.
- To provide information on thermal gradients generated from roadways, and how different forms of green infrastructures may influence these.
- To determine how morphology, scale, form and structure of grey v green/ landscape influences these thermal gradients.
- To review with wider potential eco-system services/dis-services that roadside characteristics provides (thereby helping policy makers understand the benefits and drawbacks of road-scape (Roadside typology).
- To examine the impact of environmental variables, landscape features (landscape form) and their geometry on the micro-climatic/thermal properties of urban roads

Context research and global research

1.2 Climate Change and Urban Heat Island (UH)

During the last two decades, a consensus has built up within the scientific community that the world is experiencing a climatic change, and that this is being driven by anthropogenic activities, leading to the release of 'greenhouse' gases that are causing atmospheric warming. The Intergovernmental Panel on Climate Change (IPCC), the UN body that leads scientific research on climate change, in its First Assessment Report (1990) concludes that global mean temperatures have risen by (0.3-0.6) ^{o}C over the last century. Although it is acknowledged that there can be considerable year by year and even decade by decade variation in climatic trends, scientists are concerned that the most notable temperature rises have occurred over the last few years (Fig 1.1; IPCC,2013).

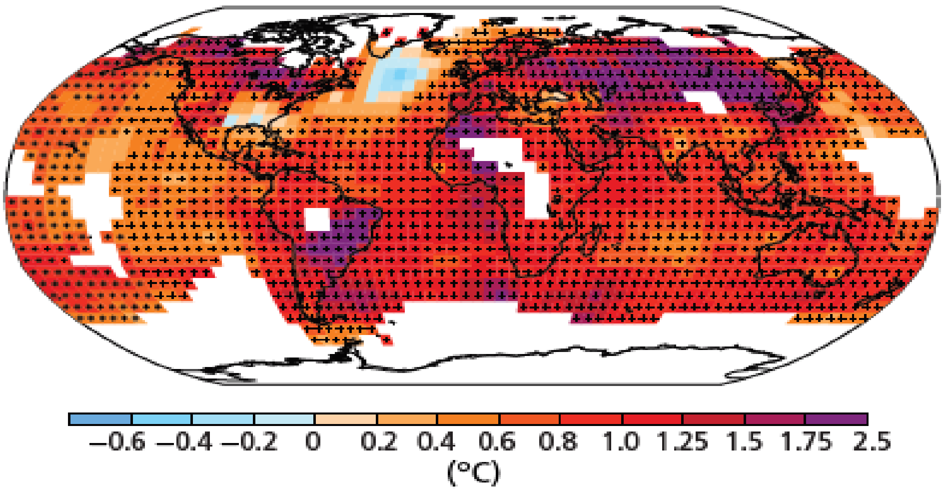
Figure 1-1 exhibited the observed globally averaged combined land and ocean surface temperature anomaly 1850-2012. The upper panel showed an upward trend annual average in temperature relative to 1986-2005 while the lower panel displayed a decadal average which has also almost upward.



Source: IPCC Fifth Assessment Report, 2013

While considering the spatial distribution of temperature increase, IPCC (2013) found a positive increase in temperature in almost all the parts of the world (Fig 1.2) with some regions experiencing a mean of a 2.5 °C increase since 1901.

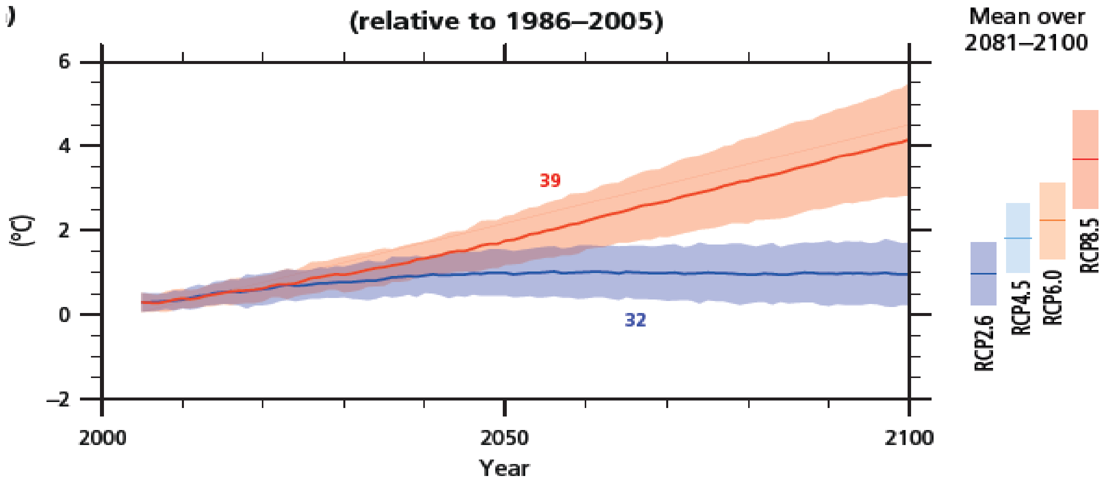
Figure 1-2 displayed observed changes in surface temperature during the period of 1901-2012 across the globe. During this period, almost all regions of the world experienced a positive increase in temperature.



Source: IPCC Fifth Assessment Report, 2013

The IPCC have used models to project what future temperatures the planet may experience based on scenarios relating to global concentrations of CO_2 as determined by current and future human activities (Representative Concentration Pathways). These indicate further mean temperature increases from between 1 °C and 4 °C (relative to the 1986-2005 mean) depending on the extent to which carbon dioxide (and other greenhouse gases) emissions are curtailed or not by 2100 (Fig 1.3).

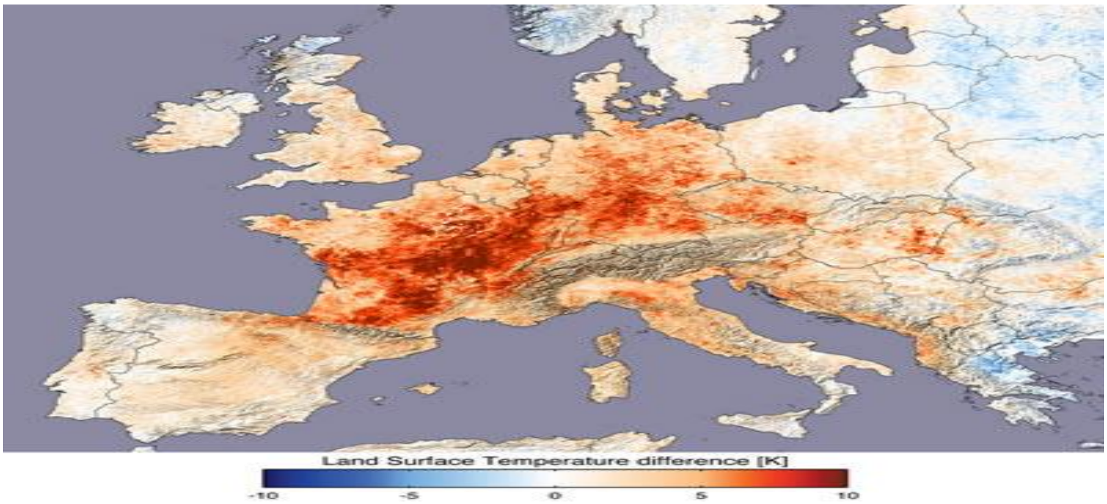
Figure 1-3 showed the global average surface temperature change scenario during the period of 2000-2100. Relative to the 1986-2005, RCP6.0 and RCP8.5 exhibited an increasing trend while the scenario for RCP2.6 and RCP4.5 showed a slight increase in temperature.



Source: IPCC Fifth Assessment Report, 2013

Although mean global temperatures are predicted to increase, this does not indicate that all regions will experience the same degree of warming uniformly (as highlighted by Fig 1.2), and this is true for Europe and even the UK. Indeed, data suggests that there is spatial variation within Europe and central Europe may experience the greatest land surface warming, by as much as 10 ºC (Fig 1.4.). In addition, there is an evidence of extreme temperature event already occurring within Europe, for example the heatwave that occurred in central Europe on 2003, is thought to be responsible for thousands of premature deaths (García-Herrera et al., 2010).

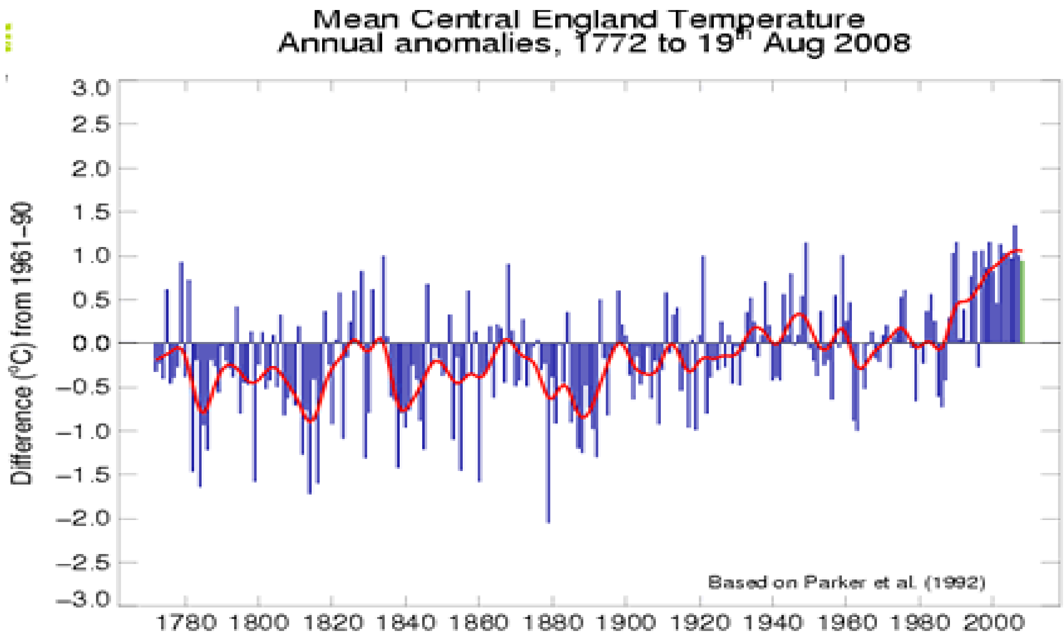
Figure 1-4 showed temperature profile of different countries in Europe. It displayed the land surface temperature difference among different countries and regions of Europe. Central and East Europe countries have higher land surface temperature difference than other countries of Europe.



Source: Metlink, Royal Metrological Society's Website, 2018

Within the UK, annual temperatures have shown increments of up to 1°C over the long-term mean values e.g. Central England (Fig 1.5).

Figure 1-5 portrays the annual anomalies in mean temperature in Central England during the period of 1772-2000 in the form of the difference in temperature from 1961-90. Till 1960, there is no pattern in this difference while since then there is an increasing trend.



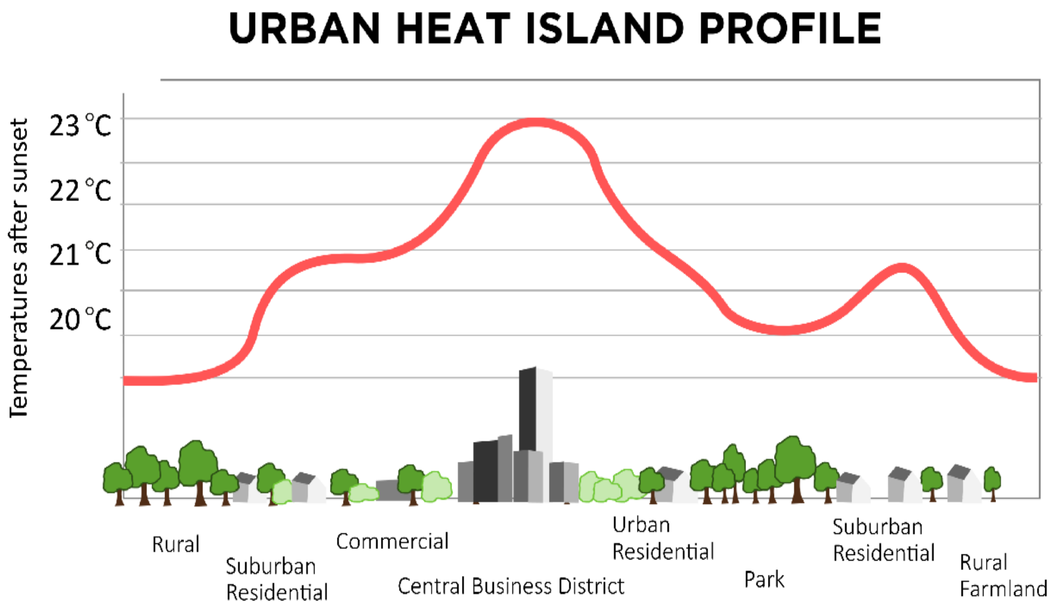
Source: Metlink, Royal Metrological Society's Website, 2018
http://www.metlink.org/other-weather/urban-heat-islands/urban-heat-island-background/

The world is experiencing rapid urbanization with approximately 54% of the global population now residing in cities (United Nations, 2014). Studies show that urban areas are particularly vulnerable to climate changes exposing huge population to the threat of climate change extreme events. For instance, the 2003 heat wave that claimed 14,802 and 2,045 excess deaths in France and England & Wales respectively, was felt particularly acutely in many urban areas. Many of these premature deaths were prevalent in urban areas because

of the joint impact effect of the heat wave with the urban micro-climate (García-Herrera et al., 2010). It is expected that the heat waves like this will become more common in the future. For instance, the conditions of summer of 2003 may turn out to be quite common by the 2050s. Much research is currently being conducted to investigate urban micro-climates, and to determine mechanisms to improve urban design and building architecture to moderate the effects of climate change and reduce the potential for temperature extremes for example both by reducing the urban heat island effect, and by finding ways to cool the interior of buildings, ideally without excess use of fossil fuels (Lynn et al., 2009; Rosenzweig et al., 2009; Zhou and Shepherd, 2010).

The urban heat island effect tends to produce a distinct temperature profile across the urban matrix, depending on the location of built and green/blue infrastructure (Fig 1.6.). For example, the central business districts that comprises of commercial units and densely built residential areas tend to have higher aerial temperatures compared to suburban residential zones with less dense residential development and more gardens. Lowest temperatures tend to be associated with parks and rural farmland (Shahmohamadi et al., 2011).

Figure 1-6 Displays a model of urban heat island profile. It shows that urban areas are occupied by commercial and urban residential structures while rural areas have rural farmland and green infrastructure (Top). Heat island's profile over urban, sub-urban and outskirt areas (A), schematic profile of UHI intensities over urban and rural areas (B), (Bottom).



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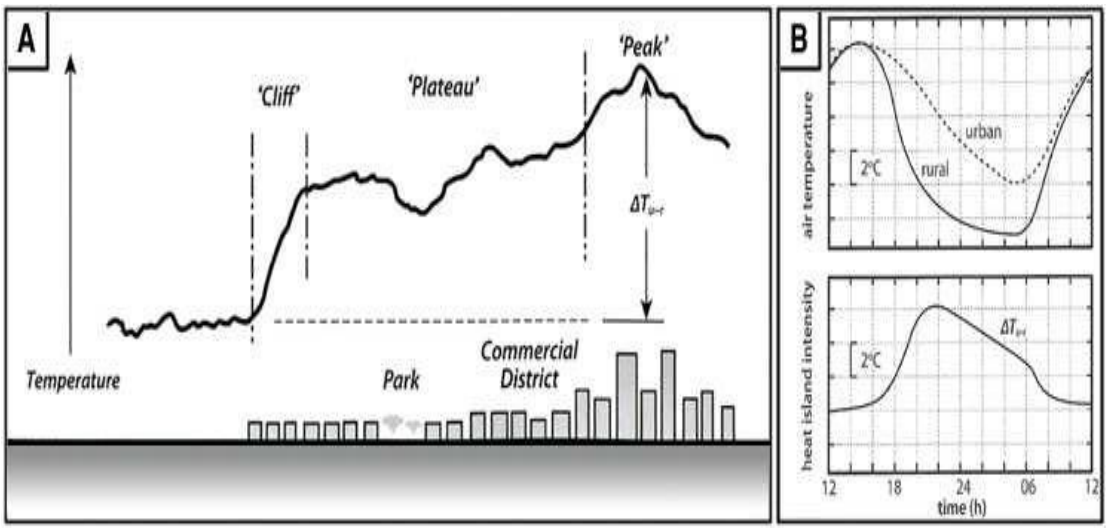
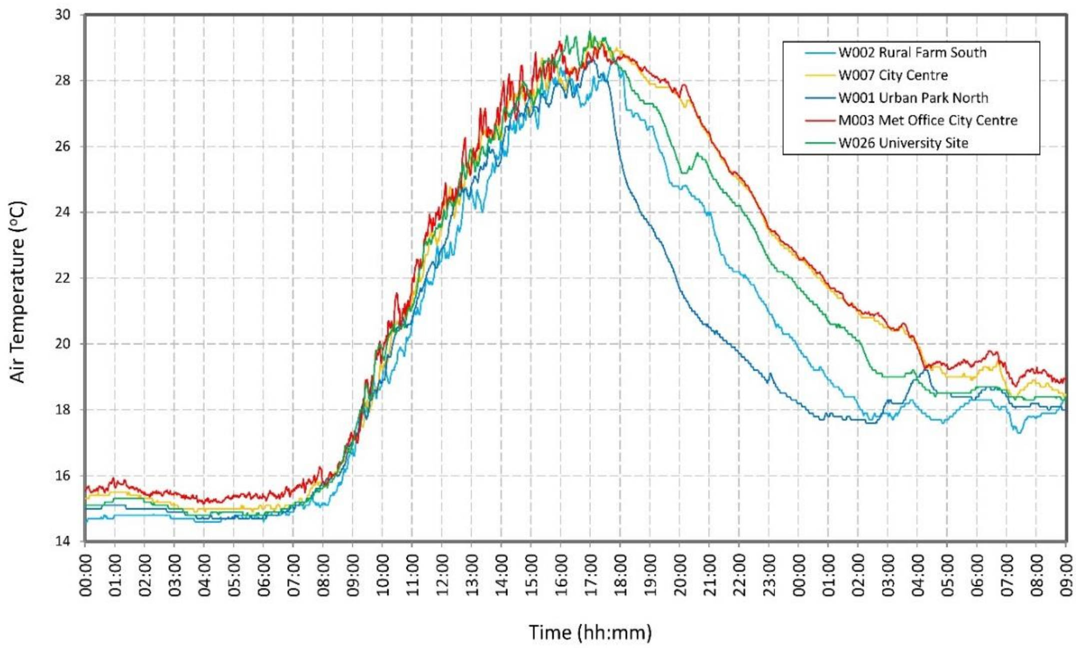


Source: Erell et al. (2011) and Oke (2002).

The development of an UHI effect in Birmingham, UK on 22 July 2013 has been depicted in the (Fig 1.7). It shows that air temperature in the midday is the highest while air temperature from the midnight to early morning (7.00 AM) is the lowest among all the time slots. Another important feature of the development of the UHI in Birmingham is that air temperatures after midday varies significantly compared to the first half of the day (midnight to midday). This indicates that nature of the coverage of the urban landscape affects the thermal profile in the urban areas. For instance, city centre has higher temperature compared to park areas of Birmingham (Metlink, Royal Metrological Society's website, 2018).

Figure 1-7 shows the development of urban heat island in Birmingham on a day, 22 July 2013. It shows that rural areas of Birmingham have lower temperature compared to the city areas and the difference is more distinct in the afternoon compared to the morning time period of a day.



Source: Metlink, Royal Metrological Society's Website, 2018
http://www.metlink.org/other-weather/urban-heat-islands/urban-heat-island-background/

1.2.1 Urban heat island: Definition, Causes and Impacts

Urban heat island (UHI) is a climatic phenomenon that was first investigated by Luke Howard in the 1810s although he didn't actual name the phenomenon. At the end of the 20th century, UHI became a widely explored phenomenon as urbanization took place rapidly and extensively across many parts of the world. Many large mega cities have evolved over the last 2-3 decades with

significant thermal changes being noted as many rural landscapes have been urbanized. Although cities occupy approximately 2% of the earth's surface, urban populations are rapidly increasing as more people leave rural areas and migrate to cities for employment and 'quality of life' opportunities (Madlener and Sunak, 2011). In this subsection, three aspects of UHI are presented- i.e. definition, causes and impact of UHI.

An 'urban heat island' is the name given to the phenomena, whereby the air temperature within / above an urban area is higher than that of adjacent rural areas, despite these locations experienced the same weather conditions (Kolokotroni, 2007; Park, 2007; Shahmohamadi et. al. 2011). Park (2007) further describes it as 'a dome of raised air temperatures that lies over an urban area and is caused by the heat absorbed by buildings and structures'.

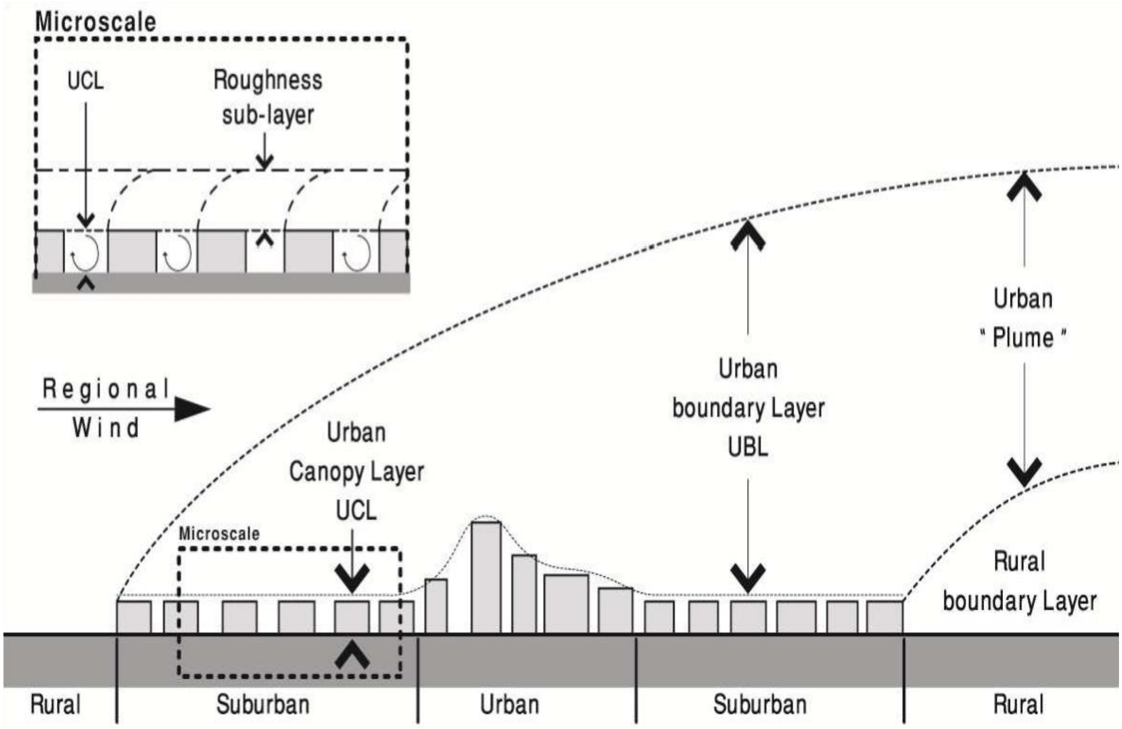
1.2.2 Types of Urban Heat Island

There are two types of UHI - (a) Urban Surface Heat Islands (USHI), and (b) Atmospheric Heat Islands. The temperature variation on the horizontal surfaces, such as buildings' roofs, streets, pavements and vegetation can be described as the urban *surface* heat island (USHI) (Weng et al. 2004). The atmospheric urban heat islands generally refer to the increased *air* temperature within and above an urban area in comparison with the non-urbanized rural areas.

- A. Urban Surface Heat Islands (USHI) is the daytime phenomenon which, thermally, influences urban areas and pronounced immediately after sunset. There are several factors that influence the intensification and spatial distribution of Surface Heat Island, those factors basically are: land cover and urban surfaces (Dousset and Gourmelon 2003) i.e. pavements, green structures, street/road surfaces and building roofs (Weng et. al., 2004); Urban structures (buildings / trees etc.)(Voogt and Oke, 2003); population density (anthropogonic heat) (Xiao et al. 2008, Fan and Sailor 2005; Elvidge et. al.,1997); urban density and canyon geometry (Bottyan and Unger 2003).

- B. Atmospheric Urban Heat Island (AUHI) can be defined as the increase in air temperature in the boundary layer above the urban matrix. The intensification of (AUHI) becomes more salient and reaches a peak in the night time as a result of the thermal exchanges between the upper layer of the surface and its air ambient. Oke, (1976) stated the division of (AUHI) into: 1- Canopy Layer Heat Island and; 2- Boundary Layer Heat Island. Canopy Layer Heat Island indicates increase in the air temperature that lies within the Urban canopy layer (UCL), the range of this UCL is between the urban ground surface and the roofs of buildings and height of the tallest trees. These urban features could extensively determine the intensity of canopy layer heat island. Boundary Layer Heat Island refers to the warm air that settled in the layer above the roof-tops (which is named urban boundary layer (UBL), essentially from roof level to approximately 100 m up at night time, but extending to around 1 km up at midday (Fig 1.8).

Figure 1-8 Shows the sub-layers of atmospheric UHI (adapted from Erell et al. (2011) and Oke (2002)), those layers are urban canopy layer (UCL) and urban boundary layer (UBL) over an urban area, sub-urban and rural area.



1.2.3 Causes and Impact of Urban Heat Island (UHI)

Causes of UHI are interconnected with the different characteristics of the urbanization process. As urbanization is a multidimensional process developed by human beings, causes of UHI are termed broadly as anthropogenic. Gartland (2008) mentioned different contributing factors to heat island formation (Table 1.1).

Table 1-1 Urban and suburban characteristics important to heat island formation and their effect on the energy balance of the Earth's surface.

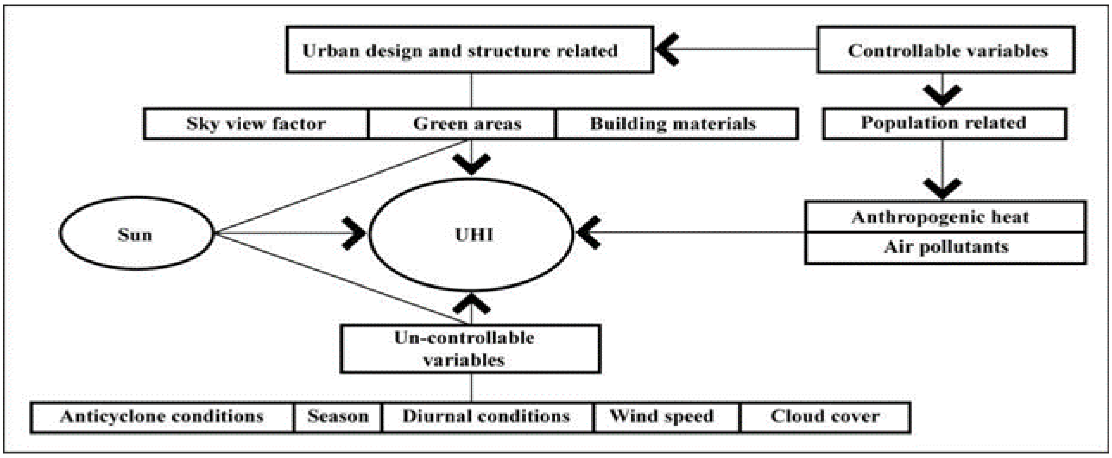
Characteristics contributing to heat island formation	Effect on the energy balance
Lack of vegetation	Reduces evapo-transpiration
Widespread use of impermeable surfaces	Reduces evaporation from soil
Increased thermal diffusivity of urban materials	Increases heat storage
Low solar reflectance of urban materials	Increases net radiation
Urban geometries that trap heat	Increases net radiation
Urban geometries that slow wind speeds	Reduces convection
Increased levels of air pollution	Increases net radiation
Increased energy use	Increases anthropogenic heat

Source: Gartland, 2008.

Along with the above stated factors, there are other manmade factors that contribute to urban heat island formation. Those are computers, cars, central heating systems, air conditioning units, power stations and other electrical goods (Oke et. al. 1991; Madlener and Sunak 2011; Santamouris et al. 2001). Near-surface air temperature changes due to increased runoff due to creation of impervious urban surfaces, further release of anthropogenic heat, reduced evapotranspiration, augmented solar radiation absorption, and changes in surface friction (Oke and Cleugh 1987; Bornstein and Lin 2000; Arnfield 2003). Different studies find that urban heat islands usually form due to increase in city size and building density (Oke 1973; Landsberg 1981; Atkinson 2003; Imhoff et al. 2010).

Rizwan et. al (2008) mention that there are two types of factors that cause UHI- controllable and uncontrollable. Natural factors like sun, wind and cloud cover are uncontrollable while buildings, air pollution and other manmade structures can be considered as controllable. Basically, controllable factors are anthropogenic (Fig 1.9).

Figure 1-9 shows a generation process of urban heat island. It indicates that there are multiple factors that contribute to the generation process of UHI. Some are controllable, such as- urban design and anthropogenic while some are uncontrollable, such as- cloud, wind speed, season and others.



Source: Adopted from Rizwan et. al (2008)

The intensification of urbanization leads to the construction of tall buildings for residential purposes for both the rising population and for commercial activities. Moreover, because of rapid urbanization, soil cover is replaced by impermeable materials such as asphalt. These impermeable materials obstruct rainfall infiltration in to the soil. The soil infiltration rate in cities is only 15% and the quantity of rainwater runoff is 55%, whereas in the natural environment, approximately 50% of rainwater infiltrates the soil and 10% runs off toward watercourses (USEPA, 2007).

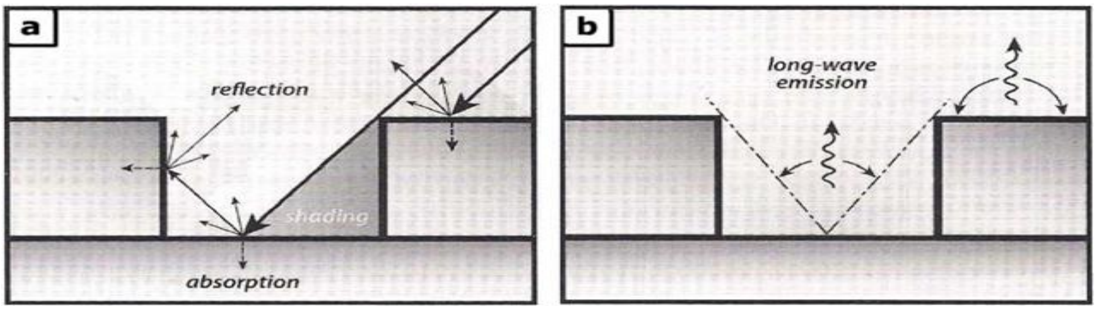
Oke (1987) and Santamouris (2001) mention the following reasons for buildings and other hard surfaces to affect temperature dynamics and increase heat build-up in city areas.

- Absorption of short-wave radiation from the sun in low albedo (reflection) materials and trapping by multiple reflections between buildings and street surface (Fig.1.10. A).
- Canyon geometry can play a key role in controlling the intensity the emitted long-wave radiation from the street facets. In other words, Obstruction of the sky by buildings results in a decreased long-wave radiative heat loss from street canyons. The heat is intercepted by the obstructing surfaces, and absorbed or radiated back to the urban tissue (Fig. 1.10. B).
- Building materials perform heat storage with large thermal admittance. As cities have a larger total surface area of hard materials due to buildings, roadways etc. compared to rural areas more heat is stored in urban areas.
- The evaporation from urban areas is decreased because of 'water-proofed surfaces' – less permeable materials. As a consequence, more energy is put into sensible heat and less into latent heat[1].

[1] Please note that more details on latent heat have been given in section 1.4 of the current chapter.

Figure 1-10 Display the influence of urban geometry to portion the solar radiation penetrated to be absorbed and reflected (a). The emission of long-wave radiation (b), (adapted from Erell et al. (2011).

Display the influence of urban geometry to portion the solar radiation penetrated to be absorbed and reflected (a). The emission of long-wave radiation (b), *(adapted from Erell et al. (2011))*.

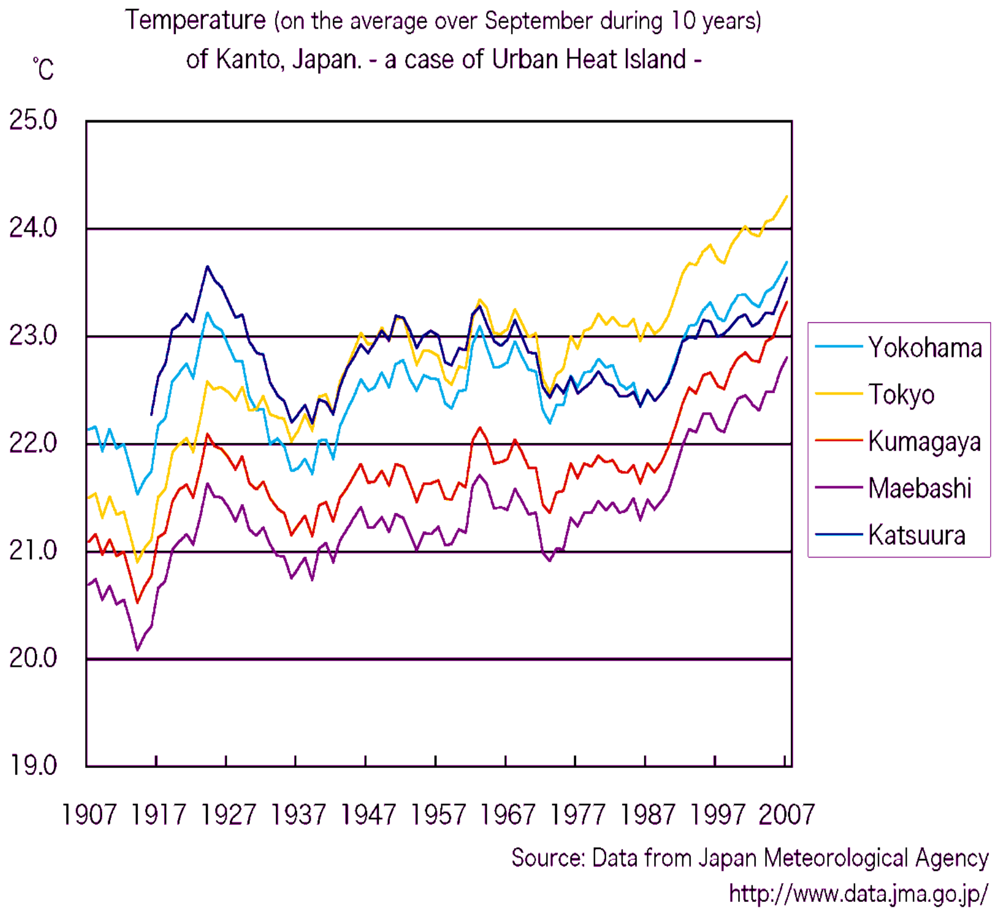


It is found in different studies that the UHI worsens air pollution. Models on air quality conducted in different studies show that air pollution aggravates with the increase in temperature (Weaver et al. 2009; Banta et al. 1998; Cheng and Byun 2008; Jacob and Winner 2009). Other studies found a correlation between temperature and air pollution (Tai et al. 2010; Bloomer et al. 2009, 2010).

Cities require high amounts of energy supply, due to the activities of their populations. Madlener and Sunak (2011) reported that city dwellers consume over 75 percent of the total energy resources. Part of this energy is dissipated in the form of heat, which is intensified by solar radiation. Under certain conditions, this heat accumulates in cities entrapped by urban structures, and at night, slowly dissipates. Therefore, cities need widespread use of air conditioning systems and consume a larger quantity of energy. Kolokotroni (2007) by analyzing the heat island in London found that the cooling load in the city was 25% higher than in rural areas, whereas the heating load diminished by 22%. Santamouris et al. (2001) analyzed the energy consumption in the urban areas of Athens. This study found that the required energy for cooling urban buildings increased twofold, and the peak electricity load for cooling increased threefold over 1996-1999. This research also found that the minimum coefficient of performance (COP) value for air conditioners decreased by as much as 25% because of high ambient temperatures. Kolokotroni et al. (2012) in a computational study of energy consumption and related CO_2 emissions for the heating and cooling of an office building due to the London heat island effect found that heating loads decreased whereas cooling loads and overheating hours increased markedly during a heat island event. Their findings suggested that this could increase the CO_2 emissions in the city of London by 5-fold by the year 2050. Hirano and Fujita (2012) studied the primary energy consumption for both heating and cooling commercial buildings based on predicted future climate scenarios, and suggest that the urban heat island results in a net increased in energy consumption within the commercial sector.

Just how much warmer can urban areas become due to the UHI effect? Voogt (2002) showed that the temperatures of urban centres can be up to 12 ^{o}C higher than neighbouring regions. (Fig 1.11) shows the long-term trend of temperature profiles for five cities within Japan and reveals that in general, all the cities experienced higher trend in their temperature in the hundred years period (1907-2007).

Figure 1-11 shows the temperature in major five cities of Japan during the period of 1907-2007. It indicates that temperature of all the five cities experienced increasing trend over the period.



In addition, cities rapidly expanding in size surpassed the temperature of those that are growing at a slower rate. In the Fig 1.11, among the five cities, Tokyo is the largest city and its temperature increased more rapidly compared to the other cities, being ranked third warmest in the early 1900s to becoming the warmest in more recent times, suggesting its rapid urban expansion has resulted in an exacerbated UHI.

1.3 Green infrastructure and thermal profile

The UHI phenomena suggests that locations with a high proportion of green infrastructure (vegetation) and / or blue infrastructure (water) are often cooler than the more densely built parts of the city or where there is a high level of industrial activity. So why should locations with a high proportion of vegetation be cooler? Similarly, what sorts of vegetation provide the greatest cooling influences? A number of studies have investigating the cooling potential of urban vegetation (Maher,2013; Weng et al., 2004; Picot, 2004; Liangmei et al., 2008; Hamida and Rchid, 2012; Roy et al., 2012, de Abreu-Harbich et al., 2015; Lin and Lin, 2010, Johansson and Emmanuel, 2006). Maher (2013) has stated that trees offer cooling in the following two key ways:

- A. blocking solar radiation, i.e. shading (Gómez-Muñoz et al., 2010), where a large proportion of the incoming solar radiation fails to reach the ground or hard urban surfaces. Solar irradiance (sunlight) is either reflected from the tree, or it is absorbed by the foliage at a distance from the building. Heat absorbed by the tree is carried away by the surrounding air mass.
- B. Evaporative cooling through evapo-transpiration. The surface of the foliage is cooled below ambient temperature by evaporation process. Water absorbed by the root system is evaporated from pores of the leaves surfaces, thereby cooling them. This process is called "evapo-transpirational cooling." The change of state between liquid water and vapour that results during evapo-transpiration results in energy being used without affecting temperature directly and it known as latent heat.

Different studies have examined the effect of vegetation structure on climatic properties using empirical methods. Those papers can be broadly classified into two types on the basis of the spatial dimension. Firstly, in terms of macro scale, some papers investigated impact of vegetation on cities (Weng et al. 2004; Picot, 2004; Liangmei et al., 2008; Hamida and Rchid, 2012; Roy et al., 2012, and Christopher et al., 2012) verified that vegetation structure has a cooling effect on cities. Secondly, in terms of micro scale, it is also true that vegetation such as trees can provide local cooling for park, buildings, corridors or for other small locations (e.g. Lin and Lin 2010, Pandit and Laband 2010; Vaz Monteiro et al., 2017). It was found that canopy of the green structure reduces surface temperatures due to shade and evapo-transpiration effects (Cameron et al., 2014), and that this then influences local air temperatures. Trees provide multiple benefits in urban areas by improving microclimatic conditions (Georgi and Zafiriadis, 2006). Trees interrupt incoming of solar radiation and prevents it from entering into canyons of the streets (Matzarakis et al., 1999).

1.3.1 The impact of green infrastructure on road temperature profiles

Micro scale research that deals with the micro-climatic effects of vegetation around roadways *per se*, has received relatively limited research to date. Vegetation structures around roadways can be diverse but can include trees (as avenues of street trees, adjacent garden trees, or due to the proximity of stands of urban forest), grass margins, hedges, shrub belts as well as e.g. in a city center – container-grown ornamental plants placed along the sides or central reservation of a road. Plants themselves are diverse, with a variety of different forms and morphologies e.g. large > 10 m high or short < 5 m high trees; large v small or narrow-leaved specimens, plants with different foliage colours, close mown lawn grass v longer meadow grassland, etc. Even the different parts of a same project specifically road/highway may have different vegetation structures. Different vegetation structures have different climatic influences or cooling capacities (Bar and Hoffman, 2000; Lin and Lin, 2010; Blanusa et al., 2013; Cameron et al. 2014; Cameron and Blanusa, 2016; Vaz Monteiro et al., 2017, Lohr et al., 2004).

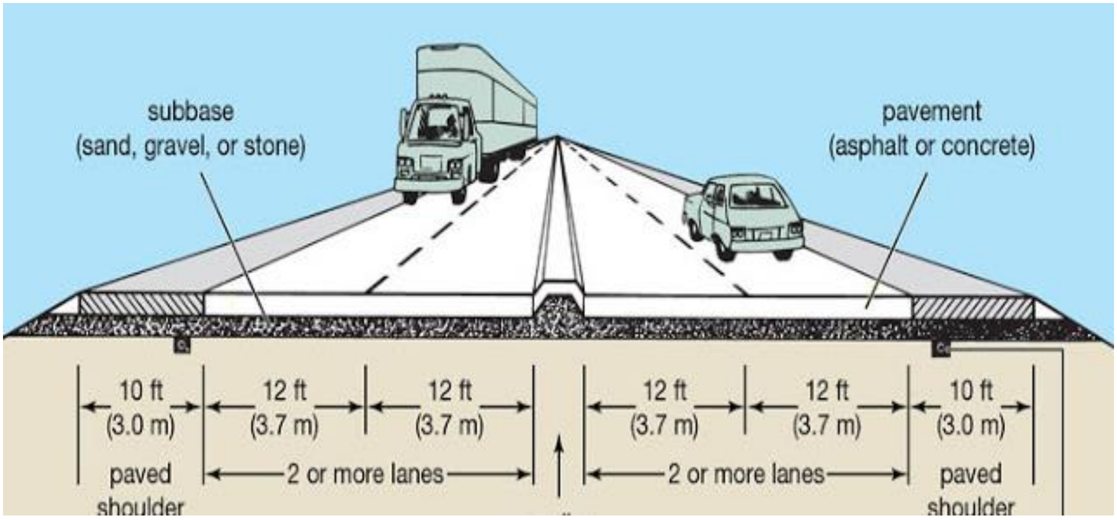
Within an urban heat island context, it is desirable to reduce the heat load associated with roadways and pavements (pedestrian side-walks). This is to improve the thermal comfort for pedestrians and vehicle occupants (assuming the latter do not have / wish to use vehicle air conditioning) and to reduce the thermal load onto adjacent buildings, e.g. from reflected infra-red radiation off the road surfaces. It is assumed that the surface temperature across the road is strongly influenced by the diversity of roadsides features and the interactions between such features, e.g. ability to block prevailing winds (Maher, 2013). Besides vegetation, the temperature of urban roads is also likely to be strongly influenced by the size, form and colour of adjacent buildings and the types of material they have been constructed from. Similarly, the construction / components of other hard infrastructure, such as pavements, walls, metal barriers, road signs, lamp posts may also have a local influence on temperature, either directly or by altering air movement. Street orientation (aspect) in relation to prevailing sunlight will also affect thermal properties, although these may vary with time of day. Lastly, temperature may also be strongly influenced by activities / functions within the streetscape itself, e.g. number of passing vehicles or pedestrians, amount of heat escaping from buildings, e.g. through shop doors or from building air conditioning units. In general, the intensification of the urbanization leads to construction of high rise buildings for residential purposes for both the rising population and for commercial activities. Oke (1987) and Santamouris (2001) relay the different reasons that buildings can increase the temperature profiles of a given city. Gill (2006), though mentions that buildings can also provide shade. Moreover, the height of the buildings can cause to change wind movement and wind speeds

(Shashua-Bar et al., 2006). The research outlined in this thesis aims to investigate the relative influences of both soft (vegetation) and hard (buildings) landscape features that may influence road surface and air temperatures, using Sheffield as a model city set within a temperate climatic zone.

1.4 Road Characteristics and Thermal Profile

There are two distinct phases of road development-namely firstly the original construction of road networks and secondly, their regular maintenance. Methods of construction and materials used are not universal across the globe. Rather, depending on the nature of the land, construction of road requires a wide range of materials. In general, however, Fig 1.12. shows that the road consists of three parts: middle street, road ways and pavements.

Figure 1-12 displays different features of the physical structure of a road. It shows that usually a road has different segments which are pavement + planting, parallel parking, bike lane and vehicle travel lane.

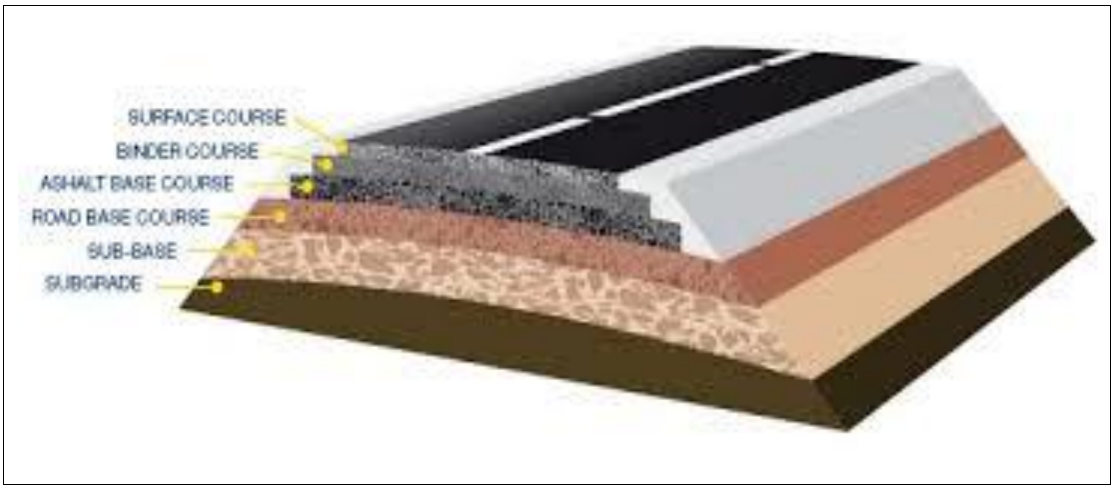


Source: Complete Street for UK.

Each section of the road consists of layers of different materials. Change is always taking place in road construction materials to make the structure more stable and cost effective. When a road is constructed, optimum load distribution from the vehicles through the road structure needs to be ensured. Usually, the loads from the vehicles spread and decrease with depth. In order to ensure optimum load distribution, upper levels of the roads are constituted by stronger and expensive materials while lower levels are constituted by relatively low strength and less expensive materials (Eurobitume, 2018).

A good fusion among the different layers of the road needs to be ensured to enhance the bearing capacity of the road. Fig 1.13 presents more details of the layers of the road construction. It shows that the three top **layers** – a *surface course*, a *binder course* and an *asphalt base course* - constitute the top layer of the road structure, also known as asphalt layer. Just beneath the asphalt layer is the road base course which is considered as the most important structural layer to effectively distribute traffic load. **The** sub-base **and** subgrade layers, the lowest levels of the road are the foundations of the road structure (Eurobitume, 2018).

Figure 1-13 shows that there are six layers of a road. Surface course is the top layer while subgrade is the lowest base. Asphalt base course is the third from the top which is widely used material for road construction.



Source: Eurobitume, Website of European Bitumen Industry, 2018

Asphalt is the most widely used material for road construction and maintenance across the world. There are different types of asphalt with different combinations of bituminous binder and minerals. Different types of asphalt have different performance characteristics in terms of sustainability. Moreover, different temperature level, asphalt mixtures are also adjusted. According to the European Bitumen Industry, Asphalt is typically a mixture of approximately 95% aggregate particles and sand, and 5% bitumen, which acts as the binder, or glue. Depending on temperature and vehicle movement, asphalt mixture determines the durability of the road surface. Composite surface is another type of road surface which combines cement concrete and asphalt. But this surface is usually used to rehabilitate existing roadways rather than in new construction. The sub-base and subgrade layers consist of unbound materials, such as indigenous soil, crushed or uncrushed aggregate, or re-used secondary material.

Between 25-50% road areas of cities are covered by pavement. The two most commonly installed types of pavement are asphalt cement concrete, and Portland cement concrete. Asphalt is black or dark grey with 5-10% initial solar reflectance during installation. With the passage of time, asphalt lightens, and its solar reflectance increases to 10-20%. Asphalt can heat to 65 ^{o}C or more in the summer time and is the second hottest feature in the urban landscape, behind traditional roofing materials. Concrete pavements start out light grey, with a 30-40% solar reflectance. Over time, concrete becomes dirtier and its solar reflectance lowers to 25-35%. Concrete pavements stay much cooler than asphalt and remain below 50 ^{o}C even under the hottest and sunniest conditions (Gartland, 2008).

Materials used in the road construction are directly interlinked with environmental performance. For instance, road surface is linked with noise pollution, water drainage and temperature. Road surface is reflected with sunlight and so it impacts temperature. In the study on the ecological potentials in the production of road materials used in Swiss road pavements, Gschösser et al (2012) performed the environmental assessment using a cradle-to-grave life-cycle assessment (LCA) approach considering all processes from the raw material extraction to the finished product. The comparison of the results of the best-case asphalt pavement and the standard asphalt pavement for Swiss highway construction shows higher ecological potentials up to 55%. Use of the best-case concrete pavement lowers the environmental impact by 53% in comparison to the worst-case concrete pavement for Swiss highways. Concerning composite pavements, the best-case variant offers an ecological potential 38% higher than the standard pavement.

The thermal characteristics of pavement have a lot of influence on the formation of heat islands. Cool paving contributes to reduce pavement temperatures by 19.5 °C or more (Asaeda et al, 1996; Pomerantz et al, 2000; Gartland, 2001). The hottest pavements tend to be impermeable and dark in colour, with solar reflectance under 25 percent. According to Gartland (2008), there are two methods to construct cool pavements: (a) making then lighter in colour raises solar reflectance to ≥25% percent, and (2) making them permeable allows water to drain through during rainstorms and evaporate back out during hot and sunny weather. Evaporating water removes heat from the paving material and keeps it cooler.

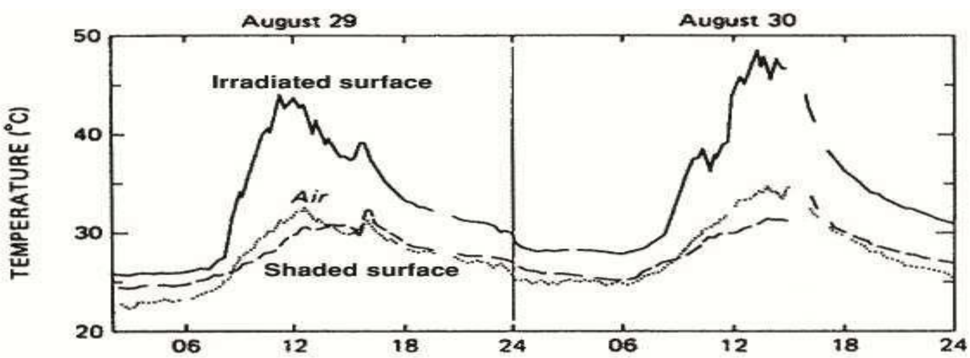
Sky view factor (SVF) can be defined as the fraction of visual sky upward seen from the surface level in a specific location and it depends on the geometry of the surrounding area Osmond (2010), Giridharan et al. (2005), Dimoudi et al. (2003). The range of this geometrical factor is between 0 (completely enclosed) and 1 (completely open) Lin et al. (2010). (SVK) is another factor that influences the thermal profile within a street canyon. Some studies have shown both a strong relationship between sky view factor and air temperature and a non-statistical relationship between them. In the former category, Yamashita et al. (1986) found a fairly strong relationship between air temperature and SVF in cities such as Fuchu and Higashimurayama of Japan. Similarly, Eliasson & Svensson (2003) revealed that both SVF and land use parameters are important factors to determine the spatial variation of air temperature in the urban areas. Postgard (2000) showed that 46% of the variation in air temperature is explained by the SVF along forested stretches of roads. In forest areas, a strong correlation was found between the SVF and both net radiation and air temperature (Karlsson, 2000). On the other hand, Eliasson (1996) and Barring et al. (1985) found no statistical significance between street canyon geometry and air temperature (AT). There is one hypothesis that the analysis of the relationship between SVF and air temperature depends on where and how measurements of SVF are taken. Bourbia and Awbi (2004) and Pearlmutter et. al., (1999) investigated the relationship between surface temperature and canyon geometry and they stated a significant positive correlation between surface temperature and SVF.

The orientation of urban roads is an important element that influences temperature distribution and ventilation efficiency in the urban areas. Cao et al. (2015) studied the effects of orientation of urban roads on the local thermal environment in Guangzhou city of China and found that orientation of the road has a great influence on the local thermal environment in windless area or with respect to high-rise buildings in low-lying areas. Sanusi et al. (2016) based on the study of Richmond, Victoria, Australia found that the reductions in air temperature under high-percentage canopy cover were greater for east-west streets (2.1 °C) than for north-south streets (0.9 °C). In the early morning, air temperature, mean radiant temperature, and solar radiation were greater on the east pavement for N-S streets and highest on the west pavement in the midafternoon. The midday thermal benefits are limited to E-W streets with the same direction as the summer sun's zenith.

Nunez and Oke (1977) stated that the magnitude of energy balance (radiation exchanged) between the surface and the space of the street canyon (air temperature) was strongly influenced by the orientation and thermal properties of the street fabric, but these also varied with time, due to the angle, direction and intensity of solar radiation. The specific features of the urban canyon can significantly influence the energy budget within the streetscape by determining the magnitude of reflection and sorption of the solar radiation penetrated into the street. Factors such as height of buildings or tree canopies and height/width ratios influence the amount of incoming solar energy, but also how it is dissipated (Nunez and Oke, 1977). In those streets which capture solar energy, it tends to be retained longer when the buildings are higher, i.e. a deeper 'canyon' effect (Pearlmutter et al., 2005; Marciotto et al., 2010). In other words, the features of the urban canyon control the intensity of emitted long wave radiation. Consequently, the radiant heat loss is faster in open, exposed streets compared to those enclosed and with deep canyons (Erell et. al., 2011).

In Kyoto, Japan, Nakamura and Oke (1988) examined variation in air temperature and speed within the urban canyon. In general, air velocity was up to 60-70% faster above roof level, compared to below, but temperature differentials were more difficult to determine based on elevation. This is in line with Armstrong (1974) and; Pearlmutter et. al., (2008), who concluded there was insignificant differences in air temperature at different heights within the canyon and that this was due to sufficient air mixing between different levels (Santamouris, 2001a). As might be expected there were differences in air temperature though, during the day, with temperature warmer during the day compared to night. These researchers though did emphasis the difference between surface temperatures and air temperatures (surfaces 14°C warmer by day and 4°C by night (which caused by the residual heat in the surface after sunset (night)); or in shaded areas 8-9 °C and 2-3 °C respectively). Proximity of the air to the surface, however, creates a more complex picture Nakamura and Oke (1988), (Fig. 1.14).

Figure 1-14 Display the differences of the thermal profile between the surface and air temperature according to the temporal variation (adapted from Nakamura and Oke (1988)).



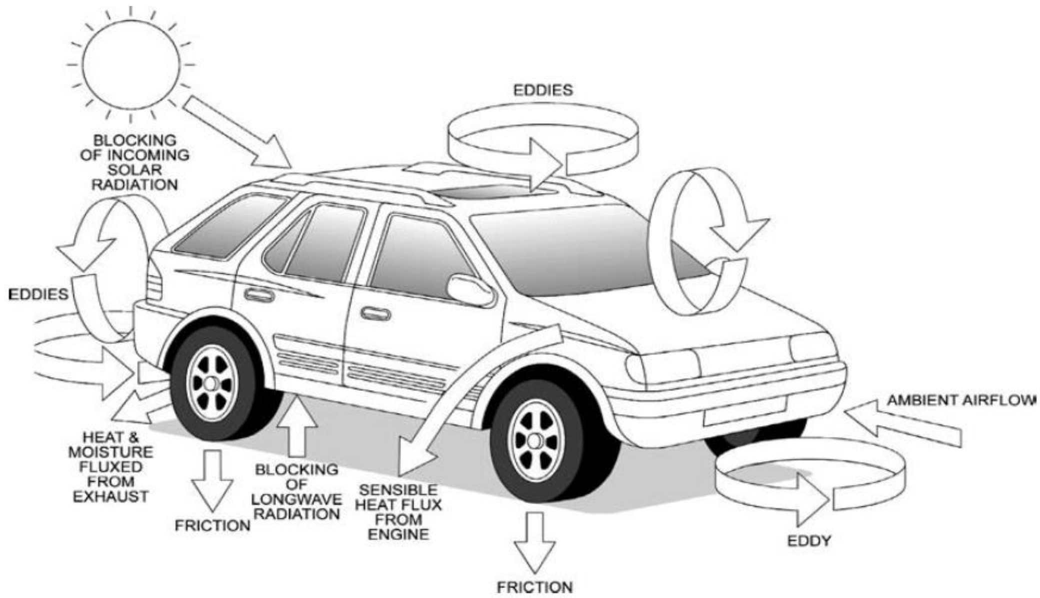
Nunez and Oke (1977) identified a 2°C warmer at 0.5 m above the street surface compared to 4m above it. Also there are incidences in streetscapes when high levels of shade within the canyon (e.g. high buildings blocking out sunlight) could result in a 5°C difference in air temperatures compared to the air above the canyon (Georgakis and Santamouuris 2006).

1.5 Traffic Movement and Thermal Profile

Urbanization involves many factors that contribute to the urban heat island through intense heat waves (Landsberg, 1981; Oke, 1982). Rapid urbanization leads to an increase in traffic mobility which ultimately has an effect on warming. A number of previous studies recognized the impact of traffic mobility on the thermal profile of urban areas. Since density of car use is concentrated more in urban areas than rural areas, cars and vehicles lead to increase in heat emission in urban areas. Vehicles emit heat (and aerial pollutants) that remains trapped within the urban matrix and destroys the comfort for numerous city people. In addition to this, this heat also contributes to the formation of the urban smog as well as CO_2 emissions that contribute to climate change (Wang et al., 2004; Watkins et al., 2007; Younger et al., 2008). The gaseous emissions from cars interferes with heat transfer from the earth's surface back to the atmosphere, thus giving rise to high air temperatures in the urban areas compared to the surrounding rural areas, a key feature of the urban heat island. Louiza et al. (2015) performed a numerical simulation of the plume generated by the exhaust gases of cars and showed that these gases form a screening effect above the urban city which induces a cause the heat island effect even in the presence of a wind flow pattern.

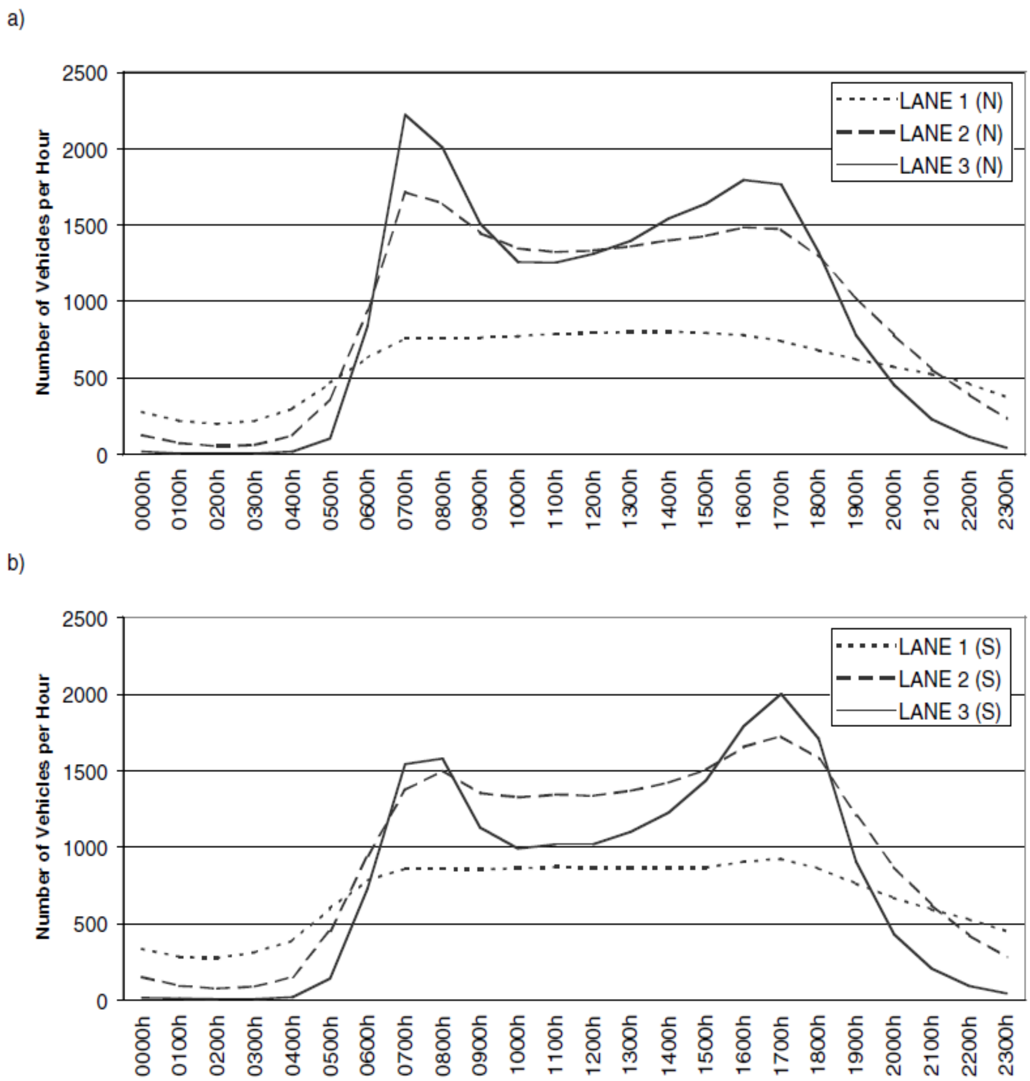
Physical structure of the vehicle and its movement on the road surface impacts on thermal profile of the road Fig 1.15 depicts the schematic illustration of the impact of traffic on road surface temperatures (RST). This shows that the body of a car as a whole blocks the incoming solar radiation and longwave radiation. In addition, different parts of the car also have different thermal impacts on road temperature. For instance, tyres of the car always cause friction with the road, thus generating heat; while the car exhaust emits heat and moisture directly on the surface of the road.

Figure 1-15 shows a schematic illustration of the impact of traffic on road surface temperatures (adapted from Prusa et al. 2002). It shows how different parts of the car get contact with road surface and produces heat by friction as well as blocking solar radiation.



But all the areas across road surfaces don't have similar volume of traffic movement. For instance, in the two lanes road, there are almost uniform pattern of traffic movement. But in the roads with more than two lanes, there is a variation in traffic movement that may eventually lead to the variation in the RST. The literature shows that different lanes of the motor ways have different thermal profile. Fig 1.16 shows that there is an inverse u-shaped pattern of vehicle movement on the road for different lanes across different hours of the day (Chapman and Thornes, 2005).

Figure 1-16 displays annual average daily traffic flow for (a) northbound and (b) southbound carriageways. These figures indicate that traffic volume has almost normal distribution where day time has higher traffic movement compared to the night time.



There are some empirical studies on the thermal impact of traffic movement. Farmer and Tonkinson (1989) showed warmer RST on heavily trafficked roads. In another study conducted in Stockholm area of Sweden, Gustavsson et al. (2001) found that RST can increase by up to 2 ^{o}C in urban areas than rural areas during the early morning peak commuting time. In the case of multi-lane road, there are variation in thermal characteristics. Parmenter & Thornes (1986) and Shao (1990) found 1 ^{o}C and 2 ^{o}C differences respectively between the inside and outside lanes. However, there are other processes other than traffic that may impact on the thermal profile of the road. Although it is difficult to isolate traffic effects from other factors, those factors need to be incorporated to quantify the actual true impact of traffic.

1.6 Urban Design and Microclimatic Profile

Rapid urbanization process during the last two centuries has resulted in remarkable change in microclimatic conditions such as the rise of air temperature in urban districts (Tsoka, 2017). This rise in air temperature in the urban places damages the comfort of the city dweller. Therefore, in order to ensure thermal comfort for the city dwellers, the urban geometry has been central in city planning and design in the recent days. This planning process, which has attracted worldwide attention as a model of sustainable urban development, is based on the principle that land use in the city can be induced, restricted, and organized (Hawken et al. 2003).

Urban geometry is a multidimensional phenomenon that makes the urban design a complex function. The fundamental morphological unit of urban geometry is namely the aspect ratio (AR), defined as the ratio of the canyon height to canyon width AR = H/W (Sosse and Tahiri, 2016). There are different components of urban design that effects the microclimatic features of an urban areas. Those components are - Aspect ratio (H/W ratio) Square, Aspect ratio (H/W ratio) Courtyard, Shading canopies, Pavement surface Albedo, Pavement surface Emissivity, Pavement Thermal capacity (J/kgC), Soil humidity 50% (pavement), Tree cover, Grass cover, Water cover (Chatzidimitrioua and Yannas, 2016).

A well-planned urban planning can turn an urban city into a garden city. Singapore is a perfect example of an urban city equipped with modern amenities that has been turned into a garden city because of urban planning. Rapid urbanization in Singapore has resulted in disappearance of its most primary rainforest. Now, 50 percent of the country is covered by greenery (Wong and Chen, 2005). Research also shows that urban planning not only shapes the urban landscape, but also ensures the outdoor thermal comfort of the people in the urban areas. People in the city areas prefer to go outdoors to avoid the high indoor humidity and enjoy more sunshine. Study based on thermal comfort survey in one urban park in Shanghai from November to January to investigate the role thermal comfort plays in affecting people's evaluation of the outdoor space and activity shows that people prefer outdoor space to enjoy outdoor thermal comfort in autumn and winter in Shanghai (Chen et al., 2015). A thermal comfort study based on outdoor urban spaces in Singapore has been carried out to explore people's perception of the thermal comfort in the outdoor areas of Singapore. The finding of the research is that people may expect a higher temperature in outdoor conditions than in semi-outdoor or indoor conditions in Singapore, suggesting that people in outdoor conditions could be more tolerant with the heat stress than people in indoor conditions in tropical climate (Yang et al. 2013). However, urban design policy at all levels is currently fragmented and it frequently suffers from lack of clarity on its status or importance (Paterson, 2012).

It has been already discussed in the current lit review that urban greening in the form of parks and trees may act as a key mechanism to mitigate high temperature in the urban areas. Many studies have already attempted to prove this claim empirically (Lynn et al., 2009; Rosenzweig et al., 2009; Zhou and Shepherd, 2010).

1.7 Water body (Blue structure) and Microclimatic Profile

Urban areas usually have deficit of water and low soil moisture level as impervious urban surfaces prevent infiltration, and runoff is rapidly spread away from urban environments. Water bodies have a positive influence upon microclimate of the surroundings urban areas with the relative cooling impact it has on evaporative procedure. Temperature tolerance of water body is often lower than the surrounding urban environment around (2–6) ^{o}C (Manteghi et al., 2015). Literature also states that the temperature of the air above and near water body is different from the temperature over the land because the water has a different system of cooling and heating. Water bodies are believed to be the best radiation absorbers, but on the other hand, they provide a very small thermal response (Wong et al, 2012; Oke, 1992).

A number of studies have examined the influences of the open water bodies (ponds, wet lands, water features or rivers) on the urban regions' climate (amongst other Xu et al, 2010; and Sun and Chen, 2012). Studies showed that temperatures closed to and downwind from water bodies are getting reduced about (1-2) ^{o}C in comparison to surrounding areas, with the highest amount of temperature reduction observed through the day (Coutts et al., 2012; Chen et al., 2009). Chen et al. (2009) has described the evaporation from the water body as the cause of the reduction of temperature. Saaroni and Ziv (2003) showed that the cooling pond effect over the warmest part of a day have decreased sensible heat flux (1.6 ^{o}C at mid-day) as the surface of the lake was cooler than the grass cover of the surrounding park (Coutts et al., 2012).

In the world, many cities are located near or next to water bodies (river, lake). Saaroni and Ziv (2003) study over a 100 m wide pond inside an urban park demonstrated higher rates of humidity and a lower amount of heat stress over the day downwind of pond. Murakawa et al., (1991) on the basis of the study on Hiroshima city of Japan, showed that downwind cooling influences from the Ota River are present in at least a few hundred meters. Wong et al., (2011, 2012) states that the thermal capacity of water is pretty large in a sense that it needs about three times more heat to raise a one-unit volume of water over the same temperature interval as the most soil. Reduced air temperatures on the rivers inside UK were reported by Hatway and Sharples (2012). Considering the cooling impact of water bodies on urban microclimate, architects and urban planners have used water bodies as their tools of design in order to influence the temperature of urban area (Coutts et al, 2013). The direction and speed of wind have the cooling impact of urban water bodies. Different patterns for temperature distribution can be generated by wind conditions (Kim et al, 2008).

There are different cooling approaches in the urban areas. Shashua-Bar et al. (2009) compared the water efficiency of different common urban cooling approaches - irrigated grass, shade trees, and shade mesh in two adjacent courtyards and found that a combination of irrigated grass and shade trees was the most effective in cooling, while the vegetation alone achieved the highest cooling efficiency per amount of water used. Since all the different cooling approaches need more or less amount of amount of water, the existence of water in the urban design is extremely critical.

1.8 Motivation and Structure of the Dissertation

1.8.1 Motivation of the Dissertation

The literature review outlined above does not give a full account of the impact of roadside morphology on the micro-climate of the streetscape, especially in a temperate European context. Few papers attempt to deal with the investigation of the linkages between typology and temperature of the road and those that do tend to focus only on a limited number of days (Bar and Hoffman, 2000; Lin and Lin 2010). Existing literature doesn't consider fully the different structures / scales of roadside structures and their impacts on the thermal properties of roads. As such, it is anticipated that this will be the first research approach to identify how variation in strcutures composition influences the thermal gradients associated with roads. Since this research will use the data from different seasons of the year, it will be able to put forward the new findings of cross seasons comparison of micro-climatic properties of the road. Ideally, the findings of this paper will be valuable to government and environmentalists when creating policy on planning and development of new road networks and identifying what sort of landscapes best ameliorate some of the negative factors associated these developments.

1.8.2 Structure of the research

There are two parts in this thesis. First part comprises of background chapters-covering the literature review and methodology of this research. Second part includes five research chapters addressing specific research questions that will end with a chapter on key findings of this dissertation.

1.8.2.1 First Research Experiment

The aim of this chapter was to determine how roadside morphology and infrastructure affected road surface temperature. The research aimed to determine whether there were systemic patterns of warming or cooling based on the features beside the roadways. As such, could universal phenomena be described by the research or are temperature profiles of individual locations influenced by so many multiple factors that it is difficult to determine overall significant effects due to the presence of trees or buildings, or other forms of infrastructure. Among all those multiple roadside characteristics and features of the road surface itself, this chapter will focus on defined roadside characteristics and specific locations within the city of Sheffield. However, the following research chapters of this dissertation will add more factors to see their impacts on temperature profile of the road. Therefore, the findings of this research will lay down foundation of further research of this dissertation. As study area, a number of roads within the Sheffield city region were chosen for the study and specific locations chosen at random to determine how in each case, road morphology affected thermal profiles across the road.

This research contributes to the literature in several ways. Firstly, it examines the effect of both vegetation and buildings on road surface temperature which is not done in similar literature. Secondly, this research is based on the primary data collected from a number of roads within the Sheffield city region which is not covered in other studies. Finally, extensive literature review found a research gap in the field of explaining the road surface thermal properties in the UK and other European countries where both vegetation and buildings were taken into consideration together.

1.8.2.2 Second Research Experiment

This chapter aims to investigate how the most common roadside characteristics in the UK and its macro attributes impact the road surface temperature, air temperature and air velocity in the summer season. In addition, it aims to report the pattern of surface temperature over the different time. This experiment utilized a single orientation which was North-West Vs South-East (NW vs SE) with several degrees difference over the various locations within the road. Also, it gives an opportunity to examine the thermal conduct of common both roadside characteristics over the road in the UK in those periods.

1.8.2.3 Third Research Experiment

The aim of this study is to investigate the influence of multiple factors on the road surface temperature. In other words, this study attempts to assess the potential influence level of each factors on the accumulative temperature of the road surface. There are many factors which may influence the road surface thermally. However, the main hypothesis of this experiment will evaluate the influence of 9 essential variables on the road surface temperature. Some of those factors are considered as environmental variables, such as- air temperature, wind speed while Sky view factor, height of the both road side characteristics, width of the road, the ratio between height and width (H/W ratio), colors of road surface and the characteristics located at both sides and blocked/opened roadside characteristics are considered as physical factors. The aim of this experiment also focuses on the influence of environmental variables, landscape features and their geometry on the micro-climatic/thermal properties of urban roads. It also evaluates the influence of these features on road surface temperatures at different times of day. The findings of this study will help to design the masterplan of the road network in the urban city by considering the thermal behavior as an essential aspect to affect the microclimates along with other aspects such as, ventilation, aesthetic side, street usage etc.

1.8.2.4 Fourth Research Experiment

This chapter mainly aimed to study the influence of traffic volume on the surface temperature of the road. The research main hypothesis is that surface temperatures increases with traffic density; surface temperatures are higher in the busy road compared to less traffic road and the park in the same time respectively and; roadside topology along with traffic movement also affect the temperature of the road surface. The result of the experiments within this chapter will also identify the influence of traffic movement compare with road side typology on the temperature of the road surface.

1.8.2.5 Fifth Research Experiment

The aim of this experiment is to assess the effect of adjacent landscape features of the roads over large sites – park (trees), river (water) and, heart of the city (buildings) on the micro-climatic/thermal properties of roads. It also identifies the influence of these features of mega-scale sites on the road surface temperatures at different times of day. It also examines the universal influences of park, river and, city center on surface temperature and the site-specific factors that may promote / negate the influence on thermal properties of the road.

Chapter 2 : Materials and Methods

2.1 Introduction

Primary data was generated by conducted research within the city of Sheffield and utilizing a number of contrasting road landscapes, many within the vicinity of the University of Sheffield. The focus was in determining temperature data – surface temperatures of roads and pavement, but also air temperature, and investigating what factors influenced these temperatures. As such a range of other meteorological, physical, biological and architectural factors were also considered and monitored, where necessary. Data set was collected largely during the summer season, this representing typically the hottest season in Sheffield. However, two experiments were carried out in the winter season.

Data was collected from the city center to the outskirts of the city including the areas near to the University of Sheffield. Coverage of these locations allows comparison between grey and green areas, whilst still within the same climatic region (i.e. less variation in weather events for example). Moreover, Sheffield, being an urban area gives the advantage of examining the effect of traffic movement on the thermal profile. It is worth noting that Sheffield is under-researched area while we consider the causes of thermal variation in urban areas as research objective. Since Sheffield is located in the middle of England, the research on Sheffield carries an additional importance in the research on the landscape form. Since Sheffield experienced a massive transformation after deindustrialization through master plan for the city, as a case study, Sheffield will bring special findings and new insights.

In this research the key parameters measured were: - the surface temperature (ST); Air temperature (AT); Air velocity (AV) and; relative humidity (RH) (those are considered as outdoor environmental variables) whereas the rest of those variables could be considered as a physical variables such as Sky view factor (SVF); height width ratio (H/W); blocked/opened roadside characteristics; colour of the road surface (both roadside (pedestrians zones) and carriage way) and the colours of the features located on the both roadside (green such as hedge/tree, grey like red, white, black or red colours of bricks of the houses/offices and number of cars passing in the road per time unit.

2.2 Environmental (Properties) Parameters

The following sections outline the environmental variables were taken in this research study.

2.2.1 Surface Temperature

In terms of examining the thermo-dynamics of the roads, the surface temperature was determined as the essential variable of this project (dependent variable). Surface temperature was measured and recorded by the researcher himself using a mobile device (thermal 'gun' - see below fig 2.3). The device was handled manually and directed perpendicularly (90^{o}) to the road surface, approx. 1 m above the road. A temperature 'profile' across the roadway was generated by measuring surface temperatures at points across one pavement, the main carriageway and then the opposite pavement (Fig 2.1) and (Fig 2.2). Thus for any given location on a road, usually 12 surfaces temperatures were recorded on each occasion (Fig 2.1); these representing the transitional 'profile' of the roadway, with road profiles (RPs) either 'a' to 'd' for experiment of chapter 3 or ‘1’ to ‘4’ for experiment of chapter 4 and 5 representing one pavement (‘a’ and ‘1’ being the edge furthest away from the road itself and closest to the structure at the side of the road, e.g. office, tree, house etc.). $RP_{e\text{-}g}$ or $RP_{5\text{-}8}$ represented temperature points across the road itself (cars way), with $RP_{i\text{-}l}$ or $RP_{9\text{-}12}$ represented the opposite pavement profile, with ‘I’ or ‘12’ being the point closest the structures adjacent to the road on this side. For chapter 6, there was less requirement for such intensive recording and only one data point was recorded for each pavement, and for the middle of the carriageway itself).

The method to collect the (ST) in terms of number of road locations recorded, duration of recording and frequency of recording during any given day could vary with the specific requirements of each experiment.

Figure 2.1 Image taken at location (B-T) U40 in the Upperthorpe Rd, explain the 12 RPa-l was measured over the location (Top). Distribution of References points (RPa-l) were taken in one location over the road (Bottom). Data set were recorded by using the thermometer device (testo 845 infrared measuring instrument).

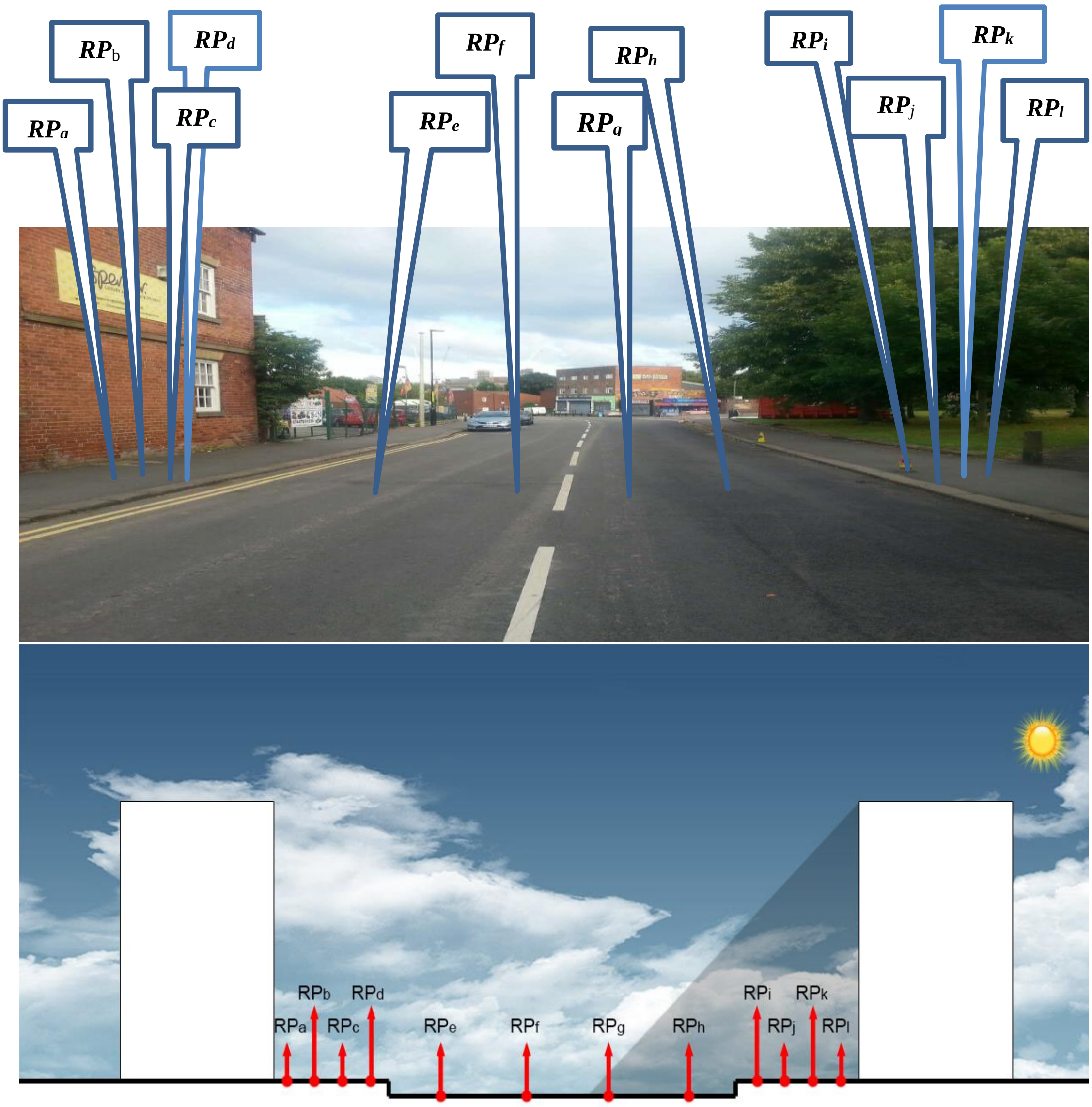
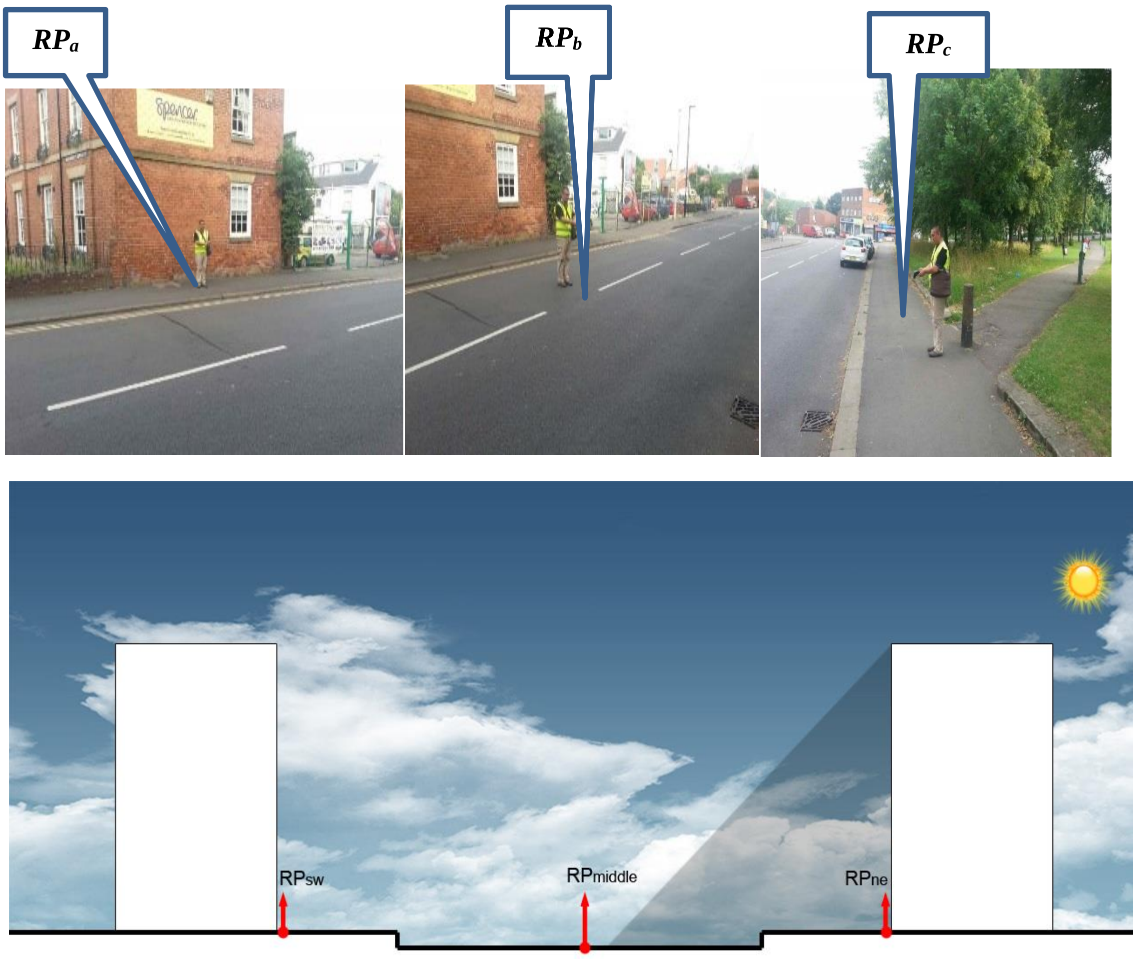


Figure 2.2 Images taken at location (B-T) U40 in the Upperthorpe Rd, showing the three zones over the location (left, right pedestrians' zones and, cars way) (Top). Distribution of References points (RPa-c) were taken in one location over the road (Bottom). Data set were recorded by the researcher himself using the thermometer device (testo 845 infrared measuring instrument).



Thermometer device (testo 845 infrared optics 75:1 / 70:1 -30 to +950 °C. Optical Zoom for far (75: 1) and near field measuring 1 mm, Distance between 70 mm ; Model No: 0563 8450; Testo Manufacturer) was used to obtain and record the surface temperatures (ST). It can still calculate the (ST) at a distance from the targeted application while the second option is close distance, which have been used for this research measurement (1 m mounted from targeted point). The device is also provided by a pinpoint laser sight to determine accurately where the measurements should be taken from the (RP). It has a temperature recording range between -35 °C and 950 °C, with accuracy of -/+ 0.75 °C.

The digital thermometer (Testo 845) works by using infrared laser beam according simple principle although the mechanism that makes this device work is indeed complex. However, any object, that has mass, radiates energy as a heat form. Because any object emits a heat, the difference between the surrounding environment and the IR rays emitted from the object itself, it can be used to determine the (ST) of that object by using an infrared thermometer. By pressing on the starting button, the device starts to turn on the laser beam on the targeted application (object) which coming from it as IR rays form and cauterized that light into a detector (thermopile). The IR radiation is converting into heat and then electricity form in the thermopile then ultimately the electricity amount which is produced by the radiations being put out by the surface that wanted to measure its temperature. The Backlit LCD screen shows the actual, minimum and maximum surface temperature °C, however, along with the experiments of this research actual temperature was used for all experiments (Fig 2.3).

Figure 2.3 Image taken for the thermometer device was used to measure the road surface temperature degree (testo 845 infrared measuring instrument).

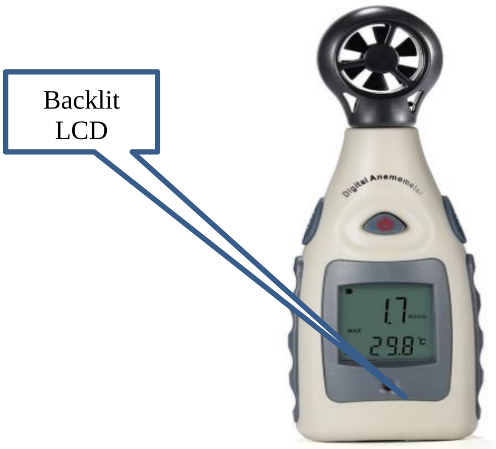
2.2.2 Air Temperature (AT) and Air Velocity (AV)

Air temperature (AT) and Air velocity (AV) were carried out for each road location, simultaneously. They were measured and logged using multi-measurements device (Digital Anemometer; ASIN: B01GPA3PEG; with manufacturer reference: UK4-windsm-FBA), which was held by manually by the researcher himself around 1.5 m level above the surface of the roads. For each location, 3 air temperatures and air velocity were recorded on each occasion (fig 2.4); these represented the transitional 'profile' of the roadway, with data recorded for the pavement on the south-west side (SW) centre of road carriageway (middle of road) and pavement on the north-east (NE) side.

Figure 2.4 Images taken at one of the locations in (Hoyle street) showing Air temperature (AT) and Air velocity (AV) being measured at three positions, i.e. both pavements and centre of the road. Note the pavement data is recorded at the very edge of the formal pavement.

The Digital Thermometer / Anemometer (Fig 2.5) is designed to measure Air temperature (AT) between -10and +45 ^{o}C and for wind speeds (AV) between 0 and 30 ms^{-1}. The device measures both maximum and average wind speed over a given period, but the average data was used in the subsequent analysis.

Figure 2.5 Image taken for the anemometer device was used to measure the Air temperature degree (AT) and air velocity (AV).



2.2.3 Relative Humidity (RH)

Relative humidity was recorded in Chapter 7, using a hand-held digital humidity meter (model ASIN: B01MYGRETM with manufacturer reference: UK4-windsm-FBA), accurate between 5% and 98% r.h. Relative humidity was recorded in the same positions as air velocity and temperature (Fig 2.6).

Figure 2.6 Image taken for the Humidity meter device was used to measure the relative humidity (RH).

2.3 Physical Properties (Parameters)

2.3.1 Sky View Factor (SVF)

In urban roads, the degree of openness or enclosure characteristics of the road can be partially determined by assessing the amount of irradiance entering a site or by the proportion of open sky that can be viewed from the site; this later component is termed the Sky View Factor (SVF). SVF illustrates the fraction of visual sky upward seen from the surface level in a specific location and depends on the geometry of the surrounding area Osmond (2010), Giridharan et al. (2005), Dimoudi et al. (2003). The range of this geometrical factor is between 0 (completely enclosed) and 1 (completely open) Lin et al. (2010). For each location, 3 SVFs were measured on each occasion (Fig 2.7); again, on SW pavement, center of road and NE pavement. The instrument being approx. 0.5 m away from the non-roadside of the pavement in those positions. The instrument was placed 1.1.m above ground road' level Lin et al. (2010) and Sanusi et al. (2016).

A fish eye lens photographers' camera named as (GoPro Hero4 Silver Edition, CHDHY-401). It is photographing a 180° viewing angle that was used to measure the SVFs of locations (Fig 2.8). It is an ultra-wide-angle lens and it outputs produced in the form of visual distortion (as a convex image instead of rectilinear appearance) (Fig 2.9) which prepared to produce a wide hemispherical picture with regular lines of perspective. An aerial image from the camera was transformed by using (Ray man software, Version 1.2 © 2000, Meteorological Institute, University of Freiburg, Germany) to calculate the SVFs of the locations by using mathematical equation to produce rectilinear frame. This software allowed the image to be scaled to allow valid comparisons between sites, and converted colours into a black and white format, thus allowing the proportion of the image representing open sky to be calculated.

Figure 2.7 Images taken at a location in St George's Terrace, showing the SVFs measurements being derived from the Fisheye camera. over the location in the middle of the road and it's both edges, by the researcher himself using (GoPro) camera.

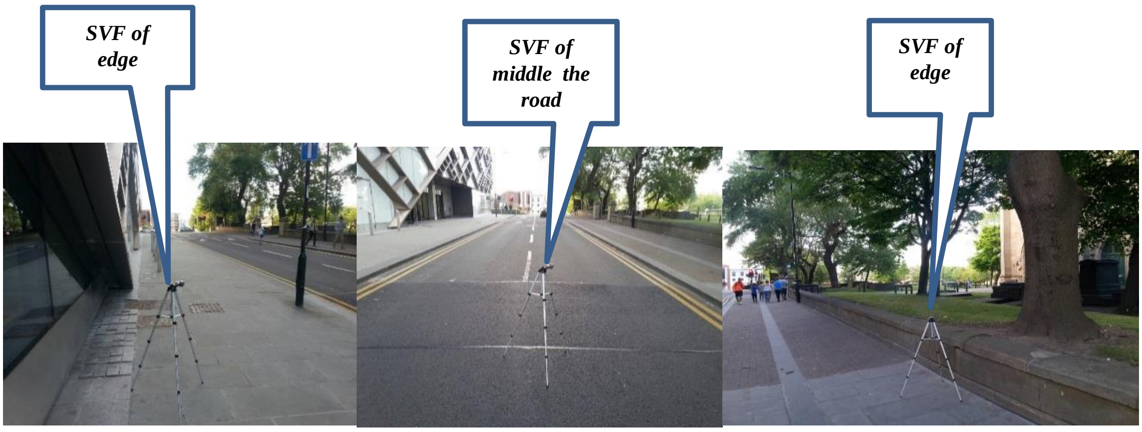
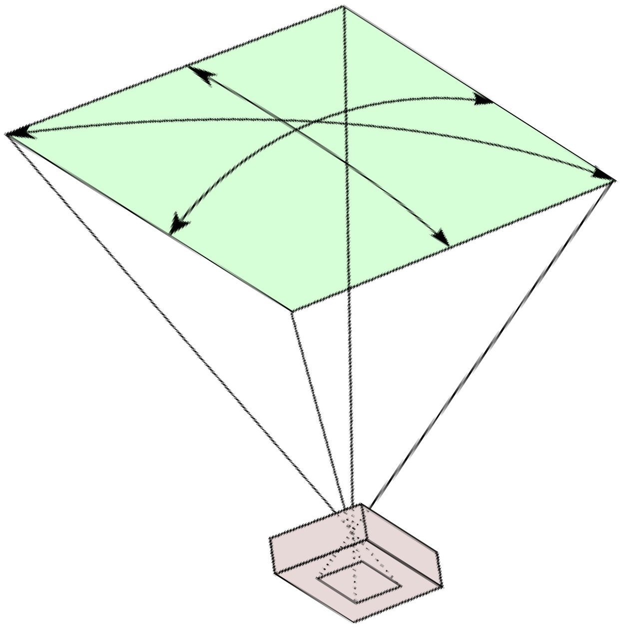


Figure 2.8 Image taken for the Fisheye photograph's camera Model (GoPro) device was used to measure the Sky View Factor (SVFs) for the locations (Top).

Figure 2.9 Diagram showing the instilling angle of the (Gopro) camera (Vertically) to take the (SVFs) and the view angle (deformed photography (quite rounded (image circle) produced by lens)) which described the angular extent of scene that taken by using the camera (upper case). Real image was taken by the camera explain the circle image produces by lens (bottom left and right).



2.3.2 Width of roads, height of adjacent objects and the determination of the Height width ratio (H/W)

The width of roads at specific locations were measured directly by calculating the distance between the structures located on either edge of the road. A handheld Laser Distance Meter (Model ASIN: B00YEEU9W2, Laser class II, accurate to 2 mm) was used to determine distance (Fig 2.12). Height (H) of both road side characteristics was calculated indirectly by using Pythagorean Theorem after measuring the width of the road (w) and the distance between the opposite edge and the top of roadside characteristic (R) (Fig 2.10) and (Fig 2.11). The height width ratio relates to the potential level of shading a particular roadside location may experience – the higher the surrounding the objects, and the narrower the road may tend to suggest the road will experience more shade. This does depend on time of day, however, and the orientation of incoming solar irradiance. For example, roads running along an east-west axis with tall buildings on the north side may still experience high levels of solar irradiance at mid-day – assuming there are few obstacles on the south side of the road. For this reason, many roads in the study were chosen based on a north west – south east alignment, i.e. with pavements at a south-west side and on a north east side. The extent to which such locations experience shade will thus depend on time of day (SW side experiencing most solar irradiance in the first part of the day, and NE side mostly in the latter part of the day), as well as the geometry and scale of surrounding infrastructure.

Figure 2.10 Images taken in the location (20 Carver St). It has (Office-Building) both roadside structures, showing the impact of (H/W ratio) to shade the road surface. It was measured in morning over the location by considering the height of NE features (Building Height) as a height value of the (H/W ratio) (Top). Image explain the height of the (H/W) ratio was considered in the morning (Bottom).

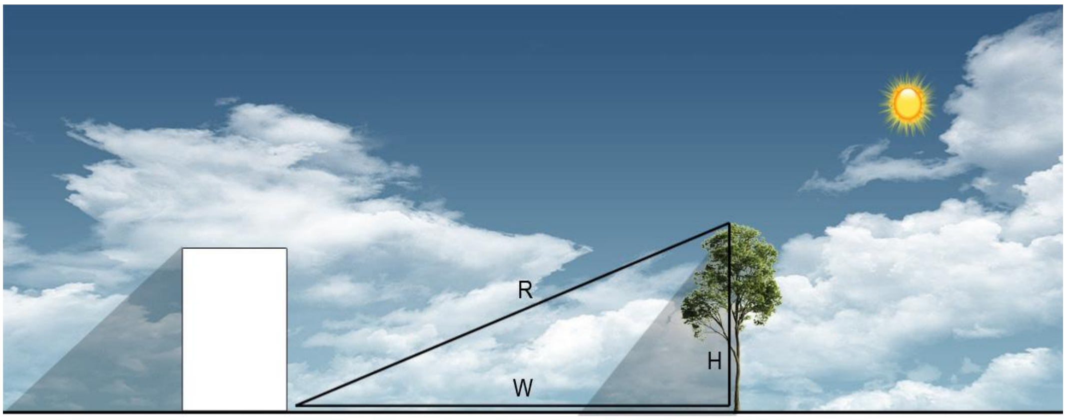


Figure 2.11 Images taken in the location (20 Carver St). It has (Office-Building) both roadside structures, showing the impact of (H/W ratio) to shade the road surface. It was measured in afternoon and evening over the location by considering the height of NE features (Building Height) as a height value of the (H/W ratio) (Top). Image explain the height of the (H/W) ratio was considered in the afternoon and evening (Middle and Bottom).

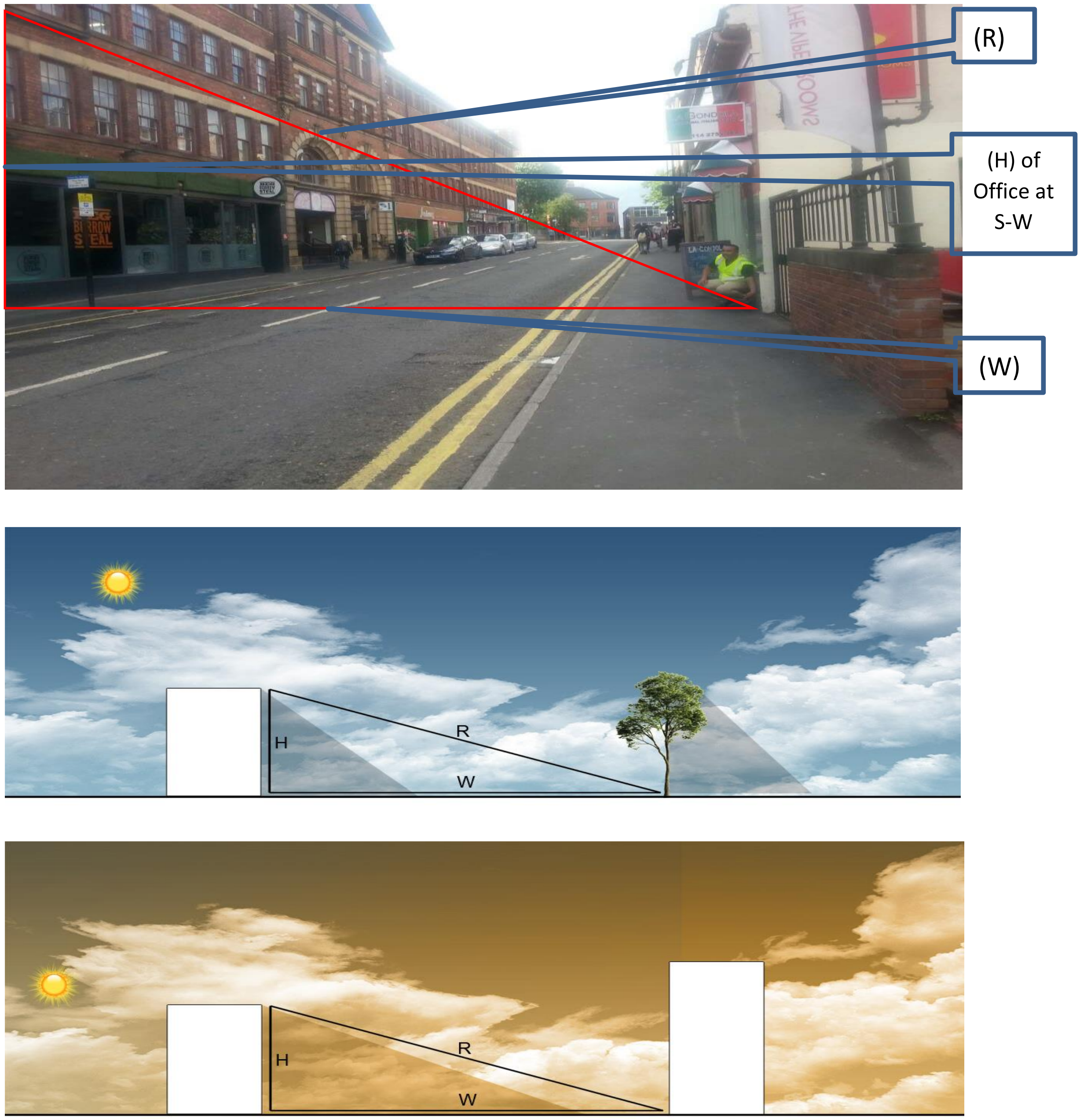
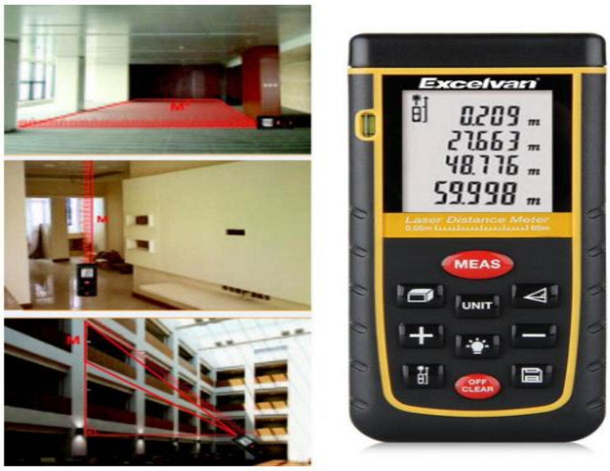


Figure 2.12 Image taken for the device was used to measure the height, width and the ratio between them (H/W), the device model is ''Handheld Laser Distance Meter (Model ASIN: B00YEEU9W2, Laser class II)''.



2.3.3 Site Selection and Degree of Openness

Depending on experiments conducted roads and site could be selected at random or through a more systematic process. In the first (Chapter 3) experiment road selection tended to be random (by viewing roads within the vicinity of the University using Google maps) and there were different features identified within a single road. These were categorized e.g. building- building indicating buildings at either side of this particular road location. Although the road selection was random, identification of contrasting roadside profiles was systematic as the objective was to compare temperature profiles in different morphologies. Distance was not treated systematically within a road, in that the aim was to compare different morphologies, however, each location in practice was at least 20 m apart, although this could be greater e.g. 40m (See Figs 3.3.-3.7 in chapter 3 for specific locations). In the second experimental chapter (Chapter 4) the processes needed to be statistically balanced so a matrix was developed to identify the different landscape morphologies (e.g. tree-tree; building-building, building tree, etc. see Table 4.1). In this case, specific examples of these morphological combinations were identified using ARCGIS so that even numbers of each were evaluated to ensure a balanced statistical design. Overall this identified 32 locations over eighteenth different roads

Specific locations within the roads were assessed for their degree of openness. This factor not only interacting with the amount of irradiance the location may experience, but also potentially further cooling factors such as exposure to (cooling) air movements e.g. cross winds. This was defined by assessing the amount of physical infrastructure around the locations (Chapter 5 mostly). For each road transect, build infrastructure was recorded 10 m in either direction (i.e. up the road or down the road, from the point of interest). The site was considered enclosed if there were no spaces located along the side of the road at that edges to allow the sunlight or ventilation to influence the road surface. Alternatively, it was considered 'open' if one or more spaces existed and thus potential could improve air movement and circulation.

Openness itself was affected by the presence and height of buildings and other infrastructure. Buildings were built structure in general (grey infrastructure) but in Chapter 4 were further categorized into two types; 'office' = a commercial building of ≥3 floors and 'house' a domestic property of 2 storeys height. Trees were identified as single stem (ie. with a trunk) specimens varying in height from approx. 7-15 m and 5-12 m diameter. Hedges could vary in length and were approx..1.2 – 2 m high.

Figure 2.13 Image explain the top view of the road surface. It is explaining the determination of opened/closed roadside by checking 10 m forward and 10 m backward from the centre point of the features located on either side.

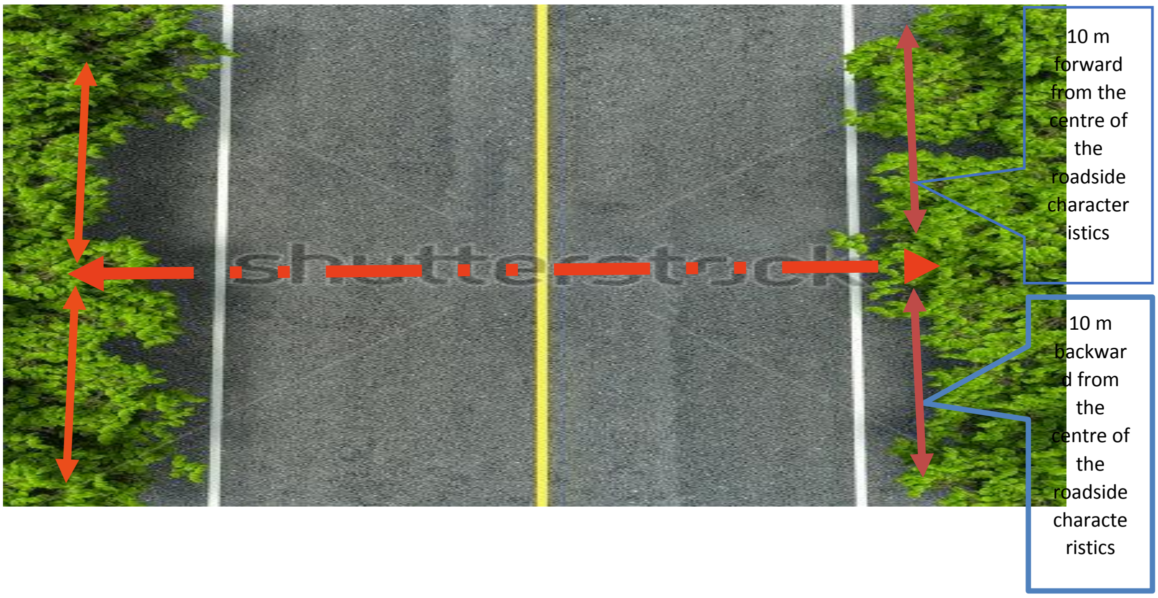


Figure 2.14 Image was taken in location (Carver St). It has (Office-Office) roadside features shows the way to determine opened/closed sides of the road by checking 10 m forward and 10 m backward from the center point of the structures located in SW and NE edges.

2.3.4 Colour of the characteristics located on roadside locations (building or tree colour) and colour of surfaces (carriageways and or pavements)

Colour (hue and tone) can affect the thermal properties of materials (dark or black objects tending absorb more solar irradiance and hence heat up, compared to white or light objects that reflect a greater proportion of incoming radiation), and so objects and surfaces associated with the road infrastructure were also defined by their colours. Vegetation was defined as green and builtwork depending on the predominant colour of the brick or façade. So a light building (e.g. surfaced with pale concrete) would be classified as a 0 in a binomial definition with a regression analysis (dark brick buildings in contrast being 1, see Figs 2.15-2.19).

Figure 2.15 Image taken at the location (Hoyle street). It has (Tree-Building), features, it shows the colors of both sides' structures (green on the SW side and red bricks in the NE side) (Top). The colours of the facade of the roadsides features (Bottom).

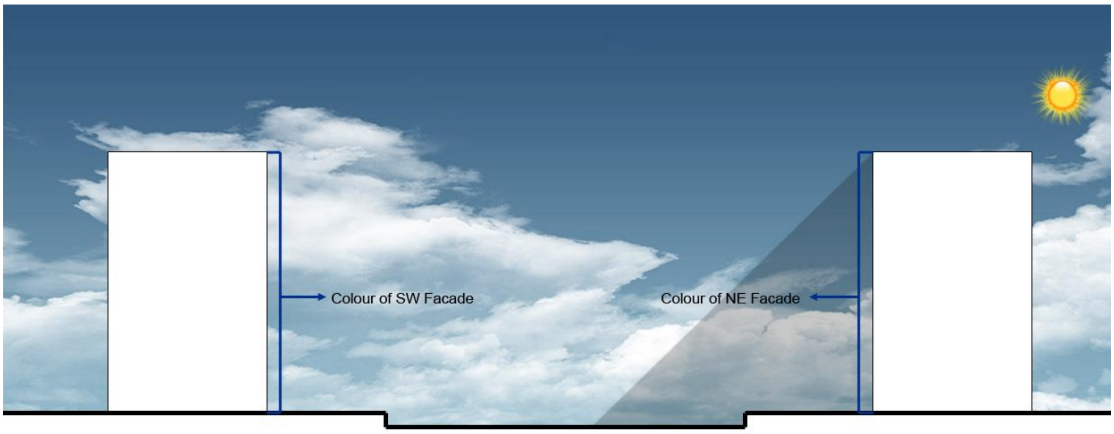


Figure 2.16 Images taken in location (15 Regent Terrace). It has (House-Office) features, it shows colours of the features in both side of the road and the colours of the surface in middle of the road (cars zones) and the both sides.

Figure 2.17 Images taken in location (15 Regent Terrace). It has (House-Office) features and it shows colours of structures in both sides of road. Figuer 1Figure illustrated white coluure of the house in SW face, the left Image shows black coluure of the office in NE face.

Figure 2.18 Images taken for the road surface in (15 Regent Terrace). It has (House-Office) features, it shows colours of the surface in the middle of the road (cars zones) and the both edges in the location.

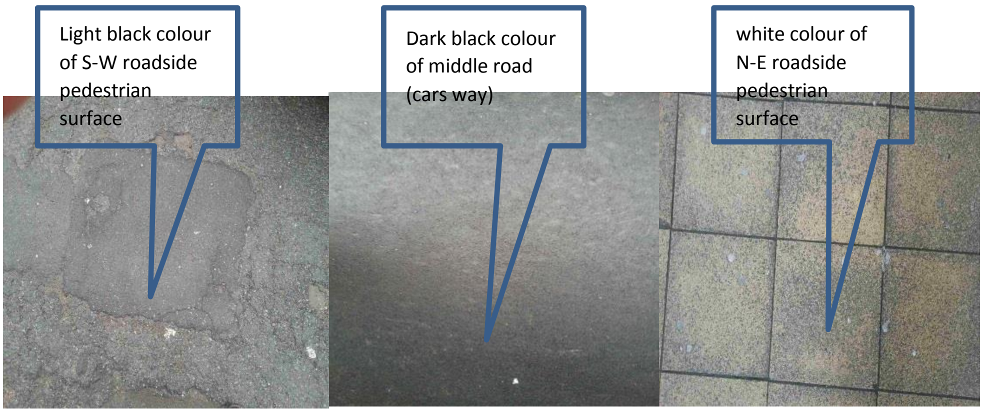
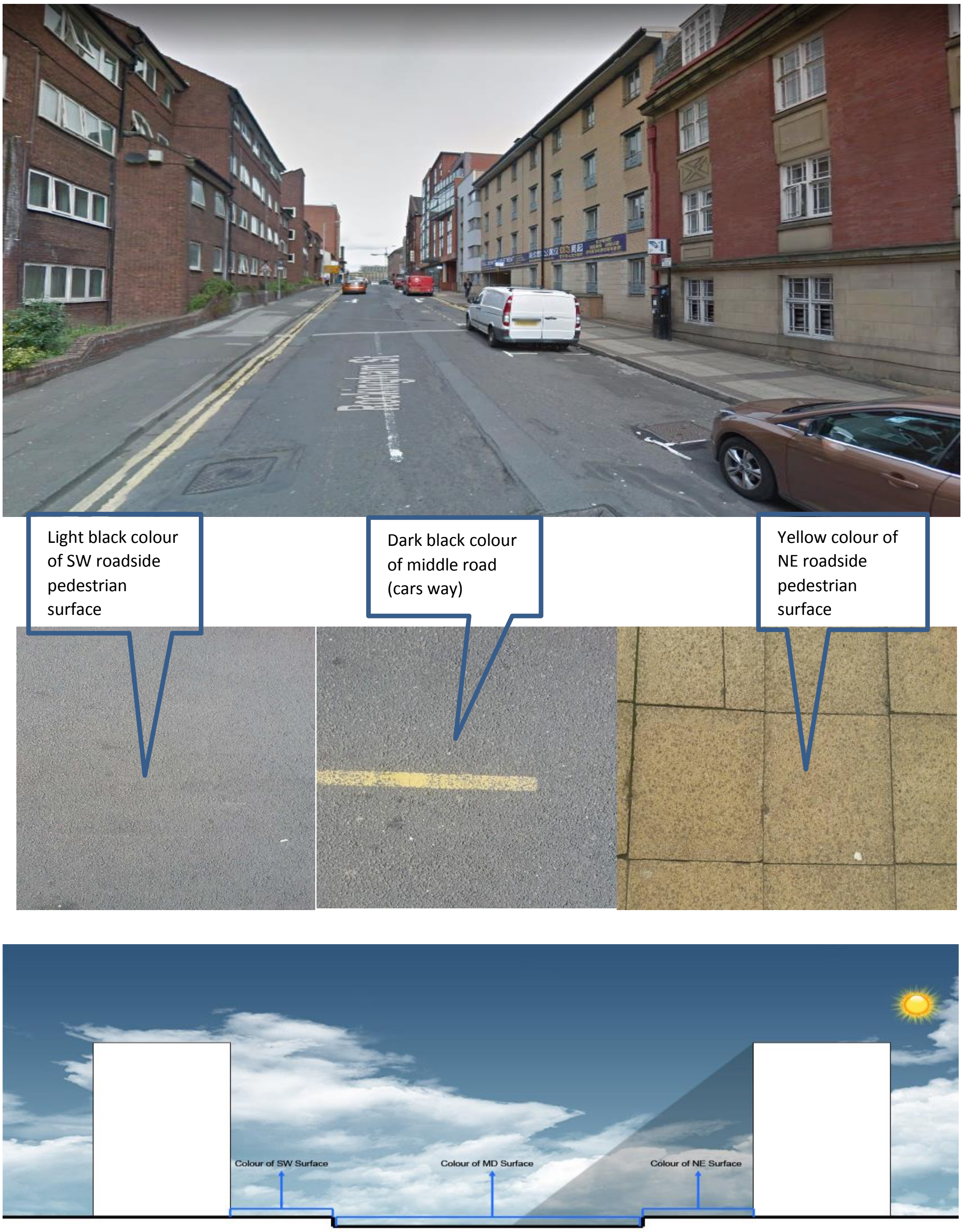


Figure 2.19 Images taken in location (Rockingham St). It has (Office-Office) roadside features (Top). Image showing colours of the surface in the middle of the road (cars zones) and sides of the same location (Middle). Image shows 3 zones of the surface colours (both edges and middle) (Bottom).



2.3.5 Number of passing cars per unit of time

Number of the cars per unit of time were recorded in some experiments (notably Chapter 6). This was to determine if relationships could be built up between temperature profiles for roads and the volume of traffic those roads experienced at certain times of day, or on certain days of the week. The researcher would place himself at the roadside and count the number of vehicles passing in both directions any given point on the roadways, using a click counter. See individual experiments for details on timings and duration of vehicle counts (the sequences and details of how long the traffic volume and other properties measurement was assessed in the individual experimental (experimental design in chapter 6).

This sort of method may give an opportunity to compare the effect of traffic volume (traffic jump and less traffic) in week and day time on the (ST).

2.4 Statistical analysis and presentation of the data

Several experiments in this dissertation conducted with various circumstances to mainly apprise the thermo-dynamic conductance of the road surface. Some of the experiments were under relatively homogenous condition (systematic of roadscape form) while the experiment of chapter one was under randomized of the field conditions. Data for each treatment, (12 min-24 max) replicates were recorded in practice to minimize the error in the thermal influence which might happened due to weather conditions.

In this dissertation, the procedure used for statistical analysis presented in the end of experimental design for each experiment. Data exploration was carried formerly to proper it for the analysis in order to estimate the degree of variance homogeneity and normality distribution using generalized Liner Model and homogeneity test options. To examine whether the data were normally distributed or not, square root value were used to modify it by using histogram test. Test which known (ANOVA) (Analysis of Variance) was used to evaluate the significance of different for the experimental variables. The significant influence of experimental variables at (1%) and (5%) was noticed when P-value was less than ($P< 0.01$) or ($P< 0.05$) respectively. The treatment average values are depicted with the graphs including the standard errors (SE). Generic of least significant difference (lsd) values were studied while an experimental variable exposed significant of effect (lsd of the interaction being presented, protected lsd). It bars for each experiment in different time will be plotted in each graphs and values presented in the captions of each graph. Its test was used to analysis the dataset of chapter (four, five, seven and eight). It generally was used to assess the influence of road-scape form on the surface temperature (ST), air temperature (AT) and wind speed (AV).

(ANOVA) test and lsd bars were automatically calculated by using the statistical package GenStat (Releases 8.1 to 10.1), provided by the University of Sheffield. Its values were carried out based on wiliams and abdi (2010) as the bellow equation:

lsd= $\mathrm{tv},\alpha\sqrt{2MS/n}$

tv, α is t critical distribution related with degree of freedom at α level, while n is number of observations was used to calculate the mean at each level, MS is error mean square.

Person's correlation was calculated to assess the relationship between traffic density and surface temperature (ST) in chapter seven. person's coefficient was used to identify the correlation level as (large, medium and small) when the coefficient are (≥ 0.50, 30-0.49 and, (≤ 0.29)) respectively (Cohen,1988).

The multiple regression model (Lu et al., 2012) was used to evaluate the relationship and (influences value) between surface temperature (ST) as dependent variable and environmental and physical properties as independent variables for example (Air temperature (AT), Air velocity (AV) and, Sky view factor (SVF), Height/ width ratio (H/W), Height of the characteristics located at both sides of the road at the experimental locations (H), width of the road (W), colour of the road surface and the features on the both sides of the road in each location respectively. Statistical package (Stata / IC 14) was using to run the multiple regression of the data set (Stata-Corp), It licenses were provided by the University of Sheffield, UK. Microsoft Excel 2016 was used to display the dissertation graphs, Scatter and box plots and scatter with precise line fit.

Chapter 3 : Thermal properties of Sheffield Roadscapes- Random selection: The Effect of green and grey structures

3.0 Hypothesis

The presence of trees along roadways reduces road surface temperature, to a greater extent than any influence due to the presence of buildings.

3.1 Introduction

Road surface temperatures are influenced by a number of factors, including the morphology of the streetscape, as determined by the presence of buildings, vegetation and other urban features. It is often considered that trees help to cool the streetscape through shading and evapotranspiration, thereby improving thermal comfort for pedestrians and car drivers (Maher, 2013). Whether this occurs and the extent to which it occurs in a temperate climate remains unclear, however. Also, there may be situations where tree canopies 'trap' in warm air, thereby exacerbating any localized heating events (Loughner et al., 2012). Because of the scientific foundation of the influence of roadside vegetation structure on thermal profiles of the road, there is a growing trend of literature that investigates the thermal influence of roadside vegetation structure. Those researches are based on a wide range of locations. Both research at the macro scale (for example – at a whole city scale) and micro scale (for example - park, buildings, green corridors or even at an individual plant scale) claim that vegetation structure has the ability to mitigate the surface and air temperature significantly (Roy et al.,2012; Liangmei et. al., 2008; Bau-Show Lin and Yann-Jou Lin 2010, Ram Pandit and David N. Laband 2010; Cameron et al., 2014). It was found that canopy of the green structure reduces the surface and air temperature because of the shade and evapotranspiration (Munoz et al., 2010).

Road temperatures are also influenced by the surrounding built structures, e.g. buildings. The intensification of the urbanization process leads to construction of high-rise buildings for both residential purposes due to a rising population and for commercial activities. Oke (1987) and Santamouris (2001) cite the different impacts buildings can have on surface temperatures and their role in affecting the urban heat island phenomenon. It needs to be acknowledged too though that buildings. Gill (2006) also provide shade and their relationship with road cooling may relate to their respective orientation to the sun at any given time of day. This research investigates the inter-relationships between buildings and trees in determining road temperature profiles in vivo, an aspect that has to date been under-researched.[2]

The aim of this chapter was to determine how roadside morphology and infrastructure affected road surface temperatures. The research aimed to determine whether there were systemic patterns of warming or cooling based on the features beside the roadways. As such, could universal 'generic' phenomena be described by the research or alternatively are temperature profiles of individual locations influenced by so many additional and different factors that it is difficult to determine overall significant effects due to the presence of trees or buildings, or other forms of infrastructure. A number of roads within the Sheffield city region were chosen for the study and specific locations chosen at random to determine how in each case, road morphology affected thermal profiles across the road. These 'case study' sites were then examined to determine how the surrounding morphology may be affecting temperatures profiles on different days and different times of day. Data sets

[2] The detailed literature related to this chapter is in the chapter 1

were then examined to determine any particular influences associated with features such as trees or large buildings. Among all those multiple roadside characteristics and features of the road surface itself, this chapter will focus on the general roadside characteristics. Therefore, the findings of this research will lay down foundation of further research of this dissertation.

3.2 Research Question

The following research questions will be investigated in this research.

- How do adjacent landscape features – (green v grey) and the different roadside structures affect the micro-climatic/thermal properties of roads?
- How is the influence of these features on road surface temperatures affected by different times of day?
- How universal are the influences of green v grey infrastructures (trees or buildings) on surface temperature, i.e. are there site-specific factors that promote / negate the influence?

3.3 Experimental Design

Road and pavement surface temperatures were recorded during the months of June, July and August 2015. Fifty separate locations (Fig 3.3- Fig 3.8) were monitored over the three-month period, with temperature data being recording in the morning (9:00-10:30), and afternoon (13:00-15:30) and early evening (19:00-20:30) for each location. For each location, 12 surface temperatures were recorded on each occasion (Fig 3.1); these represented the transactional 'profile' of the roadway, with road profiles (RP) 'A' to 'D' representing one pavement ('A' being the edge furthest away from the road itself and closest to the structure at the side of the road, e.g. building, tree grass verge etc.). RP_{E-H} represented temperature points across the road itself, with RP_{I-L} represented the opposite pavement profile, with 'I' being the point closest to structures adjacent to the road on this side. Surface temperatures were recording using thermometer device (testo 845 infrared), (see chapter 2 section 2.2.1 for details).

To evaluate the comparative cooling or warming potential of roadside structures, data was only collected on non-cloudy, clear sunlit days. (it was assumed differences would be minimal on days where heavy cloud cover or rain were predominant). As such the data profiles represent the warmest periods recorded in the City of Sheffield during 2015, not the average annual temperatures. In practice data was recorded in 6 days in June (5th, 9th, 12th, 16th, 25th and 30th), 12 days in July (1st, 2nd, 3rd, 4th, 5th, 6th, 9th, 10th, 15th, 16th 17th and, 20th) and 10 days in August (2nd, 3rd, 9th, 12th, 14th, 18th, 22nd, 23rd, 24th and 31st).

To avoid any bias due to the timing within in each recording slot (e.g. in the morning surface temperature may often be cooler at 9.00 compared to 10.30, irrespective of location; i.e. location being confounded by time) the order of recording between the 50 different locations varied on different days. So, the first recording of the day, was not in the same location every time, but was altered to help even out any diurnal influences.

The focus of the research was to identify how different roadside structures affected surface temperatures and how consistently these structures influenced temperature profiles. Therefore, road and locations were chosen that represented a diversity of roadside structures e.g. location with houses, apartments, trees, hedges, grassed verges, yet were not so far apart that climatic factors started to affect the temperatures recorded – e.g. large differences in altitude or wind exposure for example. Sites were also chosen to minimize the thermal influence of road traffic or industrial buildings. Sites also needed to be sufficiently close together (and does to the University) so that all could be recorded within the given time slots. In light of these considerations, 5 road sections were selected within 2 neighbourhoods in the west side of Sheffield. One neighbourhood (Psalter Lane [PL], 132 Hunter House Rd north-east to south–west orientation [HA] and 150 Hunter House Rd with north-south orientation [HB]) (figs 3.3- 3.4- 3.5 respectively) was approximately 1.6-2 km from the city centre, whereas the second neighbourhood (Upperthorpe Rd + Albert Terrace Rd [U] and St. Phillip's Rd [STP] was closer 0.8 km to the city centre) (Figs 3.2, 3.6 and 3.7). These were largely residential areas with some urban vegetation apparent within the streetscapes. Parts of St Philip’s Road and Upperthorpe Road also bordered the Ponderosa Park. For each of the 5 roads, 10 different locations were identified within each (see Figs (3.3)- (3.7) and Tables 3.1-3.5) and repeatedly recorded for their temperature profiles across the road profile (50 locations x 12 cross sectional temperature points x 3 recording times per day x 28 different days, i.e. 50400 data points in total). These temperatures are referred to as surface temperature data (ST), expressed in ^{o}C.

The key characteristics of each location was noted, i.e. presence of a building, tree etc. and used in the subsequent analyses in an attempt to explain the possible influences on the temperature profiles. These were used to define the location, with e.g. LT-B indicating a large tree (LT) on one side of the road and building (B) on the other. The locations were also identified by the road name (with an abbreviation being used) and the number of the location. So, location, 35 is on Upperthorpe Road (U) and has a tree present on one side and a building on the other and as such is denoted as U35 T - B.

Primarily, those roads were carefully selected from two different areas. In the first area (area-1) there are three roads named as those roads of the first area are located almost in the surrounding of Endcliff Park and extends over an area of 20 km². Besides, area-1 is far from the city centre by 1.6-2 Km and 3.5 Km from the area-2. Area-2 contains the rest two of the five roads, which are named as those roads are located in the surrounding of Pondarosa park (Fig 3.2).

Data analyses.

Analysis of variance was carried out to examine the significance of different experimental ST based on roadscape with mean values for each cross-sectional point represented in figures. Error bars are represented by Fisher's least significant difference values (at 5% level), (See section 2.4).

Figure 3.1 Image taken at location (U38 T-B) in the Upperthorpe Rd, explain the 12 RPA-L was measured over the location by using the thermometer device (testo 845 infrared measuring instrument).

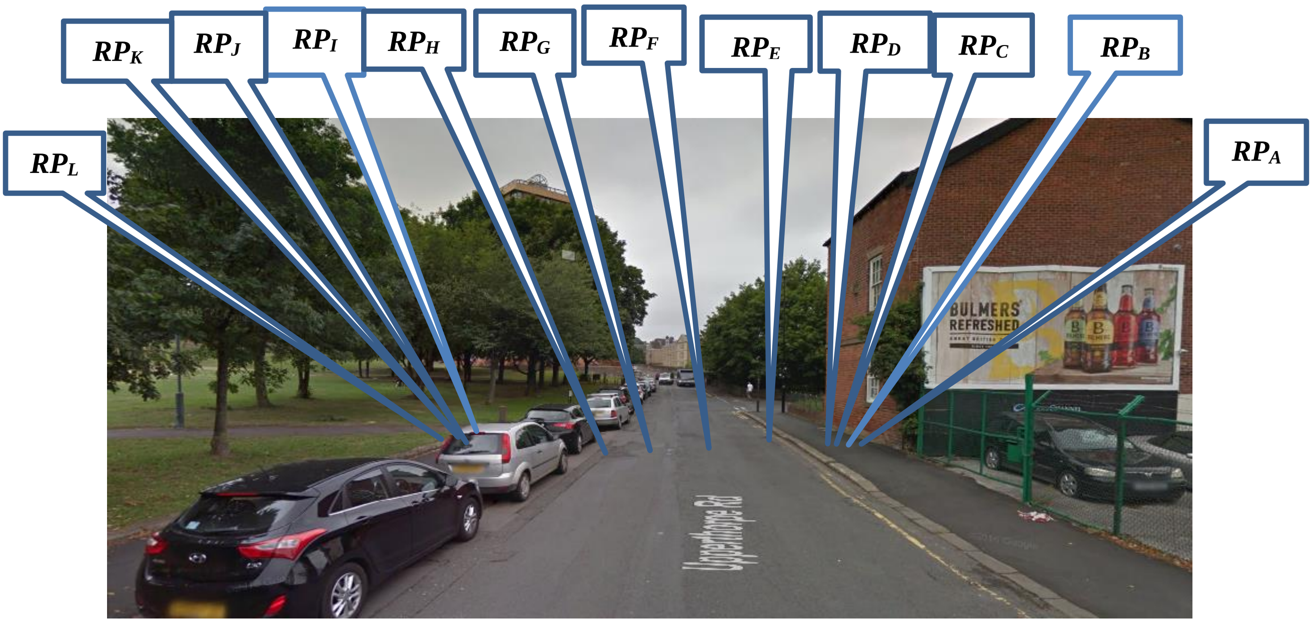


Figure 3.2 Showing Approximate diagram of work field structure of the chapter experiment, source: the author.

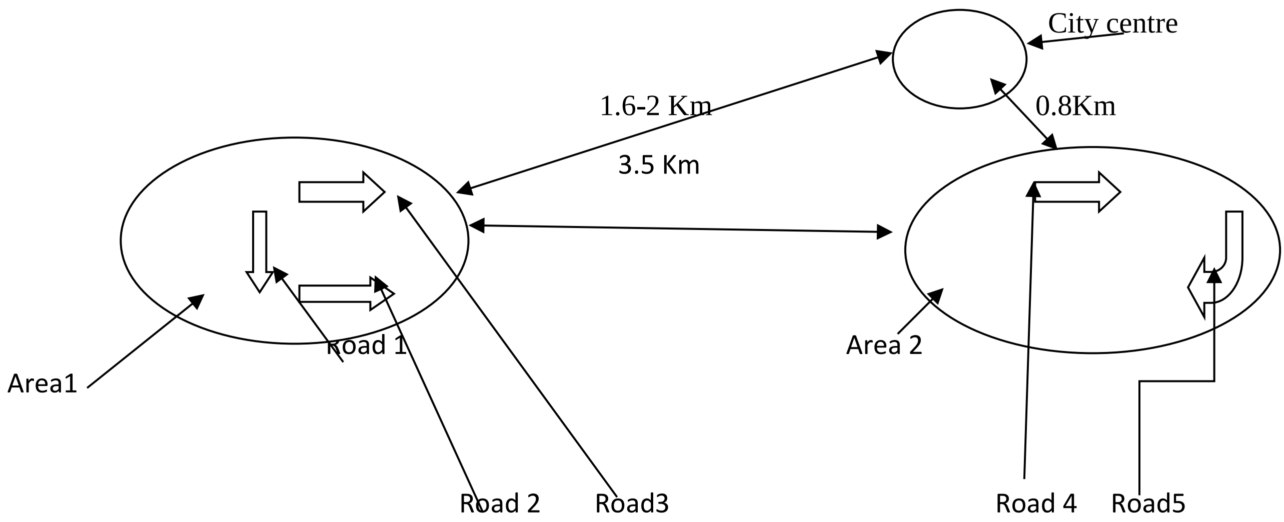


Figure 3.3 Showing the map of the of the ten locations on Psalter Lane (PL), source: The Arc GIS (Arc map).

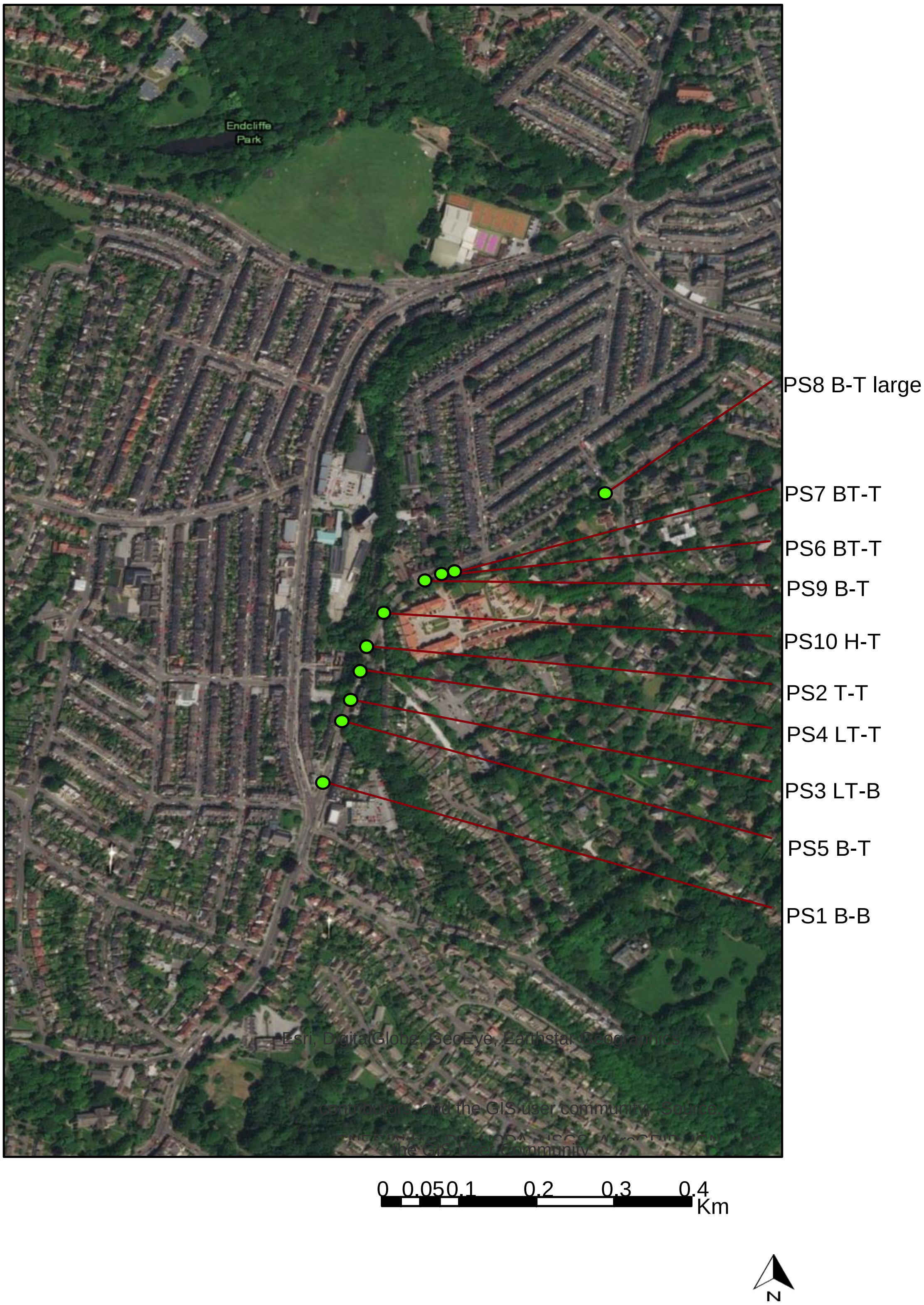


Table 3-1 Showing the exact GIS of the ten locations on Psalter Lane, by flowing the style (degree, minutes, second), (0, ‘’ , ‘), source: The Arc GIS (Arc map).

Sequences	Roadsides characteristics	Location Keys	GIS (degrees, minutes, seconds)
1	Building – Building	PS1 B - B	$1^{0}\,30'\,27.819''$ W $53^{0}\,21'\,38.838''$ N
2	Tree – Tree	PS2 T - T	$1^{0}\,30'\,25.395''$ W $53^{0}\,21'\,43.617''$ N
3	Large Tree - Building	PS3 LT - B	$1^{0}\,30'\,26.074''$ W $53^{0}\,21'\,42.453''$ N
4	Large Tree – Tree	PS4 LT - T	$1^{0}\,30'\,8.824''$ W $53^{0}\,21'\,51.216''$ N
5	Building – Tree	PS5 B - T	$1^{0}\,30'\,26.536''$ W $53^{0}\,21'\,41.473''$ N
6	Building Tree - Tree	PS6 BT - T	$1^{0}\,30'\,19.862''$ W $53^{0}\,21'\,47.784''$ N
7	Building Tree - Tree	PS7 BT - T	$1^{0}\,30'\,18.737''$ W $53^{0}\,21'\,47.642''$ N
8	Building – Large Tree	PS8 B – T Large	$1^{0}\,30'\,12.007''$ W $53^{0}\,21'\,50.112''$ N
9	Building - Tree- Heavy tree	PS9 B - T	$1^{0}\,30'\,26.997''$ W $53^{0}\,21'\,47.613''$ N
10	Hedge - Tree	PS10 H - T	$1^{0}\,30'\,26.074''$ W $53^{0}\,21'\,42.453''$ N

Figure 3.4 Showing the map of the ten locations on 132 Hunter House Road (HA).

Table 3-2 Showing the exact GIS of the ten locations on 132 hunter House Road.

Sequences	Roadsides characteristics	Location Keys	GIS (degrees, minutes, seconds)
11	Building – Hedge	HA11 B - H	1^{0} 30' 21. 156'' W 53^{0} 21' 55.485'' N
12	Building – Tree	HA12 B - T	1^{0} 30' 18.538'' W 53^{0} 21' 56.567'' N
13	Building - Building	AH13 B - B	1^{0} 30' 17.46'' W 53^{0} 21' 57.006'' N
14	Building - Building	AH14 B - B	1^{0} 30' 16.399'' W 53^{0} 21' 57.216'' N
15	Building - Building	AH15 B - B	1^{0} 30' 15.458'' W 53^{0} 21' 57.803'' N
16	Building – Building	AH16 B - B	1^{0} 30' 14.488'' W 53^{0} 21' 58.18'' N
17	Building - Building	AH17 B - B	1^{0} 30' 13.438'' W 53^{0} 21' 58.569'' N
18	Building – Building	AH18 B - B	1^{0} 30' 12.343'' W 53^{0} 21' 59.048'' N
19	Building - Building	AH19 B - B	1^{0} 30' 11.402'' W 53^{0} 21' 59.416'' N
20	Building - Building	AH20 B - B	1^{0} 30' 9.656'' W 53^{0} 22' 0.131'' N

Figure 3.5 Showing the map of the ten locations on 150 Hunter House Road (HB).

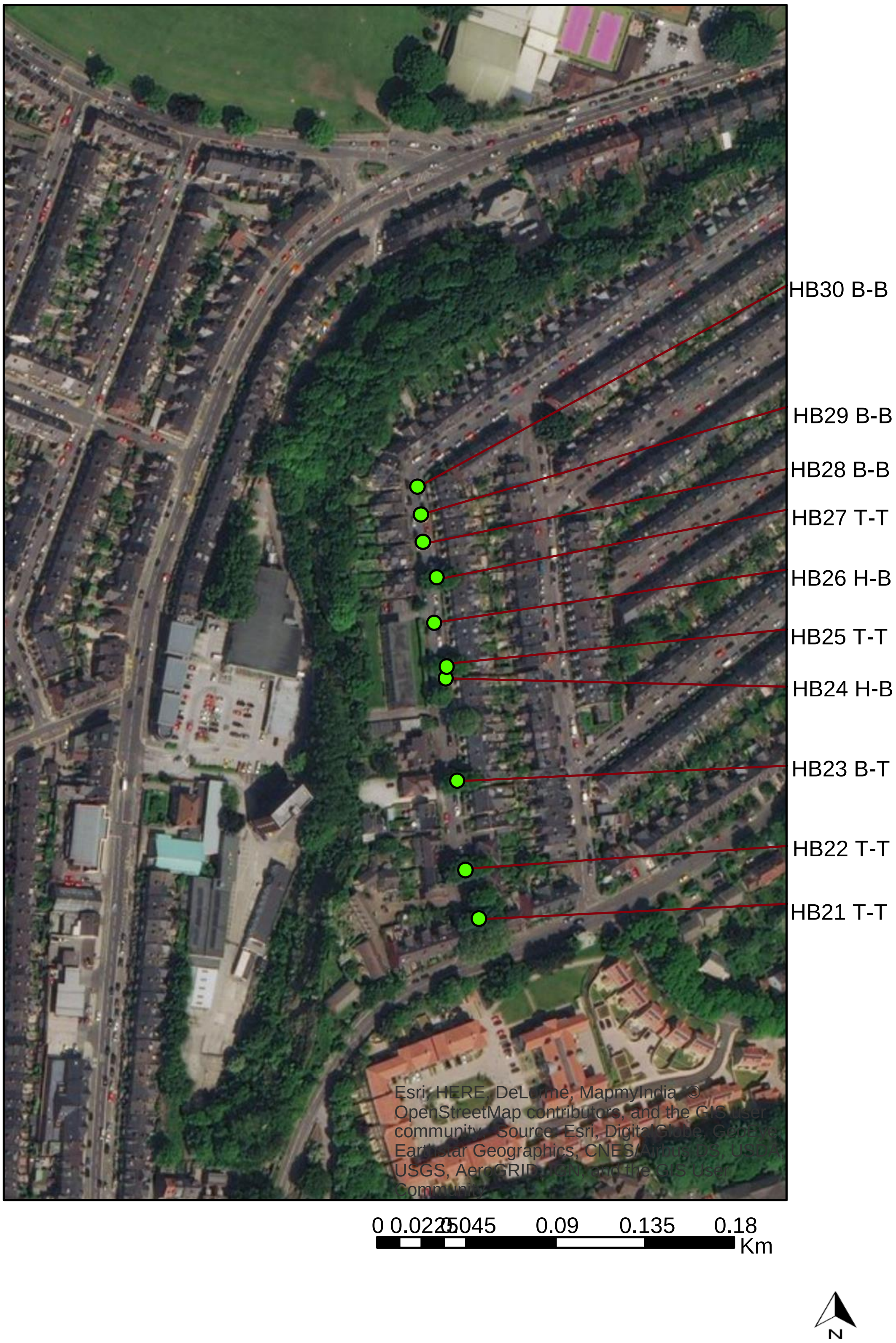


Table 3-3 Showing the exact GIS of the ten locations on 150 Hunter House Road.

Sequences	Roadsides characteristics	Location Keys	GIS (degrees, minutes, seconds)
21	Tree – Tree	HB21 T - T	1^{0} 30’ 19.796’’ W 53^{0} 21’ 48.377’’ N
22	Tree – Tree	HB22 T - T	1^{0} 30’ 20.138’’ W 53^{0} 21’ 49.13’’ N
23	Building - Tree	HB23 B - T	1^{0} 30’ 20.352’’ W 53^{0} 21’ 50.509’’ N
24	Hedge - Building	HB24 H - B	1^{0} 30’ 20.651’’ W 53^{0} 21’ 52.092’’ N
25	Tree - Tree	HB25 B - B	1^{0} 30’ 20.63’’ W 53^{0} 21’ 52.27’’ N
26	Hedge – Building	HB26 H - B	1^{0} 30’ 20.951’’ W 53^{0} 21’ 52.947’’ N
27	Tree - Tree	HB27 B - B	1^{0} 30’ 20.887’’ W 53^{0} 21’ 53.649’’ N
28	Building – Building	HB28 B - B	1^{0} 30’ 21.25’’ W 53^{0} 21’ 54.198’’ N
29	Building - Building	HB29 B - B	1^{0} 30’ 21.314’’ W 53^{0} 21’ 54.619’’ N
30	Building - Building	HB30 B - B	1^{0} 30’ 21.4’’ W 53^{0} 21’ 0.053’’ N

Figure 3.6 Showing the map of the ten locations on Upperthorpe Road and Albert Terrace (U).

Table 3-4 Showing the exact GIS of the ten locations on Upperthorpe Road and Albert Terrace.

Sequences	Roadsides characteristics	Location Keys	GIS (degrees, minutes, seconds)
31	Hedge – Hedge	U31 H - H	1^{0} 29' 0.78'' W 53^{0} 23' 27.52'' N
32	Hedge – Tree	U32 H - T	1^{0} 29' 2.682'' W 53^{0} 22' 26.346'' N
33	Building - Tree	U33 B - T	1^{0} 29' 9.065'' W 53^{0} 23' 21.917'' N
34	Hedge - Tree	U34 H - B	1^{0} 29' 6.182'' W 53^{0} 23' 24.183'' N
35	Tree - Building	U35 T - B	1^{0} 29 9.553'' W 53^{0} 23' 23.458'' N
36	Hedge – Building	U36 H - B	1^{0} 29' 0.772'' W 53^{0} 23' 20.295'' N
37	Building - Building	U37 B - B	1^{0} 29' 10.263'' W 53^{0} 23' 23.652'' N
38	Tree – Building	U38 T - B	1^{0} 29' 7.114'' W 53^{0} 23' 22.775'' N
39	Tree - Tree	U39 T - T	1^{0} 28' 59.302'' W 53^{0} 23' 19.1'' N
40	Building - Tree	U40 B - T	1^{0} 28' 57.773'' W 53^{0} 23' 18.189'' N

Figure 3.7 Showing the map of the ten locations on St Philips Road (STP).

Table 3-5 Showing the exact GIS of the ten locations on St Philips Road.

Sequences	Roadsides characteristics	Location Keys	GIS (degrees, minutes, seconds)
41	Building – Tree	Stp41 B - T	1^{0} 28' 56.486'' W 53^{0} 23' 16.335'' N
42	Tree – Tree	Stp42 T - T	1^{0} 28' 57.102'' W 53^{0} 23' 15.723'' N
43	Hedge - Tree	Stp43 H - T	1^{0} 28' 57.821'' W 53^{0} 23' 14.968'' N
44	Tree - Tree	Stp44 T - T	1^{0} 28' 58.77'' W 53^{0} 23' 13.763'' N
45	Building - Building	Stp45 B - B	1^{0} 28 59.19'' W 53^{0} 23' 12.661' N
46	Tree – Building	Stp46 T - B	1^{0} 28' 59.498'' W 53^{0} 23' 11.334'' N
47	Tree - Hedge	Stp47 T - H	1^{0} 28' 59.635'' W 53^{0} 23' 10.436'' N
48	Building - Hedge	Stp48 B - Hedge	1^{0} 28' 59.977'' W 53^{0} 23' 8.476'' N
49	Building - Building	Stp49 B - B	1^{0} 28' 59.977'' W 53^{0} 23' 7.313'' N
50	Tree – Building	Stp50 T - B	1^{0} 28' 59.908'' W 53^{0} 23' 6.069'' N

3.4 Result

For all five roads studied in this experiment, thermal profiling showed that surface temperatures tended to be highest during the afternoon compared to the morning at ($RP_{A\text{-}L}$, $P< 0.001$, lsd 5%), and the evening at ($RP_{A\text{-}L}$, $P< 0.001$, lsd 5%), (Figs 3.8 to 3.12 – see comparisons between different times). For points relating to the middle of the road ($RP_{E \text{ and } H}$) temperatures were approximately 2 to 4 ^{o}C ($P< 0.001$, lsd 5%) warmer in the afternoon compared to the same points in the morning.

A distinctive profile was attained for all locations, in that the middle of the road ($RP_{E\text{-}H}$) was usually warmer than the edges, i.e. pavements ($RP_{A\text{-}D}$ and $RP_{I\text{-}L}$) at morning ($P<0.001$) afternoon ($P< 0.001$, $P=0.01$) and, evening ($P<0.001$) respectively (Figs 3.8-3.12).

Locations within a specific road significantly affect the temperature profiles recorded across the road. For example, in Psalter Lane location (Fig 3.8.) PS8B-TLarg had significantly lower temperatures than other locations within this road at ($RP_{A\text{-}D}$, $RP_{E\text{-}H}$ and, $RPI_{\text{-}L}$) in the morning by approx. 2-3 ^{o}C ($P<0.001$, range $P=0.0014$ to 0.0165) and, ($P<0.001$, lsd 5%) in the afternoon by approx. 1.5-3 ^{o}C ($P<0.001$, range $P=0.0024$ to 0.0292) and, ($P<0.001$, lsd 5%) and in the evening by around 1.5-2 ^{o}C (range $P<0.001$ to 0.0071, range $P<0.001$ to 0.0256 and, $P<0.001$, lsd 5%), respectively. Similarly, other locations with trees, PS2T-T for example, were often significantly cooler than those surrounded by buildings alone e.g. PS1B-B. Similar trends were found across all five roads. In the data set for around 150 Hunter House Road (Fig 3.10.), all the coolest temperatures were associated with locations where trees were present, i.e. HB21T-T, HB22T-T, HB25T-T and HB27T-T at ($RP_{a\text{-}l}$), by approx. 1.5-2.5 ^{o}C, ($P< 0.001$, lsd 5%) in the morning, afternoon and, evening.

The location with the overall lowest afternoon temperature was Psalter Lane location PS8B-TLarg (Fig 3.8). Although there was a building at one side of this location, the other side was dominated by a large tree, with a mean temperature below this tree of 22 ^{o}C during the afternoon (and 18.5 and 20 ^{o}C in the morning and evening, respectively, Fig 3.8.). Although locations with trees tended to be cooler than those with buildings, there could still be significant differences in the temperature below the trees; PS8B-TLarg, for example, being cooler than PS6BT-T or HA12B-T during the afternoon (Fig 3.13).

In a similar manner, the number and dominance of trees could vary at the different locations and the cooler temperatures of PS8B-TLarg may relate to a number of trees being present (Fig 3.14) for example compared to the presence of a single tree at HB23B-T (Fig 3.15); approx. 3-3.5 ^{o}C, (range $P<0.001$ to 0.0073), (lsd 5%), difference being noted here (Figure 3.16). Orientation of the street and the angle of sunlight at the time could also be affecting the surface temperature of the road and the influence of these effects are not necessarily consistent across the different locations

Thermal profiles within specific aspects of the road morphology could be relatively consistent. For example, a streetscape where there were terraced cottages i.e. continuous buildings without spaces between them, significantly suppressed the variation of ST on that side of the road. For instance, thermal profiles of locations 132 Hunter House Road Section A (Fig 3.9) hardly changed with one side of the road (RP_{A-F} between different locations along this road. Similar trends were found in all three intervals of data collection (morning, afternoon and evening) (RP_{A-J}, range $P=0.9995$ to 0.2037), (RP_{K-L}, $P=0.0018$) and, ($P=0.0018$ to 0.0307, lsd 5%) in the morning, (RP_{k-L}, range $P=1$ to 0.201) in the afternoon and, (RP_{A-L}, range $P=0.9967$ to 0.0597).

Generally, road surface temperature differed significantly between different location at (RP_{A-L}) on the road. As the ($P<0.001$, lsd 5%) at morning, afternoon and, evening for all population are statistically significant, it indicates the significant influence of the road-scape on the surface temperatures. This is true for all five roads of this experiment. This also indicates that road side characteristics are important to make the road surface temperature differential (mitigate and increase) although the environment, orientation, materials of the road, urban context are the same.

Figure 3.8 Thermal properties of locations on Psalter Lane: - Means surface temperature (n=28 days), at 9.00-10.30 (top), 13.00-14.30 pm (middle) and 18.00-19.30 (bottom), n= 28 days. Letters relate to points across the profile of the road.

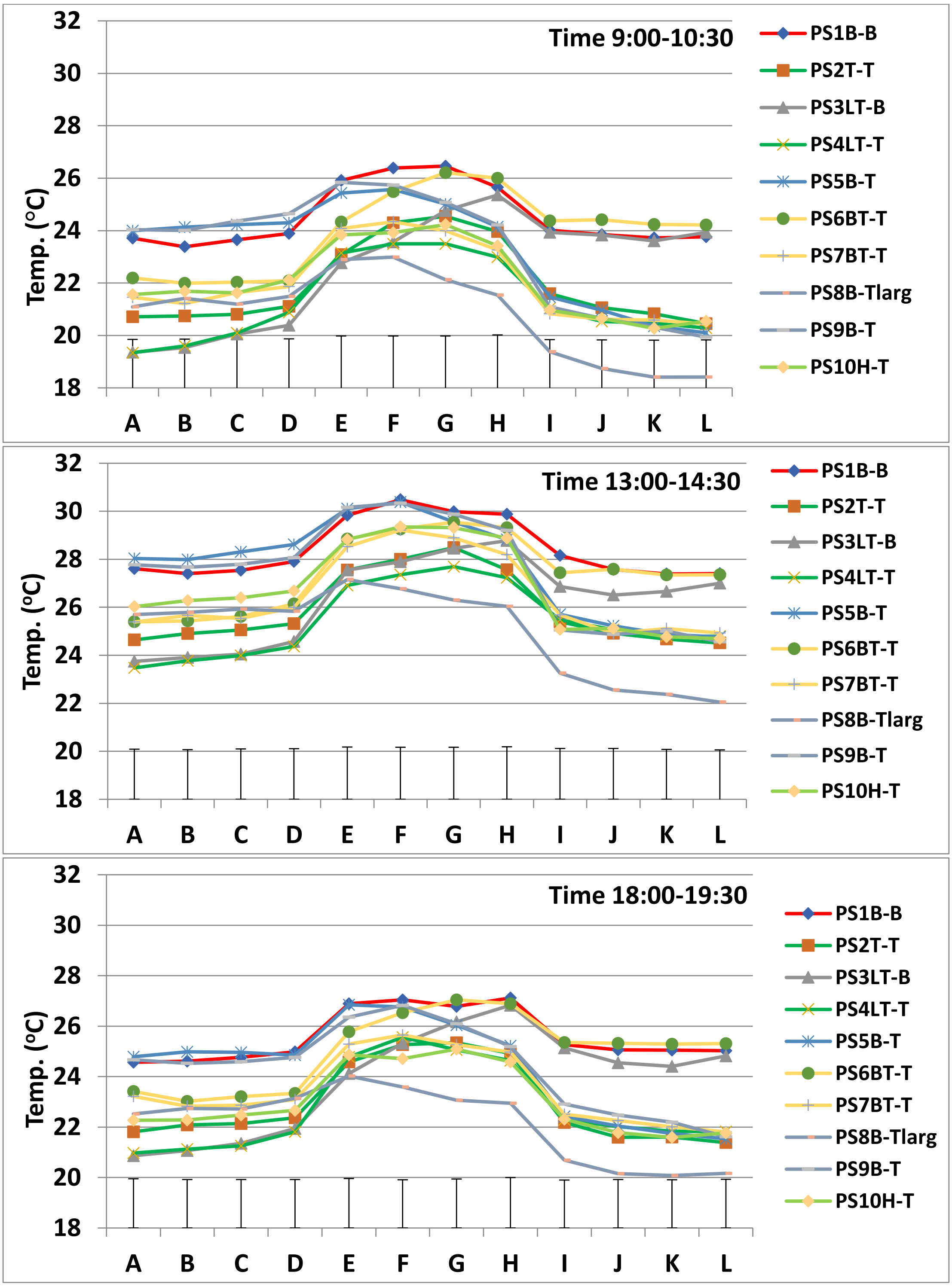


Figure 3.9 Thermal properties of locations on 132 Hunter House Road: - Means surface temperature (n= 28 days), at 9.00-10.30 (top), 13.00-14.30 pm (middle) and 18.00-19.30 (bottom).

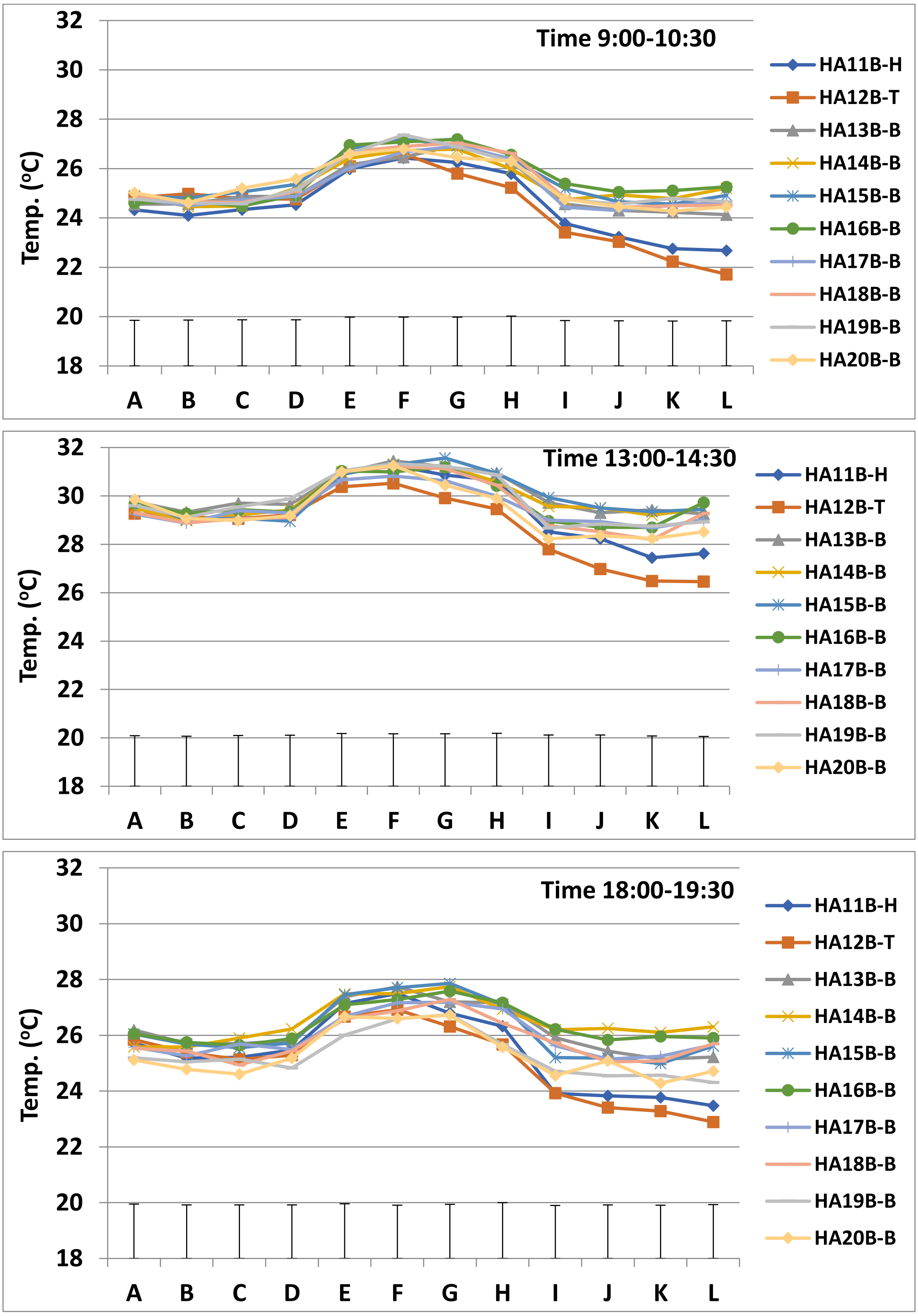


Figure 3.10 Thermal properties of locations around 150 Hunter House Road: - Means surface temperature (n= 28 days), at 9.00-10.30 (top), 13.00-14.30 pm (middle) and 18.00-19.30 (bottom).

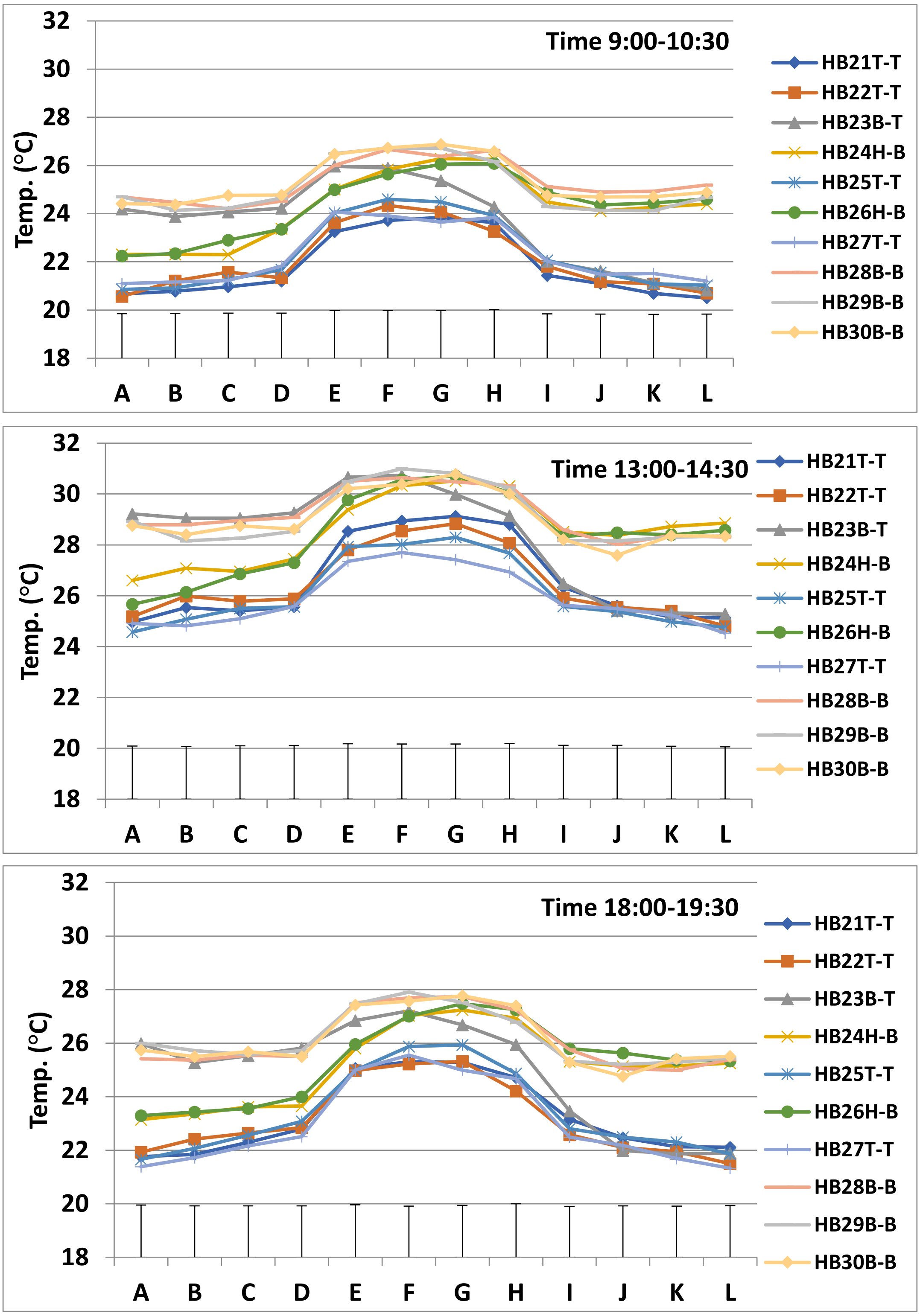


Figure 3.11 . Thermal properties of locations around Upperthorpe Road and Albert Terrace: - Means surface temperature (n= 28 days), at 9.00-10.30 (top), 13.00-14.30 pm (middle) and 18.00-19.30 (bottom).

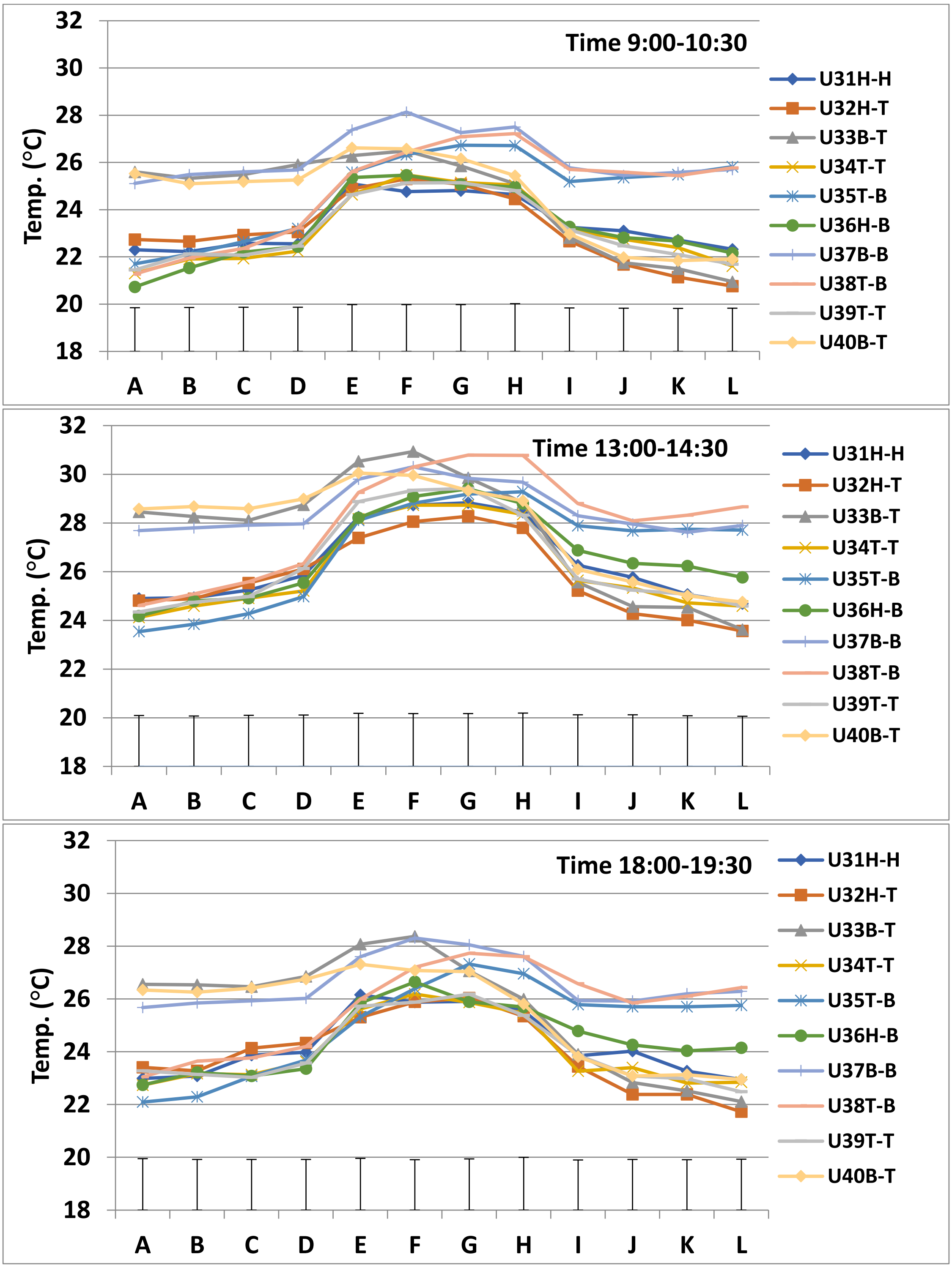


Figure 3.12 Thermal properties of St Philips Road: - Means surface temperature (n= 28 days), at 9.00-10.30 (top), 13.00-14.30 pm (middle) and 18.00-19.30 (bottom).

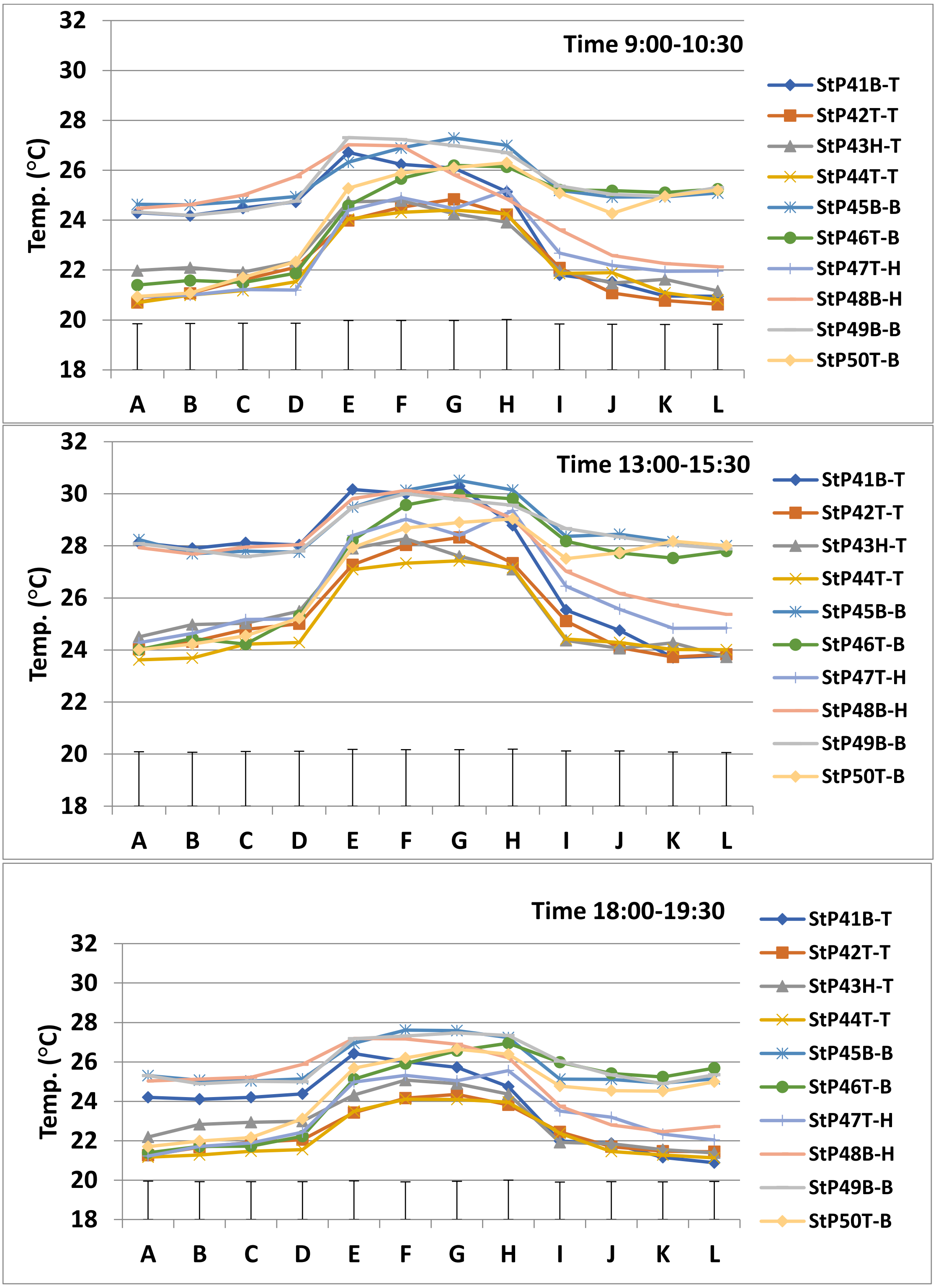


Figure 3.13 Thermal properties of selected locations with trees present - Means surface temperature (n= 28 days), at 9.00-10.30 (top), 13.00-14.30 pm (middle) and 18.00-19.30 (bottom).

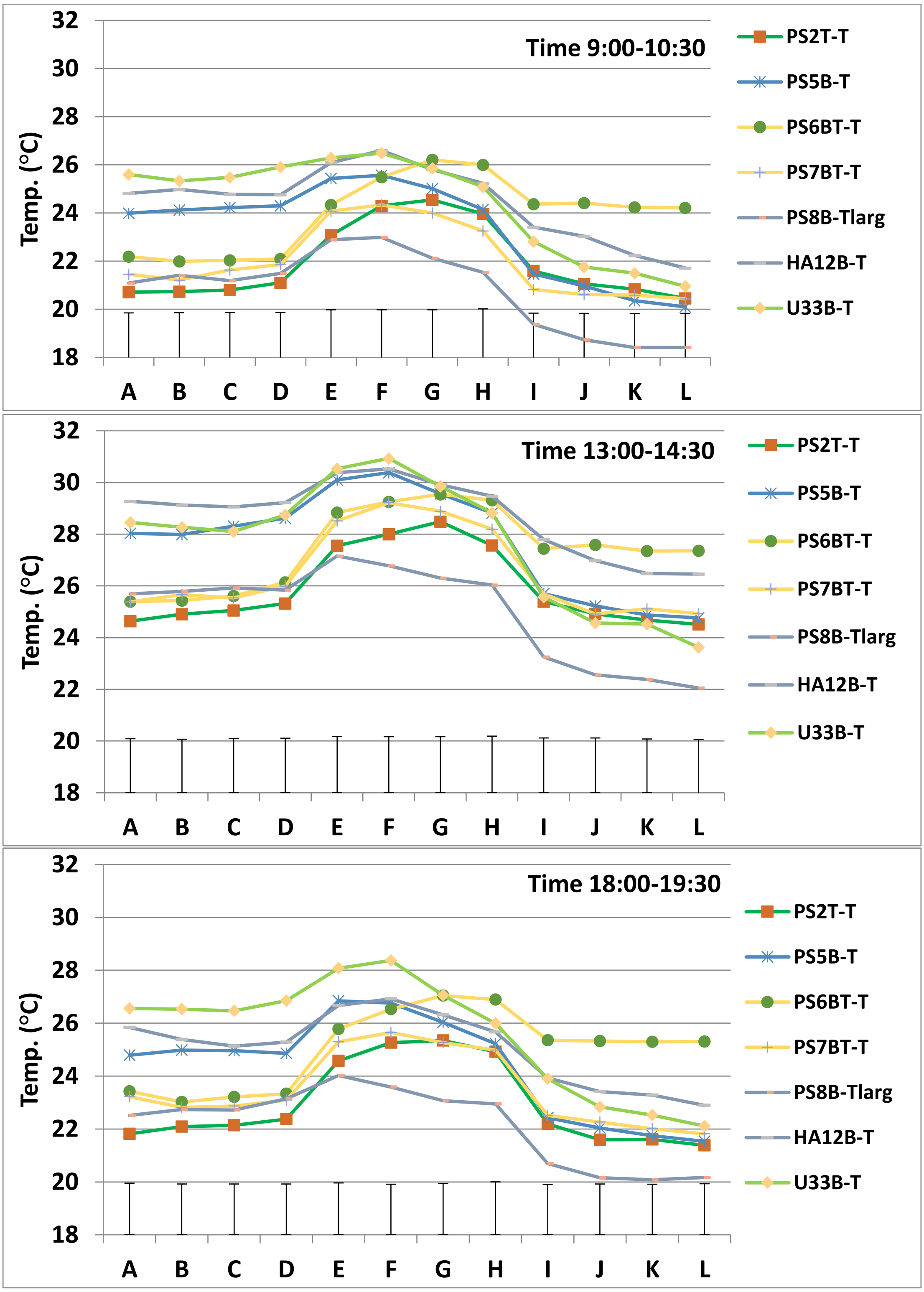
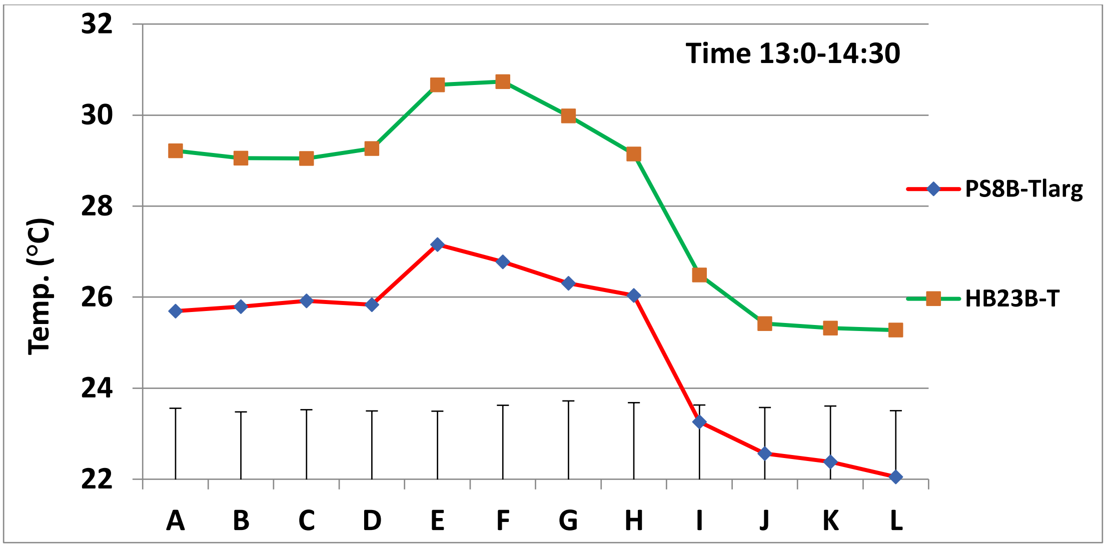


Figure 3.14 A group of trees at location 8 Psalter Lane (Building to Tree Large profile) PS8B-TLarg.

Figure 3.15 A single tree at location 23 Hunter House Road (Building to Tree profile) HB23B-T.

Figure 3.16 Thermal properties of two selected locations with trees present – afternoon 13.00-14.30 data. Comparison between mean of surface temperature (n=28 days) of location 8 Psalter Lane (Building to Tree Large profile) PS8B-TLarg and 23 Hunter House Road (Building to Tree profile) HB23B-T.



Locations dominated by buildings could also show differences in their temperature profiles, although these were not always significantly different. For example, there could be 1.4 ^{o}C difference between PS1B-B and HA15B-B in the morning, especially at points $RP_{A,B,C,D,}$ (Fig 3.17.). This was due to the one location being in shade during the morning, but also because of the different surface materials at the edge of the road. PS1B-B was grass and clay, whereas HA15B-B was tarmac. Other building profiles showed variation in their temperature profiles, for example, location 13 and 15 were almost 1.5 ^{o}C different from location 45 (Fig 3.18.); possibly due to the fact that location 45 (Fig 3.19.) was located close to a large park – 'The Ponderosa'.

Figure 3.17 Thermal properties of 2 selected locations with buildings present– morning 9.00-10.30 data. Comparison between mean of surface temperature (n=28 days) of location 1 Psalter Lane (Building to Building profile) PS1B-B and location 15 Hunter House Road (Building to Building profile) HA15B-B.

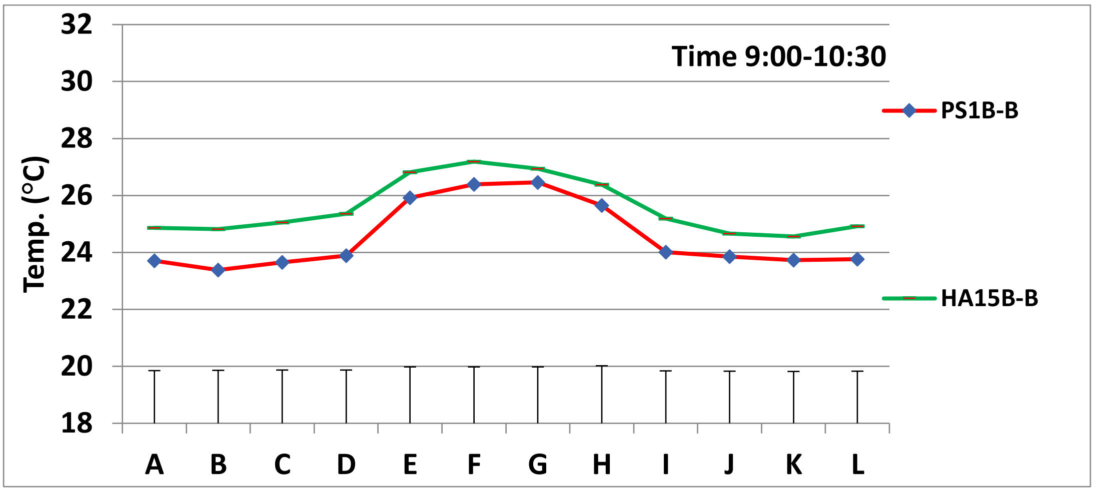


Figure 3.18 Thermal properties of 3 selected locations with buildings present – afternoon 13.00-14.30 data. Comparison between the mean of surface temperature (n=28 days) of locations 13 and 15 Hunter House Road (HA14B-B and HA15B-B) and location 45 St Patricks Road (StP45B-B).

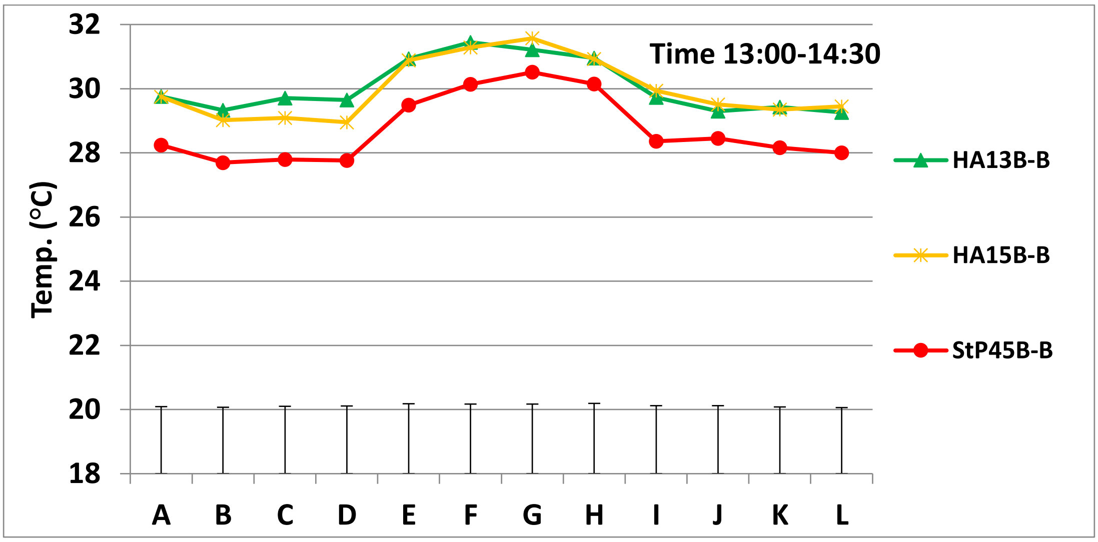


Figure 3.19 Roadsides characteristics (Building-Building) at locations 45 of (St Phillip's Rd) near to the Ponderosa Park (StP45B-B).

Other factors could dictate differences in temperature profiles. During mornings, temperatures at PS3LT-B were lower than U35T-B by approx. 2 ^{o}C, (RP_{A-G}) (range P=0.009 to 0.0112), (RP_{H-L}),(P= 0.0435 to 0.0813), (lsd 5%), (Figure 3.18) possibly due to the presence of other vegetation e.g. a hedge, but also the more open nature and perhaps higher altitude of the site (this road being on a hill, Fig 3.21) compared to that of U35T-B (Fig 3.22). Values were significantly different for the two locations for the points $RP_{A,B,C,D}$.

Figure 3.20 Thermal properties of two selected locations with buildings and trees present– morning 9.00-10.30 data. Comparison between mean of surface temperature (n=28 days) of location 3 Psalter Lane (Tree Large to Building profile) PS1B-B and location 35 Upperthorpe Road (Tree to Building profile) H35T-B.

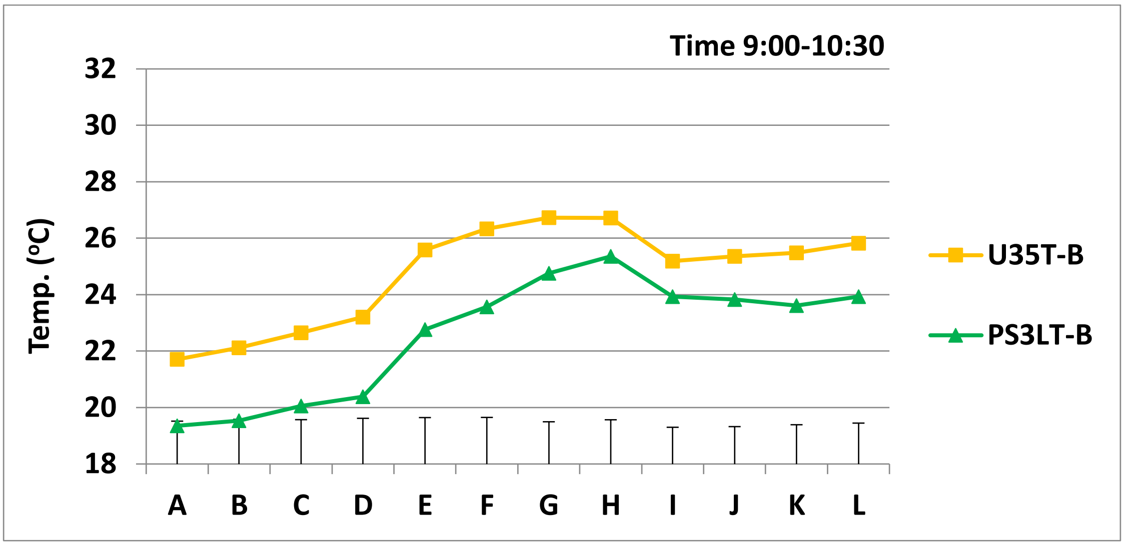


Figure 3.21 Roadside characteristics at location 3 (Tree to Building profile) in Psalter Lane (PS3LT-B).

Figure 3.22 Roadsides characteristics at location 35 (Tree to Building profile) at Upperthorpe Road and Albert Terrace junction (U35T-B).

3.5 Discussion

Graphical presentation of the thermal profile of the five roads showed that all the coolest road surface temperatures were associated with locations with trees. This indicates that green infrastructure such as street trees, plays a significant role in mitigat in groad surface temperatures. This is in line with previous, For instance, Roy et al. (2012) found that the urban green infrastructure has the ability to mitigate both surface and air temperatures within busy locations of town/city centres. Givoni (1991) showed that green infrastructure including parks, tree planting along streets, and green roofs reduces surface air temperature. Armson et al. (2012) investigated the effect of green infrastructure on the surface temperature of small plot and parks in Manchester, UK based on the data of several days of 2009 and 2010 and found that both grass and trees effectively cool adjacent surfaces. Other studies (Gillner et al., 2015) found that the surface temperatures areas exposed to full sunlight are up to 15.2 Kelvin warmer than that in the tree shaded areas. The current research found that trees along roads have a cooling effect on the road surface temperature by around 3.5-4.5 ^{o}C.

Different researches that attempted to explain the variation of surface thermal temperature used different study fields. Some papers used land plots, parks or surface of urban areas while some used building roofs. In the present research, however, we have used only different roads located near the city of Sheffiled, UK as study field. From this point of view, this is the novelty of this experiment in this research arena. In addition, the study field location near the city provides a unique set of roadside structures where green and grey infrastructures are combined together.

Results of the experiment also found that the middle of the road temperatures were approximately 2 to 4 ^{o}C warmer in the afternoon compared to the same points in the morning. This is to some extent to be expected as solar irradiance is at a maximum at this point in the day, and that heat is building up throughout the day in the road surface materials (heat absorbing black tarmac). It does conflict however, with the concept that heat energy is accumulating from car traffic movement (friction for tyres) as the middle of the day is probably one of the quieter periods for traffic movement (after morning 'rush-hour' and before evening 'rush-hour'. If traffic movement was having a significant effect, it might be anticipated that peak temperature in the middle of road occur at the start and end of the daylight period. The influnce of road traffic movement will be examined in later chapters. However, in some individual cases, pavement can be warmer than the middle of the road. This may be due to solar energy being trapped on some areas of pavement and materials used to build them.

Along with green infrastructure, there are some other structures that have an effect on surface temperature. It is also found that thermal profile within a specific aspect of the road with continuous buildings significantly reduces the variation of ST. It also indicates that similar kind of roadside structure can reduce the variation in road surface temperature that has an important implication in planning of road side structure. As Gill (2006) mentions that buildings can also provide shade. But the position of the trees and building beside roads, distance among them, characteristics of the buildings (height, colour, materials) are not specifically documented in this chapter.

The present experiment explains the variation on the road surface temperature considering only two aspects- green infrastructure and buildings. The current experiment found that although locations with trees tended to be cooler than those with buildings, there could still be significant differences in the temperature below the trees. But this experiment only considers the presence and absence of these aspects rather than the specific characteristics (height, width, canopy of trees etc.). But we need to look at the specific characteristics of the green infrastructure. For instance, if a large tree stands at one side of the road at one point while a small tree is on another point, it is likely that the first point will have cooler road surface compared to the second point. Research found that canopy of the green structure reduce the surface and air temperature degree because of the shade by the canopy of green infrastructures (Gómez-Muñoz, Porta-Gándara and Fernández, 2010). Therefore, specific charactertistics of the green infrastruture may lead to create variation on the road surface temperature which has also been studied in other researches. For instance, Dousset and Gourmelon (2003) mentioned different reasons for the urban/rural temperature variance which are – (1) changes in the physical characteristics of the surface (albedo, thermal capacity, heat conductivity); (2) replacement of vegetation by asphalt and concrete; (3) the decrease of surface moisture available for evapotranspiration; (4) changes in the radiative fluxes and in the near surface flow, resulting from the complicated geometry of streets and tall buildings; and (5) anthropogenic heat emissions.

Although it is almost impossible to cover all the factors to determine the surface temperature variation in a single chapter, the following experiments of this dissetation will expand to factors other than buildings and trees. Moreover, there are other factors- traffic movement, colour of the road, road materials etc which also effect the road surface temperature. Considering all these, this research provides a partial result of road surface temperature variation. The following experiments will add more parameters (orientation of the street, geometry, road colour, traffic movement etc.) that will provide more refined results of the causes of road surface temperature variation. Nevertheless, this chapter establishes the foundation of this dissertation with the findings that green and grey roadside infrastructures effect the road surface temperature significantly. However, the findings of this study provide a basis for the urban planning related policies to reduce urban temperatures and thus reduce urban heat island effects.

3.6 Concluding points from Chapter 3:

- Temperatures across all roads had a distinctive profile, with temperature generally lower at the sides and rising towards the middle of the road.
- Locations with trees tended to be cooler than locations with buildings, surface temperatures being up to 5 to 6 ^{o}C cooler at the base of the tree.
- There could still be variation in temperatures with a single landscape typology. For example, the number of trees present, the height/exposure of the location or the proximity of other green space nearby appears to be further influencing temperature profiles.
- Thermal profiles show that specific characteristics could dominate the surface temperature of opposite roadside at the same location, while the different roadsides characters generated the source of thermal variation.
- Terrains and open spaces are a source to reduce the thermal impact and create variation of thermal profiles, while concentration of buildings (houses design in the UK) is unlikely to generate the thermal variation over the road surface, this might happen due to lack of green infrastructure, less ventilation as a function of open space, proportion of improbability might higher etc.

3.7 Implications from chapter 3

This data used a random approach to identify how landscape morphology might influence temperature profiles. However, it did not systematically evaluate the key morphologies and the following chapter (4) aims to see if the data is strengthened using a more robust statistical approach. In essence, designing the experiment to ensure *even numbers* of the key morphologies, thus allowing for greater confidence in understanding statistically significant differences and error margins.

Chapter 4 : Thermal properties of Sheffield Roadscapes-systematic selection- Effect of landscape typology

4.0 Hypothesis

Surface temperature (ST) is lower in the presence of green infrastructure compared to locations dominated by grey infrastructure.

Road Surface temperatures (ST) are generally cooler in the morning and evening than in the afternoon.

Air temperature (AT) and wind speed (AV) are not systematically influenced by road-scape form in time difference.

4.1 Introduction

In addition to the impact of green/grey roadside characteristics on the ST in different times of the day which have been investigated in the first experiment in chapter four of this dissertation, this chapter aims to examine the thermal dynamics and distribution of the road surface based on the systematic form of road side characteristics (common urban typology). This experiment was conducted during July, August and September of summer season of 2016 corresponding to a period of the year with high solar irradiance and warm air temperatures. Indeed, at this time of year thermal influences can extend into the evening period within the city. As a result, (ST) was observed at evening in addition to morning and afternoon time periods. Inclusion of evening time will aid understanding of residual thermal heat, i.e. any thermal effects within the city even after sunset.

This chapter aims to investigate how the most common roadside characteristics in the UK and its macro attributes impact the road surface temperature, air temperature and air velocity in the summer season. In addition, it aims to report the pattern of surface thermo-dynamics in the roads over time. Roads of a similar orientation were selected - running North-West Vs South-East, to avoid any conflicts between aspect, typical shading, time of day and thermal profiles, when determining mean data. As such, NE facing façades (SW side) received some direct solar radiation in the morning, whereas the SW facing facades (NE side) tended to receive direct solar energy in the afternoon and evening. This created thermal profiles across roadways that varied with time of day (Figure 4.1). (see tables 4.1., and 4.2).

A number of studies have illustrated how roadside characteristics and design of urban roads can determine the environmental aspects of the road, including how roadside form affects thermal comfort. Features such as buildings, trees and road orientation have a strong influence on thermal comfort, through the way they affect urban microclimate within the Urban Canopy Layer (UCL; i.e. the air space between ground and roof-top / tree canopy height) (Golany, 1996 ; Ali-Toudert and Mayer, 2006 ; Gulyás et al., 2006 ; Johansson and Emmanuel, 2006 ; Berkovic et al., 2012). Other work has investigated the direct effects of green infrastructure such as trees, green facades/roofs etc. on urban thermal dynamics / human comfort; (Lin et al., 2010; Shashua-Bar et al., 2011; Lin et al., 2013). This study however, aims to illustrate in a more systematic way, how roadside features, at a relatively small scale can influence road micro-climate, especially surface temperatures. This being carried out within a single district of the city of Sheffield (to provide a degree of uniformity of climate for any given recording day) and using repeated measurements to build in confidence that differentials between specific identified locations are genuine.

Table 4-1 Matrix of roadside forms (structures) chosen to determine their influence on road surface temperatures in NW/SE orientated roads within the city of Sheffield. Combinations of form gave 16 treatments, each replicated in two separate locations (i.e. 32 locations in total).

NE side / SW side	Office	House	Tree	Hedge
Office	Office-Office	Office-House	Office-Tree	Office-Hedge
House	House-Office	House-House	House-Tree	House-Hedge
Tree	Tree-Office	Tree-House	Tree-Tree	Tree-Hedge
Hedge	Hedge-Office	Hedge-House	Tree-Hedge	Hedge-Hedge

4.2 Research Questions

The following questions were investigated:

- How do adjacent roadscape forms – (e.g. green or grey) affect the micro-climatic/thermal properties of the road surface (ST), air temperature (AT) and air velocity (AV).
- How is the influence of these features on ST, AT and AV affected by the time of day (i.e. position of direct solar irradiance)?
- How universal are the influences of green structure (trees, hedge) or grey (buildings, office) on ST, AT and AV, i.e. are there site-specific factors that promote/negate the influence?

4.3 Experimental Design

Road and pavement surface temperatures (ST), Air temperature (AT) and Air velocity (AV) were recorded during the months of July, August and September 2016. Thirty-two separate locations (see table 4.2.) were monitored over a three month period, with temperature data being recording in the morning (9:00-11:00), afternoon (15:00-17:30) and early evening (18:00-20:30) for each location. For each location, 12 surface temperatures (Reference points RP_{1-12}), and 3 for each air temperature (RP_{1-3}) and air velocity (RP_{1-3}) were recorded on each occasion (method of data collection of surface temperature was as described in chapter 3; these represented the cross –sectional transect 'profile' of the roadway, with road profiles (RP) '1' to '4' representing one pavement ('1' being the edge furthest away from the road itself and closest to the structure at the side of the road located on south-west side, e.g. building, tree, office etc.). RP_{5-8} represented temperature points across the road (carriageway) itself, with RP_{9-12} represented the opposite pavement profile, with '12' being the point closest to structures adjacent to the road on this side (north-east). Surface temperatures were recording using the thermometer device (model testo 845 infrared measuring instrument, see section 2.2.1 in chapter 2 for details).

To evaluate the comparative cooling or warming potential of roadside structures, data was mostly collected on non-cloudy, clear sunlit days, (it was assumed differences would be minimal on days where heavy cloud cover or rain were predominant). As such the data profiles represent the warmest periods recorded in the City of Sheffield during 2016, not the average annual temperatures. In practice data was recorded in 11 days in July (12^{th}, 13^{th}, 14^{th}, 15^{th}, 16^{th}, 17^{th} ,18^{th} ,19^{th} ,20^{th} ,26^{th} and,29^{th}), 7 days in August (2^{nd}, 4^{th}, 12^{th}, 18^{th}, 23^{th}, 28^{th} and, 30^{th}) and, 6 days in September (2^{nd}, 3^{rd}, 4^{th}, 6^{th}, 9^{th} and, 13^{th}).

The focus of the research was to identify how specified roadside structures affected surface temperatures and how consistently these structures influenced temperature profiles. Therefore, road and locations were chosen that represented a diversity of roadside structures e.g. location based on systematic landscape features (See table 4.1) yet were not so far apart that larger scale climatic factors started to affect the temperatures recorded. Sites were also chosen to minimize the thermal influence of road traffic or industrial buildings, e.g. major trunk roads with high traffic volumes were excluded. Sites also needed to be sufficiently close together (and the University) so that all could be recorded within the given time periods. In light of these considerations, some of the 32 locations were on the same road.

In other words, (32 locations x 12 cross sectional temperature points x 3 recording times per day x 24 different days, i.e. 27648 data points were monitored in total). These temperatures are referred to as surface temperature data (ST), expressed in ^{o}C.

Air temperature (AT) and velocity (AV) were recorded at the same time as ST. with 3 points being noted for each cross sectional profile 'South-West side', 'Middle of the road' and 'North-East' side Both AT and AV were simultaneously recording using Digital Anemometer instrument was used as a mobile station to measure the air temperature AT and velocity AV, (see section 2.2.2 in chapter two for details). For each of AT and AV repeatedly recorded for their temperature profiles across the road profile (32 locations x 3 cross sectional temperature points x 3 recording times per day x 24 different days, i.e. 6912 data points in total). These data are referred to as AT and AV, expressed in ^{o}C and meter/second (m/s) respectively. To avoid any bias due to the timing within in each recording slot (e.g. in the morning surface temperature may often be cooler at 9.00 compared to 11.00, irrespective of location; i.e. location being confounded by time) the order of recording between the 32 different locations varied on different days. So, the first recording of the day, was not in the same location every time, but was altered to help even out any diurnal influences.

Data analyses.

Analysis of variance (ANOVA) was carried out by using the statistical package GenStat (Releases 8.1 to 10.1. To estimate the assumption of a normal distribution of ST, AT and AV data, a normal probability plot and a plot of residuals against plotted values were tested for it. In the necessary cases, the way of square root of the values were taken to transfer the data to obtain approximate normal distribution.

So, the mean values for each cross-sectional point are represented in figures. Error bars are represented by Fisher's least significant difference values (lsd 5%) level to give statistical evidence of significant effect among treatments (ST, AT and AV) (see section 2.4 in chapter two for more details).

Arc Gis (Arc Map), (Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/ Airbus DS, USED, USGS, AeroGRID, IGN, and the GIS User Community), which provided by the University of Sheffield, was used to display the accurate coordinate of the locations of the experiment by using (degree, Minutes, Seconds) style. Sketch up software version (2015) and 3D Max (2011) was used to simulate the locations of the actual work field of this experiment in this chapter.

Table 4-2 Dominant roadside forms under study and locations in Sheffield used in Experiment of chapter 4.

Locations with different Roadside characteristics located on (SW face-NE face)	Road name	Specific location on GIS
1- Office - Office	25 Division	1^{0} 28′ 32.172′′W 53^{0} 22′ 49.716′′N
2- Office - Office	Rockingham St	1^{0} 28′ 31.53′′W 53^{0} 22′ 48.507′′N

3- House - Office	15 Regent Terrace	1^{0} 28′ 52.556′′W 53^{0} 22′ 48.743′′N
4- House - Office	Canning St	1^{0} 28′ 34.484′′W 53^{0} 22′ 45.109′′N

5- Tree - Office	Infirmary Rd	1^{0} 29′ 4.896′′W 53^{0} 23′ 31.274′′N
6- Tree - Office	Infirmary Rd	1^{0} 29′ 7.206′′W 53^{0} 23′ 32.548′′N

7- Hedge - Office	192 Infirmary Rd	1^{0} 29′ 9.259′′W 53^{0} 23′ 33.772′′N
8- Hedge - Office	216 Infirmary Rd	1^{0} 29′ 10.928′′W 53^{0} 23′ 35.15′′N

9- Office - House	20 Carver St	1^{0} 28′ 26.766′′W 53^{0} 22′ 50.249′′N
10- Office – House	6 Carver St	1^{0} 28′ 26.356′′W 53^{0} 22′ 49.3′′N

11- House - House	2 Trafalgar St	1^{0} 28′ 36.469′′W 53^{0} 22′ 49.851′′N
12- House – House	Ganning St	1^{0} 28′ 32.516′′W 53^{0} 22′ 50.739′′N

13- Tree-House	Hoyle St	1^{0} 28′ 49.06′′W 53^{0} 23′ 20.163′′N
14- Tree-House	Infirmary Rd	1^{0} 28′ 53.099′′W 53^{0} 23′ 25.837′′N

Locations with different Roadside characteristics located on (SW face-NE face)	Road name	Specific location on GIS
15- Hedge - House	Hoyle St	1^0 28′ 50.703′′W 53^0 23′ 20.979′′N
16- Hedge - House	Infirmary Rd	1^0 28′ 54.399′′W 53^0 23′ 26.449′′N

17- Office - Tree	Dimond	1^0 28′ 45.501′′W 53^0 22′ 53.952′′N
18- Office - Tree	Dimond	1^0 28′ 64.699′′W 53^0 22′ 56.708′′N

19- House - Tree	Upperthrope Rd	1^0 29′ 23.844′′W 53^0 23′ 24.905′′N
20- House - Tree	Upertherope Rd	1^0 29′ 26.24′′W 53^0 23′ 26.155′′N

21- Tree - Tree	Gell St	1^0 28′ 58.554′′W 53^0 22′ 41.918′′N
22- Tree - Tree	Gell St	1^0 28′ 58.489′′W 53^0 22′ 43.592′′N

23- Hedge - Tree	Ashberry Rd	1^0 29′ 29.656′′W 53^0 23′ 19.026′′N
24- Hedge – Tree	Ashberry Rd	1^0 29′ 30.404′′W 53^0 23′ 19.792′′N

25- Office - Hedge	8 Broomhall st point	1^0 28′ 46.231′′W 53^0 22′ 43.046′′N
26- Office – Hedge	8 Broomhall st point	1^0 28′ 47.087′′W 53^0 22′ 42.344′′N

27- House - Hedge	8 Addy CI	1^0 29′ 21.22′′W 53^0 23′ 19.345′′N
28- House - Hedge	16 Addy CI	1^0 29′ 20.992′′W 53^0 23′ 19.919′′N

29- Tree – Hedge	Albion	1^0 29′ 22.383′′W 53^0 23′ 13.859′′N
30- Tree – Hedge	Albion	1^0 29′ 23.131′′W 53^0 23′ 14.242′′N

31- Hedge – Hedge	Tesco entrance	1^0 28′ 53.504′′W 53^0 23′ 24.575′′N
32- Hedge – Hedge	Tesco entrance	1^0 28′ 54.574′′W 53^0 23′ 24.958′′N

4.4 Result

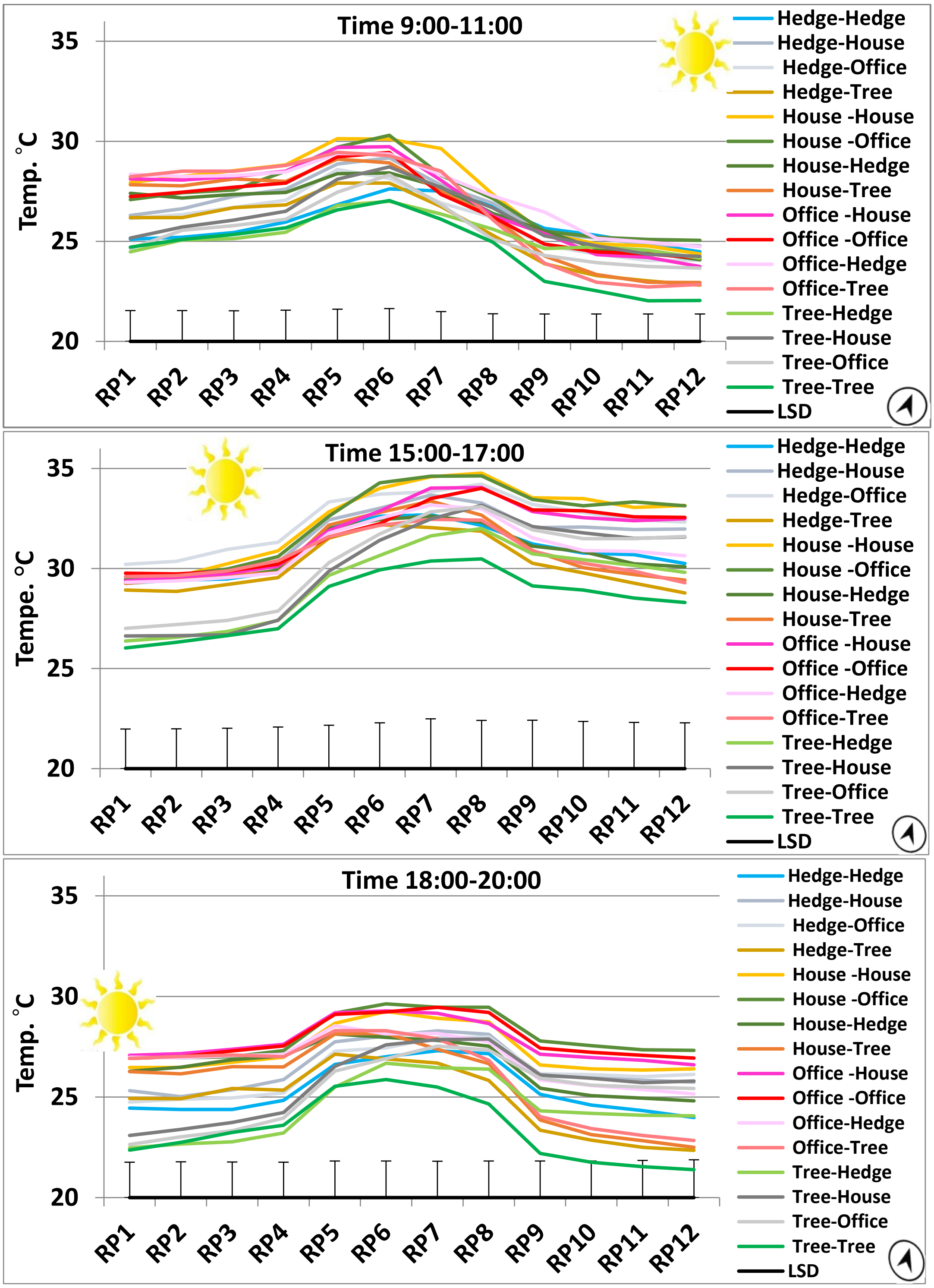
4.4.1 Result of Surface Temperature (ST)

Overall, thermal profile across three times of the day (Fig 4.2.) indicated that ST were highest in the middle of the road ($RP_{6 \text{ and } 7}$) by around 30 °C ($P<0.001$) in the morning, 34 °C (range $P=0.001$- $P=0.07$) in the afternoon and, 29.5 °C ($P<0.001$) in evening.

In the morning, the general pattern of thermal profile also shows that SW edges ($RP_{1 \text{ to } 4}$) exposed to full sunlight were around 3.5 °C ($P<0.001$) warmer than NE sides (Figs 4.1. and 4.2.). However, the process at noon time is totally reversed as by this point the SW side was shaded and the NE experiencing full sunlight. But the structures located at SW sides blocked the sunlight and create shaded surface based on the dimension and the sorts of the roadside's features located in SW sides (Figs 4.1. and 4.5.).

In the evening (18.00-20.00), the influence of the roadside features were still evident and overall the middle of the road ($RP_{5\text{and } 8}$), retained greater warmth by 2 - 4 °C ($P<0.001$) compared to both edges.

Figure 4.1Thermal properties of thirty-two locations located at various roads with, each curve represented the average of each same roadsides characteristics: - Means surface temperature (n=24 days) at (9.00-11.00 top), (15.00-17.00 middle) and (18.00-20.00 bottom), letters related to points across the profile of the road. Error bars lsd 5%.



4.4.1.1 Surface Temperature (ST) in Morning (9:00-11:00)

Warmest temperatures were in the middle of the road 25-30 ^{o}C (range $P<0.001$ to 0.004) for most locations (Fig 4.2). However, the range of ST (22-25 ^{o}C, $P<0.001$) on the NE sides (RP $_{9-12}$) were lower than SW sides (RP $_{1-5}$, 25-28 ^{o}C, $P<0.001$) largely due to shading of this side of the roads in the morning. Irrespective of this general factor, certain locations were cooler than others, with those with a tree present on the NE side being coolest. (Fig 4.2). The Tree-Tree treatment showing reduced temperatures throughout the profile. Conversely, House-House was relatively high throughout the profile. Differences between these treatments were significant throughout. Similarly, other locations with trees in either side; for example, Tree-Hedge and Hedge-Tree, were often significantly cooler than those surrounded by grey structures such as House Vs House by around 3-3.5 ^{o}C. Indeed, all the coolest temperatures were associated with locations where trees were present, i.e. Office-Tree, Tree-Office and House-Tree.

Moreover, ST in the roads surrounded by tree on both sides justify the essential role of green structures to significantly mitigate the temperatures. Furthermore, the shaded and sunlit area, which are determined by the position of the sun could also dictate differences in temperature profiles by around 3 ^{o}C ($P< 0.001$) in the both edges because the SW sides was exposed to full sunlight whilst on the shaded NE side they decreased (Fig 4.3).

This indicates a remarkable ability of roadside features to increase and lower ST but by different levels with respected the angle of the sunlight (shaded and exposed to sunlight) (Fig 4.2 and Fig 4.3).

Figure 4.2 Hypothetical form of shaded/lit to explain the effect of roadside structures in morning (9.00-11.00, Top); Thermal properties of thirty-two locations with various roads structures showing the mean of ST (n=24 days) at morning (9.00-11.00, Bottom), letters relate to points across the profile of the road, (P< 0.001, error lsd bars 5%).

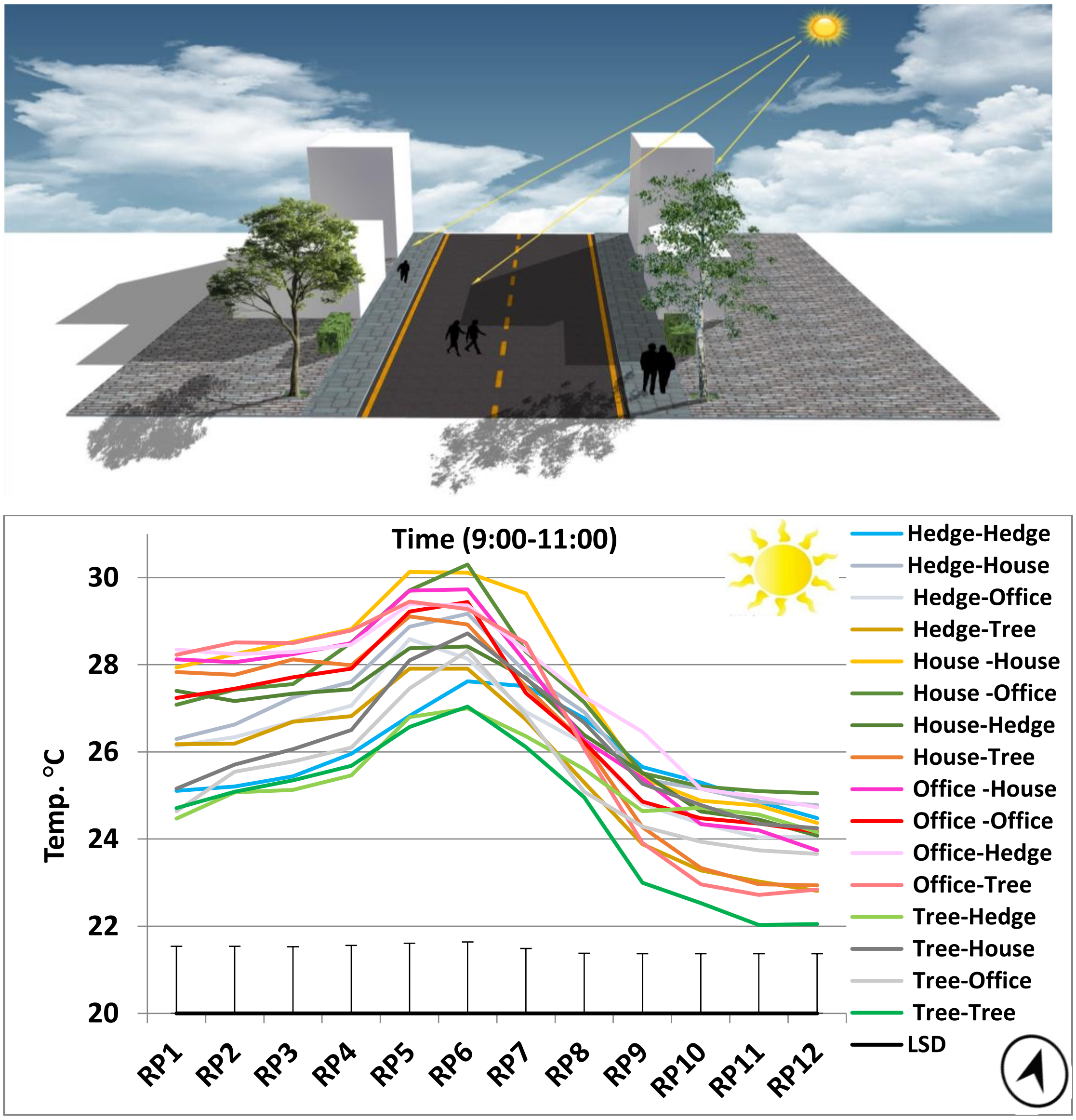
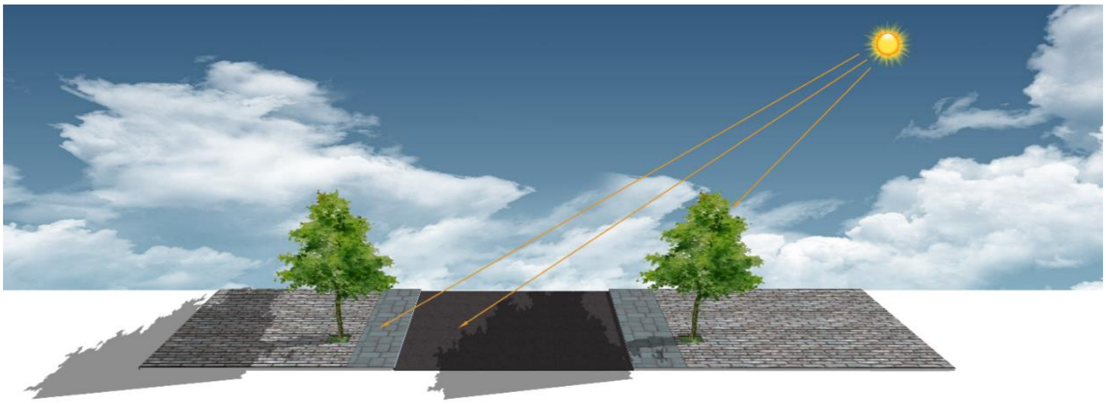
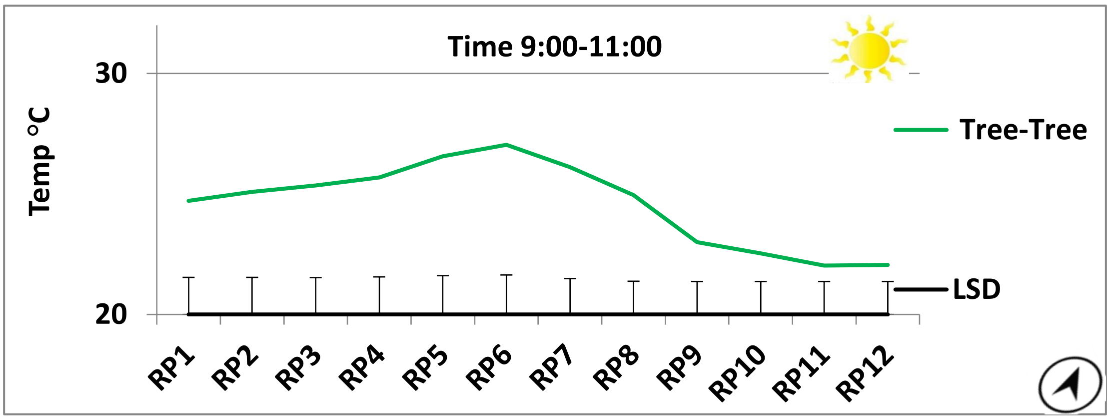
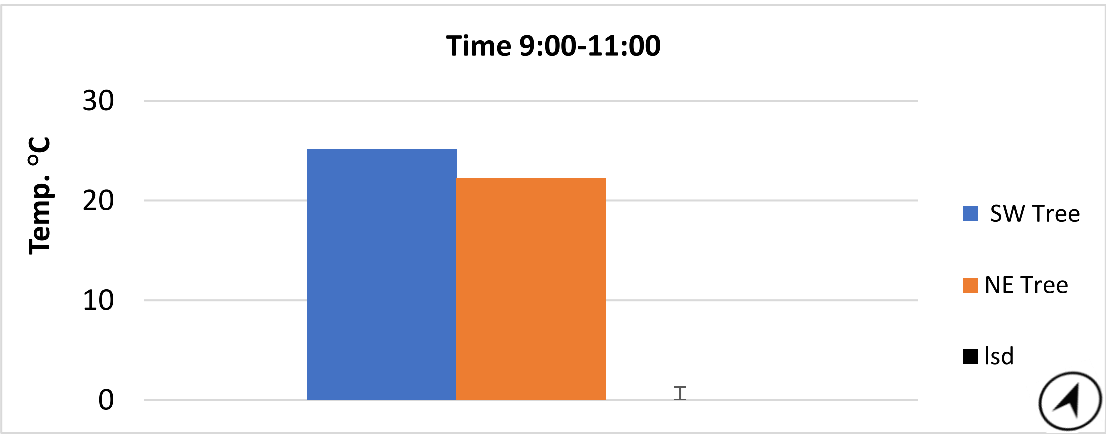


Figure 4.3 A diagram illustrates: - Specific thermal properties of Tree-Tree locations at Gell St, (Top); Mean of ST (n=24 days) of both locations with (Tree Vs Tree) in morning, (Middle); the Average of ST at both edges of the locations (p<0.001), error bars lsd 5% (Bottom) letters related to points across the profile of the road.







4.4.1.2 Surface temperature in afternoon (15.00-17.00)

In general, thermal profile tendency in afternoon were intensified at higher temperatures over all the locations compared to both morning and evening. This is due to the fact that sunlight was nearly perpendicular affecting the surface of roads. Hence, it reduced the effect of the roadside features to mitigate high ST by increasing the proportion of road surface exposed to sunlight. However, ST in the SW (RP $_{1-4}$) side were less than both NE (RP $_{9-12}$) sides and middle (RP $_{5-8}$); possibly due to the fact that these were more fully exposed to sunlight during the afternoon (Fig 4.4).

As with the morning the greater ST cooling was associated with the Tree-Tree treatment –almost 4-5 ^{o}C cooler in the middle of the road compared to House-House (Figs 4.4 and 4.5), with corresponding significantly lower temperatures at either edge too. These temperatures directly under the tree on the SW side being significantly cooler than the middle of the road (Fig 4.6). Hedge-Tree (Fig 4.4) also produced a low temperature profile, although perhaps it was less likely to have the same shading influence as Tree-Tree. House-House and House-Office had highest ST profiles (Fig 4.4), especially on the NE side and in the middle of the road (Fig 4.7), suggesting that built structures were interacting with solar irradiance to enhance ST.

Figure 4.4 Hypothetical form of shaded/lit explain the effect of roadside structures in afternoon (15.00-17.00, Top); Thermal properties of thirty-two locations of various roads structures showing the means of ST (n=24 days), bottom), (letters relate to points across the profile of the road, P< 0.001).

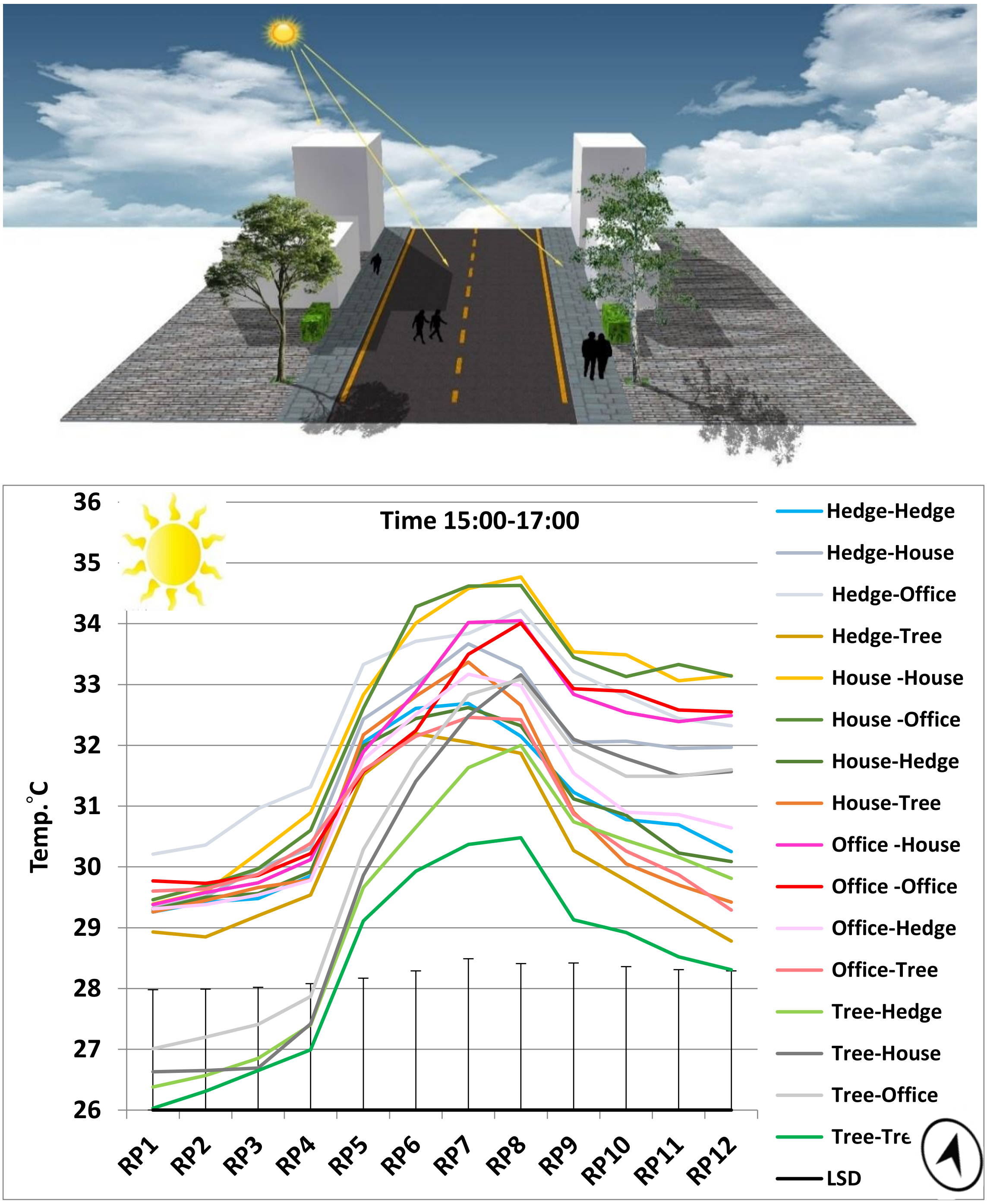


Figure 4.5 Explaining the thermal properties of specific selective locations (House-House) at 2 Trafalgar St (Top) and, Canning St and (Tree-Tree) at Gall Rd (Middle): - Means of ST (n=24 days) in (afternoon 15.00-17.00) for both locations (P<0.001, Bottom), letters relate to points across the profile of the road.

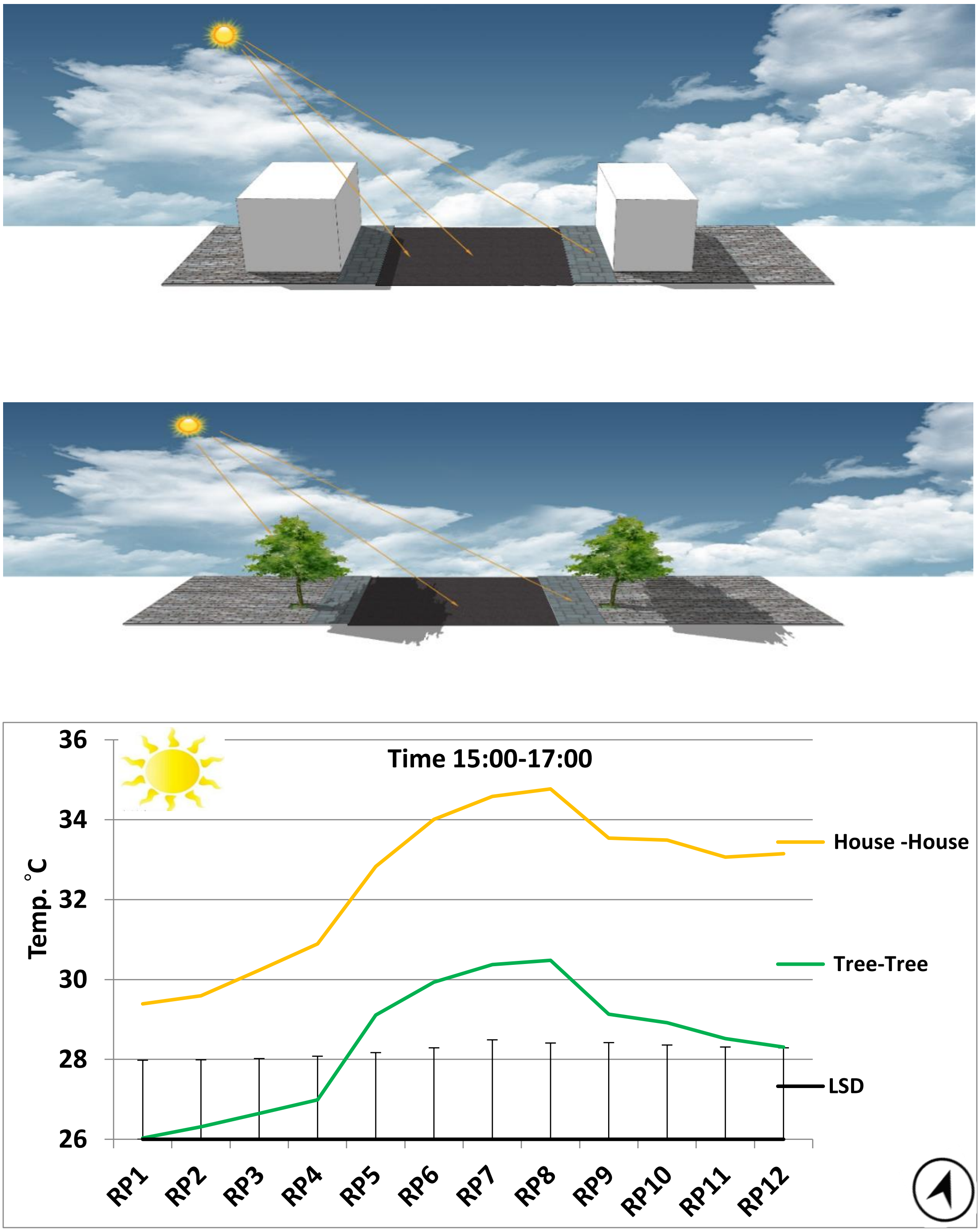


Figure 4.6 Means of ST (n=24 days) of tree Vs tree in locations at Gill Rd in the (afternoon 15:00-17:00) showing thermal properties of the SW side (RP 1-4) compared to the middle of the road (PP 5-8) and the NE edges (PP 9-12), (P<0.001).

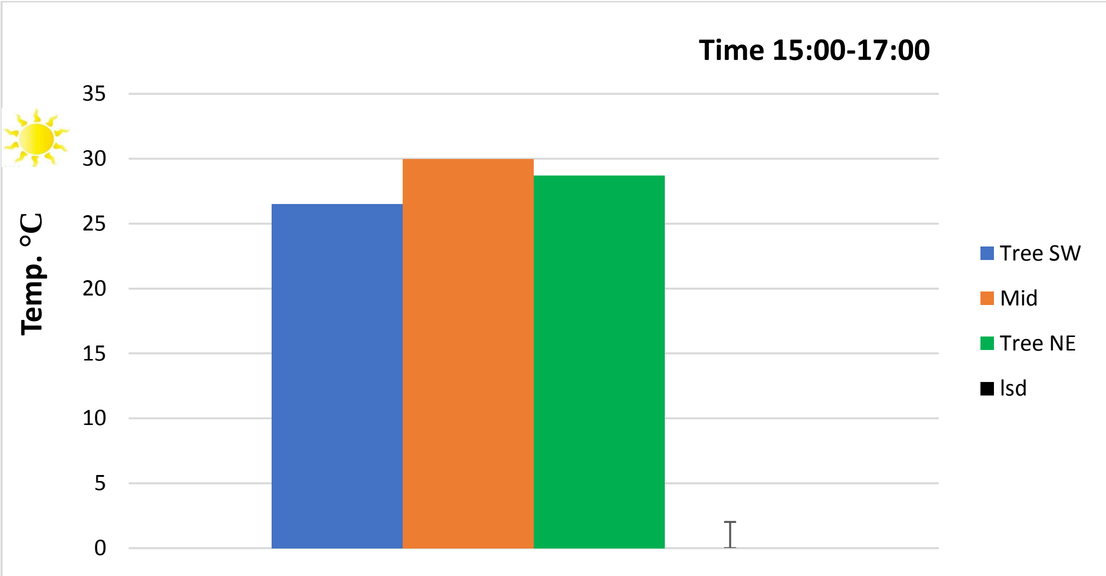
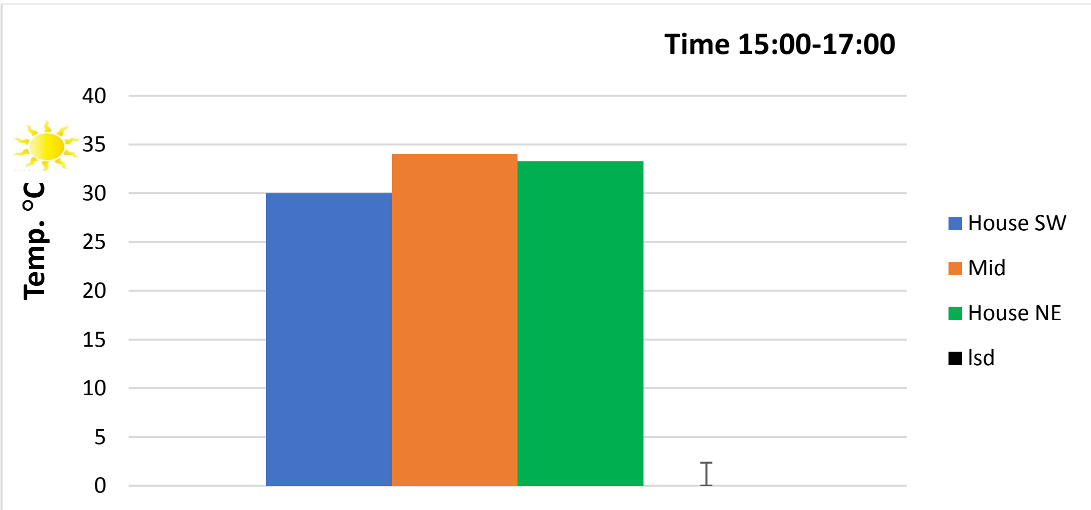


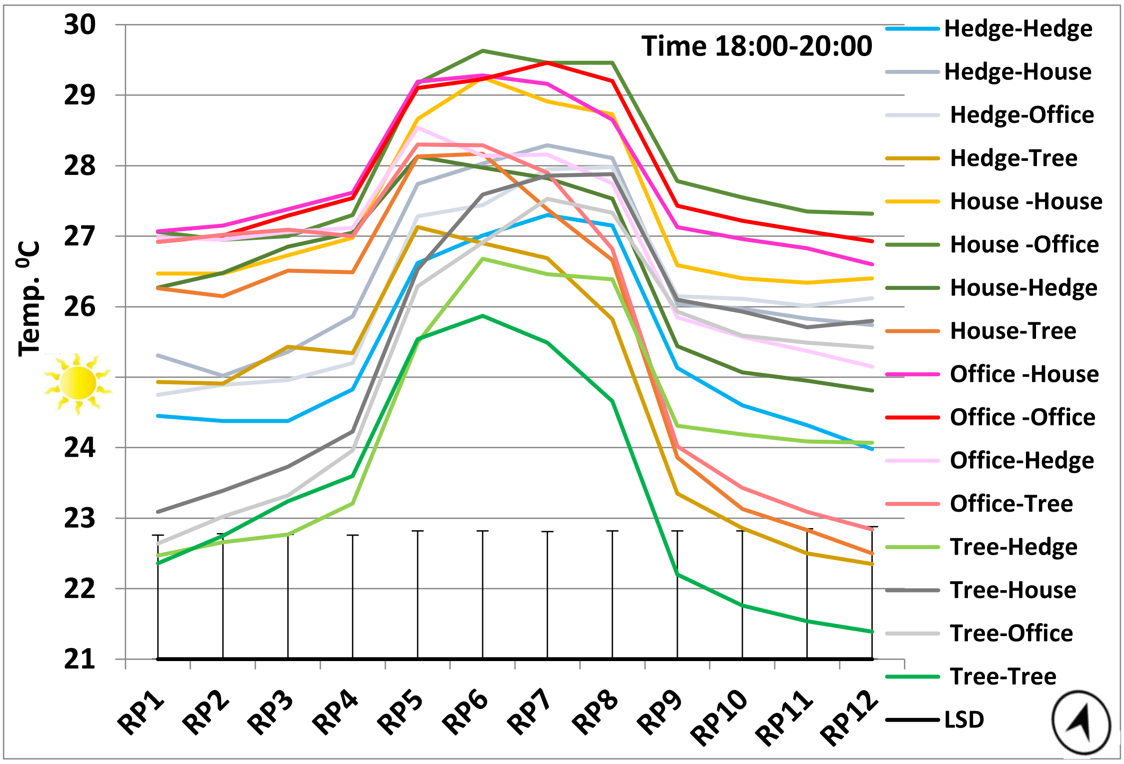
Figure 4.7 Means of ST (n=24 days) in House-House locations at 2 Trafalgar St, and Canning St in afternoon showing thermal properties of SW side (RP 1-4) compared to the middle of the road (RP 5-8) and, the NE edges (RP 9-12), (P<0.001).



4.4.1.4 Surface temperature in the evening (18.00-20.00)

Temperature profiles in the evening were more symmetrical than those of earlier times during the day (Fig 4.8). There was still disparity between thermal profiles of different locations, however, Tree-Tree still being associated with the coolest profile and House-Office and Office-Office with the warmest (significantly warmer than tree-tree across the entire profile, Fig 4.8). and with various roadside characteristics were evidently still existing in every sections over the location (RP_{1-12}), ($P < 0.001$) although the intensity of the solar radiation on the road surface was much reduced due to the shade in the evening (Fig 4.8.).

Figure 4.8 Hypothetical form of shaded/sunlit explain the effect of roadside structures in evening (18.00-20.00, top); thermal properties of thirty-two locations of different roads structures explaining means of ST (n=24days, bottom, P<0.00), error bars lsd 5%.



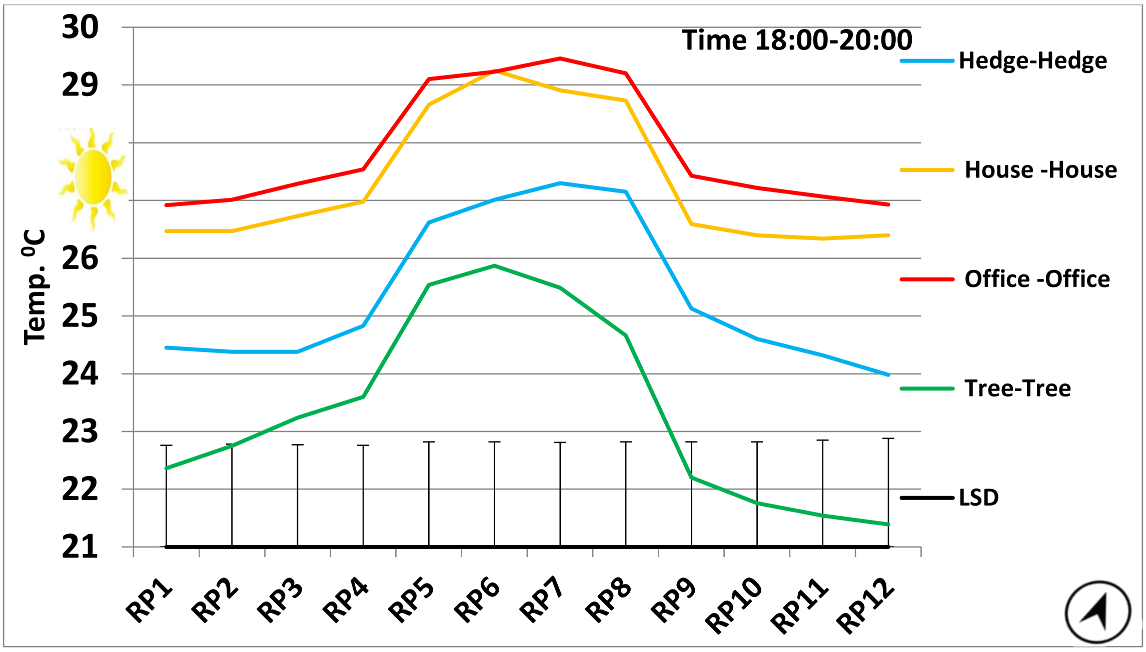
4.4.1.5 The influence of green Vs grey structures on surface temperature in evening

Thermal profiles of selective locations (Fig 4.9) shows that there were significant differences in ST at the three different sections (SW, Middle, NE) of different locations in the evening (18:00-20:00) based on different roadside structures, although in many cases solar radiation was having no direct effect on the road surface in the evening but it could still be residual heat though- still reradiating energy from earlier in the afternoon. Differences in thermal profiles of both treatments ''Tree-Tree'' and ''Hedge-Hedge'' across the different sections of the locations were in the range around 4-5 ^{o}C ($P<0.001$). Little differences of thermal profile were noticed between the mean surface temperature of the ''Office-Office'' and ''House-House'' locations by around 2.5 ^{o}C ($P<0.001$). Distinctive thermal profile was noticed at ''Office-Office'' locations by approximately 27 ^{o}C and 29.5 ^{o}C at both edges and middle of the locations, respectively (Fig 4.9.).

As mentioned above the coolest profile is ''Tree-Tree''. This is perhaps due to the presence of the tree canopy which may shade the entire locations during daytime and avoid the road surface from heating via solar gain. Some mitigation was occurring at the middle of the road and both edges in the thermal profile of the ''Hedge-Hedge'' locations by around 27 ^{o}C and 24 ^{o}C ($P<0.001$) respectively, although it was still significant, but, it did not provide the same degree of alleviation as the Tree-Tree treatments.

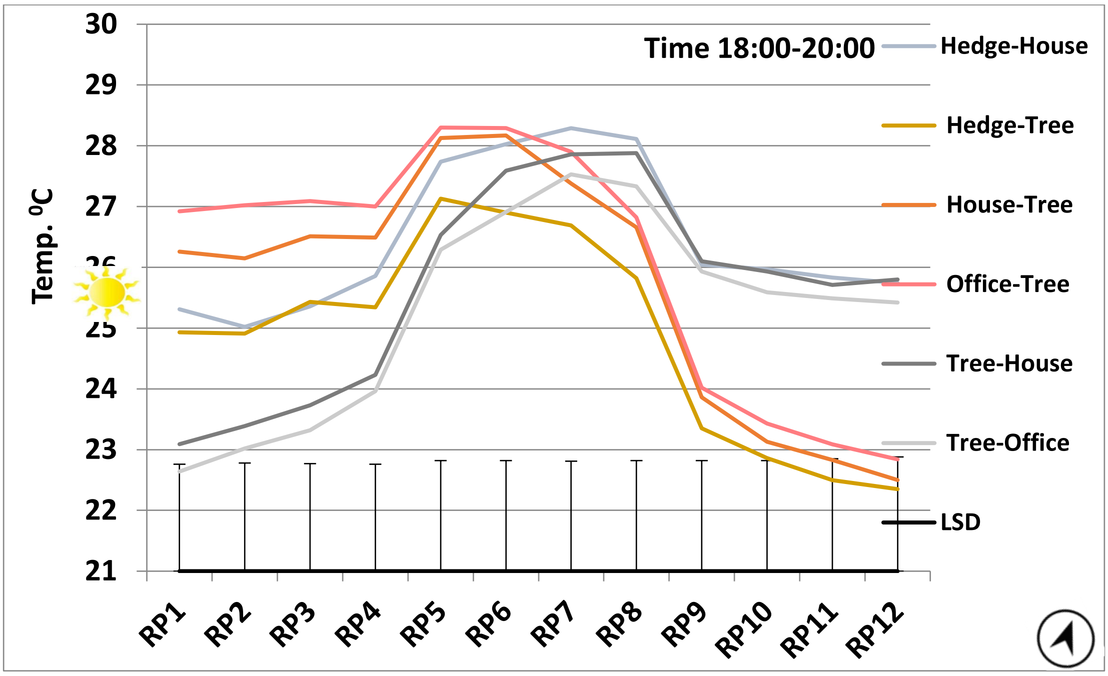
Overall, the selective treatments presented in Fig 4.9 were showing lower temperatures ST in both edges compared to the middle of the road at the most treatments by around 2.5-3.5 ^{o}C, although the impact of the sunlight was less in the evening as the surface of the locations were shaded compared to the morning and afternoon time.

Figure 4.9 Thermal properties of specific distinctive locations: - Mean of ST (n=24 days), at 18.00-20.00, letters relate to points across the profile of the road, (P<0.001).



When altering the roadside features at the two opposite sides of the road (Fig 4.10.) further information is gained about the specific structures and their local influence. For example, the data confirms that trees can reduce ST by 4 °C compared to the office location directly across the road. Similarly, the presence of a tree reduces temperatures by 3 °C compared to the houses opposite. This demonstrates that even in the evening the presence of vegetation is having a marked cooling influence.

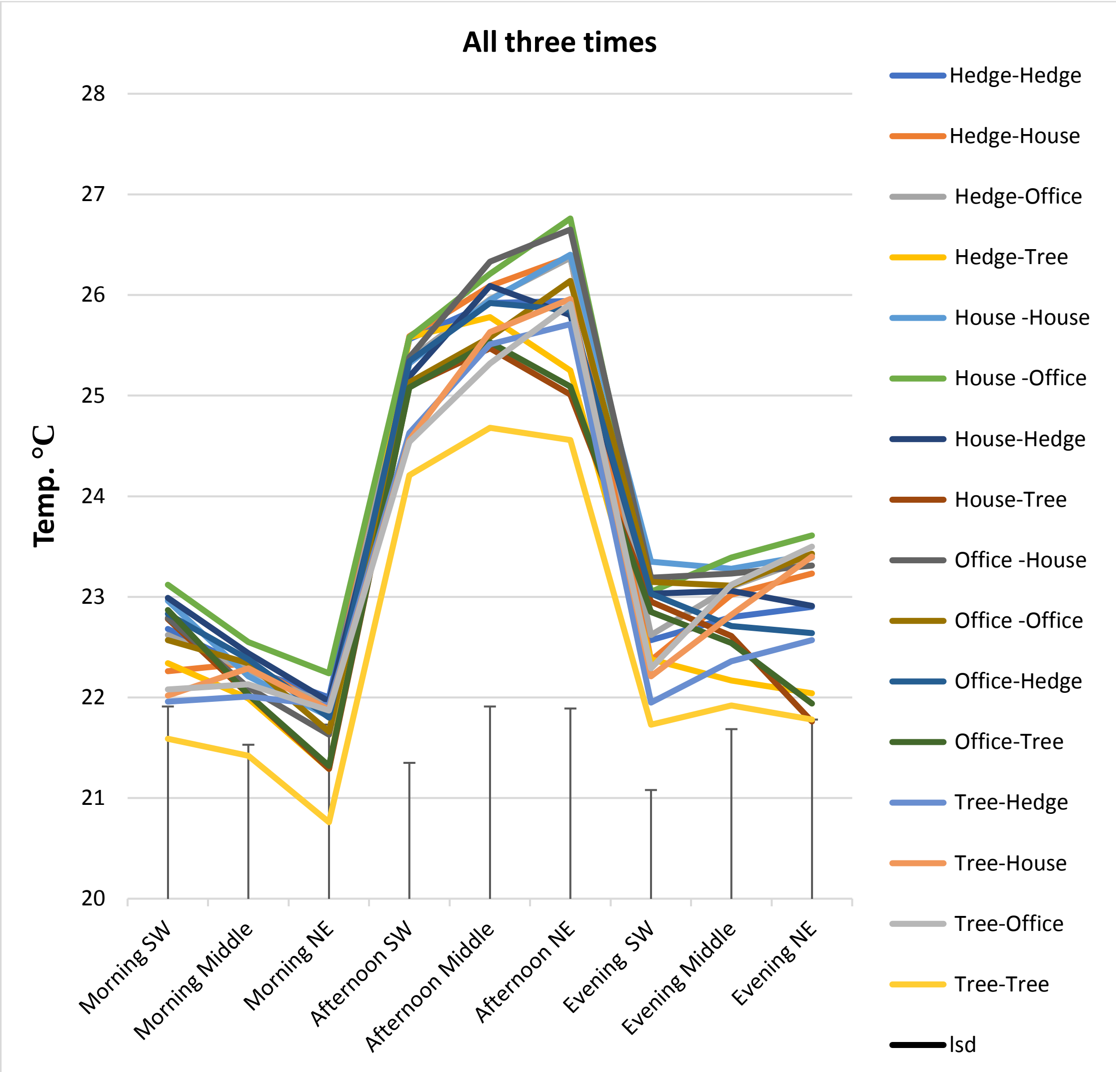
Figure 4.10 Thermal profiles of specific selective locations showing the mean of ST (n=24 days) at 18.00-20.00, (P = 0.61 to P< 0.001).



4.4.2 Air Temperatures

The overall highest temperature was in the afternoon period compared to morning and evening, however, AT was almost insignificant influenced by roadside features expect in evening periods especially at both edges with some mitigation by green infrastructures (range P= 0.32 to 0.0139, range of lsd= 1.93-1.15). The range of AT in that period of data collection were around 21.5-27 °C, (Fig 4.11).

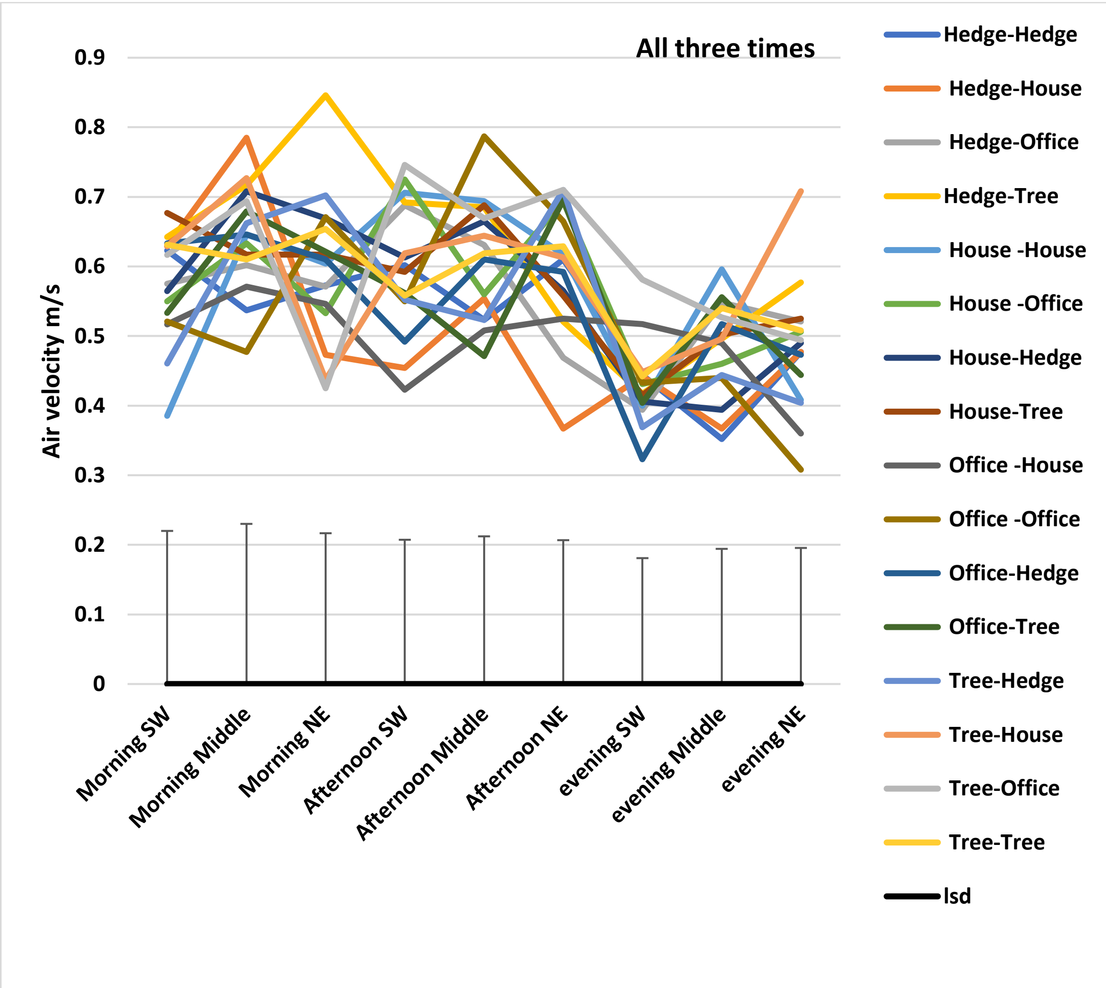
Figure 4.11 Mean of Air temperatures profiles (n=24 days) of all locations at three different sides South-West, Middle, and, North-East for the three different intervals (9:00-11:00, 15:00-17:00 and, 18:00-20:00), (range of P= 0.32 to 0.0139, (range of lsd= 1.93-1.15, error bars lsd 5%).



4.4.3 Air Velocity ($m.s^{-1}$)

Generally, for all three intervals, wind speed profiles were often higher in both morning and afternoon timings compared to the evening time in the overall locations, however, the range of air velocity at overall locations within periods measurement was 0.3-0.8 ms^{-1} ($P<0.001$), (Fig 4.12).

Figure 4.12 Mean of Air Velocity profiles of all locations at three different sides South-West, Middle, and, North-East for three different time intervals (9:00-11:00, (15:00-17:00 and 18:00-20:00), (P< 0.001), error bars lsd 5%.



4.5 Discussion

This research finds an important role of different roadside characteristics to enhance and suppress the ST. This seems to relate to factors such as time / duration of exposure to solar radiation, level of shading and perhaps other features of the roadside morphology e.g. degree of openness (Fig 4.1). The results from this systematic approach agree with those of the previous chapter. Road locations that are dominated by green infrastructure tend to be 4-5 ^{o}C cooler (ST) than equivalent locations dominated by build structures, such as offices and houses. Trees particularly are effective at providing localized cooling. This has assumed to be via direct shading from solar irradiance, but the fact that cooling was also noted around hedge-hedge locations, where the effect of shading may be much more limited, indicates that at least some of the cooling influence from plants may come from evapotranspiration – i.e. moisture release acting as latent heat – thus energy is being dissipated without a rise in surface (and perhaps) air temperatures (Cameron et al., 2014; Vaz Monteiro et al., 2017) .

Trees are conferring their cooling benefits during the hottest part of the day, but interestingly the data here also shows this cooling effect extends into the evening period. It has been thought that tree canopies can block in heat at night resulting in potential thermal discomfort for residents (Rahman et al. 2017), but the data here on surface temperatures at least (air temperatures are more ambiguous) would indicate that actually these locations are tending to remain cooler that those around the build structures. The reasons around this are less evident however, compared to afternoon and morning situations, as the impact of sun *per se* is relatively weak compared to the earlier periods. The effect though may be a carry-over from the previous heating influence of the sun –

shaded, cooler areas, will re-radiate less heat during the evening than those retaining thermal loads from full sun during the day. It is this re-radiation of heat that often causes thermal discomfort in cities during heat waves as the most uncomfortable periods can be between 22.00 to 0.00 hours. Alternatively, there may be a localized cooling effect from plants themselves due to late afternoon / evening evapotranspiration – retaining a cool and moist atmosphere in their locality into the night. Thus, roadside characteristics are dictating local micro-climates at all times of the day, and the data here is identify how different vegetation types are influencing this. This data builds on previous findings that different vegetation structures have different climatic influences or cooling capacities (Bar and Hoffman, 2000; Lin and Lin, 2010; Blanusa et al., 2013; Cameron et al. 2014; Cameron and Blanusa, 2016; Vaz Monteiro et al., 2017) which supported the claim of this research.

As can be seen in the Fig 4.4, ''Hedge-Tree'' location is dominated by the green structure which helps to mitigate the surface temperature by producing low temperature. The other explanation of having low temperature at hedge is that the height of hedge is likely to be shorter than other roadsides characteristics (house and building) that caused ventilation which might help to mitigate the ST. Moreover, location with hedge has high SVF that helps to release the ST and prevents the surface of the road to retain the temperatures. House-House and House-Office had highest ST profiles, especially on the NE side and in the middle of the road because of those locations are constructed by grey and impervious materials. It can also be noted that NE sides of both locations face the solar radiation which cause to trap the heat and eventually increase the ST. Moreover, those locations are unlikely to create a ventilation which significantly helps to increase the heat and ultimately increase the ST.

The air temperatures did not show the same margin of difference as the surface temperatures and overall treatment effects were deemed non-significant, nevertheless, there were incidences where air temperatures did vary based on location, specifically around evening time in the SW side of streets in the presence of trees (Fig. 4.11). Recording differences in air temperature due to vegetation tends to be much more challenging than determining differences on hard surfaces and other solid objects, due simply to the fact that air masses move around. Although studies that investigate temperatures profiles over a larger scale can pick up differences in air temperature due to green and blue infrastructure (Roy et al. ,2012, Givoni, 1991, Armson et al., 2012 and Gillner et al., 2015) detecting differences at this scale is relatively novel. Hence this data is notable and is testament to the value of high replication rates used in this study. Identifying genuine changes in air temperature due to vegetation has much greater impact than surface temperatures alone as the former is readily translatable to the influences on human thermal comfort. The fact that trees are cooling the air within the city of Sheffield has direct implications for the planning and design of the city in future, as the city authorities attempt to deal with climate change and a greater likelihood of heat island events in the future.

Air velocities showed a much more haphazard pattern, indicating both the variability induced by 'weather' on different days, but also that even within the one treatment there may be variation between the two sites in terms of openness to the wind.

In the analysis significant differences were noted in surface temperature due to the profile across the road. The middle being warmer than the two edge positions, often irrespective of the sun's position. Interestingly enough, even the presence of hedges (Figs 4.4 and 4.9) were keeping the middle of the road cooler than similar sites surrounding by buildings, again demonstrating the influence of the 'edge' effects on the main carriageway. The literature review of this dissertation has already discussed the role of green structure to alleviate ST. Maher (2003) showed that green structure plays an important role to alleviate the ST which is scientifically straightforward. Furthermore, the role of green structure to alleviate ST has been found empirically in a number of relevant research (Roy et al., 2012, Liangmei et al., 2008; Bau-Show Lin and Yann-Jou Lin, 2010, Ram Pandit and David N. Laband 2010). Therefore, the findings of this research corroborate the claims of all these researchers.

4.6 Concluding points of Chapter 4:

- Temperatures across different locations had distinctive profiles, with temperatures generally lower at the both roadsides and rising towards the middle of the locations in almost all roads.
- Either sides of the locations within the road with green structures particularly trees tended to be cooler than locations with grey structures particularly houses, surface temperatures being up to 3 to 6 ^{o}C cooler at the base of the green structures.
- There could still be variation in temperatures with a single sort of roadsides features depends on the side within the locations of the roads in different time.
- Road with specific orientation play a significant role to alter the trends of surface temperatures jointly with roadsides structures.
- Afternoon time shows the intensive surface temperatures compare with morning and evening.
- Evening time shows the continuation of distinct profiles due to roadsides structures, although overall the effect of the sunlight is lower than that in the afternoon and probably morning.
- Houses / offices on both sides of the roads still induce higher temperatures compared to other features, irrespective the time and other edge effects of the road.

4.7 Implications from chapter 4

The data from this chapter emphasises the need to understand solar gain with respect to urban design and how time of day affects the thermal profiles of the streetscape. Areas that may be particularly warm in the morning may be coolest in the evening and vice versa. So, more thought needs to be given to the location of buildings and trees with respect to ensuring human thermal comfort and the impacts of the morphology on the surface temperature of the roadway. Other factors may influence the temperature of urban road infrastructure and these are explored in the next chapter, by using regression approaches on the data generated here to better understand the 'hierarchy' of influences. This introduces other elements, however, not discussed in detail here, i.e. road colour, sky view factor etc.

Chapter 5 : Thermal properties of Sheffield urban roadscapes - systematic selection - Key variables affecting temperature

5.1 Hypothesis

The surface temperature (ST) in different locations of the road in different time of the day (morning, afternoon, and evening) could be impacted in different manner and levels by the physical and environmental variables jointly such as; grey / green (buildings/trees), Air temperature (AT), Air velocity (AV), height/width ratio (H/W), Sky view factor (SVF), colour of the structures located in both edges of the roads and colour of pavements (pedestrian walkways) and, open / close roadside features.

5.1 Introduction

The thermal profile of an urban road is likely to be affected by multiple factors. In addition to roadside green and grey infrastructure, many other factors including air temperature and velocity, sky view factor (SVF, amount of open sky viewed from the site essentially how enclosed the site is), colour of the road, form and colour of the roadside features, orientation of the road with respect to-incoming solar irradiance, nearby thermal influences such as other large areas of hard standing, water bodies and heat emissions from nearby domestic or industrial properties may all affect the road surface temperature. Many of these factors have been considered as reasons for buildings and other hard surfaces to affect temperature dynamics and increase heat build-up in city areas (Oke 1987 and Santamouris 2001). How much area of a landscape is exposed to sky view is also important determinant of the thermal profile of the surface (Yamashita et al. 1986, Eliasson & Svensson 2003, Karlsson, 2000, Postgard, 2000). These researches found significant statistical relationship between air temperature and SVF mainly in urban areas. Sky view indicates the openness of a site which influences the airflow and sunlight that ultimately determine thermal profile of a place. The orientation of urban roads also affects temperature distribution and ventilation efficiency. Cao et al. (2015) and Sanusi et al. (2016) investigated the impact of the orientation of the road on the local thermal environment and found a great influence on the local thermal environment by increasing the average of air velocity to mitigate the mean of air temperatures in windless area or with respect to high-rise buildings in low-lying areas and tree canopy density. Colour of the road and of the roadside characteristics have a lot of influence on the formation of heat islands. One mitigation strategy of urban heat island (UHI) influences is installing Collar case paving materials, that strategy contributes to reduce pavement temperatures by 19.5 °C or more (Asaeda et al, 1996; Pomerantz et al, 2000; Gartland, 2001). The construction of the road network became one of the essential factors to generate the UHI phenomena (Cao et al., 2015). Most of this research investigated a single factor in isolation, and this thesis builds on this by investigating the effect of multiple factors on ST by employing multiple regression models.

5.2 Research Question

The following questions will be investigated in this research.

- How do environmental properties, landscape features and their geometry affect the micro-climatic/thermal properties of urban roads?
- How are the road surface temperatures influenced by environmental and physical properties of the road?

- How is the influence of these features on road surface temperatures influenced by time of day?

The rest of this chapter is structured as follows. Section 5.3 provides the empirical methods of this research. Sections 5.4, 5.5 and 5.6 presents the regression results at morning, afternoon and evening time periods respectively. Section 5.7 and 5.8 presents the discussion of the results and concluding points from chapter 6 respectively.

5.3 Empirical methods

This chapter presents the estimation results of the regressions in the three different times (morning, afternoon and, evening) respectively, by considering the surface temperature (ST) at middle and both edges of the roads (-SW side, middle, and NE side) – the dependent variable. The influence of other factors (independent variables) on the temperature at these locations is investigated. These include other environmental variables such as air temperature (AT) or velocity (AV) as well as physical variables such as height of roadside characteristics (buildings trees, etc), width of road, height / width (H/W) ratio, SVF at both sides and middle of the roads, the dominant colours of roadsides structures (both those on the SW and, NE sides) and the surface colour of the pavements (SW and NE). The aim of the regression is to examine the extent to which key factors account for the temperature effects encountered. The equation of the regression was: -

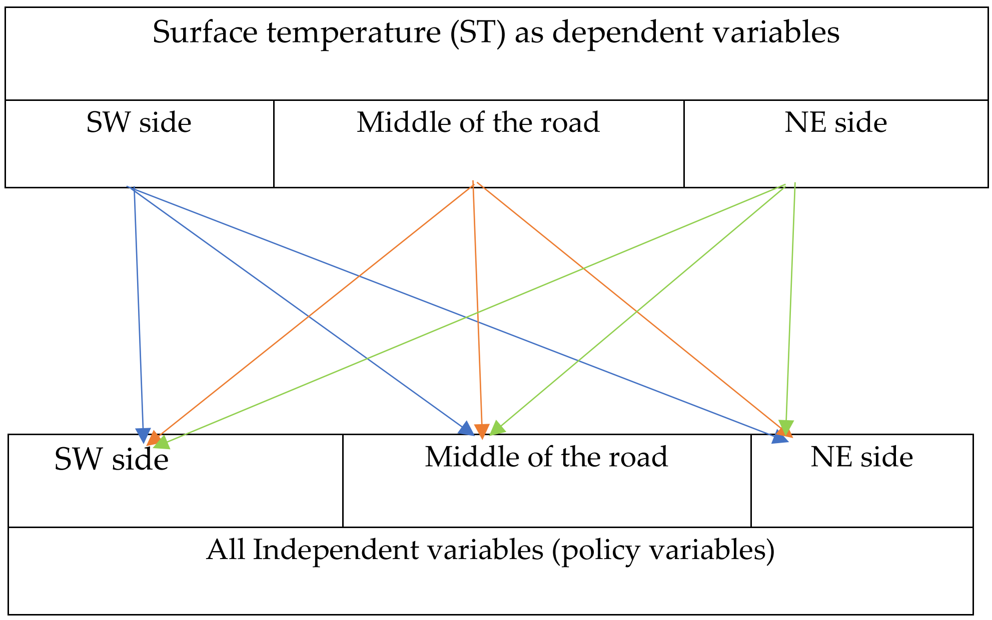
$$
\begin{aligned}
&\boldsymbol{ST(m,a,e)\ sw, middle, ne}\ ℃ \\
&\qquad = (\ (\boldsymbol{AT})℃)\boldsymbol{sw} + \big((\boldsymbol{AT})℃\big)\ \boldsymbol{middle} + \big((\boldsymbol{AT})℃\big)\boldsymbol{ne} + ((\boldsymbol{AV})\boldsymbol{m/s})\boldsymbol{sw}\ ) \\
&\qquad + ((\boldsymbol{AV})\boldsymbol{m/s})\ \boldsymbol{middle}) + ((\boldsymbol{AV})\ \boldsymbol{m/s})\ \boldsymbol{ne}) + ((\boldsymbol{Hight\ of\ sw})\boldsymbol{m}) \\
&\qquad + ((\boldsymbol{Hight\ of\ ne})\boldsymbol{m}) + (((\boldsymbol{W})\ \boldsymbol{Width\ of\ the\ ST\ middle})\boldsymbol{m}) \\
&\qquad + (\left(\boldsymbol{h}/\boldsymbol{w}\right)\ \boldsymbol{ratio})\boldsymbol{m} + ((\boldsymbol{SVF})\boldsymbol{sw}) + ((\boldsymbol{SVF})\ \boldsymbol{middle}) + ((\boldsymbol{SVF})\ \boldsymbol{ne}) \\
&\qquad + (\boldsymbol{Colour\ of\ sw\ charactrestics}) + (\boldsymbol{Colour\ of\ ne\ charactrestics}) \\
&\qquad + (\boldsymbol{Colour\ of\ sw\ surface}) + (\boldsymbol{Colour\ of\ ne\ surface}) \\
&\qquad + \boldsymbol{open\ /\ close\ \ roadside\ features}\,.
\end{aligned}
$$

- Surface temperature (ST) were considered at three times separately (°C), it is considered as the dependent variable.
- AT (air temperature) was measured at three sides separately in °C.
- AV (air velocity or wind speed) was measured both sides and middle of the road separately in ms^{-1}.
- H: Height (m) of the roadside's characteristics at SW and NE locations were measured.
- W: Width of the road (m) between roadsides characteristics present at either side.
- (H/W) ratio: Height / width ratio were measured using the height of structures at either the SW or NE side.
- (SVF): Sky view factor was measured at both roadsides characteristics and middle of the road the range of the (SVF) are being in between (0-1), values closer to zero represented a more open sky view (less structures around).
- Colours of roadsides characteristics located at both sides: Red colour was considered for building (red brick) and green colours for the trees and hedges.
- Colours of the Pavement surface at SW and NE sides: light grey and dark grey (near black) colours were considered.

- Open/ closed sides were considered at SW and NE sides: Trees and hedges at roadsides characteristics were considered as open while office and houses were considered as closed roadsides.

The influence of time (location of sunlight relative to the features of the road) was considered with respect to the temperature profiles (Table 5.1). The same empirical data was used as that of Chapter 5. Statistical package (Stata / IC 14) was using to run the multiple regression of the data set (StataCorp) (see section 2.4 in chapter 2 for more details).

Table 5-1 Linkages between ST at three locations (SW, middle and, NE) separately, with independent (policy) variables of all three locations. It was considered in three different periods separately, at the periods (9.00-11.00, 15.00-17.00 and 18.00-20.00) respectively.



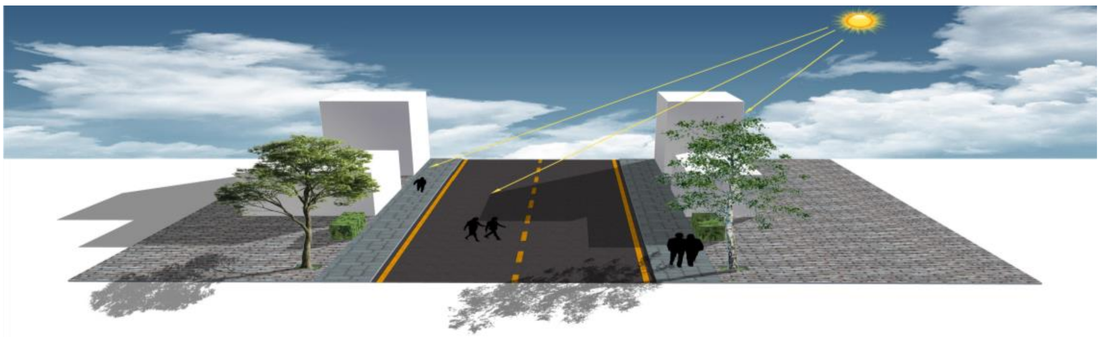
5.4 Results

5.4.1 Morning

The influence of different factors (independent (policy) variables) on surface temperatures recorded in the morning are outlined in Table 5.2.

5.4.1.1 Regression results for morning

Table 5-2 Regression result between ST at both edges and middle of the roads (SW, middle and, NE) separately, with independent (policy) variables of the same (SW, middle and, NE). Data for the morning period (9.00-11.00).



Variables	ST (SW)	ST (middle)	ST (NE)
Environmental variables			
Air T-SW	0.2***	0.3***	0.2**
Air T_-Middle	0.18*	0.6	0.1
Air T -NE	0.2**	0.2*	0.2**
Air Velocity-SW	-0.1***	-0.06	-0.8***
Air Velocity-Middle	1.02***	0.7***	-0.4***
Air Velocity-NE	-0.3**	1	-0.8***
Physical variable			
A- Scale variables			
Height-SW	0.1***	0.02	-0.1*
Width of the roads	0.16***	0.4**	-0.4
Height-NE	-0.5***	-0.6***	-0.6***
H/W ratio	-0.13	-0.24**	-0.27*
SVF-SW	5***	2.2*	0.2
SVF-Middle	6.5***	3.8***	0.4
SVF-NE	0.3**	1.6**	1.2*
B- Nominal variables			
Green color SW characteristics	-0.7***	-0.4	-0.2**
Red color SW characteristics	0.5	-0.8	0.7

Green color NE characteristics	-1.7***	-1.6***	-1.4***
Red color NE characteristics	0.6*	0.2	0.2
Light black of surface SW	-0.2	0.06	-0.3
Dark black of surface SW	0.5**	0.4*	-0.03
Light black of surface NE	0.5*	0.4	0.6**
Red surface NE	-0.4	-0.5	-0.2
C- Binary			
Open-Close SW	-0.4**	-0.56*	0.5**
Open-Close NE	-0.2	0.5*	0.2**
----------------------		-	6.6
Constant	5.6	8.6	0.6880
R^2	0.7658	0.7358	768
No of observation	768	768	

Note: ***, **, * indicate 1 % (p<0.001), 5% (p<0.05) and 10% (p<0.1) significant levels.

5.4.1.2 Environmental and physical properties during morning

During the morning period there was a small, but significant positive association between air temperature along both the SW and NE sides and ST (Table 5.2). Increases in air velocity on the NE side of the road, decreased surface temperatures (-0.1 to -0.8 ^{o}C; range of P<0.001 to P=0.048), whereas increases in wind speed in the middle of the road were seen to raise temperatures in the middle (0.7 ^{o}C; P=0.002) and on the SW side (1.02 ^{o}C; P<0.001). Increasing the height of features on the SW side and the width of the road, increased temperatures by a marginal amount on the SW side, whereas taller features on the NE side tended to reduce ST (Table 5.2). Increasing width of the road showed slight increases in ST on the SW side and the middle of the roadway in the morning; by approx. 0.16 ^{o}C (P=0.001) and 0.4 ^{o}C (P=0.042) respectively, for every 1 m increase in width. Height / width (H/W) ratio had a significant effect the ST on the middle of the road (P=0.022) and NE side (P=0.086) (Table 5.2) with a higher ratio decreasing temperature by 0.2 ^{o}C.

The largest temperature shifts, however, were noted with the sky view factor (SVF) (not un related to the height of features at the side of the road, of course).

Surface temperatures on the SW side were enhanced by 5 to 6.5 °C (both P<0.001) by more open aspects relating to the SW and middle locations, respectively. The middle of the road also showed enhanced ST (3.8 °C, P<0.001) with a greater SVF at this location. In contrast the temperature shifts on the NE side were less affected by this factor (i.e. 0.2 to 1.2 °C). Analysis of the colour of roadside objects, indicated cooling effects due to green infrastructure, although the mitigation effects was greatest with trees or hedges located on the NE side, lowering temperatures by 1.7 °C (P = 0.008), on the SW, 1.6 °C (P = 0.006) in the middle and 1.4 °C, (P = 0.003) on the NE side. Black coloured pavements on the SW side increase ST at this location by 0.5 °C, (P=0.025)

Open features on the SW side of roadways tended to cool ST on the SW location (by 0.4 °C, P=0.048) and, in the middle of the road (reduced by 0.56 °C, P=0.071). Interestingly, more open spaces in the NE sides slightly increase the ST on the NE sides (by 0.55 °C, P=0.087) and, the middle of the road (0.2 °C, P=0.078).

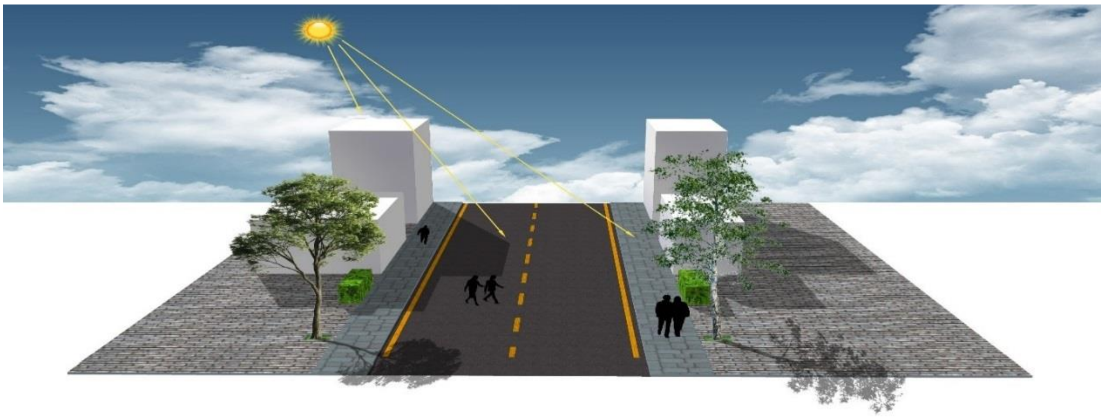
This implies that open aspect on the NE side of roads were increasing the amount of solar irradiance penetrating these areas during the morning period (Fig 5.3).

5.4.2 Afternoon

The influence of different factors (independent variables) on surface temperatures recorded in the afternoon are outlined in Table 5.3.

5.4.2.1 Result of the Regression at afternoon period

Table 5-3 Regression result between ST at both edges and middle of the roads (SW, middle and, NE) separately, with independent (policy) variables of the same (SW, middle and, NE). Date for the afternoon period (15.00-17.00).



Variables	(ST) SW	(ST) middle	(ST) NE
Environmental variables			
Air T-SW	0.5***	0.3**	0.4***
Air T_-Middle	0.3**	0.2	0.5***
Air T -NE	0.5***	0.7***	0.5***
Air Velocity-SW	-0.7***	-1.8	-1.3***
Air Velocity-Middle	-0.2	1***	-1.3***
Air Velocity-NE	-1.3***	-1.4	-1***
Physical variable			
Height-SW	-0.3	-0.5**	-0.5**
Width of the roads	0.1	0.1	0.02
Height-NE	1 **	0.6***	1**
H/W ratio	-0.5***	-0.5***	-0.6***
SVF-SW	6.5***	5.6***	1.7***
SVF-Middle	7.3***	6***	2.7***
SVF-NE	3	4***	6.5***
Nominal variables			
Green color SW characteristics	-1.3***	-0.3***	-0.3***
Red color SW characteristics	0.2	-0.33	-0.3
Green color NE characteristics	-0.14	-0.3	-1.3**

Red color NE characteristics	0.3	0.2	0.08
Light black of surface SW	-0.4	-0.1	0.01
Dark black of surface SW	1 **	0.1	-0.04
Light black of surface NE	0.1	0.45	-0.6**
Red surface NE	0.2	-0.8	0
Open-Close SW	0.5***	0.5***	0.08
Open-Close NE	-0.05	-0.25	-0.5***
---		-----------------	---------------------------------
-----------------------------		------	-3
Constant	-0.177	-3.4	0.7683
R^2	0.7023	0.7802	768
No of observation	768	768	

Note: ***, **, * indicate 1 % (p<0.001), 5% (p<0.05) and 10% (p<0.1) significant levels.

5.4.2.2 Environmental and physical properties during afternoon

There were strong positive relationships between air temperature (AT) and surface temperatures (ST) in the afternoon, the exception to some extent being the middle of the road location where there was no significant effect between air and surface here (Table 5.3). Increasing air velocities tended to decrease ST, by as much as 1.3 °C cooler at the edge of the roadways (e.g. on the SW side by 1.3 °C when air velocity increased on the NE side, P<0.001). Again the exception to some extent, was the middle of the road location where higher air velocity here increased ST on average by 1 °C (P<0.001). Increasing the sky view factor (SVF), had the strongest influence on ST, with large and significant increases being noted when the location had a more open characteristic (e.g. up to 7.3 °C warmer on the SW side when the middle of road had a high SVF, P<0.001). Allied to this increasing the Height-Width ratio significantly decreased ST. The location of taller features buildings, trees etc., had some influence on ST, with higher structures on the NE side tending to increase ST, whereas higher structures on SW side tended to decrease ST. The degree of openness of the roadway also influenced ST, with a more open SW side increasing ST by 0.5 °C on the SW side and in the middle of the road (P<0.001), whereas a more open NE side could reduce temperatures by a similar margin on the NE side

(P<0.001), (Table 5.3). The presence of green artifacts (trees, shrubs, grass) on SW side also had a significant negative influence on ST across the entire roadway. Colour of pavement also had a localized effect – dark pavements enhancing ST on the SW and lighter coloured pavements reducing temperatures on the NE side.

5.4.3 Evening

The influence of different factors (independent variables) on surface temperatures recorded in the evening are outlined in Table 5.4.

5.4.3.1 Regression results in the evening period

Table 5-4 Regression result between ST at both edges and middle of the roads (SW, middle and, NE) separately, with independent (policy) variables of the same (SW, middle and, NE). Data for the morning period (18.00-20.00).

SW Middle NE

Variables	(ST) SW	(ST) middle	(ST) NE
Environmental variables			
Air T-SW	0.3**	0.3***	0.3***
Air T_-Middle	0.5*	0.6*	0.6*
Air T -NE	0.5*	0.3***	0.4**
Air Velocity-SW	-0.3	-0.2	-0.8
Air Velocity-Middle	-0.8*	-1*	-1*
Air Velocity-NE	-0.8*	-1*	-0.7*
Physical variable			
Height-SW	0.2	0	0.06
Width of the roads	0	0	-0.07
Height-NE	0	0	-0.08
H/W ratio	-2.8	-2	-3.1
SVF-SW	5.7**	2.5	-2.5
SVF-Middle	-8.5*	-3.6**	2
SVF-NE	-1.2	-1.8	-0.6
Nominal variables			
Green color SW characteristics	-3.5*	-2**	-1.8**
Red color SW characteristics	-0.6	-0.5	-0.6

Green color NE characteristics	-0.6	-1.5***	-2.4*
Red color NE characteristics	-0.3	-0.4	-0.5
Light black of surface SW	0.3	0.12	-0.02
Dark black of surface SW	-0.8	-0.5	-0.4
Light black of surface NE	-0.1	- 0.17	-0.8
Red surface NE	-0.7	-0.30	1
Open-Close SW	0.4	0.4	-0.14
Open-Close NE	-0.04	0.13	0.4
--		---------------	-----------------------------
------------------------		------------	8.55
Constant	9.01	11.2	0.5644
R^2	0.5648	0.4896	768
No of observation	768	768	

Note: *, **, *** indicate 1 %, 5% and 10% significant levels.

5.4.3.2 Environmental and physical properties during evening

During the evening period, ST and air temperatures were positively correlated in all locations (Table 5.4). Increasing air velocity had a non-significant or marginally significant negative effect on ST (e.g. enhanced wind speed on the middle of the road reducing temperatures by 1°C at the middle and on the NE side, P<0.05). As with the afternoon the SVF was associated with the largest temperature changes, but in this case the direct was not always positive. Although a high SVF in the SW could enhance temperatures on the SW side (up by 5.7 °C, P<0.01) a high SVF in the middle of the road could reduce temperatures by as much as 3.6 °C (P<0.01, middle) and 8.5 °C (P<0.05, SW), respectively. Other significant influences noted in the evening was the presence of green features in the SW or NE sides (cooling ST throughout). Features such as pavement colour or degree of openness generally had less influence on ST compared to those recorded during the morning or afternoon periods.

5.5 Discussion

This chapter incorporates both environmental and physical variables together employing the multiple regression model to investigate the impact of the environmental and physical variables on the thermal profile of the road. Some factors were consistent throughout the day, whereas the influence of others could vary with time of day and the specific location within the roads. These latter factors were often associated with the relationship between time of day and the location of incoming solar radiation. In effect which part of the road was in shadow, when, and what features were influencing this. These points are discussed below.

5.5.1 Air V Surface temperatures

This research finds a positive impact of air temperature on road surface temperature irrespective of time of day. Quite whether air temperature is influencing surface temperature or vice versa, however, is a mute point. Large pockets of warm air will influence the temperature of objects around them, particularly so when discussed at a larger meteorological scale. In the scenarios presented here, however, air temperatures may actually be influenced more locally through the action of heat being radiated off the road surface and surrounding buildings. In essence solar radiation is heating roads and buildings, and energy (infra-red radiation) re-radiating from these is influencing the air temperatures. Due to air moving across the urban matrix these influences will distribute themselves relatively effectively. So warm air will distribute itself to the shady locations of the streetscape and air temperature is more likely to be relatively uniform across the street profile compared to surface temperatures, where exposure to solar irradiance has more of a direct influence on the temperatures recorded.

The data here is corroborated by other research. For instance, Kawashima et al. (2000) found high correlation coefficient between the air temperatures and the surface temperatures in the urban areas and showed that surface temperature alone explained 80% of the observed variation in air temperature.

5.5.2 Air Velocity

The relationship between air velocity (wind speed) and surface temperatures was somewhat more complex. Greater air movement, especially during the afternoon and evening was generally associated with a cooling effect on the road surfaces. This constant movement of air over the surface of the road allowing heat to dissipate more effectively from the road surface, compared to still air conditions. There were some occasions however, where surface temperature did not decrease when air movement increased, and this may relate to the direct solar irradiance effect over-riding the influence of the air temperature and movement (in these occasions the location was always exposed to direct sunlight), or where the air movement was recorded in a different location to that of surface temperature (and so was not necessarily having a direct effect, due to some sheltering influence on the road surface at these locations). Overall the data here is in line with the notion that faster wind speed cools down the surface more readily. For example, Wooten (2011) and Thangprasert and Suwanarat (2017) found strong correlation between wind speed and surface temperature in urban areas. But as also suggested here, the characteristics of the road and presence of other objects may interfere with this relationship.

5.5.3 Height of roadside features, width of road and height to width ratios

The data here shows that the impact of the height of the roadside characteristics, the width of the road and the height width ratios on surface temperatures is not straightforward. This is due to interactions between time of day, direction of incoming solar radiation and the aspect and features of the roads themselves. In some places, the height of roadside buildings, or the width of the road alleviates the road surface temperatures while in other locations, they induce an opposite effect. Locations that 'trap' solar irradiance in the morning (e.g. SW sides) may be in shade in the evening, and likewise NE locations may be shaded in the morning, but catch late evening solar radiation. Specific locations and the extent of the road profile that are affected by shade will be determined by the presence of buildings, trees, etc. and the width of the road (Figs 5.2 and 5.2).

Figure 5.1 The influence of building height on incoming solar irradiance, during morning (top), afternoon (middle) and evening (bottom).

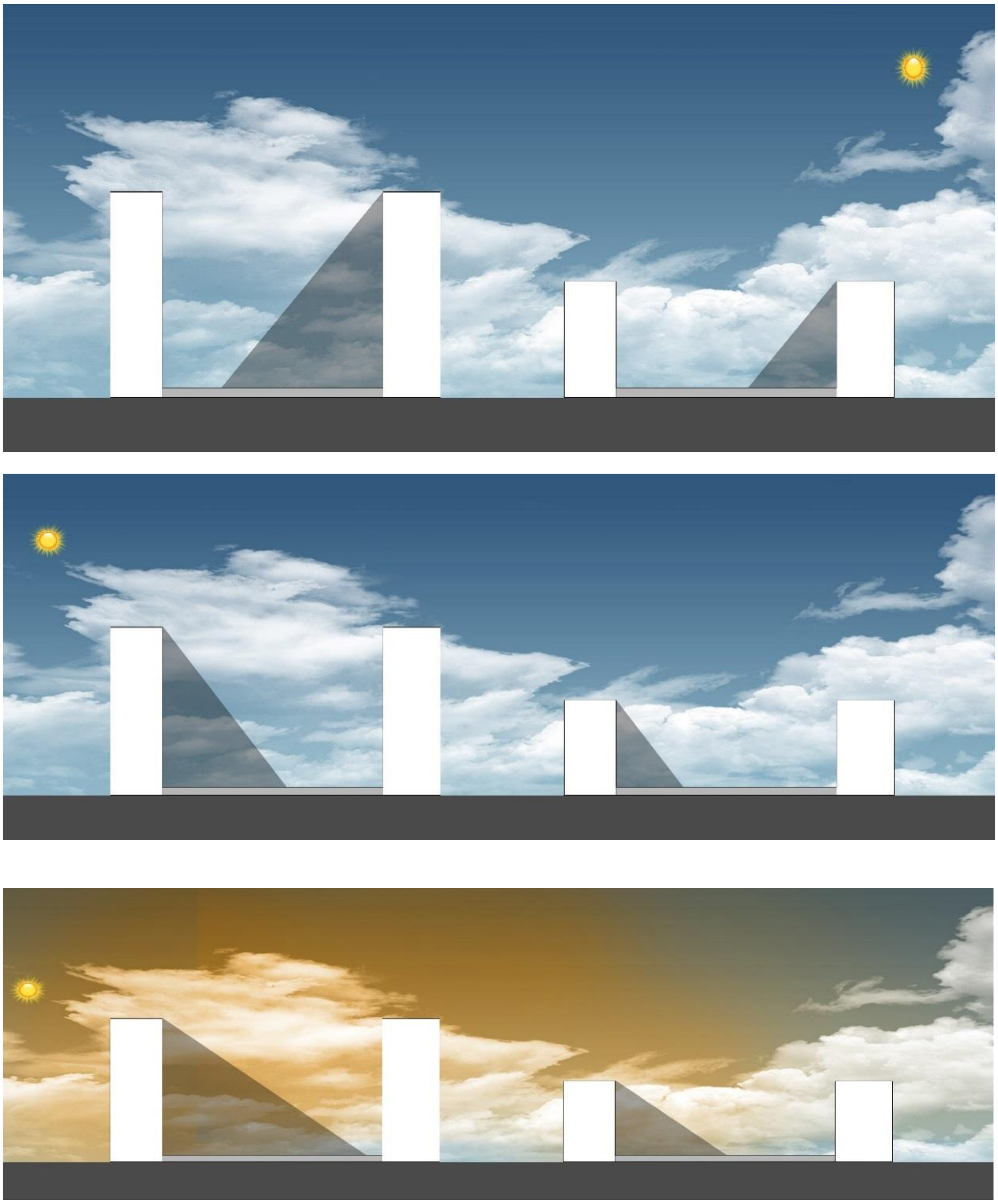
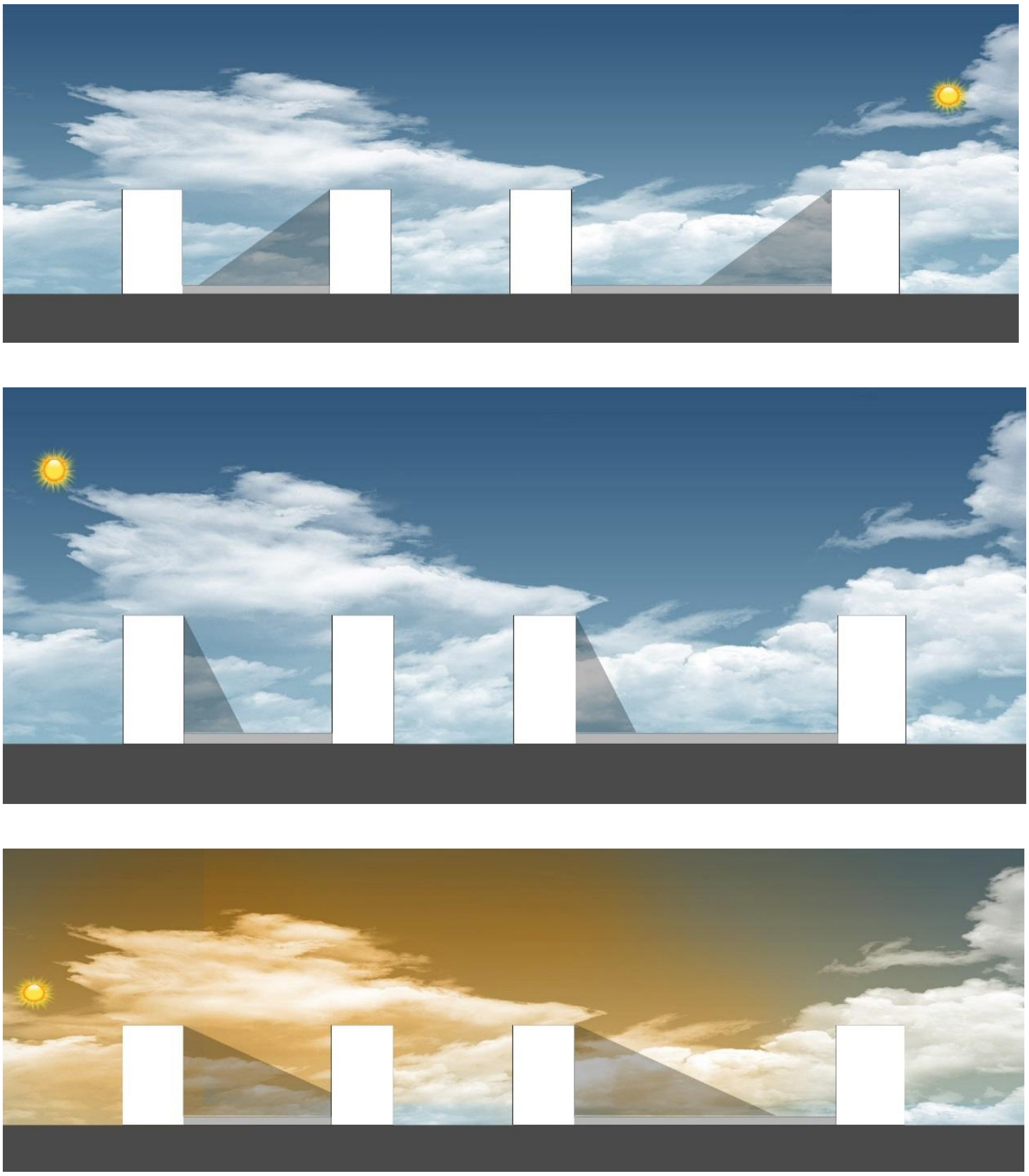


Figure 5.2 The influence of road width on incoming solar irradiance, during morning (top), afternoon (middle) and evening (bottom).



Increasing the width of the road and height of buildings on the SW side tends to increase surface temperatures on the SW side in the morning, due to allowing more incoming solar radiation and effectively trapping in more of the resultant heat energy. Increasing the height of buildings on the NE side has a similar effect in the afternoon. The height/width ratio of the roadside objects affects the thermal profile in the morning and afternoon significantly (cooling the street canyon down as less solar irradiance enters the streetscape), while in the evening period, the effect is not significant.

A very strong association was found between surface temperature and sky view factor, further confirming the strong influence of the amount of incoming solar irradiance on surface temperatures. More open skies significantly enhanced surface temperatures, during the morning and afternoon periods (due to less shade being present). This finding corroborates the other research to find the relationship between the SVF and air temperature (Yamashita et al., 1986; Eliasson & Svensson ,2003; Postgard, 2000; Karlsson, 2000). In the evening, however, a high sky view factor over the middle of the road in this research – possibly associated with a lack of tree canopy - resulted in more rapid cooling on the (by now shaded) SW and central locations (Table 5.4).

5.5.4 Green Infrastructure

Green infrastructure plays an important role to alleviate surface temperatures (Maher, 2013). The role of green infrastructure to alleviate surface temperature has been found empirically in a number of relevant research (Roy et al., 2012, Liangmei et al., 2008; Bau-Show Lin and Yann-Jou Lin, 2010, Ram Pandit and Laband 2010). The findings of the current research on the effect of the road side structures on surface temperature is that when the road side is occupied by green infrastructure, temperature on the road has been lower compared to other structures. This finding completely aligns with the findings of the other scientific and empirical research on this issue. when the roadside structure is red in colour, its effect on the ST is not significant at any time periods of the day.

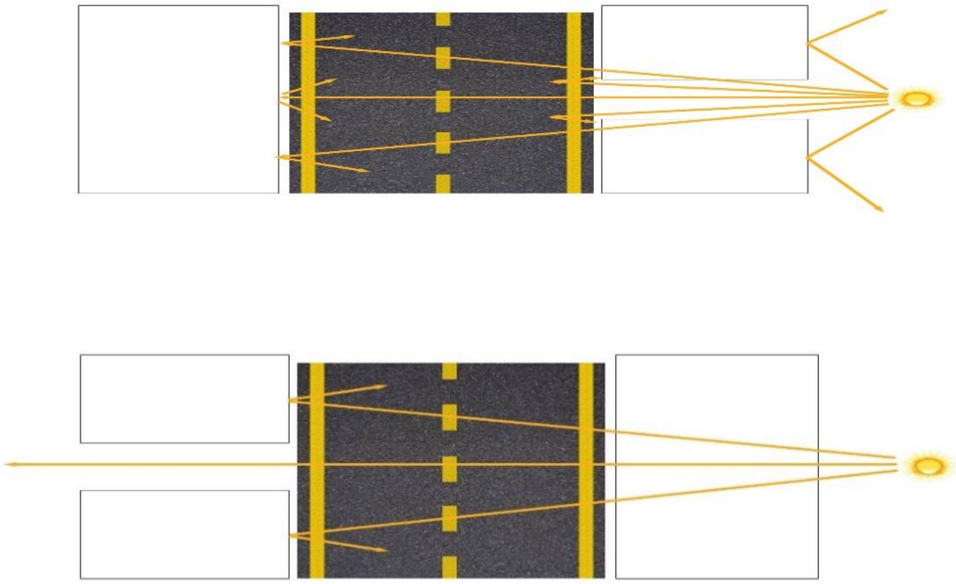
5.5.5 Surface colour

Colour of the pavements of the road also affects the road surface temperature. In the morning and afternoon, when the dark black pavements are exposed to sun light, the surface temperatures of the adjacent road area (SW) are higher compared to the other two areas (Middle and NE) significantly. This is in line with the scientific relation between pavement colour and surface temperature that new asphalt pavements are relatively dark and this will result in high pavement surface temperatures during hot, sunny periods while the surface is lit by the solar radiation and there is no shaded by grey and green structures (buildings or trees) (Li et al. 2013).

5.5.5 Open Space

In this research, trees, hedges and grass at roadsides were considered as open while office and houses were considered as closed. Open road sides in the morning have significantly lower surface temperature compared to the closed roadside (Fig 5.3). This is possibly due to the fact that open characteristics at the SW sides could allow the heat to be released to the adjacent space at the side of the road, or that the more open aspect encourages air movement across the road profile, thus increasing ventilation.

Figure 5.3 Open spaces in the roadway allow warm air to escape and encourage cross movement of wind, both factors tending to reduce surface temperatures.



5.6 Implications for Policy

This research bears some important policy implications in designing roads in the urban region. Where excessive heat may be problematic, for example by beginning to impact on human thermal comfort during heat wave events, then increasing the amount of shade to the streetscape whilst still encouraging cross-flow air movement seems prudent. Buildings themselves can provide shade, but this does depend on their orientation to the prevailing sunlight at any given time of day. Trees and other forms of green infrastructure provide a cooling influence – but again design in specific locations is important, for example in letting heat and poor air quality (Vardoulakis et al., 2017) escape the urban canyon, when required.

Conversely, the research also shows that a number of factors can increase the temperature of the streetscape, for example by optimizing solar gain. Although not the focus of this study, such factors could be important in winter scenarios where the aim is to raise temperatures for thermal comfort e.g. for pedestrians, or to reduce energy loss from buildings during inclement weather.

5.7 Concluding points from Chapter 5:

- A positive correlation between air temperature and road surface temperature irrespective of time of day has been found in this research.
- Wind speed reduces surface temperature significantly.
- The influence of height of the roadside characteristics on surface temperature can be significant, but whether it warms, or cools depends strongly on the direction of incoming solar irradiance, i.e. time of day and aspect of road.
- Similarly, the impact of the width of the road on surface temperature is not linear across the different times of the day.
- The height/width ratio of the roadside objects affects the thermal profile in the morning and afternoon significantly, while in the evening period, the effect is not significant.
- High sky view factor is one of the most effective variables that impact surface temperatures in all the time periods of the day.
- When the road side is occupied by green infrastructure, surface temperatures tend to be lower compared to the presence of other structures.
- Open road sides have lower surface temperature compared to the closed roadside significantly.

5.8 Implication from chapter 5

This research bears some important policy implications in designing roads in the urban region. Where excessive heat may be problematic, for example by beginning to impact on human thermal comfort during heat wave events, then increasing the amount of shade to the streetscape whilst still encouraging cross-flow air movement seems prudent. Buildings themselves can provide shade, but this does depend on their orientation to the prevailing sunlight at any given time of day. Trees and other forms of green infrastructure provide a cooling influence – but again design in specific locations is important, for example in letting heat and poor air quality (Vardoulakis et al., 2017) escape the urban canyon, when required.

Conversely, the research also shows that a number of factors can increase the temperature of the streetscape, for example by optimizing solar gain. Although not the focus of this study, such factors could be important in winter scenarios where the aim is to raise temperatures for thermal comfort e.g. for pedestrians, or to reduce energy loss from buildings during inclement weather.

The data generated in the last 2 chapters identifies how roadside morphology and other factors affect the thermal gain. What the data does not embrace is the actual influence of traffic *per se*, nor does it link to our understanding of larger scale influences of temperature. These components are thus further researched in Chapter 6 and Chapter 7, respectively.

Chapter 6 : Thermal properties as influenced by traffic volume and road-scape form

6.0 Hypothesis

Traffic volume at the peak daily traffic (rush hours or traffic jam period) increases the surface temperature of the road in comparison with the surface temperature with minimum daily traffic.
Surface temperatures due to congested roads are higher compared to those in parks and the roads with less traffic or where traffic is absent.
Roadside typology (roadside structures) along with traffic movement will interact to affect surface.

6.1 Introduction

Urbanization is an indicator of rapid world development (Louiza et al., 2015). Rapid urbanization leads to an increase in traffic mobility and volumes of flow which ultimately impacts urban warming. The literature recognizes the impact of traffic mobility on the thermal profile of the urban areas. As number of cars increase in urban areas (e.g. due to people commuting from the suburbs or outlying districts) and speed of travel decreases (due to congestion), and thus duration of cars on the roadways actually increases, temperature is included to rise. This is due to thermal emission from petrol and diesel engines. Vehicles emit both heat and aerial pollutants that can remain trapped within the urban matrix, resulting in poor air quality and potentially thermal discomfort for citizens. In addition to this, this heat also contributes to the formation of the urban smog as well as CO_2 emissions that contribute to climate change (Wang et al., 2004; Watkins et al., 2007; Younger et al., 2008).

Sheffield, as with many other UK cities has seen a rise in commuting and the use of the car to get people to and from work, as well as visit the city centre for recreation and shopping. This has led to increases concerns over the environmental damage caused by cars. Most of these concerns have been about engine emissions in terms of particulate and gaseous pollutants, (Louiza et al., 2015) but this research aims to explore further the influence on urban thermal considerations.

This chapter tries to identify the impact of the mobility over the road network on the thermal properties of their surface. Also based on the results of experiments in previous chapters, it was noticed that the impact on the surface temperature of the roads were dramatically appeared particularly in the middle section of the road (Vehicles Zones) in the peak daily traffic compared to different sections over the road ((both edges) shoulders) (see figures). So, vehicles and cars might contribute to heating the road surface possibly due to the friction between the wheels of the vehicles and the surfaces of the road. Also the accumulative heat and poor ventilation in urban canyons may trap the heat, particularly in rush hour traffic, hence, these factors may increase the surface temperature of the road. Temperature profiles that peak in the middle of the road may relate to both frictions from types, but also more direct solar influence (less shade compared to the side of the road). Emissions and the heat of the cars engines could exacerbate the formation of urban smog which in turn may contribute to heat build-up (Wang et al.,2004; Watkins R.a Palmer, 2007; Young et al., 2008).

Within this chapter three different experiment were carried out to examine the impact of traffic volume on the surface temperature across road profiles by comparing the following situations:

- Surface temperature in peak daily traffic and less traffic volume of the same road with respect of the roadsides features and its participation.
- Surface temperature in peak daily traffic and normal traffic density in three different roads with different circumstances: congested road, no/less traffic road, and park.
- Surface temperature in the peak and minimum weekly traffic of the same road with respect of the effect of roadside structures.

6.2 Research Questions

The following research questions will be investigated in this chapter:

- How does different traffic volume of the road at different time affect the micro-climatic/thermal properties of road surface?
- How does different traffic volume in the different road at the same time affect the micro-climatic/thermal properties of road surface?
- How does adjacent landscape features – (Green/ Gray) contribute to the micro-climatic/thermal properties of road surface along with traffic volume?

6.3 Experimental design of traffic and temperature profiles along the same road

Surface temperature was recorded during the months of February and March of the year 2016. The sequences of the data recording steps were as follows:

Firstly, twelve separate locations over one road (Glossop road, Fig 6.1) were monitored over two months, with temperature data being recorded in the late afternoon of the period between (17:00 – 18:30) as this period represented the pick daily traffic when the majority of students and employees started to return home from the University of Sheffield, stores around the city, offices and so on. Numbers of cars passing through the road in either direction for 1 hour was observed in the period (17:00-18:00); then STs for half an hour were observed in the period (18:00-18:30).

Secondly, number of cars passing through the road in either direction for 1 hour was observed in the period (20:00-21:00); then STs for 30 min were observed in the period (21:00-21:30). This time reflects the minimum daily traffic (or less than average daily traffic) as the people are usually staying at home after working time. For each location, twelve surface temperatures were recorded on each occasion using Thermometer device (model testo 845 infrared measuring instrument), (See chapter two, section 2.1.1 for more details).

The twelve locations over the road of this experiment are located between four types of both roadsides' structures. Each type of them has equally four locations - Building- Building, Tree-Tree, Building-Tree and, Tree-Building.

In both periods, after measuring and recording the surface temperature, the researcher manually counted the number of vehicles per hour to evaluate the comparative cooling and warming potential of traffic volume on the surface temperature considering the interaction of the road features (see section 2.3.5. in chapter 2). February and March of 2016 represent the coldest period of the year in the city of Sheffield. Data was recorded in eight (8) days in February (1^{st}, 3^{rd}, 5^{th},7^{th},9^{th}, 11^{th}, 13^{th} and 29^{th}), six (6) days in March (2^{nd}, 4^{th}, 6^{th}, 8^{th}, 10^{th}, 12^{th}).

Surface temperature may often be different between the beginning and the end of each period irrespective of the locations (as the site has 12 different locations) (see table 1.6 below). To avoid any bias due to the timing within each recorded slot in both times (late afternoon and early evening), the order of recording the

ST among 12 different locations varied across different days. Here, the data recording of the day does not start with the same location every time. Eventually, it was done to remove any diurnal influences.

The focus of the research was to identify how different traffic volumes affected surface temperatures and how the roadside structures might contribute to suppress or enhance the surface temperature by grey and green infrastructure located on the both sides along with traffic. Therefore, 12 locations within the road were carefully chosen so that they contain different roadside structures. Roads with heavy traffic site were also chosen to maximize the thermal influence of road traffic as the experiment of the current chapter is investigating the effect of traffic volume on the road thermal profiles. So, in light of this consideration, Glossop Road was carefully selected as it has all the major features of the experiment (see Fig 6.1).

For each location, the road side characteristics have been defined with the existence of building, tree etc. In this experiment, ''T-T'' indicates tree on the both sides of the road and B-B refers to the building on the both sides.

Analysis of variance was carried out to test the effect of traffic volume on ST in the rush hour and lean traffic volume with respect to the influence of various structures located on both side of the road. Mean values for each cross-sectional point have been presented in the corresponding figures. Error bars are represented by Fisher's least significant difference values (at 5% level).

Correlation between two continuous variables was carried out to investigate the relation between (traffic volume and ST). The values between these two variables are defined based on the following range: ≤ 0.29 - a small correlation, range between 0.30 to 0.49 - a medium correlation and ≥ 0.50 - a large correlation (Cohen,1988).

Figure 6.1 Satellite image of the surveyed sites within the study area on Glossop Road. Source: The Arc GIS (Arc map).

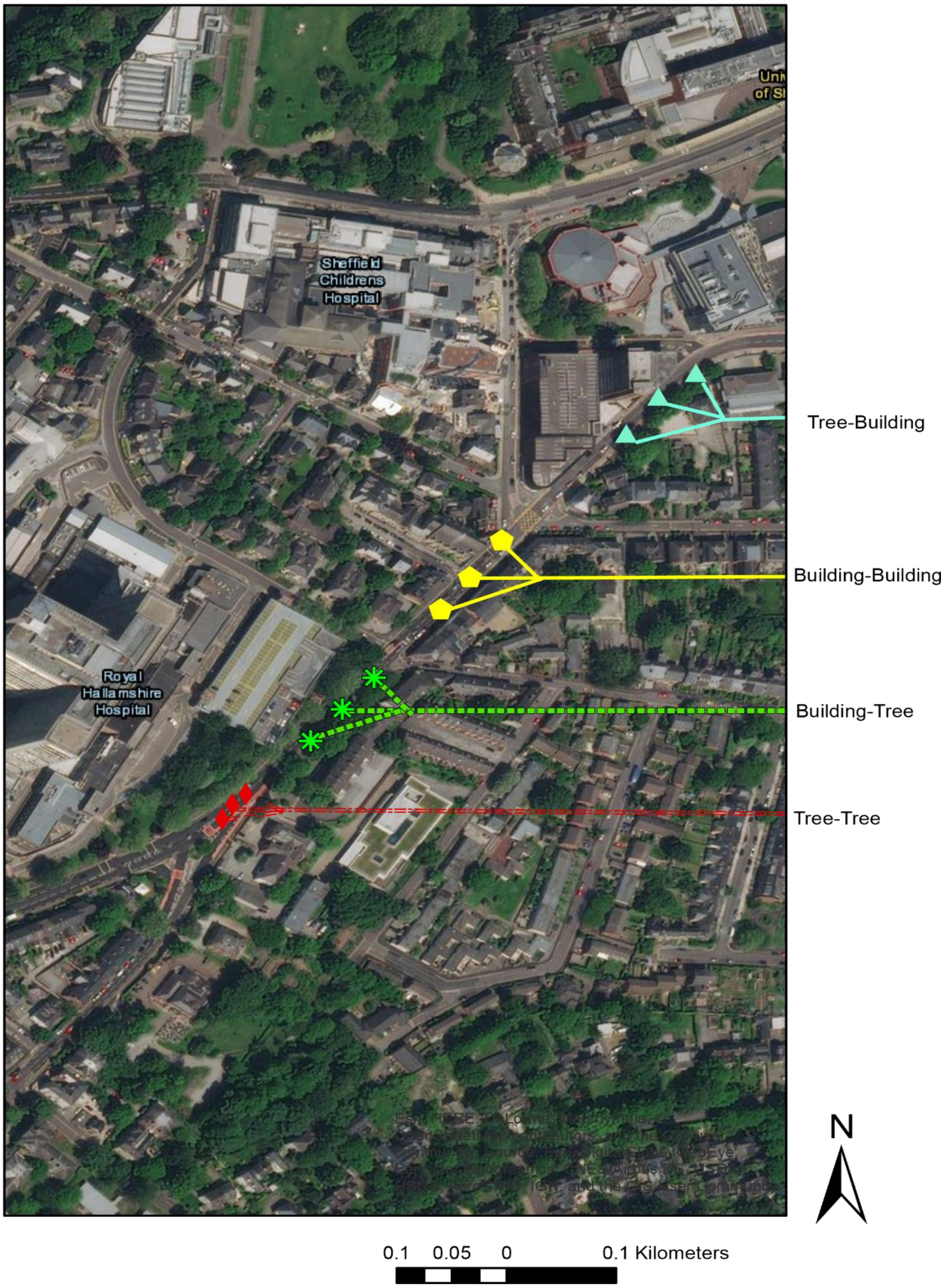


Table 6-1 Detailed showing the 12 treatments of the experiments in Glossop Rd and its coordinating on GIS.

Locations with different Roadside characteristics located on (Glossop Rd)	Coordinating on GIS
1- Tree-Building	1^0 29′ 29.466′′W 53^0 22′ 40.115′′N
2- Tree-Building	1^0 29′ 17.419′W 53^0 22′ 47.907′′N
3- Tree-Building	1^0 29′ 30.287′′W 53^0 22′ 39.748′′N

4- Building-Building	1^0 29′ 22.152′′W 53^0 22′ 45.151′′N
5- Building-Building	1^0 29′ 22.981′′W 53^0 22′ 44.334′′N
6- Building-Building	1^0 29′ 23.837′′W 53^0 22′ 43.824′′N

7- Building-Tree	1^0 29′ 29.227′′W 53^0 22′ 40.506′′N
8- Building-Tree	1^0 29′ 29.997′′W 53^0 22′ 39.996′′N
9- Building-Tree	1^0 29′ 29.142′′W 53^0 22′ 40.404′′N

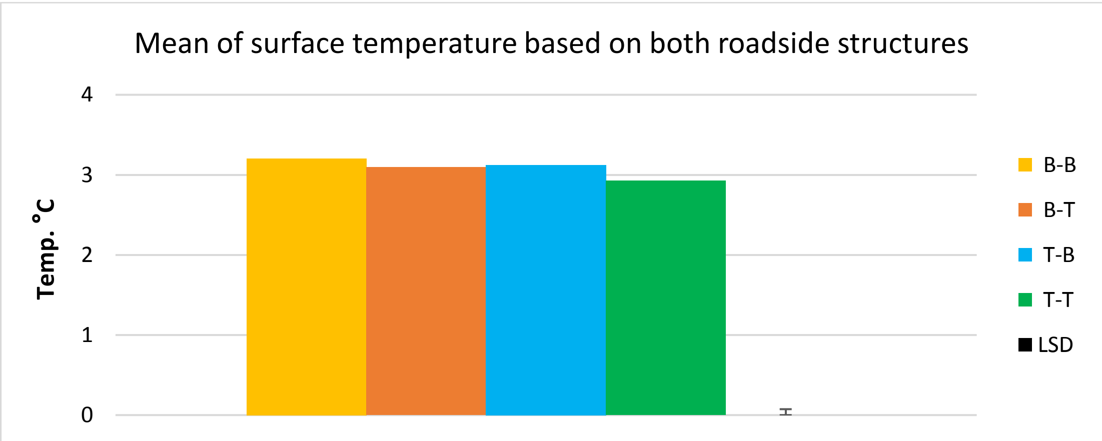
10- Tree-Tree	1^0 29′ 25.719′′W 53^0 22′ 42.395′′N
11- Tree-Tree	1^0 29′ 26.831′′W 53^0 22′ 41.731′′N
12- Tree-Tree	1^0 29′ 27.773′′W 53^0 22′ 41.272′′N

6.4 Result

6.4.1 Effect of roadsides typology on the road surface temperature in winter season

ANOVA result indicated a significant influence on the means of surface temperature ST by roadside structures (Topology). The highest temperatures were adjacent to B-B characteristics by around 3.2 °C while T-T was the lowest by around 2.9 °C, (P< 0.001, lsd=0.07, lsd 5%, Fig 6.2).

Figure 6.2 Frequency distribution of mean surface (n=14 days) temperature for both periods together in the day (17:00-18:00 and 20.00-21:00), based on the roadside structures, (P <0.001, lsd = 0.07), error bars lsd 5%, letters relate to points across the profile of the road.

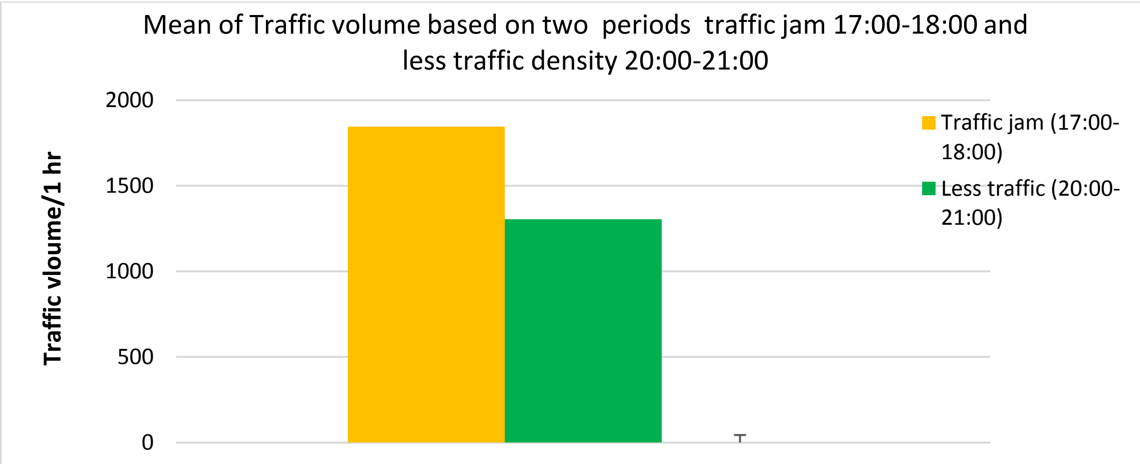


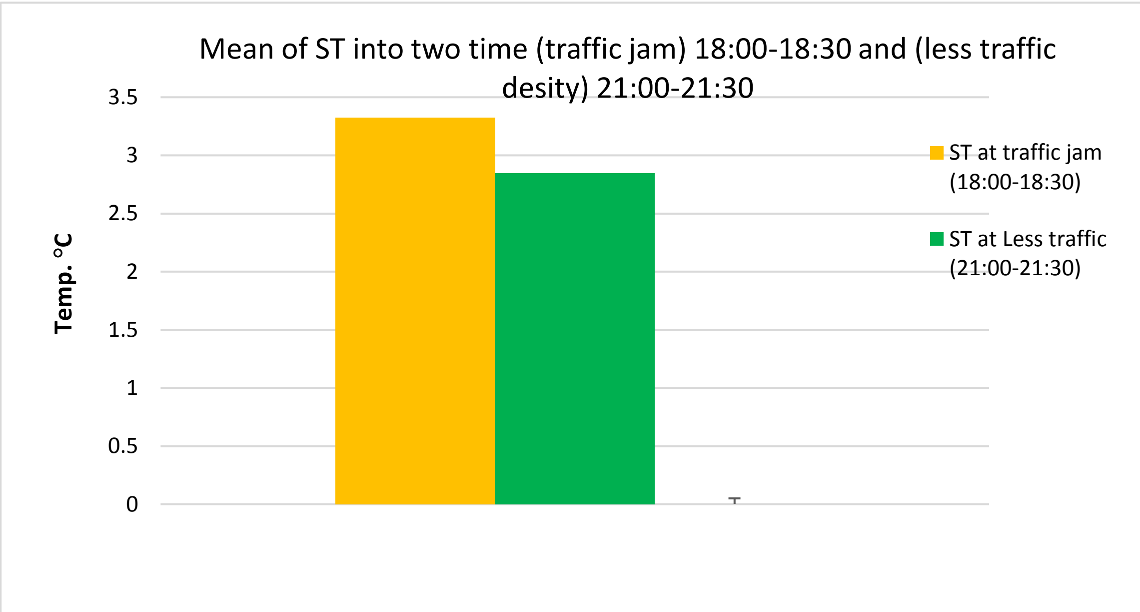
6.4.2 Effect of traffic volume in the periods between 17:00-18:00 (traffic jam) and 20:00-21:00, (less traffic density) on the surface temperature of the road in the periods 18:00-18:30 and 21:00-21:30 respectively

Analysis of variance indicated that the mean of traffic volume was significantly different between two-time measurements ($P < 0.001$, lsd= 44.5, Fig 6.3). It varied between the periods 17:00-18:00 and 20:00-21:00 by approximately 1843 and 1302 cars per hour respectively (Fig 6.3 Top).

Besides, ANOVA analysis indicated that mean of surface temperature ST was strongly influenced by different time measurement. It was around 3.32 ^{o}C in traffic jam period and around 2.85 ^{o}C in the less traffic period ($P < 0.001$, lsd = 0.05, Fig 6.3 Bottom). This indicated that traffic volumes significantly influenced the surface temperature.

Figure 6.3 Mean traffic volume (n=14 days, top) in the periods between (17:00-18:00, traffic jam) and (20:00-21:00, less traffic density) and surface temperature (n=14 days, bottom) in the periods between (18:00-18:30, traffic jam) and (21:00-21:30, less traffic density), (lsd 5%, P <0.001).





6.4.3 Effect of traffic volume in periods of traffic jam and less traffic volume jointly with roadsides topology (structures) on road surface temperature

There was a significant effect due to the roadside features at both time periods on the ST ($P < 0.001$, lsd=0.07), with the green location –''Tree-Tree'' being cooler than grey ''Building-Building'' as outlined before. Overall, trends showed that ST was altered by time and different traffic volumes. For instance, at the ''T-T'' location, temperatures rose significantly by 0.5 ^{o}C when recorded at the higher traffic volumes. Increases at other locations were similar (Fig. 6.4). As with previous experiments there was a pattern to temperatures across the road profile with the presence of a tree cooling that side, but not necessarily the middle or other side of the road (Fig. 6.5); possibly because in this case the trees were not large / near enough to shade the road or provide evapo-transpirational cooling. Note too that in this scenario, when ambient temperatures were quite low how surface temperature rise marginally at each end of the line as they near a building – indicated heat diffusion from the building or solar irradiance being specifically 'trapped'' here. Profiles across the road also clearly demonstrate that road traffic volume or time affects the temperature, with a significant 0.3 to 0.75 ^{o}C higher level at the earlier, busier time of 17-00 – 18.30 (Fig. 6.6). This may be due to increased traffic volume, but a natural decrease in overall temperatures between late afternoon and evening cannot be ruled out too.

Figure 6.4 Frequency distribution of mean surface temperature (n=14 days) based on the roadside topology into two-time (18.00-18:30, Traffic jam) and (21.00-21:30, less traffic density), (P <0.001, lsd = 0.1), eror bars lsd 5%, letters relate to structures across the both sides of the locations.

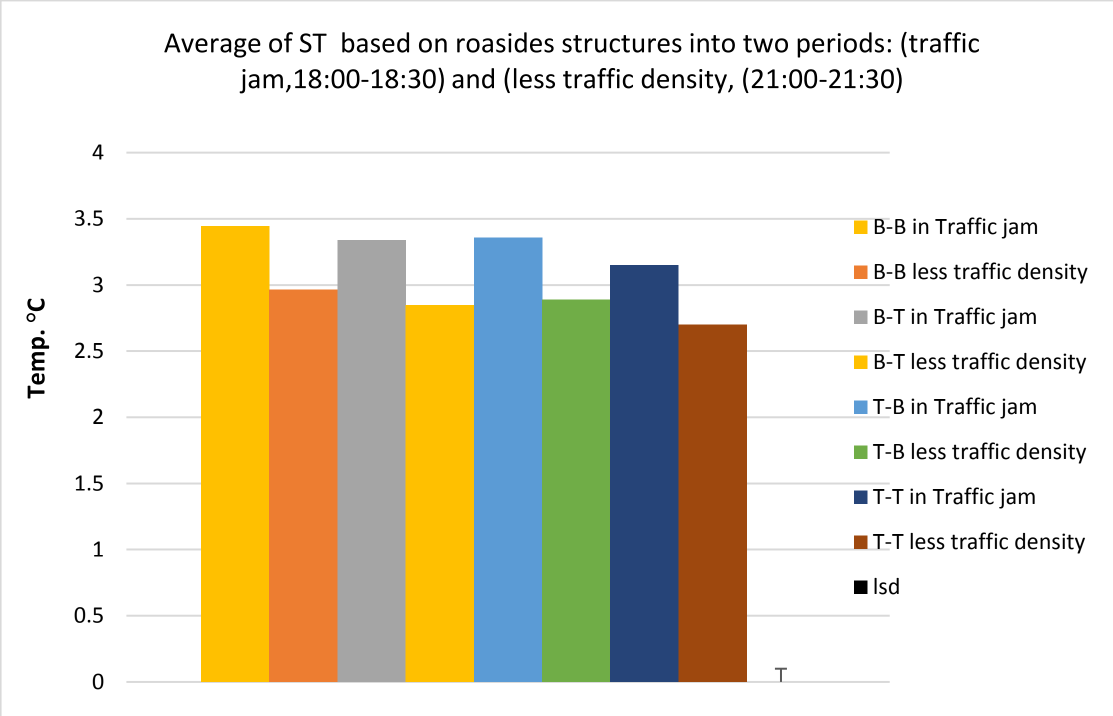
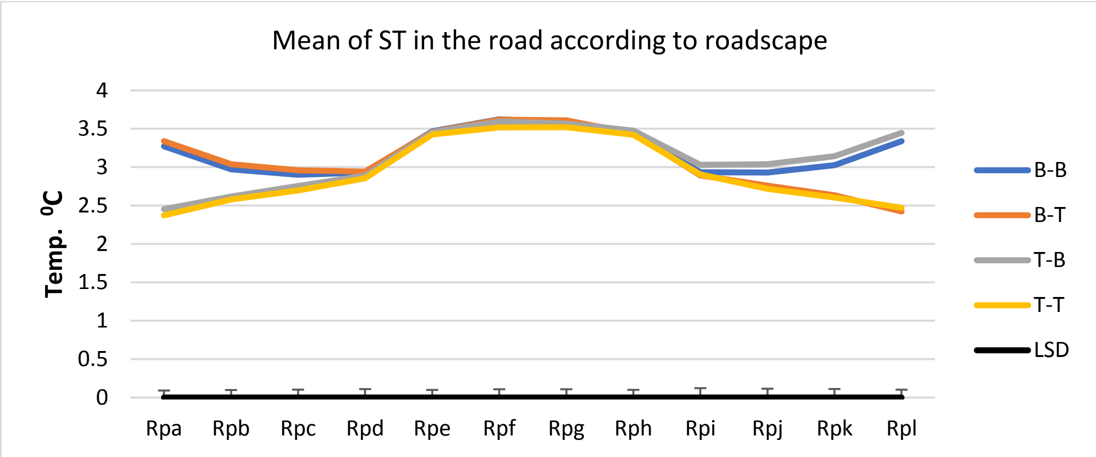


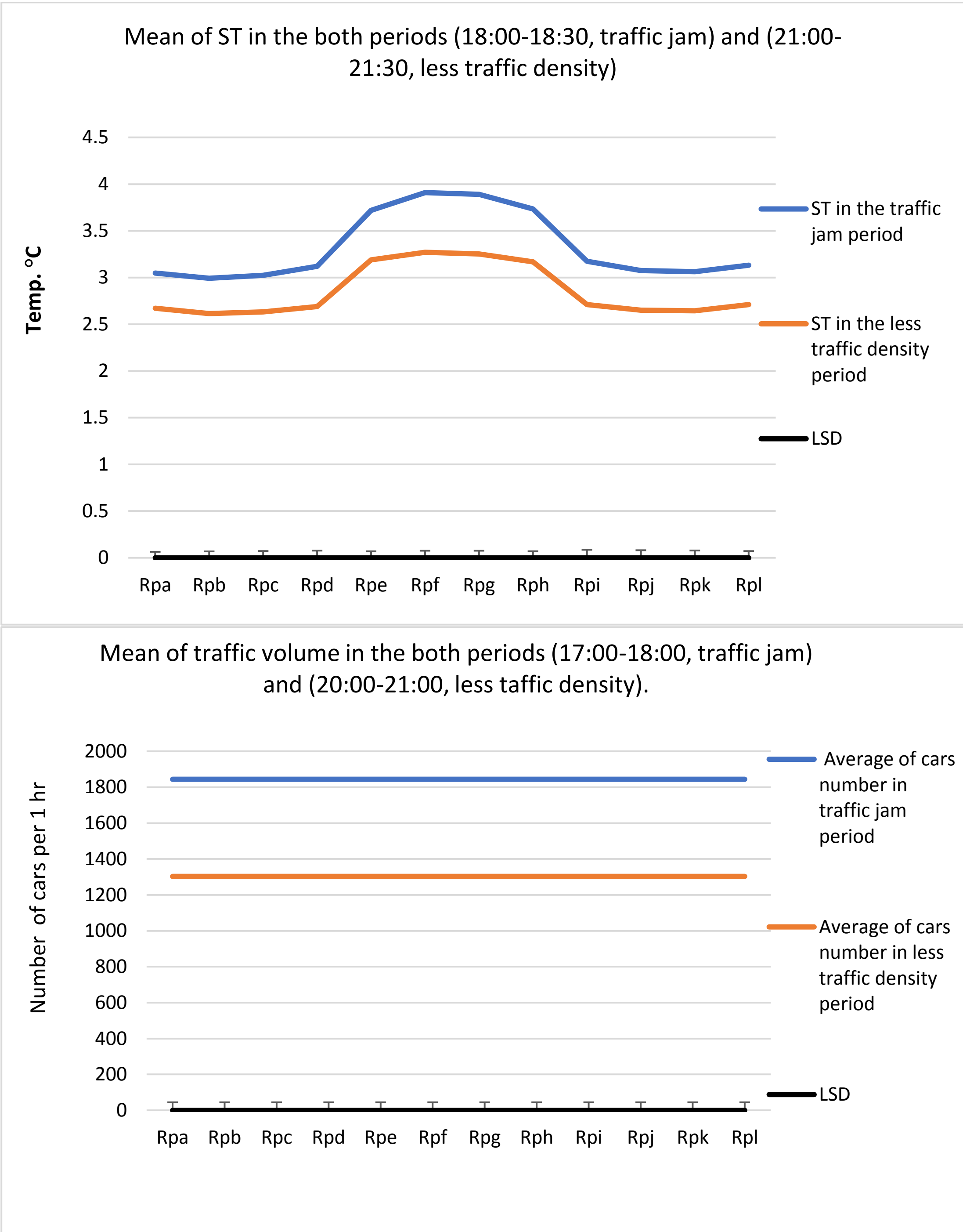
Figure 6.5 Thermal properties across the roadway at various locations with contrasting roadside topology in both periods (18:00-18:30, Traffic jam) and (21:00-21:30, less traffic density): Mean surface temperature (n=14 days) over the locations (P_{value} RPa-c and RPj-l > 0.001) at both pedestrians' zones and (P_{value} RPe-h= 0.107-0.84) in the middle of the road (cars zone), error bars 5%, letters related to points across the profile of the road.



6.4.4 Effect of traffic volume (traffic jam, 17:00-18:00) and (less traffic density, 20:00-21:00) on the surface temperatures across the road

Analysis of variance indicated that thermal profile of mean surface temperature of all locations over the road could also show a significant difference in their temperature profiles into two-time intervals (18:00-18:30) and (21:00-21:30). For example, there could be around 1°C differences between both periods ($P_{Rba-Rpl}$ >.001) (range of lsd=0.06-0.08) (Fig 6.6 Top); possibly due to the fact that the mean of the traffic volume was higher in the traffic jam period (1844 cars/ hr) compared to less traffic period (1303 cars/hr) (Fig 6.6 bottom). This suggested that traffic volume significantly affected the ST.

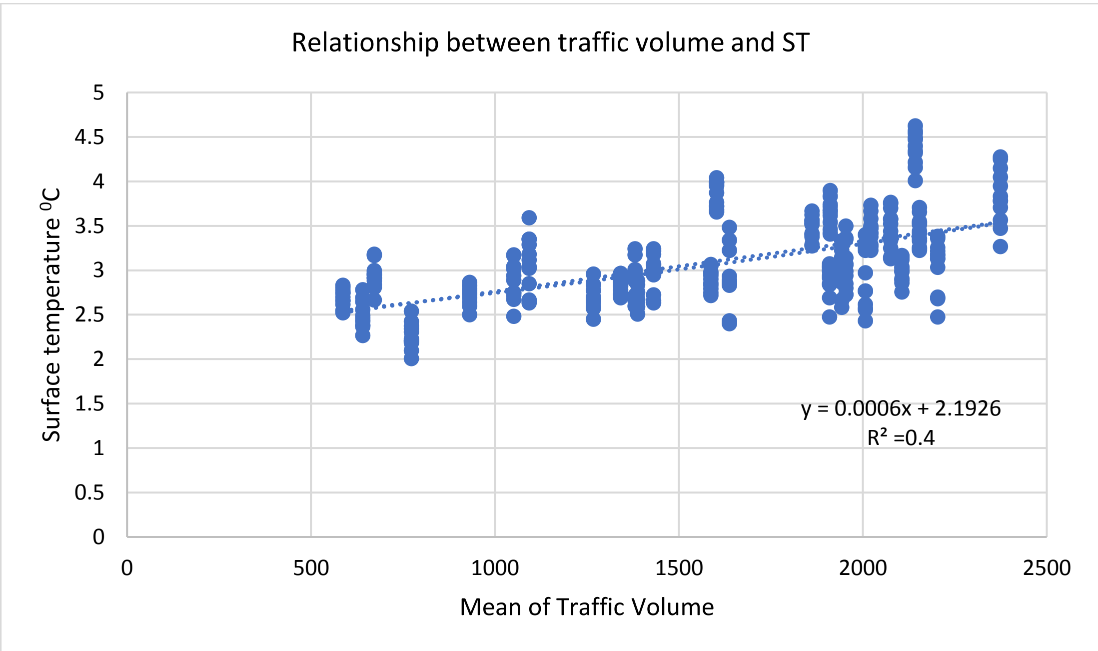
Figure 6.6 Thermal properties (n=14 days, top) into two time periods (18:00-18:30, traffic jam) and (21:00-21.30, less traffic density) and traffic volume (n=14 days, bottom) in both periods (17:00-18:00, traffic jam) and (20:00-21.00, less traffic density).



6.4.5 The correlation between traffic volume and surface temperatures of the road

A regression model of traffic movement factors indicated an average effect on the ST and it indicates a positive significant influence of traffic movement on the ST ($p<0.001$). The regression model indicated that traffic volume could explain 36% of the temperature variation of the road in both periods (Fig 6.7). Data showed that traffic volume positively affected surface temperature, though the coefficient values of traffic volume in middle indicates a least effect on temperature. R^2 value is around (0.4), indicating that only approximately 40% of the variation in the surface temperature of the road was explained by traffic volume.

Figure 6.7 The relationship between mean of surface temperature in the periods of 18.00-18:30 and 21:00-20.30 and average of cars passing in periods 17:00-18:00 and 20:00-21:00, letters relate to points across the profile of the road. Regression equation, R^2 and correlation coefficient are showed in the graph.



6.5 Experimental design of second experiment

Road and pavement surface temperatures were recorded during the months of December, January, February and March. Three separate locations (heavy use 'trunk' road, 'quiet' link road and tarmacked road within park – see below Fig 6.8.) were monitored over four months' period, with temperature data being recording in the late afternoon (17:00–18:35) as a traffic jam period and early evening (20:00 – 21:35) as less traffic volume for each location. The data - surface temperature (ST), air temperature (AT), air velocity (AV) and number of car passing per/ 30 min were repeatedly observed in each time period (two attempts within each periods). The order of the locations surveyed though were varied to avoid any build-up of bias due to some sites being surveyed consistently earlier than others

For each location, three surface temperatures (ST) were recorded on each occasion (Fig 6.9); these represented the transactional 'profile' of the roadway, with road profiles (RP) 'a' to 'c' representing one pavement (both 'a' and 'c' being the both edges farthest away from the road itself and closest to the both structure at the side of the road (in the road shoulders), RP_b represented temperature point in the centre of the road (cars zone). Surface temperature were recorded using the Thermometer device, (see chapter two, section 2.2.1 for details).

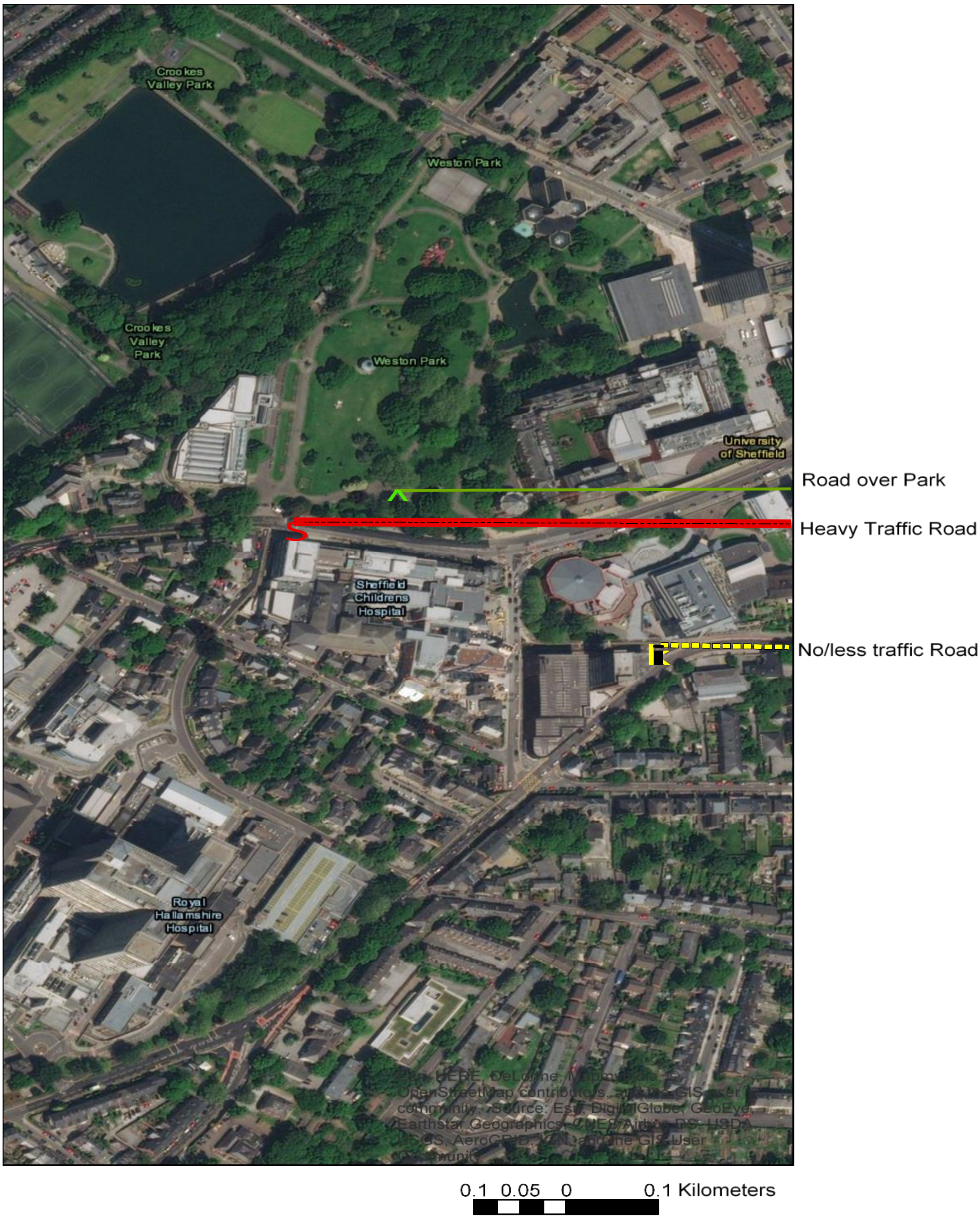
The three locations for this experiment were relatively close together, i.e. in:- A57 Rd as a busy road (1^0 29′ 29.465′′ W 53^0 22′ 52.004′′ N); Durham Rd as a less traffic density (1^0 29′ 16.733′′ W 53^0 22′ 48.911′′ N); and in Weston Park (1^0 29′ 25.923′′ W 53^0 22′ 52.77′′ N); (Fig 6.8) – to avoid any larger scale climatic influences, but also to allow rapid recoding between sites, within a short time frame. Data was recorded across 13 evenings in December 2016 and 14 each in

January, February and March 2017 (55 days x 2 times x 2 reps = 220 data sets for each location.

These data sets were used to determine if there was any variation in temperatures on a uniform surface during the recording of each sort of the road in this experiment also to determine the impact of the road's traffic volume on the surface temperature by different times (traffic jam and quieter traffic period).

Air temperature and wind speed also were recording instantaneously with Surface temperature using the (Digital Anemometer instrument as a mobile station), (see chapter two, section 2.2.2 for details) and it was recorded exactly at the same cross-sectional temperature points of surface temperature points ($RP_{a\text{-}c}$), and it was around 1 m level above the level of the road surface. Also, the key characteristics of those two variables of each location were recognized, for example, (RP_a), (RP_b), and (RP_c) were referred to the air temperature and wind speed at the left, middle and right sides of the road respectively.

Figure 6.8 Satellite image of the surveyed sites within the study area on A57 (busy road), Durhan Road (less traffic road) and, Weston bank (park). source: The Arc GIS (Arc map).

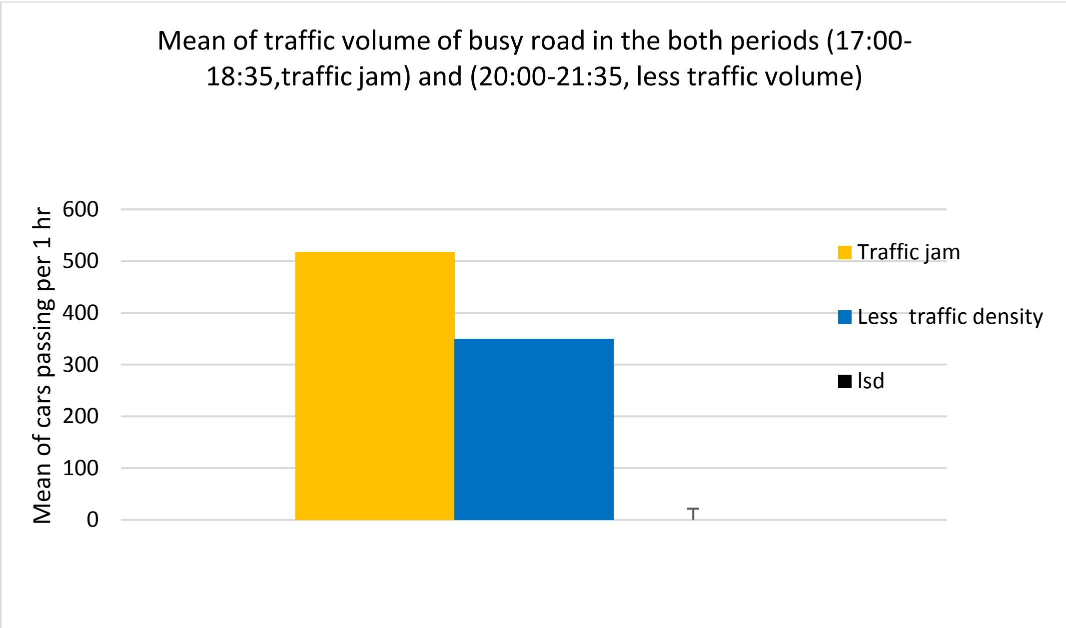


6.6 Result

6.6.1 Effect of traffic volume (traffic jam) Vs (less traffic density) on surface temperatures of the busy road

Regression analyses of traffic volume indicated that there were significantly different traffic volumes between the two-time periods, mean for late afternoon = 519 and evening = 350 ($P < 0.001$, lsd=40.5), (data for the busy trunk road shown in Fig. 6.9). Road typology had a strong effect on surface temperatures with surface temperatures of 9.4 ^{o}C, 5.4 C and, 6.5 ^{o}C ($P<0.001$, lsd = 0.4) in the busy road, no traffic road and park respectively (Fig 6.11). Such differences were apparent in the road profiles too, with a distinct temperature peak in the middle of the road with the busy trunk road, which was not apparent in the quieter road or the park situation (Fig 6.13). The volume of road traffic in the trunk road also influenced temperature (Figs 6.10 and 6.12).

Figure 6.9 Frequency distribution of mean traffic volume (n=55 days) in (17:00-18:35, traffic jam period) and (20:00-21:35, less traffic volume period), (P <0.001, lsd=40.5, error bars lsd 5%, top). Mean of traffic volume (n=55 days, same periods above) in both attempts (1st and 2nd) within the same periods (above) separately, (p < 0.001, lsd =57.3, error bars 5%, bottom).



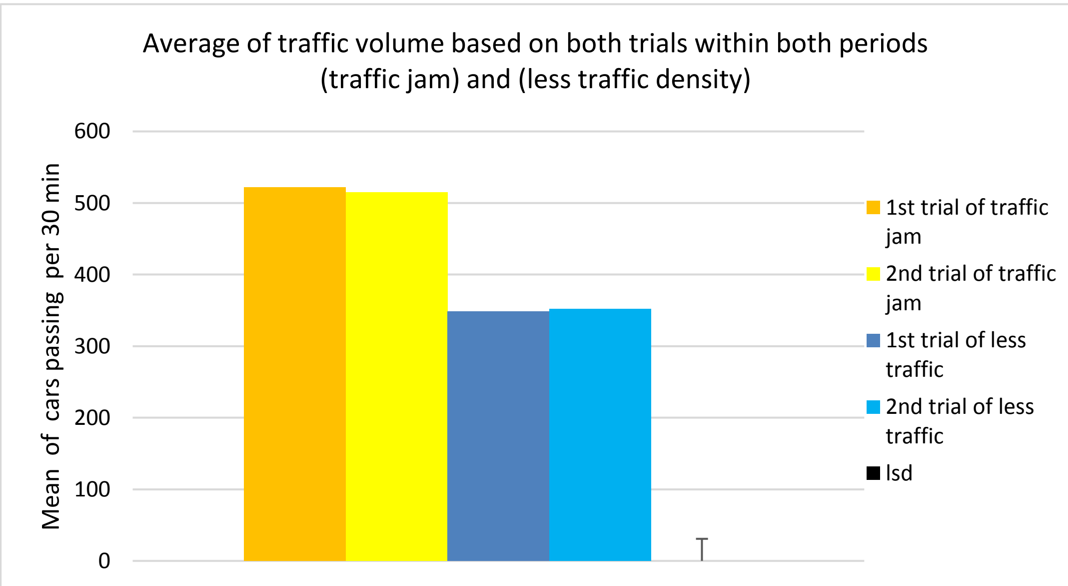
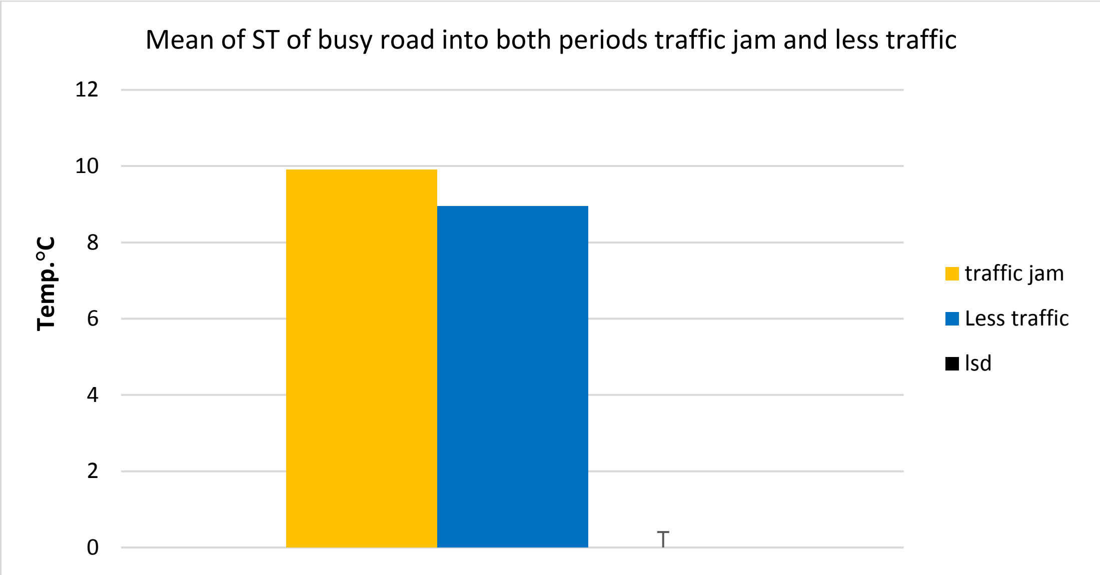
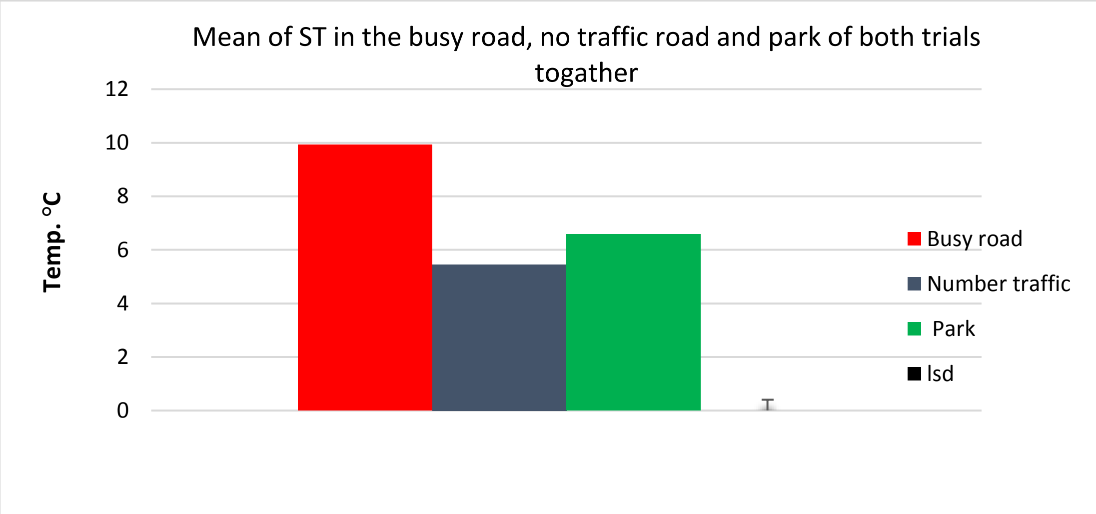


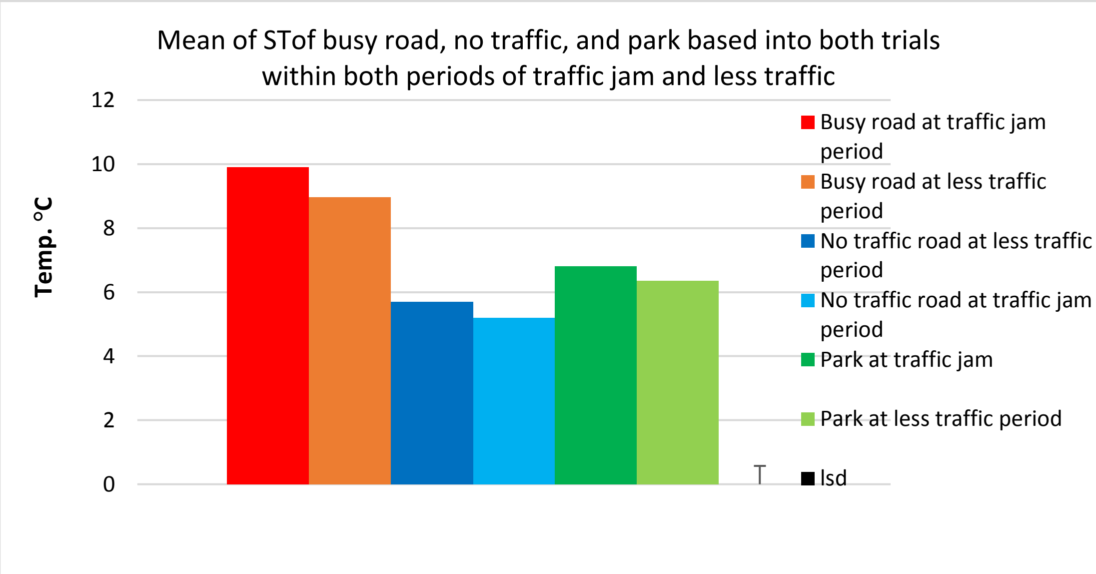
Figure 6.10 Frequency distribution of mean surface temperature (n=55 days) of busy road into two periods (traffic jam) and (less traffic), (P<0.001).



6.6.2 Effect of various types of roads (busy road, no traffic road and park) on the surface temperatures based on traffic density (traffic jam Vs less traffic density)

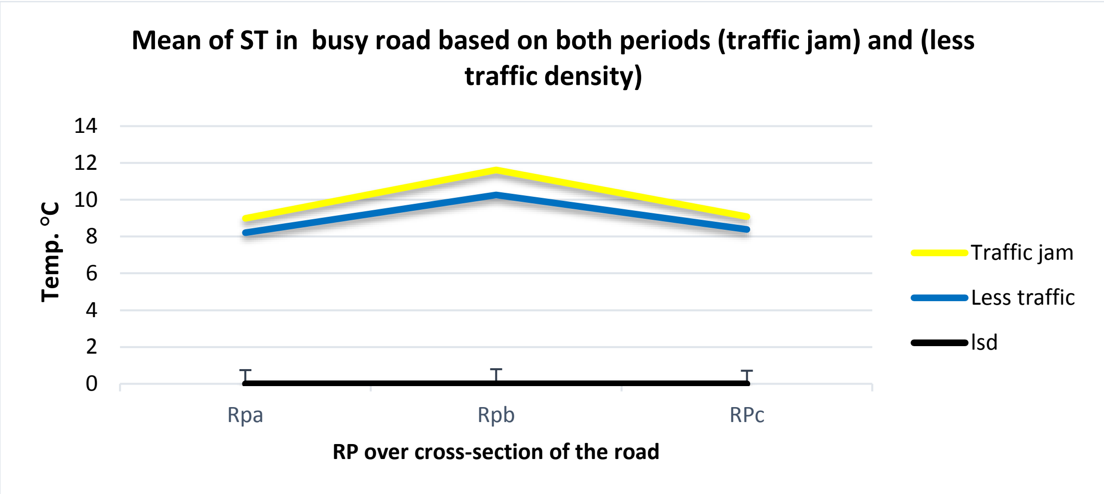
Figure 6.11 Frequency distribution of mean surface temperature (n=55 days) in the busy road, no/less traffic and park (P<0.001, lsd = 0.4, error bars lsd 5%, top). Frequency distribution of mean surface temperature in the same types of the roads based on both trials within both periods (17:00-18:35, traffic jam period) and (20:00-21:35, less traffic volume period), (P< 0.001, lsd=0.57, error bars lsd 5%, bottom).





6.6.3 Effect of Traffic volume (traffic jam Vs less traffic density) on the cross-wise of the surface temperatures in of busy road

Figure 6.12 Thermal properties of mean surface temperature (n=55 days) in the busy road in both periods (traffic jam, 17:00-18:35) and (less traffic, 20:00-21:35), (P_{value} RP(a-c), P_a=0.7, lsd=0.58, P_b=0.05, lsd=0.6 and P_c=0.8, lsd=0.57 respectively, error bars lsd 5%, top. Mean surface temperature of the same roads in the same period above (n=55 days) at the 1st and 2nd attempts within both periods above, (P_{value} RP(a-c), P_a=0.7, lsd=0.58, P_b=0.052, lsd=0.6 and P_c=0.7, lsd=0.57, error bars lsd 5%, bottom).



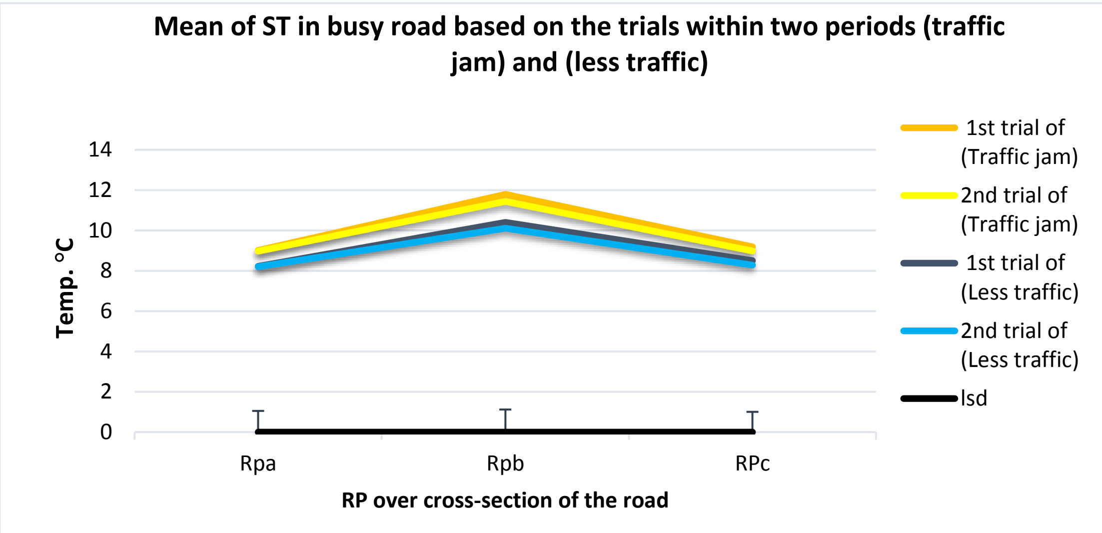
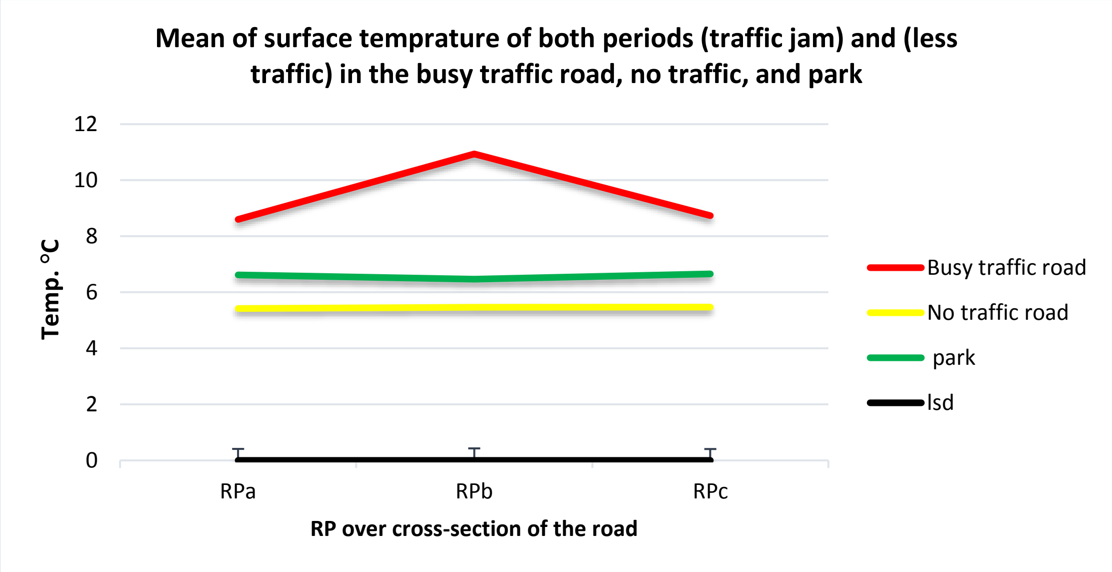
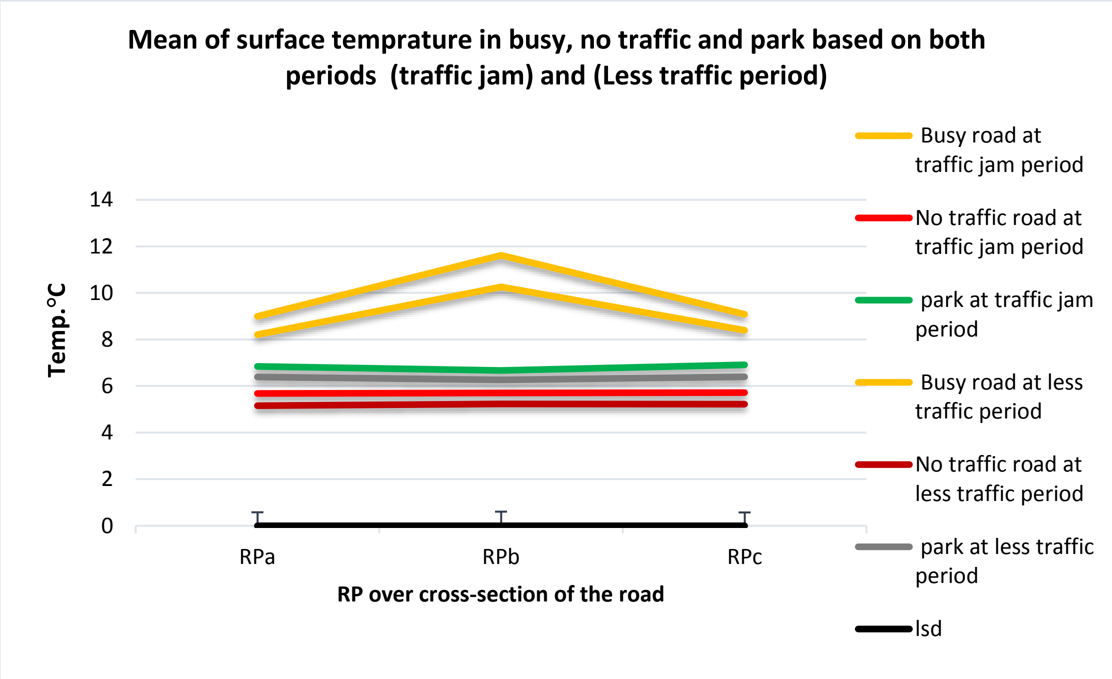


Figure 6.13 Thermal properties of mean surface temperature (n=55 days) in the busy road, no traffic and park of both time together 17:00-18:35 and 20:00-21:35, ($P_{value\ RP(a-c)} < 0.001$, lsd=0.41, lsd=0.42 and lsd=0.4 respectively, error bars lsd 5%, top). Mean surface temperature of the same roads in the same days above (n=55 days) at 1st and 2nd attempts within both periods 18.00-20.00, ($P_{value\ RP(a-c)} < 0.001$, lsd =0.58, lsd=0.6 and lsd=0.57 respectively, error bars lsd 5%, bottom).

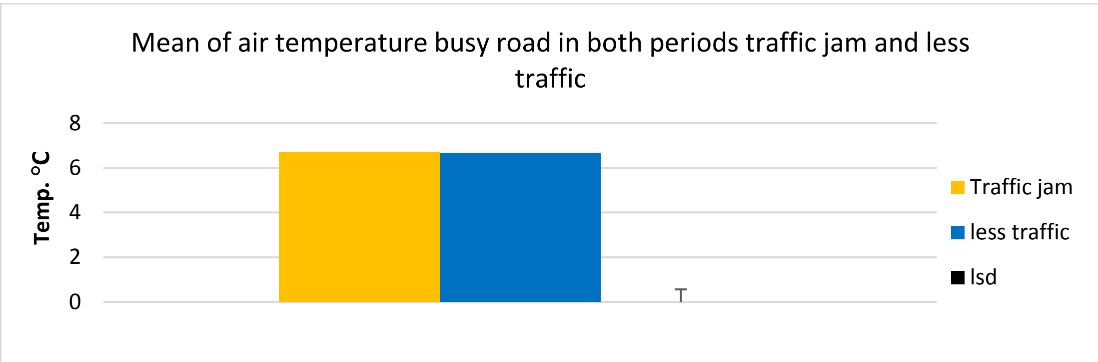


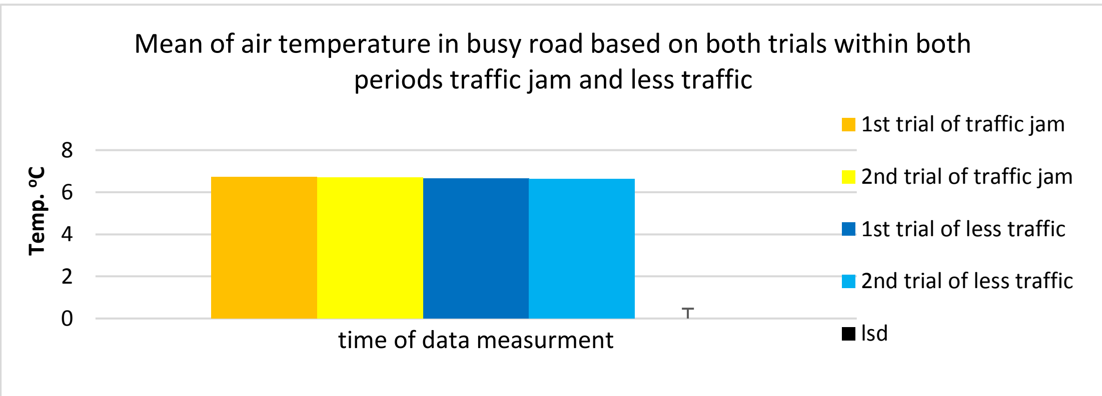


6.6.4 Effect of traffic volume (traffic jam) and (less traffic density) on the air temperatures (AT) in the busy road

The effects of road type and traffic volume on air temperatures were less evident. No significant difference was noted in air temperatures on the busy trunk road between busy and quiet periods (Fig. 6.14). Data showed that mean of air temperatures around 6.71 °C in the traffic jam and 6.65 °C in less traffic (P=0.92, lsd=1.09). Similarly, air temperatures at the different locations were not significantly different, despite large differences in the amount of vehicle movements (Fig 6.15).

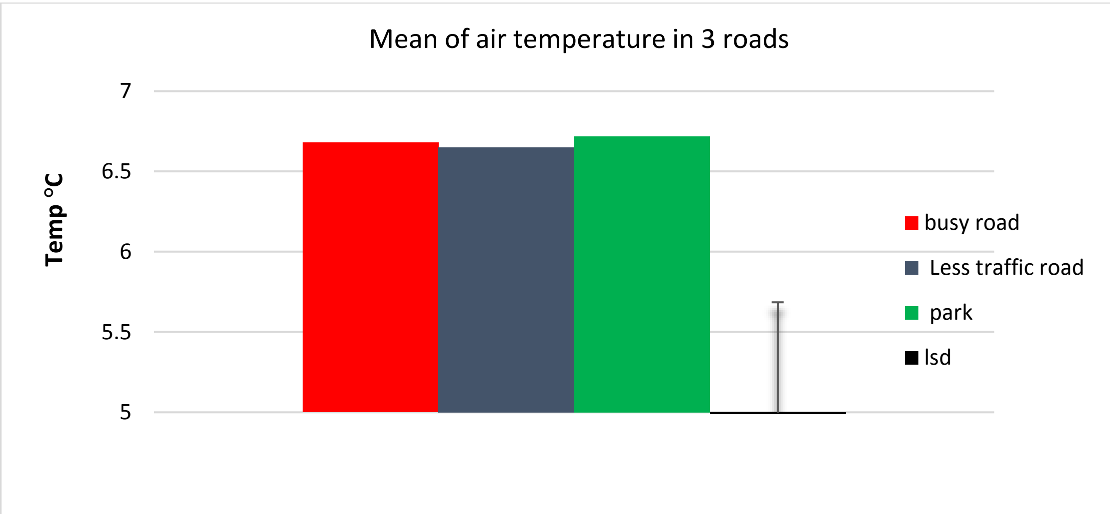
Figure 6.14 Frequency distribution of mean of air temperature (n=55 days) in the busy road of both periods: Traffic jam and less traffic, (P =0.92, lsd=1.09), error bars lsd 5% (Top). Mean of air temperature in the same road in both trials 1st and 2nd within both periods (traffic jam) and (less traffic), (same period above, n=55 days), (P=0.98, lsd= 0.46), error bars lsd 5% (Bottom).

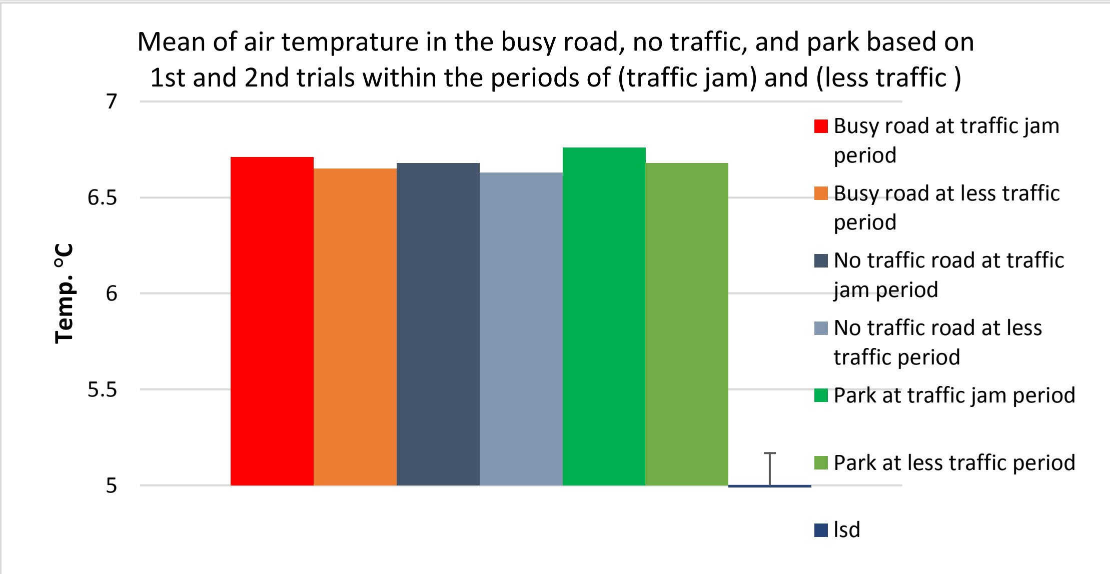




6.6.5 Effect of various types of the roads (busy road, no traffic road and park) based on Traffic volume in traffic jam period) and less traffic density period on the air temperatures

Figure 6.15 Frequency distribution of mean of air temperature (n=55 days) in the busy road, less traffic road and park (P =0.97, lsd=0.68), error bars lsd 5% (top). Mean of air temperature in both periods (traffic jam and less traffic) in the same 3 sorts of roads and same periods above, (P =0.99, lsd=0.96), error bars lsd 5% (Bottom).

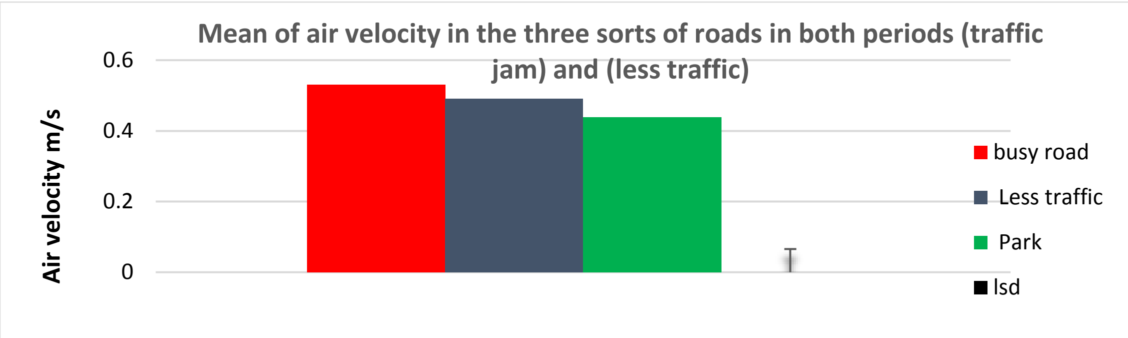


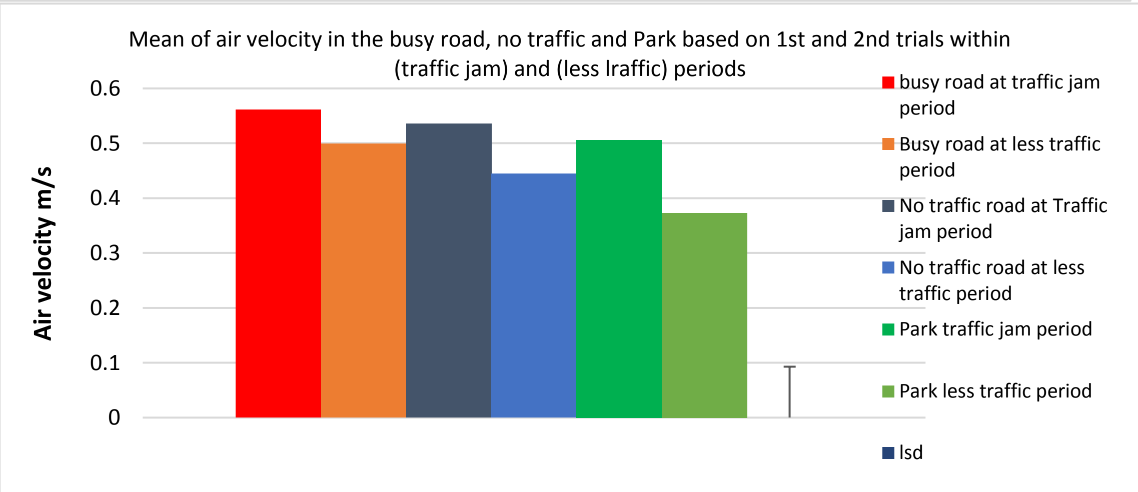


6.6.6 Effect of traffic volume (traffic jam) and (less traffic) on the air velocity

Air velocities did vary significantly between recording times, but as the largest difference (Fig 6.16) was associated with the park, this may have more to do with the time of days these data sets were collected, rather than any influence from traffic per se. Site locations did differ too, suggesting that local topography and features (e.g. presence of trees) were influencing wind speed too.

Figure 6.16 Frequency distribution of mean of air velocity (n=55 days) in the busy road, no traffic road and park in the both periods of (traffic jam) and (less traffic), (P=0.024, lsd=0.0656), error bars lsd 5% (top). Mean of air velocity in the 1st and 2nd attempts for both periods (traffic jam and less traffic), (P= 0.56, lsd=0.092), error bars lsd 5% (Bottom).





6.7 Experimental design for third experiment

The aim of this experiment was to determine how road ST were influenced by traffic volumes, when other factors should be comparable. In essence the aim was to investigate if higher traffic volumes associated with commuting on a Friday induced greater temperature shifts compared to Sundays, with notably less traffic flow. Comparisons were also made however, with time of day as late afternoon traffic on a Friday could be heavier than earlier in the day, but that solar influence of the road surface could be less. Differentials with traffic volume on a Sunday, however, may be less clear. In addition to these days of the week / time of day influences, data was also collected in three locations along the same road (B6539 near to mapping building) to assess if local geographical / landscape typology was further influencing temperature profiles and whether that was contributing traffic volume influencing. These were chosen as locations with office-office (O-O), tree-tree (T-T) or grass-grass (G-G) which are coordinating at:- (1^{0} 28′ 37.347′′ W 53^{0} 22′ 58.895′′ N); (1^{0} 28′ 53.322′′ W 53^{0} 22′ 55.55′′ N) and; (1^{0} 28′ 51.984′′ W 53^{0} 22′ 55.572′′ N) respectively (Fig 6.17.).

Temperatures on road and pavement surface were recorded during the months of July, August, September, and October 2017. Three separate locations in Glossop road (see below Fig 6.17.) were monitored over the four-month period, with temperature data being recording for each location within the road in the two periods of afternoon time (14:00-15:00 and 17:00-18:00) on Friday and Sunday only. For each location, three surface temperatures were recorded on each occasion (Figure 2.2 in chapter 2); these represented the transactional 'profile' of the roadway, with road profiles (RP)- 'a' to 'c' representing the cross section ('a' being the edge furthest away from the road itself and closest to the structure at the side of the road, e.g. office, tree, and grass; 'b' the middle of the road and 'c' the opposite side). Structure temperatures were recording using the Thermometer device, (see section 2.2.1 in chapter two for details). However, AT and AV were observed only once for each occasion in the middle of the road (at the RP_b of the ST), (see section 2.2.2. in chapter 2).

In practice, data was recorded in 32 days separate days i.e. every Friday and Sunday in the period between July and September inclusive.

The sequences of data recoding were occurred based on the following steps: - For early afternoon period (14:00-15:00), number of cars passing through that road in the 30 min was observed in the period (14:00-14:30), then ST, AT and AV were recorded simultaneously for three sites in the period between (14:30-15:00) (each location within the site took 10 min). Same process was repeatedly followed for the 2nd period (17:00-18:00) in the following phases: - Traffic volume/ 30 min was counted in the period between (17:00-17:30); then ST, AT and, AV were recorded in the periods between (17:30-18:00). To avoid bias with order of recording / change in solar influence the different locations were randomised with respect to which was recorded first, second and last. For each of the 3 locations within this road, data was repeatedly recorded for their temperature profiles across the road profile (3 locations x 3 cross sectional temperature points x 2 recording times per day x 32 different days (only Sundays and Fridays), i.e. 576 data (ST), expressed in ^{o}C.

Analysis of variance was carried out to test impact of traffic volume on ST in the rush hour and least traffic volume with mean values for each cross-sectional point represented in figures. Error bars are represented by Fisher's least significant difference values (at 5% level), (same with previous experiment's chapters).

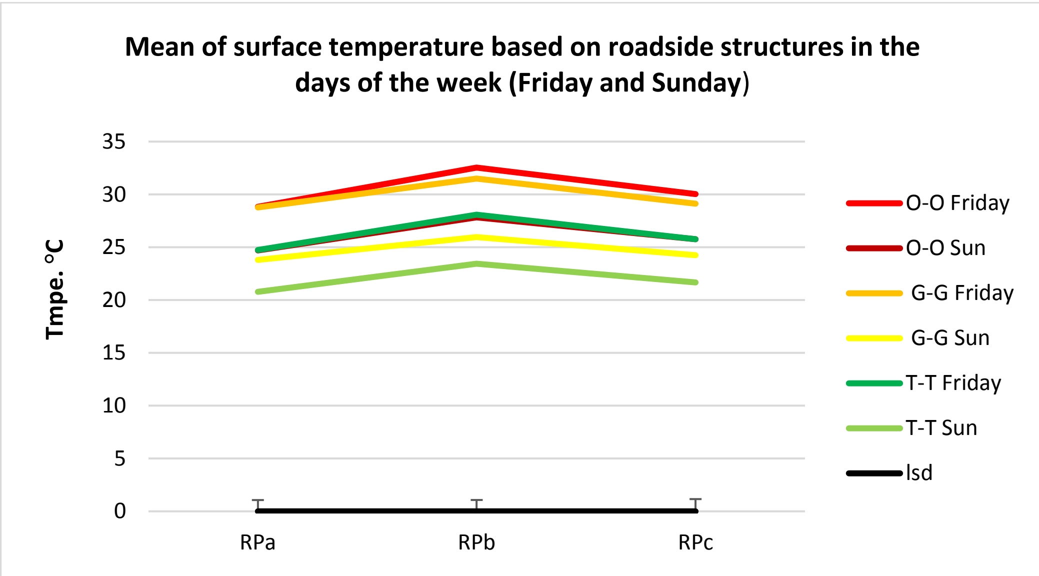
Correlation between two variables (traffic volume and ST) was carried out to investigate the relation between them. The limits of this values were defined in the experimental design of the 1st experiment based on Pallant, 2010, (see section 2.4 in chapter two for more details).

Figure 6.17 Satellite image of the surveyed sites within the study area on B6539 road. source: The Arc GIS (Arc map).

6.8 Result

Highest road ST were associated with heaviest traffic periods (Fig. 6.19). Greatest volume of traffic was associated with Friday at 17.00, but even traffic at 14.00 on a Friday was greater than either time on a Sunday. Despite 17.00 being a cooler time of day naturally than 14.00, road ST were actually higher for the later time on the Friday – corresponding to greater road traffic. Temperatures were higher in the Friday at the period 17:30-18:00 than ST in Sunday at the same period by around 5.9, 6.2 and, 6 ^{o}C and by around 2.8, 3.7 and, 2.8 ^{o}C in the period between 14:30-15:00 of the same days in the $P_{Rba\text{-}Rpb\text{-}Rpc}$ <.001, lsd=0.87, 0.87 and 0.96 respectively) (Fig 6.19 Top). This further emphasis that road ST are being most strongly influenced by volume of traffic, not necessarily just the climatic conditions at the time. As before the centre of road is warmer than either side (Fig 6.19). Roadside typology also affected temperatures with locations with trees or grass being cooler than offices, and these temperatures being significantly cooler on the quieter, less traffic, Sundays (Fig 6.18).

Figure 6.18 Thermal properties of mean surface temperature (n=32 days) in the busy road based on roadsides structures on (Friday and Sunday) ($P_{value\ (a-c)}$ <0.001, lsd=1.085, lsd=1.069 and lsd=1.15 respectively, top). Mean surface temperature (n=32 days, bottom) in the different time within the day (14:30-15:00) and (17:30-18:00), ($P_{value\ (a-c)}$ < 0.001, lsd = 1.085, lsd=1.069 and, lsd=1.15 respectively), error bars lsd 5%.



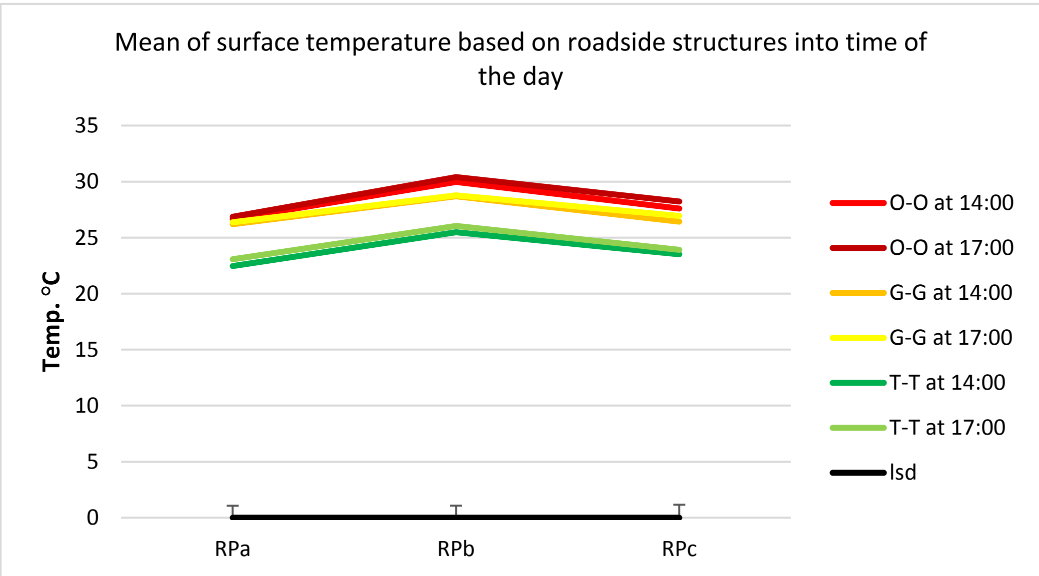
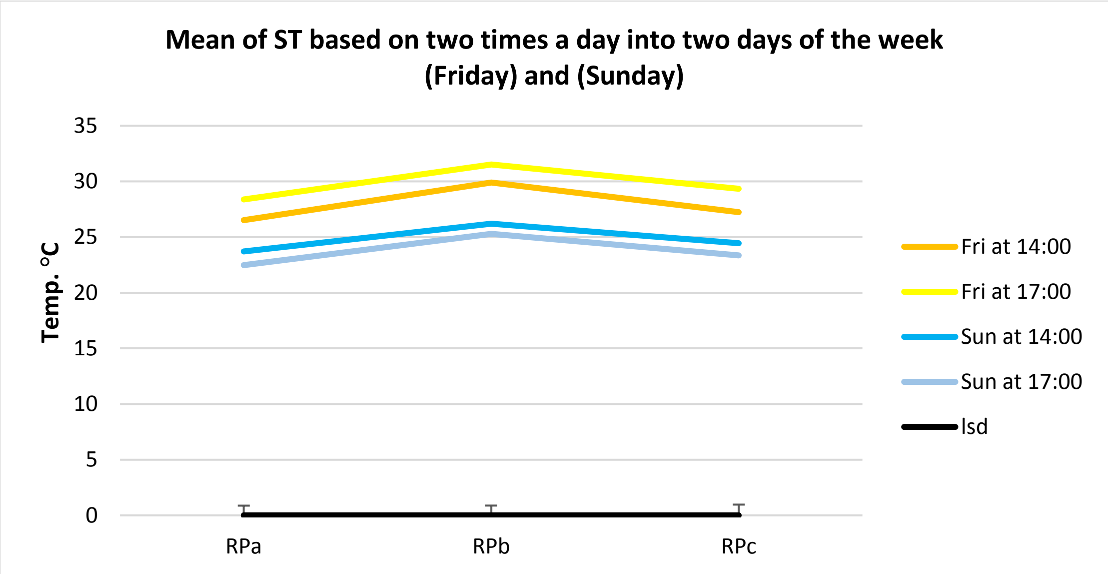
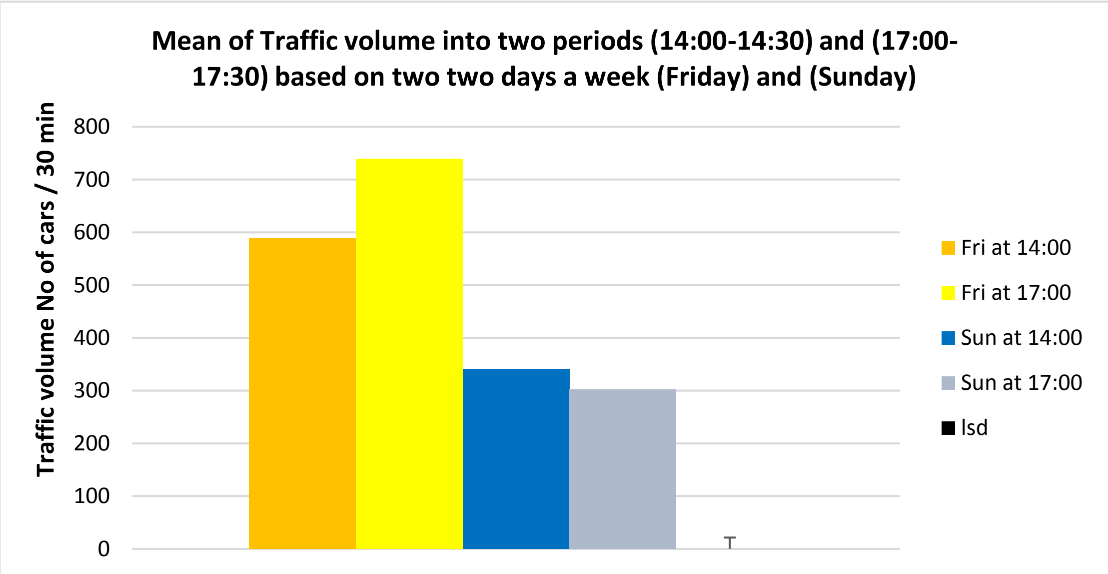


Figure 6.19 Thermal properties of mean surface temperature (n=32 days) in the busy road based on both times within the days (Friday) and (Sunday), ($P_{value\ (a\text{-}c)}$ <0.001, lsd=0.87, lsd=0.87 and lsd=0.96 respectively, Top). Mean of traffic volume (same period above, n=32 days) in both periods of the day (Friday and Sunday, P<0.011, lsd=21.52, error bars lsd 5%, bottom).

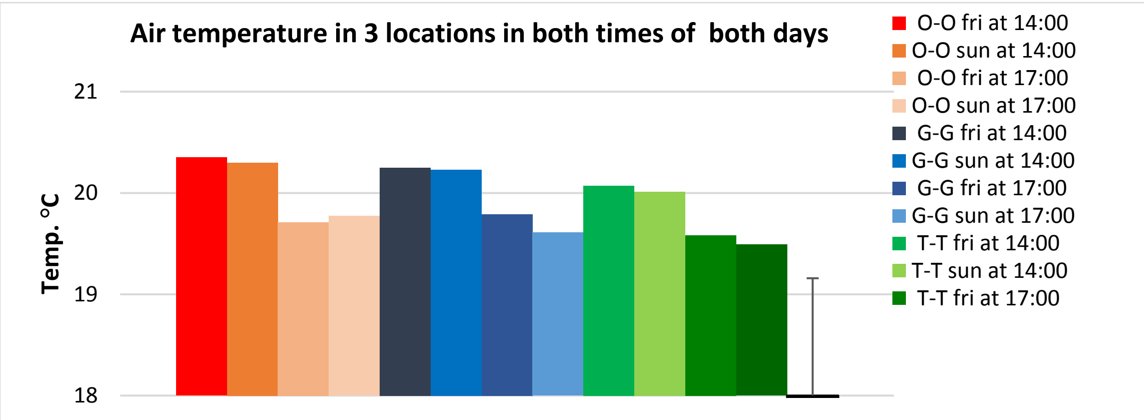




6.8.1 The effect of traffic volume of two periods of a day 14:00-14:30 Vs 17:00-17:30 of the Friday (busier traffic volume) Vs Sunday (less traffic volume) on air temperature and velocity

Unlike ST, significant differences in AT due to traffic volumes or even locations were not apparent (Fig 6.20). Air velocity data suggest that the office environment was the least exposed and the grass location the most exposed as this the latter had the highest and most consistent wind movement (Fig 6.24). No relationship was discerned based on traffic volume or surface temperature though.

Figure 6.20 Frequency distribution of mean air temperature in the busy road at three different sites in the two times of both days (P =0.972, lsd=1.158, n=32 days, top). Mean of traffic volume in both periods of the day Friday and Sunday, (P<.001, lsd=21.52, n=32 days, bottom, error bars lsd 5%).



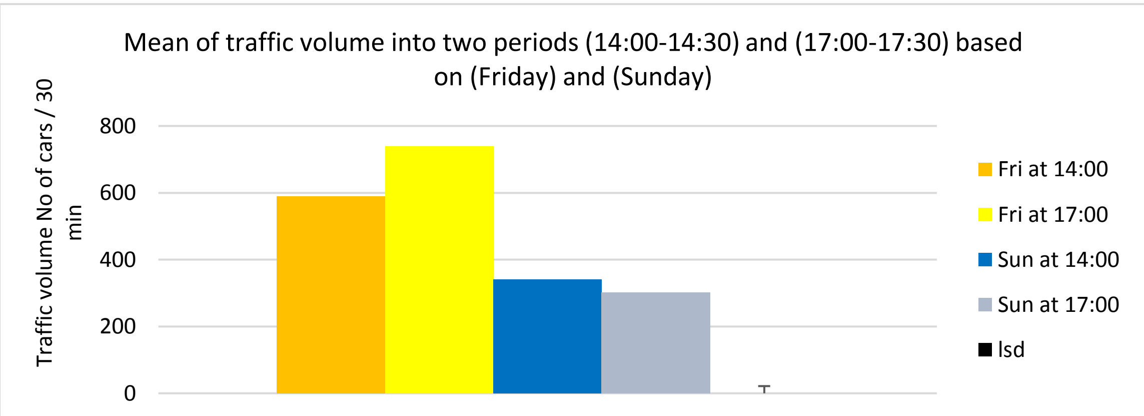
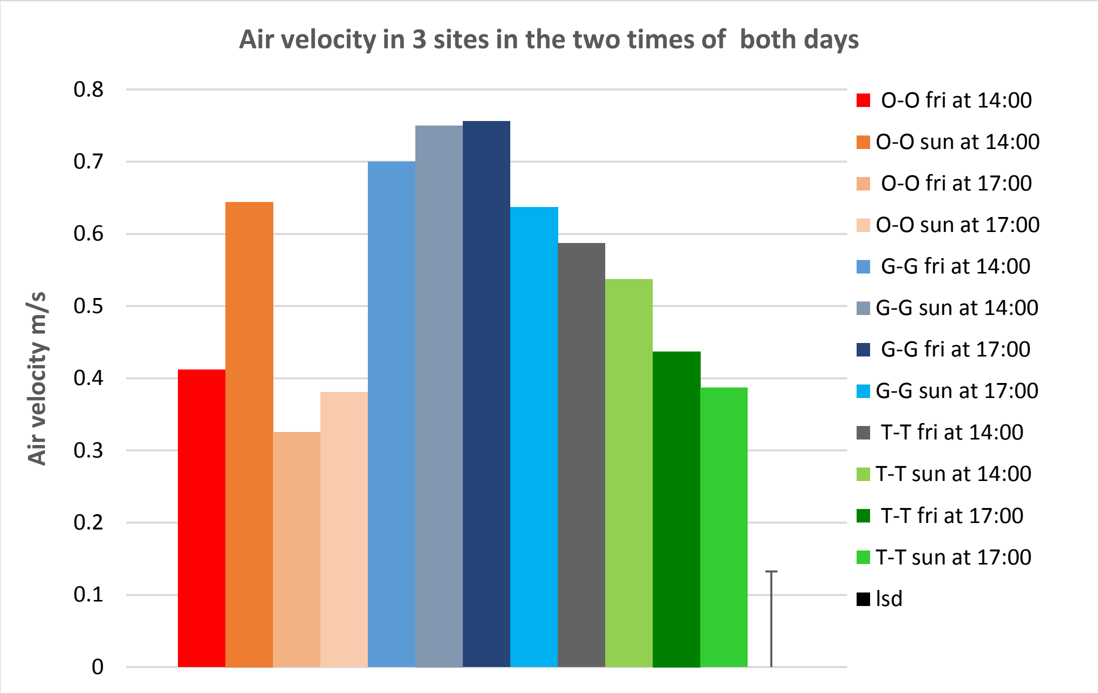
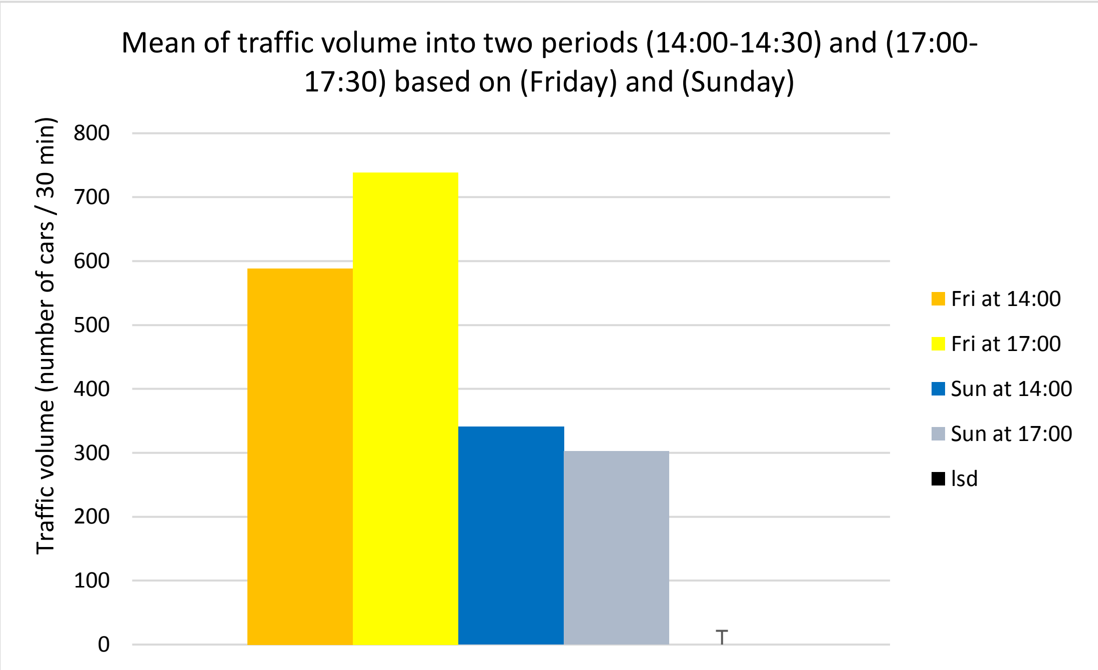


Figure 6.21 Frequency distribution of mean air velocity (n=32 days) in the busy road at 3 different sites in the two times of both days (P =0.081, lsd=0.132), (Top). Mean of traffic volume in both periods of the day (Friday) and (Sunday), (P<.001, lsd=21.52), (bottom), error bars lsd 5%.

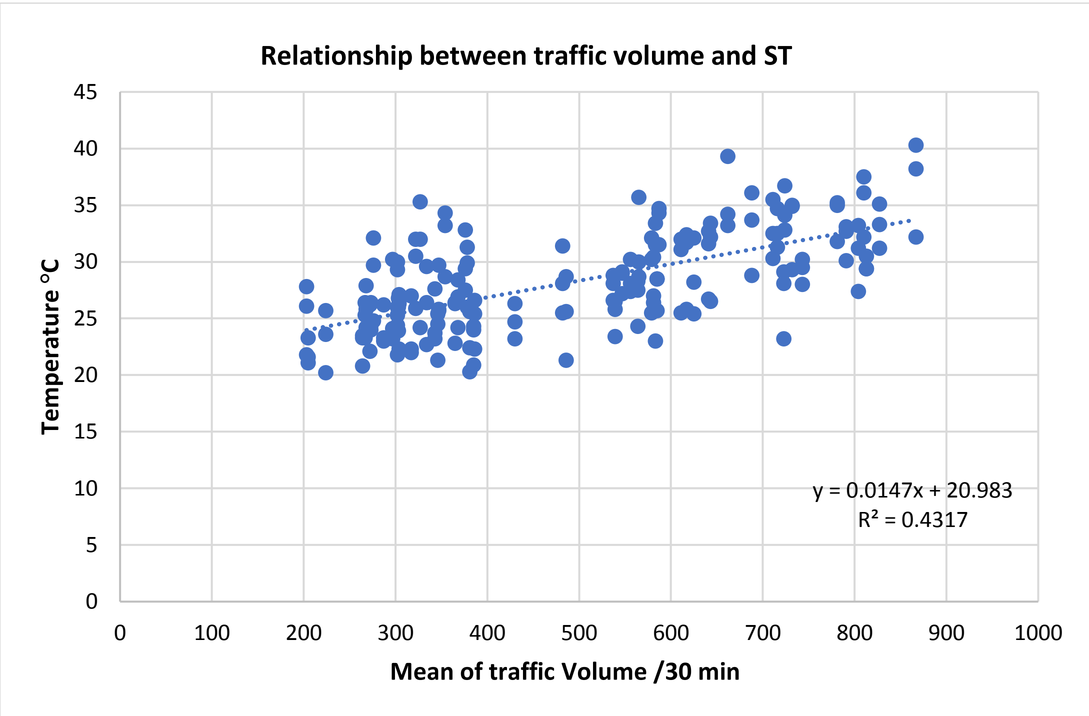




6.8.2 the correlation between traffic volume and surface temperatures in the busy road with various roadside features

The regression model indicated that traffic volume could explain 43% of the thermal variation of the road in both periods (Fig 6.22). Data showed that traffic volume positively affected the surface temperature, though the coefficient values of traffic volume is low indicating a least effect on temperature. R^2 value is around 0.43 that indicates that only approximately 43% of the variation in the surface temperature of the road was explained by traffic volume.

Figure 6.22 The relationship between mean of surface temperature of both periods, 14:30-15:00 and 17:30-18:00, and average of cars passing in both periods, 14.00-14:30 and 17:30-18.00. Letters relate to points across the profile of the road. Regression equation, R^2 and correlation coefficient are showed in the graph.



6.9 Discussion

These experiments, especially the last one, clearly demonstrate that traffic volumes are having a strong influence on road ST. Roads are warmer later in the day on a Friday, than at an earlier time on a Sunday (even though solar influence will be greater in the latter case). This difference seems to be largely due to the influence of road traffic – greater volumes of cars, but also perhaps these cars idling for longer, with their engines on, in the one location due to congestion. The data can therefore conclude that road thermal properties are being impacted by the volume of traffic they experience.

Nevertheless, the regression (Fig 6.21) indicated that this might only account for 43% of the variation encountered, and of course, variations in weather and solar intensity on different days may help explain the majority of the other variance.

Like the findings of the previous experiment, this experiment also found a significant influence of roadside structures (topology) on the road surface temperature (ST). Specifically, the highest temperatures were found adjacent to Building-Building characteristics while locations with Tree-Tree were the lowest. These results indicate that roadside green infrastructure reduces the road surface temperature while roadside grey infrastructures increase the road surface temperature. These findings of the experiment are corroborated by other literature (Roy et al., 2012, Liangmei et al., 2008; Bau-Show Lin and Yann-Jou Lin, 2010, Ram Pandit and David N. Laband 2010). As we know, other than green and grey infrastructure, there are different factors to influence the ST of road. Since vehicles used the space of the road to move, traffic volume is considered as one of the important factors to influence ST of road.

Unlike ST, the effect of traffic volume on air temperature is not straightforward as found in the research. This research found that AT in both periods of busy road were not significantly affected by traffic volume as analysis of variance indicated insignificant influence on the air temperature of the interaction of the traffic volume and the structures of the three sites into two times of a day. Similarly, analysis implied that there was significant effect of traffic volume (traffic jam period) and (less traffic period) on the air velocity in the busy road depending on the roadside structures. ANOVA indicated a significant influence of the interaction between the traffic volume and roadside structures on the air velocity.

Some empirical studies investigated the impact of traffic movement on thermal profile of the road. For instance, Farmer and Tonkinson (1989) found warmer road ST on heavily trafficked roads while Gustavsson et al. (2001) in another study conducted in Stockholm area of Sweden found that ST can increase by up to 2 ^{o}C in urban areas than rural areas during the early morning peak commuting time. Findings of all these research findings are in line with the findings of this research. However, in some cases, the current experiment is more intuitive compared to the other existing literature as factors other than traffic (for instance, different road side green and grey structure and landscape nature) have been incorporated in this research.

This research bears some important policy implications in designing the road in the urban areas with the aim of ensuring thermal comfort of the passengers. As previous experiments, this experiment has the most common but important policy implication that urban road should be designed with roadside green infrastructure to alleviate temperature on road surface. Moreover, roadside open space with grass field or park also lead to greater air ventilation through the road that can ensure thermal comfort of the passengers. In addition, another important policy implication of this research is that traffic congestions on the road in the urban areas need to be addressed to ensure thermal comfort of the passengers, as well as other important factors such as exposure to particulate matter and NO2, linked to health risks for humans

6.10 Concluding points from Chapter 6

- Features on the both sides of the roads along with traffic movement were contributing to affect the ST. However, the effect of traffic volume was more evidential compared to the influence of roadside structures.
- Temperatures across different locations in the busy road, park and less traffic volume had distinctive profiles, with temperatures generally lower at the both roadsides and rising towards the middle of the locations in almost all roads as a result of traffic movement and the temperatures trends tend to be higher in traffic jam periods.
- Temperatures across different locations in the busy road had distinctive profiles, with temperatures generally higher in the middle of the roads by around 5.6 ^{o}C and 4.6 ^{o}C than the middle of the park and no/less traffic density respectively. Also, its higher at both edges in the busy road by around 2 ^{o}C and 3 ^{o}C than the edges of the park and no/less traffic density respectively.
- Generally, ST in the park tended to be slightly higher than the ST in the road with no/less traffic particularly in winter.
- Road with different sites with various circumstances had distinctive temperatures profile with higher temperatures in the busy road compared to the park and less/no traffic by around 4 ^{0}C and 2.9 ^{o}C respectively.
- Traffic movement had no influence on the air temperatures.

- Traffic movement had slightly influenced the air velocity particularly in the open space within high traffic period.
- Traffic volume had created significant difference in temperatures of the road in the different periods of a day and different days a week.

6.11. Implication from chapter 6

The influence of traffic on thermal properties is significant and the data somewhat unexpected in that traffic can sometimes over-ride the natural climatology and diurnal factors of the city locations. In essence, surface temperatures can be warmer in the evening than earlier during the day due just to the energy expended from car engines and friction associated with vehicle types on the road surface. This data should re-inforce the need for policy makers to further understand the negative impacts of traffic movement on the environmental performance of the city.

Chapter 7 : Thermal properties of the roads as influenced by green, blue and, grey structures: The effect of river, park and city centre

7.0 Hypothesis

The presence of trees along roadways in the park reduces road surface temperature, to a greater extent than any influence due to the presence of grey structures in the city centre and blue structures in the river: case study from a larger scale perspective.

7.1 Introduction

Urban areas will accommodate about 60% of the world's population by the year 2030 (Golden, 2004). Because of rapid urbanization, urban areas experience higher temperature compared to temperatures in adjacent rural regions, known as the urban heat island (UHI) effect (Tiangco et al., 2008; Weng, 2009). How the landscape of an urban area is used, is critical for forming UHI. In urban areas, types of various landscape and their spatial patterns create a complicated microclimate system (Oke, 1982), and this landscape heterogeneity may create large intra-urban surface temperature differences (Buyantuyev and Wu, 2010). In a pioneer study published in 1818, Howard investigated the climate of London and found that city centre is warmer than the surrounding countryside. This point has been found in a strand of papers that has evolved in large scale in the recent decades (Fogelberg et al. 1973; Heino,1978; Ekholm,1981; Laaksonen,1994; Landsberg, 1981; Hinkel et al., 2003; Yamashita, 1996; Voogt and Oke, 2003; Magee et al., 1999; Steinecke 1999; Eliasson and Svensson, 2002; Svensson and Eliasson 2002).

Water surface include Reservoirs, lakes, and rivers, usually called wetlands, form many "urban cooling islands" (UCIs) (Chang et al., 2007; Cao et al., 2010). A number of literature (Chen et al. 2006; Hou et al. 2009; Schwarz et al. 2012; Katayama et al. 1991; Murakawa et al.1991; Givoni et al., 2003; Oláh, 2012; Ranhao et a., 2012; Steeneveld et al. 2014; Jin et al., 2017) investigated the effect of wetland on urban heat island and found a significant impact on temperature in the urban areas. These papers also found that there were significant effects of various types of sites at different times of the day on the air velocity and humidity. In this perspective, the final experiment of this dissertation investigated how adjacent landscape features in the roads over neighbourhood scales park (trees), river (water) and heart of the city (buildings) affect the micro-climatic/thermal properties of roads by different times of day whether there are site-specific factors that promote/negate the influence. One of the motivation of this research is that along with temperature, the author wished to compare air velocity and humidity profiles within the neighbourhoods. Moreover, a key factor was could the local influences of green infrastructure identified in previous chapters be evident at a larger scale across the city of Sheffield.

7.2 Research Questions

The following questions will be investigated in this research.

- How do adjacent landscape features to roads over larger scales- parks (green structures), river (water body/ blue structures) and, heart of the city (dominance of buildings/ grey structures) affect the micro-climatic/thermal properties of roads?

- How do the influences of these features of neighbourhood -scale sites affect the road surface temperatures by different times of day?
- How universal are the influences of park, river and, city center on surface temperature, i.e. are there site-specific factors that promote / negate the influence?

7.3 Experimental Design

Road ST, AT, AV and humidity (Hy) were recorded during the months of July, August and September 2017. Thirty (30) separate locations (see Fig 7.1) were monitored over the three months' period, with environmental data being recorded in the early afternoon (12:00-13:30) and late afternoon (18:00-19:30) for each location. For each location, one (1) Reference Point (RP) represented Road ST, AT, AV and, humidity (Hy), which were recorded on each occasion. There were three (3) roads in this experiment, each road of them is extended on different sites with various landscape form (park, river and city centre). Ten locations were recorded for each site; these represented the transitional 'profile' of the roadway, with road profiles (RP) '1' to '2' representing the data ('1' being the edge furthest away from the heart of the site closest to the area out the impact of the site. RP '3' to '8' represented the data over the road across the site itself, with RP '9' to '10' represented data opposite edge, with '10' being the point furthest away from the central of the sites. Data were recorded using various sorts of the devices (see chapter 2, sections 2.2.1, 2.2.2 and, 2.2.3. for more details).

To evaluate the comparative cooling and warming potential of the road surface temperature over various sites, data was collected in clear sunlight. In practice, data was recorded in seven (7) days in June (10^{th},11^{th}, 12^{th}, 13^{th}, 25^{th}, 26^{th} and 27^{th}), nine (9) days in August (1^{st}, 2^{nd}, 3^{rd}, 21^{st}, 22^{nd}, 23^{rd}, 24^{th}, 28^{th} and 29^{th}) and 5 days in September (4^{th}, 5^{th}, 6^{th}, 18^{th} and 26^{th}).

Again, to avoid any bias due to the timing with each recording slot (e.g. in the early afternoon (12:00-13:30), ST may often be warmer at 13:00 compared to 12:00, irrespective of location within the site as well as the site itself; i.e. location as well as the site confounded by time) the sequence of recording of the day and the time period within the day, was not in the same site and the location within the site every time, but was altered to help even out any diurnal influences.

The focus of the research was to identify how different sites within different city neighbourhoods affected the ST and how consistency these landscape forms influenced temperature profiles. Therefore, roads were chosen that represented a diversity of landscape features e.g. road over different sites with different landscape (green represented by the road over the park, blue represented by the road over river and road over city-centre which represented the grey landscape). Site also chosen to minimize the thermal influenced by traffic volume which have been proven in previous chapter (chapter 6). Sites also need to be sufficient close to each other and close to University of Sheffield so that all could be observed within the specified time slots. Based on the previous consideration, three (3) roads were selected within three (3) vicinity sites. One neighbourhood (Ponderosa park contain the road Northwest-Southeast orientation) was approximately (0.3) km from the city centre. Whereas the second neighbourhood (8 Ball St over the Ball St bridge) were 0.48 km from the citer) and the road orientation were approximately Northeast-Southwest while the third site was over (Scotland St) in the city center itself.

For each of those three (3) roads, 10 different locations (each location has one (1) RP) were identified within each (see figure 7.1) and, (table 7.1) and repeatedly recorded for their data set across the roads over those sites (30 locations x 1 RP each location x 2 recorded times ped day x 28 different days, i.e. 1680 data points in total for each one single variable ST, AT, AV and Hy (6720 data set in total for 4 of all sites). ST, AT, AV and Hy are referred to a surface temperature, air temperature, air velocity and humidity expressed in (^{o}C for first two variables, $m.s^{-1}$, %RH) respectively.

These data set were used to determine if there was any variation mainly in a temperature on a uniform surface during the recording of each road over various big-scale of landscape, i.e. and marginally had the variation of air temperature, air velocity and altered humidity influenced by various sited affected ST? To evaluate this, (ANOVA) was used to determine the significance of different experimental variables by using the statistical package GenStat (Releases 8.1 to 10.1), provided by the University of Sheffield (see section 2.4 in chapter two for more details).

Figure 7.1 Satellite image of the surveyed sites within the study area on ponderosa park, (city centre) and, 8 Ball St over the Ball St Bridge. source: The Arc GIS (Arc map).

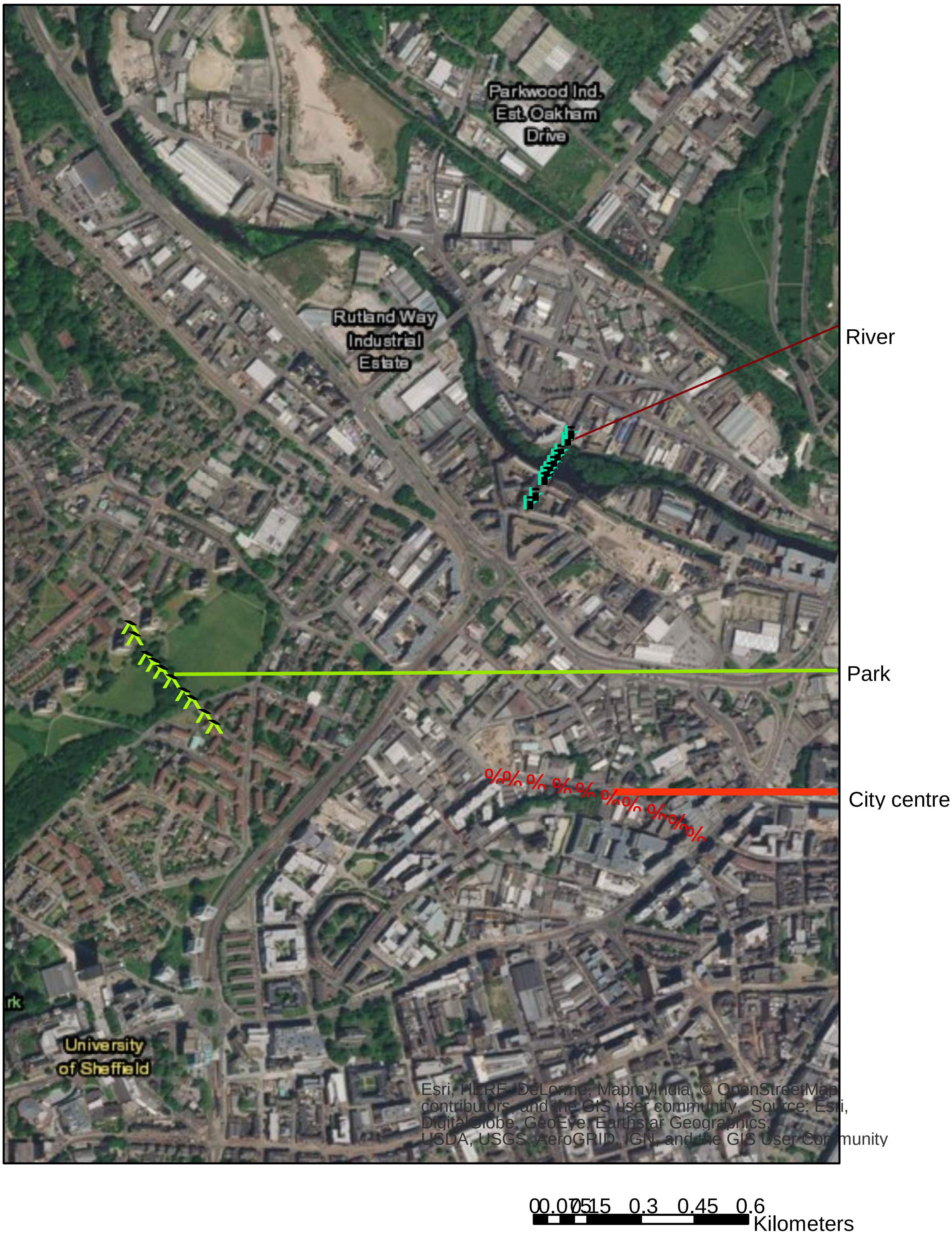


Table 7.1: Detailed showing the 30 treatments of the experiment in the Ponderosa park, 8 BALL St and, city centre and its coordinating on GIS.

Locations in the sites	Coordinating on GIS
Park	
1- 1st	1^{0} 29′ 10.561″W 53^{0} 23′ 16.799″N
2- 2nd	1^{0} 29′ 10.15′W 53^{0} 23′ 16.146″N
3- 3rd	1^{0} 29′ 9.123″W 53^{0} 23′ 15.166″N
4- 4th	1^{0} 29′ 8.439″W 53^{0} 23′ 14.819″N
5- 5th	1^{0} 29′ 7.72″W 53^{0} 23′ 14.411″N
6- 6th	1^{0} 29′ 6.83″W 53^{0} 23′ 13.88″N
7- 7th	1^{0} 29′ 5.735″W 53^{0} 23′ 13.145″N
8- 8th	1^{0} 29′ 4.982″W 53^{0} 23′ 12.717″N
9- 9th	1^{0} 29′ 3.887″W 53^{0} 23′ 11.982″N
10- 10th	1^{0} 29′ 2.963″W 53^{0} 23′ 11.451″N
River	
1- 1st	1^{0} 28′ 34.453″W 53^{0} 23′ 23.535″N
2- 2nd	1^{0} 28′ 34.008′W 53^{0} 23′ 23.984″N
3- 3rd	1^{0} 28′ 33.152″W 53^{0} 23′ 24.862″N
4- 4th	1^{0} 28′ 32.912″W 53^{0} 23′ 25.127″N
5- 5th	1^{0} 28′ 32.673″W 53^{0} 23′ 25.392″N
6- 6th	1^{0} 28′ 32.365″W 53^{0} 23′ 25.698″N
7- 7th	1^{0} 28′ 31.988″W 53^{0} 23′ 26.025″N
8- 8th	1^{0} 28′ 31.68″W 53^{0} 23′ 26.372″N
9- 9th	1^{0} 28′ 31.037″W 53^{0} 23′ 26.984″N
10- 10th	1^{0} 28′ 30.688″W 53^{0} 23′ 27.311″N

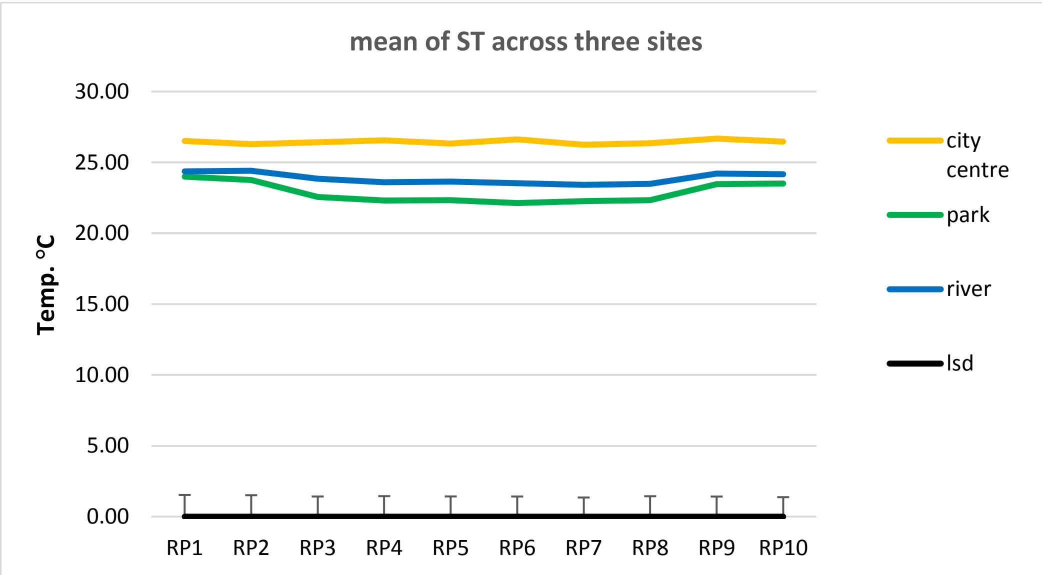
Park	
1- 1st	1^{0} 28′ 19.637″W 53^{0} 23′ 5.606″N
2- 2nd	1^{0} 28′ 20.921′W 53^{0} 23′ 6.263″N
3- 3rd	1^{0} 28′ 22.939″W 53^{0} 23′ 6.919″N
4- 4th	1^{0} 28′ 24.773″W 53^{0} 23′ 7.247″N
5- 5th	1^{0} 28′ 27.158″W 53^{0} 23′ 7.685″N
6- 6th	1^{0} 28′ 29.542″W 53^{0} 23′ 8.013″N
7- 7th	1^{0} 28′ 31.377″W 53^{0} 23′ 7.685″N
8- 8th	1^{0} 28′ 34.128″W 53^{0} 23′ 8.65″N
9- 9th	1^{0} 28′ 35.962″W 53^{0} 23′ 8.65″N
10- 10th	1^{0} 28′ 37.613″W 53^{0} 23′ 8.76″N

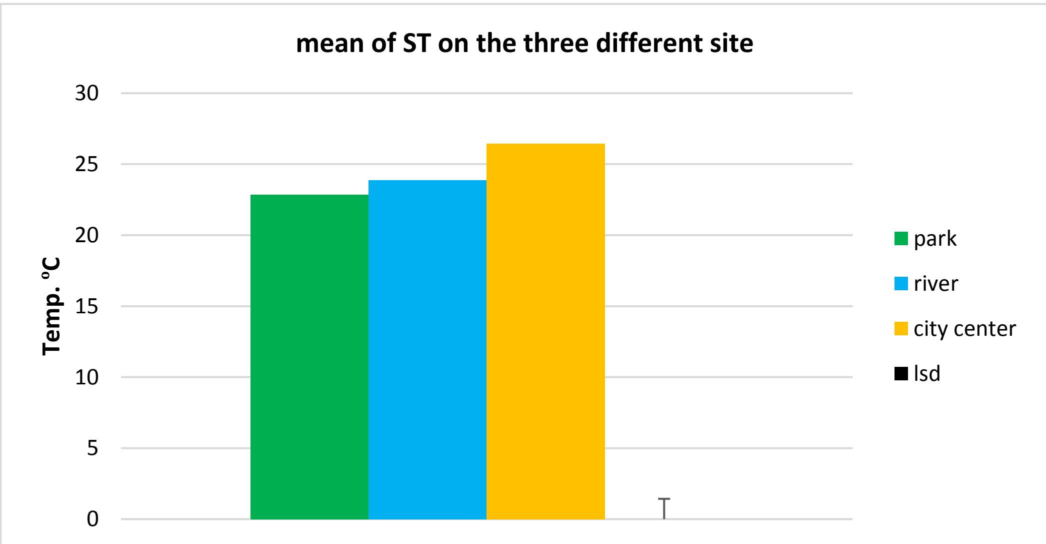
7.4 Result

7.4.1 Effect of sites typology of the road on the surface temperature

ANOVA result indicated a significant influence in the means of surface temperature (ST) across the sites based on different typology (park, river and city centre). The highest temperatures were in the centre of the city by around (26.2-26.6 ^{o}C) while ST in the park and river were the lowest around 22.1-24 ^{o}C, and 23.2-24.4 ^{o}C respectively (range $P< 0.001$- $P=0.038$), (range lsd=1.35-1.53), (lsd 5%), (figure 7.2). Similar trend was found in the average ST based various sites, it was around 22.8 ^{o}C in the park, 23.8 ^{o}C by the river and 26.4 ^{o}C in the city center respectively ($P<0.001$, lsd=1.44). This suggests that various types of typology over big scale of the sites influence the ST of the road.

Figure 7.2 Mean of surface temperature (n=21 days) for both periods together in the day (12.00-13:30 and 18.00-19:30), over different sites typology (park, river and city centre), ($P< 0.001$-$P=0.038$, lsd =1.35-1.53,lsd%5, top, letters relate to points across the profile of the road. Frequency distribution of the surface temperature in the same period (above) based on the different sites ($P< 0.001$, lsd=1.44), error bars lsd 5%.





7.4.2 Effect of sites typology on the surface temperature of the road based on two periods 12:00-13:30 and 18:00-19:30.

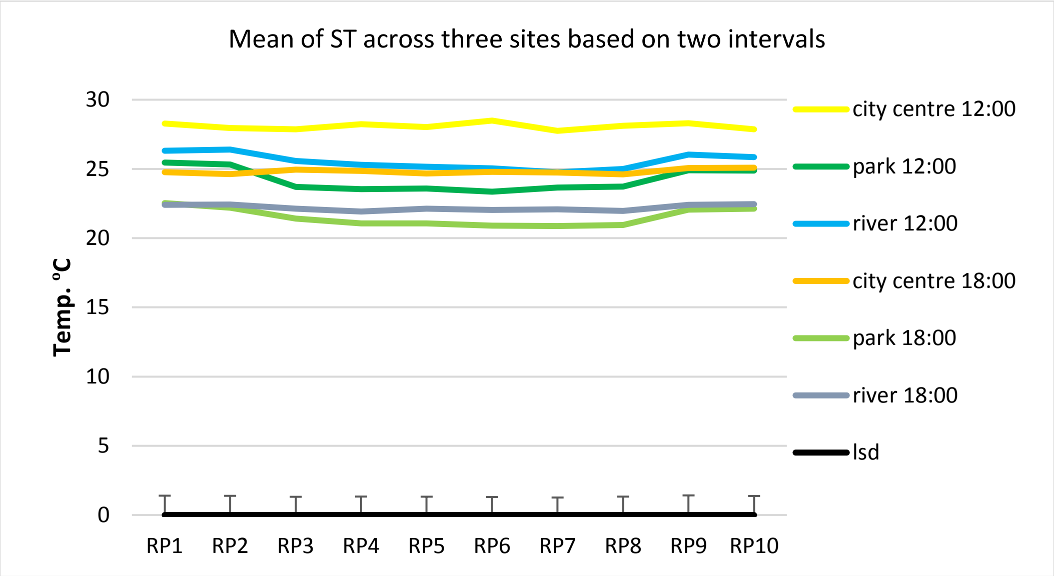
Analysis of variance indicated that the mean of ST across different sites was significantly different based on two-time measurements ($P_{RP\ (1-12)} <0.001$), (RP $_{(1-12)}$ lsd =1.3-1.4), (Figure 7.3). It also varied at the periods 12:00-13:30 and 18:00-19:30 by approx. 28.4-27.7 ^{o}C and 25-24.6 ^{o}C in the city centre which represented the highest in both periods; by around 26.4-24.7 ^{0}C and 22.4-21.9 ^{o}C in the river and 25.4-23.3 ^{o}C and 22.5-20.8 ^{0}C in the park which represented the lowest respectively (Fig 7.3 Top).

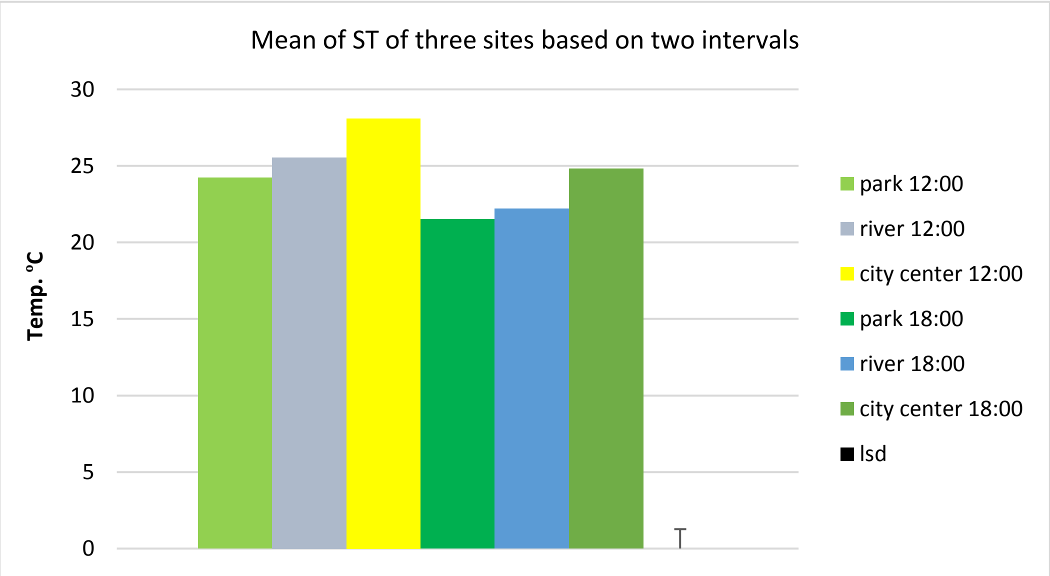
Besides, ANOVA analysis indicated that frequency distribution of surface temperature ST over 3 sites strongly influenced by different time measurement, overall it was higher in the period 12:00-13:30 than 18:00-19:30 by around 2.7 ^{o}C, 3.35 ^{o}C and 3.27 ^{o}C in the Park, river and city centre respectively ($P <0.001$, lsd = 1.27) (Fig 7.3 Bottom).

Temperatures in the city centre represented the highest at 28 ^{o}C and 24.8 ^{o}C whereas the lowest temperatures profiles presented in the park by around 24.2 ^{o}C and 21.5 ^{o}C in the both periods respectively.

This indicated that ST was significantly influenced by different times in the different sites.

Figure 7.3 Mean of surface temperature (n=21 days) based on both periods 12.00-13:30 and 18.00-19:30, over different sites typology (park, river and city centre), ($P_{RP\ (1\text{-}12)}$ <0.001), $lsd_{max\text{-}min}$ =1.27-1.42, top), letters relate to points across the profile of the road. Frequency distribution of the surface temperature in the same periods (above) based on the different sites ($P_{RP\ (1\text{-}12)}$ < 0.001, lsd= 1.27, bottom), error bars lsd 5%.

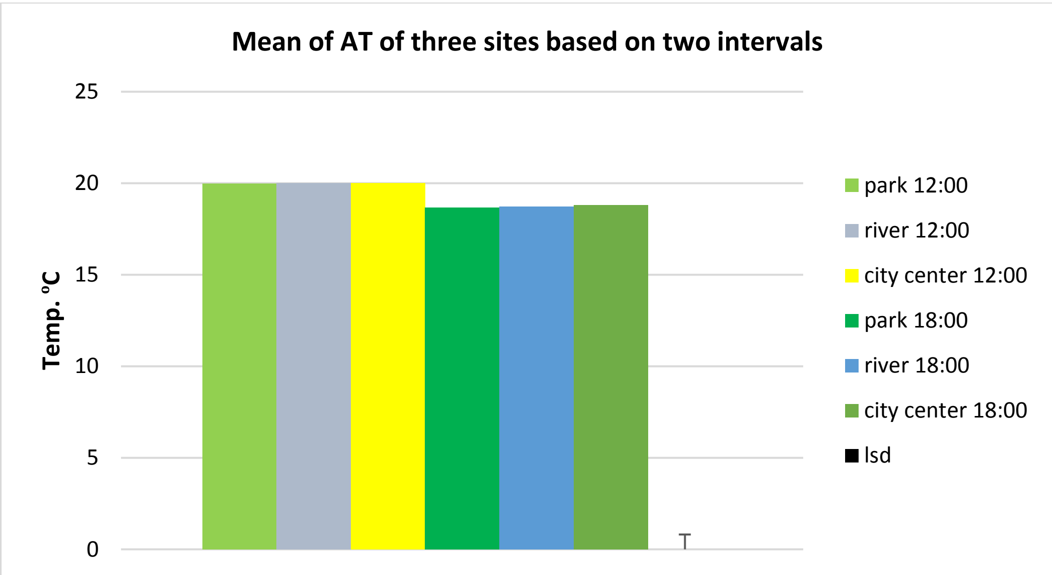




7.4.3 Effect of sites typology on the air temperature of the road

Descriptive analysis indicated that there was significant interaction between time of day and location for air temperature recorded over road surfaces. Temperatures being significantly cooler at 18:00-19:30, 18.6 ^{o}C, 18.7 ^{o}C and, 18.8 ^{o}C than 12:00-13:30, 19.9 ^{o}C, 20 ^{0}C and, 20 ^{o}C for park, river and city centre respectively (P>0.001, lsd=0.85) (Fig 7.4). There were no significant differences though in AT between the three locations at each time, however.

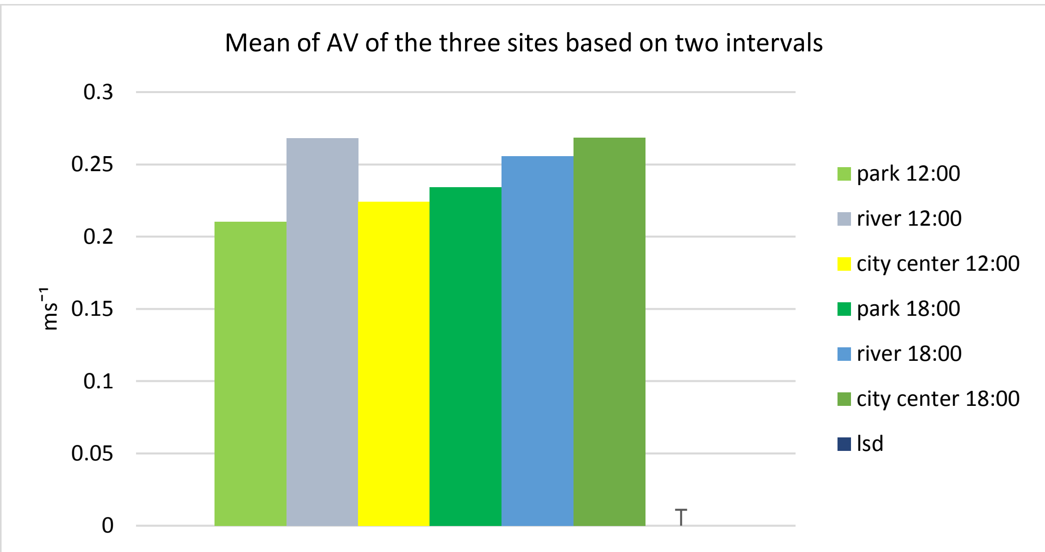
Figure 7.4 Frequency distribution of air temperature based on the interaction of three sites into two times in the day, 12.00-13:30 and 18.00-19:30 over different sites typology (park, river and city centre), (P<0.001, lsd =0.81), error bars lsd 5%.



7.4.4 Effect of sites typology on the air velocity of the road

There was no significant effect on air velocity due to locations (P=0.094, lsd=0.011). Roads within the park presented the lowest speed of air in both periods compared with other sites by around 0.21 $m.s^{-1}$ and 0.23 $m.s^{-1}$ respectively; possibly due to the fact that presence of trees (trees density) supressing the wind speed. Although differences were not significant, AV were generally higher towards the river or in the city centre, but not significantly so based on the derived LSD. Both river by around 0.27 $m.s^{-1}$ and 0.26 $m.s^{-1}$ and city centre by around 0.22 $m.s^{-1}$ and 0.27 $m.s^{-1}$ in both times respectively compared to the park sites although those sites presented the highest ST compared with the park (Fig 7.5). The lack of correlations between AV and ST suggest other factors are playing a role in determining microclimate.

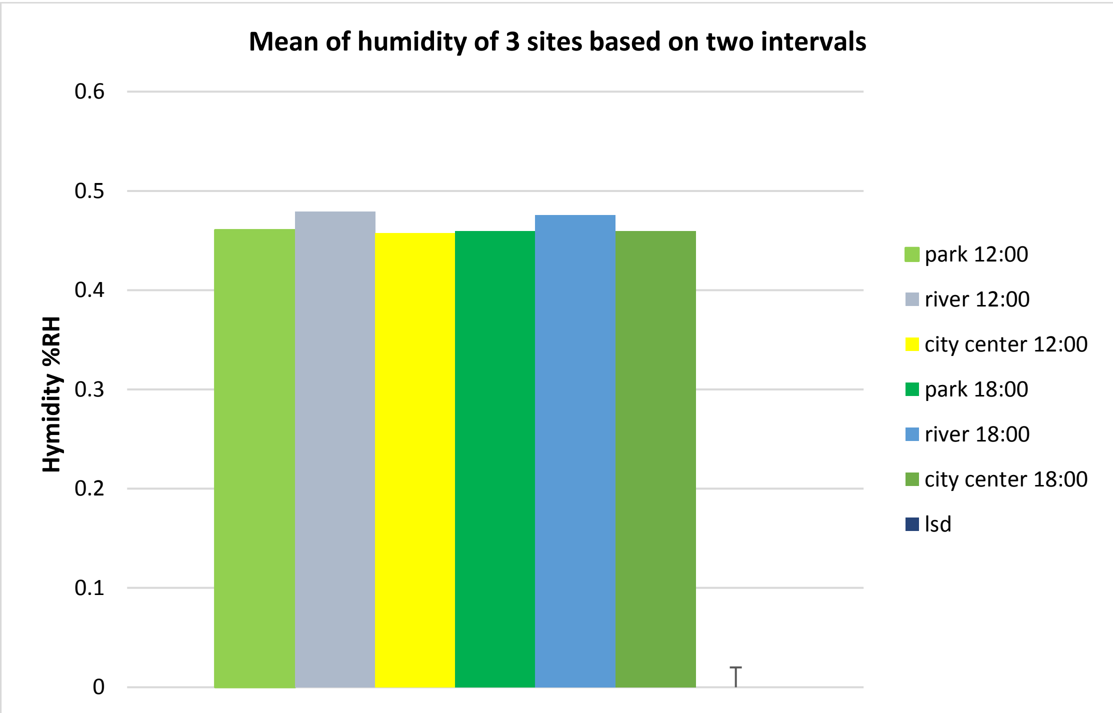
Figure 7.5 Frequency distribution of air velocity (n=21) based on the interaction of three sites into two times a day 12.00-13:30 and 18.00-19:30 over different sites typology (park, river and city centre), (P =0.094, lsd =0.011), error bars lsd 5%.



7.4.5 Effect of sites typology on the humidity of the road

There was a significant interaction between locations and times with respect to humidity data (P=0.014, lsd=0.02). Overall, although highest values were associated with the neighbourhood around the river (Fig. 7.6), these were not consistently greater than the other two locations – suggesting local effects and climate variation between recording days were also dictating results.

Figure 7.6 Frequency distribution of humidity based on the interaction of three sites into two times a day 12.00-13:30 and 18.00-19:30, over different sites typology (park, river and city centre), (P=0.014, lsd =0.02), error bars lsd 5%.



7.5 Discussion

This research found a significant influence in the means of surface temperature ST across the sites based on different typology (park, river and city centre). The highest temperatures were found in the city center sites while ST in the park and river were the lowest. These findings are in line with other existing literature (Ranhao et a., 2012; Jin et al., 2017). This research also found that there were no significant consistent effects due to site on air temperature, velocity and humidity. So even though scale of study was increasing compared to previous experiments, detecting differences in air temperature between sites remained elusive. Surface temperatures, although possibly influenced by factors such as air velocity or humidity levels, were also not closely linked with them, directly. As such variations in ST between the neighbourhoods could not be attributed to these factors alone. More likely is that ST of roadways is being influenced by factors such as the shade of trees and perhaps direct affects due differences in transpiration and evapo-transpiration rates (but points not being detected by the rather crude assessment of humidity in tha air above such locations).

7.6 Concluding points from Chapter 7

- Temperatures across the roads over larger scale areas (neighbourhoods) with different landscape features (green in the park, blue in the river and grey structures in city center) had a distinctive profile, with surface temperature of roadways generally lower at the park and gradually rising at the river and the City Centre.
- Temperatures across the roads over the park and river tended to be cooler in the heart of those sites and rising towards the edges of those sites.
- Air temperature and humidity had no overall significant influence on thermal profiles of the roads surface over different sites; suggesting that these factors measured in the air above the surfaces did nor correlate closely with the temperatures experienced at ground level.

7.8 Implication from chapter 7

The data here support previous chapters in that more built areas (grey infrastructure) tends to have warmer surfaces than those locations surrounding by a greater component of green. This is encouraging and indicates that smaller scale events are scaling up towards a whole heat island phenomenon. In contrast though, air temperature differences were difficult to discern, due to probably greater air movement over the larger scales.

Chapter 8 : Discussion

8.1 General Discussion

It is well known that city centre districts are often 7-10 ^{o}C warmer than outlying rural districts (Chan, 2017), but we know relatively little of the variability that occurs within a city itself. This research helps to address this. What is the influence of the small pockets of green space that occur within the city itself, or even microclimatic effects due to individual trees – do such features have cooling effects that are discernible? This was the aim of this study – to identify if specific roadside locations within the City of Sheffield were warmer or cooler than others based on the morphology of the immediate landscape and the activities that take place within that landscape. This study was particularly useful in that it used a relatively 'cool' northern European city as its study site, and thus any impacts due to heat stress may be particularly noteworthy.

Rather than set up numerous (and expensive and easily damaged monitoring sites), this project used a 'roving' temperature probe to determine the surface and air temperatures of various sites within the City of Sheffield. As such very large replicated data sets were generated. Variations due to climatic factors tended to be nullified by the repeated procedure and the large numbers of samples taken per site. Both land surface temperatures (ST) and air temperatures (AT) were monitored.

8.1.1 Green or Grey

A key finding of the research was that surface temperatures were significantly cooled by the presence of trees and other types of vegetation. During particularly warm days ST under trees could be 5 ^{o}C cooler than equivalent. These findings are in line with previous literature (Lin and Lin 2010, Pandit and Laband 2010; Vaz Monteiro et al., 2017), but clearly demonstrate that even in a relatively cool climate the presence of trees are important in providing an ameliorating effect of excessive temperature, when warm days do occur. As climate change continues and there is increasing building development in cities such as Sheffield – leading to greater frequency and magnitude of heat island events, trees will become increasing important in redressing these and retaining human thermal comfort.

Despite the strong cooling effect on surfaces, there was only limited and inconsistent evidence of trees actually cooling air temperatures, see for example 'evening South-west locations' in Fig. 4.11. In other cases though, the lack of perceivable differences in air temperatures are likely to relate to the interactions with air movement, in that the movement of air pockets over the surfaces were dissipating the thermal benefits even at a local level. Blanusa et al (2017) have found similar results when working on green roofs; vegetation is cooler than surrounding surfaces and can reduce soil temperature beneath leaves, but cooling of the adjacent air was much more difficult to detect. This is not to say that the cooling effect on air is not important; trees and other vegetation are providing environmental cooling across the city matrix, it is just that the effect is being moved away from the local areas, and being diluted over a greater geographical area.

Interestingly, not all cooling was attributed to trees. Hedges and turf grass also provided localised cooling. For example, the presence of hedges at the edge of a roadways could reduce the ST in the *middle* of the road by 2 to 3 ^{o}C. Not all 'green' locations provided the same level of cooling indicating that factors such as height or area of tree canopy, density of canopy, extent of grass coverage and angle of sunlight and direction of prevailing wind, may also be playing a part in determining the specific micro-climate. Some influence of these factors are mentioned briefly below, but overall, further research is required to elucidate these influences more fully, for example tree canopy density was not investigated in this research.

8.1.2 Larger scale impacts of green and blue

The research showed in Chapter 7 that scaling up these areas of 'green' (parks) and indeed 'blue' (rivers), replicated the results of the smaller scale studies. In urban areas, various landscape types and their spatial patterns create a complicated microclimate system (Oke, 1982), and this landscape heterogeneity can create large intra-urban surface temperature differences (Buyantuyev and Wu, 2010). Wetlands include reservoirs, lakes, and rivers, form many "urban cooling islands" (UCIs) (Chang et al., 2007; Cao et al., 2010). Within this context Chapter 7 aimed to explore if such neighbourhood scale typologies affected road surface temperature profiles within Sheffield. Transects across green areas (parks) or towards rivers or across the high built city centre were used to compare temperature profiles. The data showed a significant effect on surface temperature (ST) due to the landscape typologies traversed. The highest temperatures were found in the city center while ST in the park and river were the lowest. These findings support other literature (Ranhao et al., 2012; Jin et al., 2017) and confirm the value of such spaces in providing relief from the urban heat island effect. Even at this scale though significant differences in air (AT) temperature were not apparent.

8.1.3 Other factors affecting road surface temperatures

The literature recognized that along with green/grey infrastructure on road side, there are many other factors, such as- air velocity, sky view factor (amount of 'open sky' / potential shade the site receives), colour of the road side features road surface colour and orientation of the road that affect the road surface temperature (Oke, 1987; Santamouris, 2001; Yamashita et al.,1986; Eliasson & Svensson, 2003; Karlsson, 2000; and Postgard 2000). The research here employed a multiple regression model to help determine relative influence of such factors on ST, and how time of day (sunlight angle) affected their interactions and hierarchy.

Despite the fact that differences in road ST between locations were not necessarily mirrored by differences in AT, there seemed to be relationships between the two parameters. Air temperatures – which could correlate closely with amount of solar irradiance (sunny days being warmer) overall influenced ST from the regression model. But there was also some suggestion that ST may influence AT on occasions. For example, the model could also suggest that ST alone could explain 80% of the observed variation in air temperature. Care needs to be taken here in interpretation though, because correlations do not necessarily explain cause and effect (i.e. surface temperatures may rise with air temperature, because of solar irradiance is increasing not because the air temperatures per se are having a strong and immediate, direct effect). There were also incidences where it was evident that wind speed reduced ST significantly, this being in line with the scientifically found relationships between wind speed and surface temperature (Wooten, 2011; and Thangprasert and Suwanarat, 2017).

The sky view factor also showed strong correlations with ST, by influencing the amount of light and shade across the road (Yamashita et al.,1986; Eliasson & Svensson,2003; Postgard,2000; Karlsson,2000). Sites with a high sky view factor were often warmer in the middle of the day compared to those with less open sky views – presumably because overall more solar irradiance was entering the site. The research also illustrated that the impact of the height of the roadside characteristics on the ST is not straightforward as the shadow on the road from the height of the building will depend of the orientation of the building with the road (warmest sides in the evening could be the cooler in the morning and vice versa). So solar gain is having a large impact on the temperature profiles of different positions even within the one site. The architecture and features at the side of the road not only influenced where shadows formed but also affected temperature by influencing exposure to prevailing winds and altering wind patterns across the roadway. Size and orientation of building thus affecting not only where sunlight penetrated, but also how wind moved over the site. The road dimensions themselves had some influence over these factors too. Impacts due to the width of the road on ST though are not consistent across all the times of the day; for example, in the morning, the angle between the solar radiation and the roads surface is smaller compared to the afternoon, and thus provides more shadow on a greater proportion of the road area. Similarly, the height/width ratio as determined by the size of roadside objects and road width influences solar gain; interestingly though the effects were greater in the morning and afternoon compared to the evening, possibly due to residual heat effects – the buildings and roads continuing to radiate infra-red energy even after being shaded form direct sunlight.

As discussed above, the colour of roadside features affected temperature, in that green areas (i.e. grass) provided a localised cooling influence. But what about other colours, particularly those of the surrounding hard surfaces – tarmac, concrete and brick? The data suggests that red bricks did not have a strong influence on temperature per se, but the dark colour of pavements did. Colour of pavements / roadways could have a significant effect on the regression model – with dark colours when exposed to sunlight showing enhanced temperatures. This is in line with our understanding of thermal absorbance properties of different materials and that new asphalt pavements, which are particularly dark will result in high pavement surface temperatures during hot, sunny periods when exposed to solar radiation and not shaded by green/ grey structures (trees or buildings) (Li et al. 2013).

8.1.4 Air speed and humidity

There were relationships too between air velocity and humidity with some of the factors outlined above. Naturally air velocity could increase in locations that were more open (high sky view factor). There were also some relationships with time (lower wind speeds noted in the evening (Fig 4.12 in section 4.12), for example) or higher humidity as transects approached the river (Fig 7.6).

8.1.5 The influence of road traffic on road thermal properties

One of the most striking pieces of this research was the fact that thermal profiles due to volume of traffic was discernible from the data sets generated. Farmer and Tonkinson (1989) and Gustavsson et. al., (2001) highlighted that road traffic could be a source of anthropogenic heat and contribute to urban heat islands.

The most powerful data set in this regard related to the comparison of road ST between Fridays (heavy traffic volumes- peak 'rush hour') and Sundays (low traffic volumes). For the evening periods (17:30-18:00) ST on Sundays were approx. 6 ^{o}C lower across the road (5.9 left, 6.2 middle and, 6 ^{o}C right) than the equivalent time on Fridays. Similarly, during the afternoon (14:30-15:00) temperatures were 2.8 (left) 3.8 (middle) and, 2.8 ^{o}C (right) cooler than the equivalent period on a Friday. The reason for this is due primarily to differences in traffic volumes. Overall though, solar irradiance still accounts as the main factor determining road ST, with temperature profiles strongly affected by time of day, degree of shadow and prevalent weather conditions at the time of assessment. As with other assessments divergence in surface temperatures were not necessarily replicated by alterations in air temperature. No significant differences were noted in air temperatures due to different traffic volumes encountered. Therefore, direct relationships between traffic volumes and movements and any human thermal discomfort still need to be established. Nevertheless, it is logical to assume that slow moving traffic and large numbers of cars are adding to the urban heat island effect by heating solid objects associated with the road structure.

This research contributed to the literature in many ways. Firstly, the unique feature of this research is that it encompasses a number of factors (green infrastructure, grey infrastructure, morphology, topography, traffic movement and nature of landscape especially road-scape) in one dissertation which is not existing in similar literature. Secondly, this research is based on the primary data collected from a number of roads within the Sheffield city region which is not covered in other studies. Finally, extensive literature review found a research gap in the field of explaining the road surface thermal properties in the UK and other European countries where the above-mentioned factors were taken into consideration together.

This research also found that there were significant effects of various types of sites at different times of the day on the air velocity and humidity. One of the novelty of this research is that along with temperature, it has also considered air velocity and humidity in the same research which don't exist in other literature. The important policy implication of this research in the urban planning is that urban area needs to establish green and wetland to mitigate the influence of UHI phenomena.

8.3 Further scope of research

This research does not encompass the specific criteria of green roadside characteristics, such as canopy density and extent, nor indeed alterations due to species. Moreover, it does not cover specific properties of grey infrastructures in details which may influence road surface temperature, such as, usage of buildings (residential building, business building, dimensions of the building etc.) that leaves the scope of further improvement of this research. In addition, the surface temperature has been collected by using thermal gun device as a mobile station. But, using fixed stations instead might enhance the accuracy of the data by minimizing the error of data was reporting. Various orientation of the roads (in chapter 4 and chapter 5) could improve the result of this research. In addition, incorporating elevation of different roads could also improve the findings. Existing study was carried out in the exclusiveness of Sheffield city with respect to the properties of this city environmentally. Therefore, extent of the field area might improve this sort of research.
Contributing highway capacity of the roads could, environmentally, open the door to improve the conductance of roads. Using advanced devices (for instance, fixed station device) could overcome many of current limitations and increase the level of data accuracy and even could extend the number and types

of parameters obtained. It will also extend the time of data observation for whole day rather than intermittent periods. Extending the data observation of different experiment to four seasons instead of one season, could likely give various findings that could significantly improve the policy of the designer and planner to consider the impact of different seasons on surface temperature of the roads.
Increasing number of parameters, such as, emissivity, convection, conductivity and permeability could also significantly improve the finding of this research.

Using the current factors included in this dissertation, the analysis of this research provides a major finding of the thermal properties of the road but still not comprehensively. Nevertheless, it provides the foundation for further study that will consider the road thermal properties to produce advance findings and policy implications.

8.4 Limitation of this research

This project attempts to fill a research gap by investigating the thermal effect of various roadside features focusing green/ grey infrastructure, traffic density and larger, neighbourhood scale of influence on surface temperature. Nevertheless, some limitations do exist here.

Firstly, data collection required approximately 90 minutes for a single time point for each period (morning, afternoon and evening). Therefore, weather condition might change within this 90-minute period, which might vary the surface temperature. Secondly, due to physical distance among the roads, it has been almost impossible to collect the surface temperature of all locations in different sites at a single point of time. Thirdly, the survey of this research considers only three-time periods of the day within (morning, afternoon and evening) for data collection which is a potential limitation of the research. Increasing number of time periods on the day may improve the research. Fourthly, traffic flow on the road and pedestrian movement along the pavement sometimes hinder the smooth data collection. Fifthly, this research considers some specific features of the road such as tree, hedge Vs building or office. But there is other form (vertical construction, usage of the building, building materials of the grey structure, species of the green structures -leafy, not leafy, evergreen etc.) which are not included in this research. The experiments of this dissertation were mainly carried out in the summer due to time limitation (except one experiment in the chapter 6 which was carried out in winter). Therefore, the result of this dissertation could be more developed by collecting the data for four seasons. Chapter 6 (the effect of traffic movement on the thermal properties of the road) did not consider the car properties such as the size of the cars, personal car or truck and model of the cars which could significantly influence the surface temperature of the road. Trunk roads, two lane dual carriageways and motorways were largely avoided in the current dissertation. However, the interaction between road-scape form and thermal properties of highway surface could create a significant implication for future study. Chapter 7 investigated the impact of the macro-scale places of the land, focusing on the influences of the typography of the land, such as, park, river and, city centre on the thermal properties of the road while the width of the river is not fairly enough to identify the river influence in comparison with the city centre and the park.

8.5 Summary of key findings

A number of important points were generated by this thesis. These include:

- Green infrastructure – trees particularly, but also hedges and to some extent grass had a significant effect on cooling surface temperatures.
- Locations with trees tended to be cooler than locations with buildings, surface temperatures being up to 5 to 6 ^{o}C cooler at the base of the tree.
- Moreover, the data indicated that under certain circumstances trees could reduce air temperatures too, a significant finding as determining effect on air temperature at the scale studied can be elusive.
- Further information is required on how vegetation, most notably trees, should be designed around roadscapes to ensure thermal comfort is optimised, whilst accounting for other ecosystem services provided by the trees, but also other requirements of road-users (e.g. maintaining sightlines, avoid of leaf litter blocking drains etc.).
- When scaled up to neighbourhood scale it was still evident that green spaces were having a cooling influence on road profiles (those near to parks being cooler).
- Transects across roads showed that roads had distinct thermal profiles, with the centre of the road and to some extent solar 'heat traps' e.g. where sunlight hit a south-facing wall, were usually higher than other parts of the road.
- The enhanced heat profile at the road centre was caused by the impermeable tarmac and black colour absorbing/re-radiating high levels of heat as well as local effects of vehicle engines and tyres.
- Houses / offices on both sides of the roads induce higher temperatures compared to other features, irrespective the time and other edge effects of the road.

- The influence of height of the roadside characteristics on surface temperature can be significant, but whether it warms, or cools depends strongly on the direction of incoming solar irradiance, i.e. time of day and aspect of road.
- Road orientation interacting with time of day – (location of incoming solar irradiance) determines the warmest / coolest part of the road.
- In general, however, afternoon time shows warmer surface temperatures compare with morning and evening.
- Evening time though shows a continuation of distinct profiles due to roadsides structures (lag effect), although overall the effect of the sunlight is lower than that in the afternoon and probably morning.
- A positive correlation between air temperature and road surface temperature irrespective of time of day has been found in this research.
- Wind speed reduces surface temperature significantly.
- High sky view factor is one of the most effective variables that impact surface temperatures in all the time periods of the day.
- Open road sides have lower surface temperature compared to the closed roadside significantly.
- Temperatures across the roads over the park and river tended to be cooler in the heart of those sites and rising towards the edges of those sites.
- Air temperature and humidity had no overall significant influence on thermal profiles of the roads surface over different sites; suggesting that these factors measured in the air above the surfaces did not correlate closely with the temperatures experienced at ground level.
- Traffic volumes had a strong and significant effect on road surface temperature – i.e. busier traffic more heat.
- Traffic volume had created significant difference in temperatures of the road in the different periods of a day and different days a week.

- Roads with different sites with various circumstances had distinctive temperatures profile with higher temperatures in the busy road compared to the park and less/no traffic by around 4 ^{0}C and 2.9 ^{o}C respectively.
- Traffic movement had no influence on the air temperatures.

8.6 Implication of results for policy makers

A number of recommendations can be offered by this research:

- Most notably that green infrastructure is important in mitigating local heat effects, and was detected as significant even in a 'northern' English city within a temperate climate. With increasing urban heat island effects policy makers need to incorporate effect tree design and management strategies to ensure optimum thermal comfort.
- Where there is limited space for trees, planners may wish to consider hedges or other small scale green interventions to help cooling.
- Other features of the streetscape – especially location and size of buildings are impacting the thermal profiles and although these aspects are currently acknowledged by planners and architects, more emphasis needs to be given to these to help harmonise temperatures within the streetscape.
- Open locations that exploit natural ventilation are underused and designers need to exploit this more effectively especially where there is a tendency for city densification – i.e. gaps in roads that allow cross winds, can help localised cooling. 'Filling' in all these gaps adds to road heating. This aspect should be given greater prominence not only in new

roads that are built but when giving consideration to redesigning existing roads.

- Cars elicited a surprising amount of heat energy. This aspect is often under-reported when discussing the problems of cars and city environments – yet it adds to the growing call that alternative forms of transport are required for the cities of the 21st Century.
- Although this data deals specifically with Sheffield, U.K., the implications have an international significance. For example, many other cities around the globe have more grey infrastructure and greater volumes of traffic. Planners should 'take heed' of the need to mitigate temperatures through effectively designed green infrastructure and more sustainable traffic policies.

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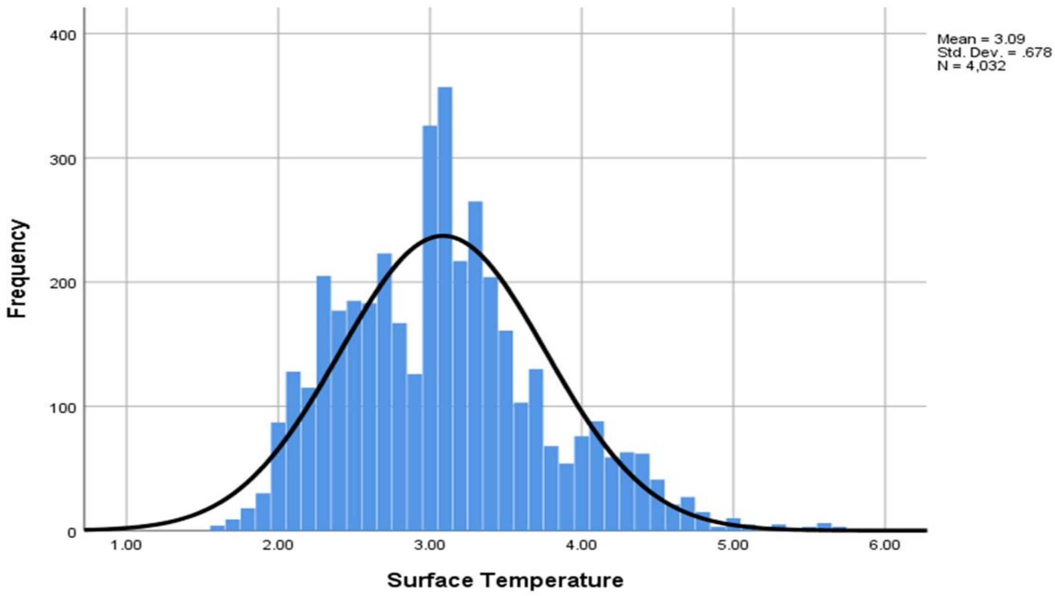
Appendix:

1- Examples of statistical analysis

1.1. Examine the assumption for the data to prepare it for the ANOVA test

The First step in this progress was to check the assumption of normal distribution of the residual. In case the residual was very deviate, Data transformed by using (square root) (example 1).

Example 1:



1.2. Conducted Analysis Of Variance test (ANOVA) and LSD bar

Analysis of variance (ANOVA) test was conducted for the data to examine the influence of the treatments (roadside features) on the surface temperature (ST) (example 2). Result of the treatment effect was considered statistically significant when P-value ($P \leq 0.01$) and, ($P \leq 0.05$). LSD value were calculated at Error bars lsd 5% based on the question below (example 3).

Example 2:

. anova RPI threesite

	Number of obs -	126		R-squared=o. 0919	
	Root MSE=3 . 54867			Adj R-squared=0.0772	
Source	Partial SS	df	MS	F	Prob>F
Model	156.8273	2	78.413651	6.23	0.0027
threesite	156.8273	2	78.413651	6.23	0.0027
Resi dual	1548 . 9474	123	12 593068		
Total	1705 . 7747	125	13 646197		

. anova RP2 threesite

	Number of obs =	126		R-squared=0.0868	
	Root MSE=3 . 51353			Adj R-squared -_ 0.0720	
Source	Partial SS	df	MS	F	Prob>F
Model	144.32762	2	72.16381	5.85	0.0038
threesite	144.32762	2	72.16381	5.85	0.0038
Resi dual	1518.4245	123	12 . 344915		
Total	1662 . 7521	125	13 . 302017		

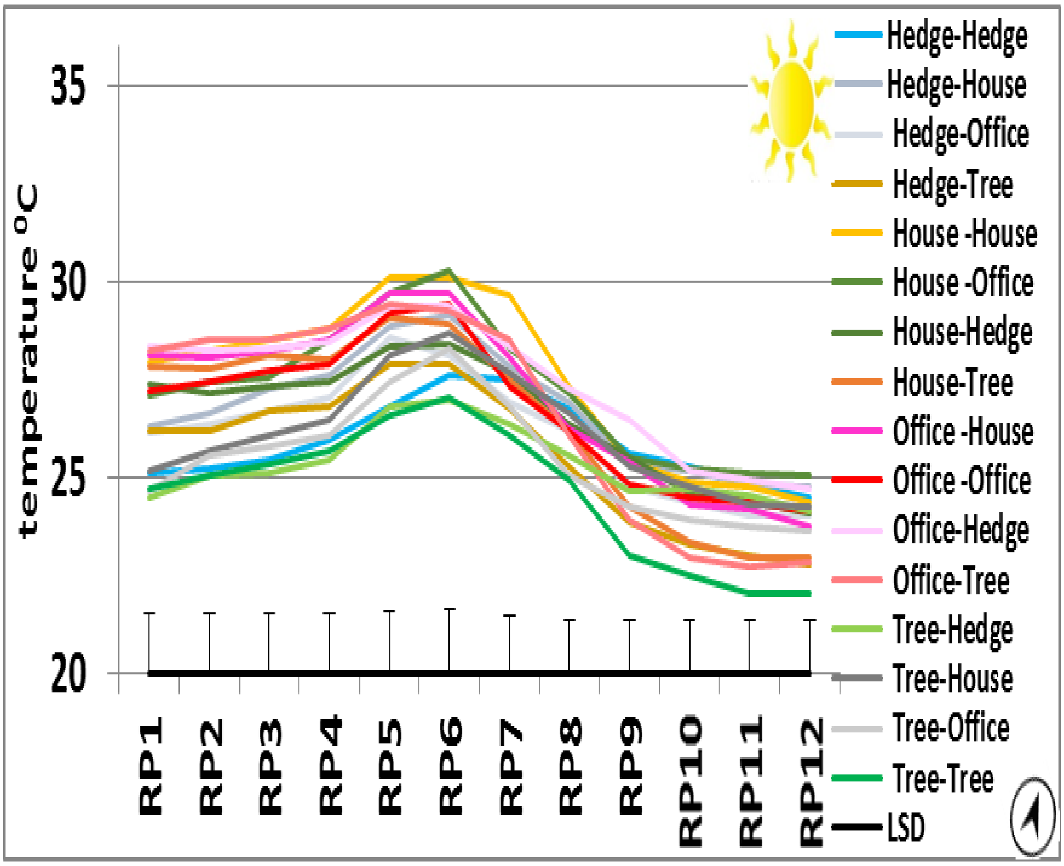
Example 3:

Lsd= tv,$\alpha\sqrt{2MS/n}$

tv, α for df 188 at α 0.05= 1.97

LSD=1.97$\sqrt{2(17.05)/48}$ = 1.42

When tv, α is t critical distribution related with degree of freedom at α level, while n is number of observations was used to calculate the mean at each level, MS is error mean square.



temperature °C
35
30
25
20
RP1
RP2
RP3
RP4
RP5
RP6
RP7
RP8
RP9
RP10
RP11
RP12
Hedge-Hedge
Hedge-House
Hedge-Office
Hedge-Tree
House -House
House -Office
House-Hedge
House-Tree
Office -House
Office -Office
Office-Hedge
Office-Tree
Tree-Hedge
Tree-House
Tree-Office
Tree-Tree
LSD

1.3. Multiple Regression Model

The multiple regression model was used to evaluate the relationship and (influences value) between surface temperature (ST) as dependent variable and environmental and physical properties as independent variables (Policy variables) example 4.

Example 4:

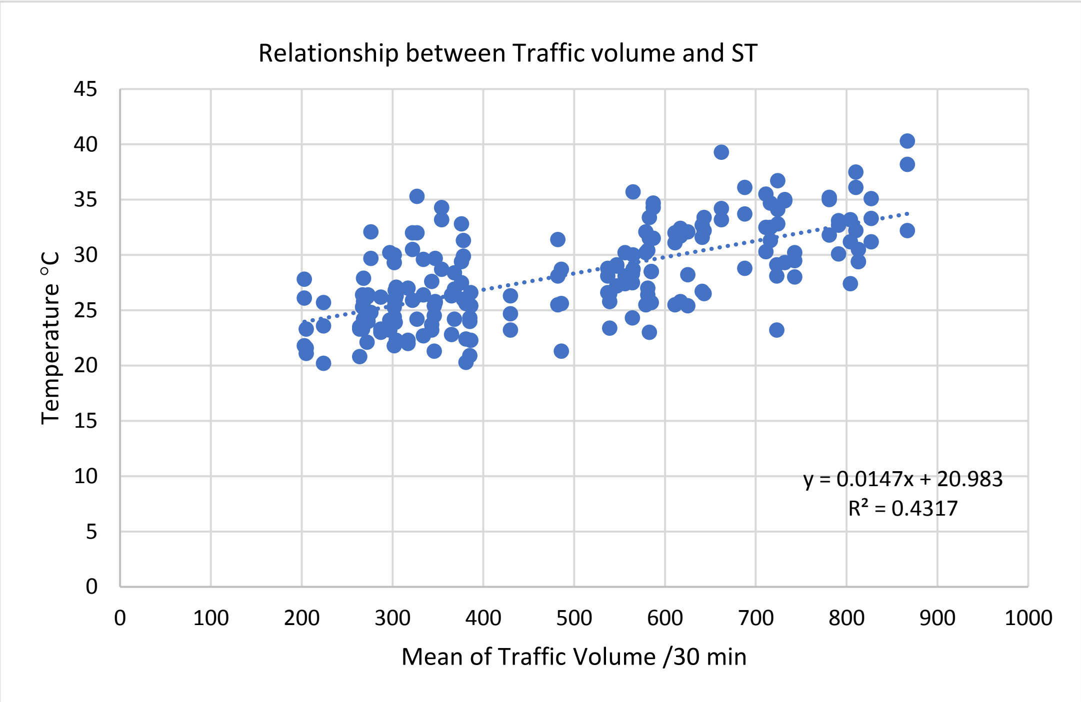
Variables	ST (SW)	ST (middle)	ST (NE)
Environmental variables			
Air T-SW	0.2***	0.3***	0.2**
Air T_-Middle	0.18*	0.6	0.1
Air T -NE	0.2**	0.2*	0.2**
Air Velocity-SW	-0.1***	-0.06	-0.8***
Air Velocity-Middle	1.02***	0.7***	-0.4***
Air Velocity-NE	-0.3**	1	-0.8***
Physical variable			
A- Scale variables			
Height-SW	0.1***	0.02	-0.1*
Width of the roads	0.16***	0.4**	-0.4
Height-NE	-0.5***	-0.6***	-0.6***
H/W ratio	-0.13	-0.24**	-0.27*
SVF-SW	5***	2.2*	0.2
SVF-Middle	6.5***	3.8***	0.4
SVF-NE	0.3**	1.6**	1.2*
B- Nominal variables			
Green color SW characteristics	-0.7***	-0.4	-0.2**
Red color SW characteristics	0.5	-0.8	0.7
Green color NE characteristics	-1.7***	-1.6***	-1.4***
Red color NE characteristics	0.6*	0.2	0.2
Light black of surface SW	-0.2	0.06	-0.3
Dark black of surface SW	0.5**	0.4*	-0.03
Light black of surface NE	0.5*	0.4	0.6**
Red surface NE	-0.4	-0.5	-0.2
C- Binary			
Open-Close SW	-0.4**	-0.56*	0.5**
Open-Close NE	-0.2	0.5*	0.2**
Constant	5.6	8.6	6.6
R^2	0.7658	0.7358	0.6880
No of observation	768	768	768

Note: ***, **, * indicate 1 % (p<0.001), 5% (p<0.05) and 10% (p<0.1) significant levels.

1.4. Correlation and regression analysis

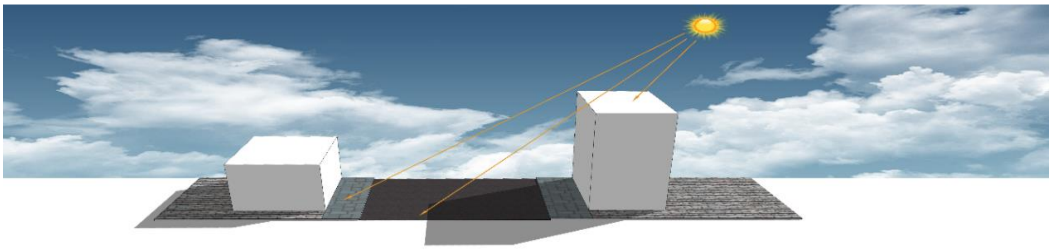
Correlation was carried out to analysis the relationship between two continuous variables such as (traffic movement on surface temperature). person's coefficient was used to identify the correlation level as (large, medium and small) when the coefficient are (≥ 0.50, 30-0.49 and, (≤ 0.29)) respectively example 5.

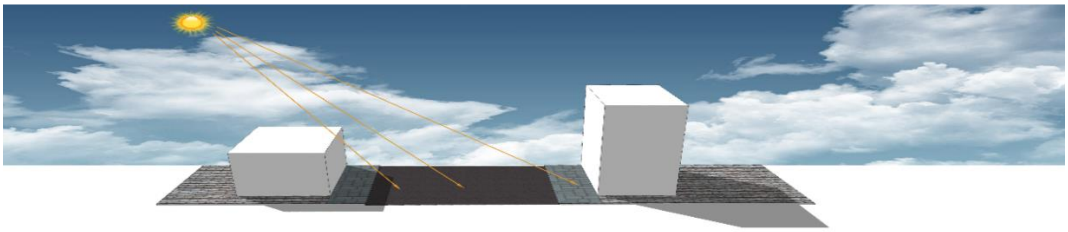
Example:5 5:

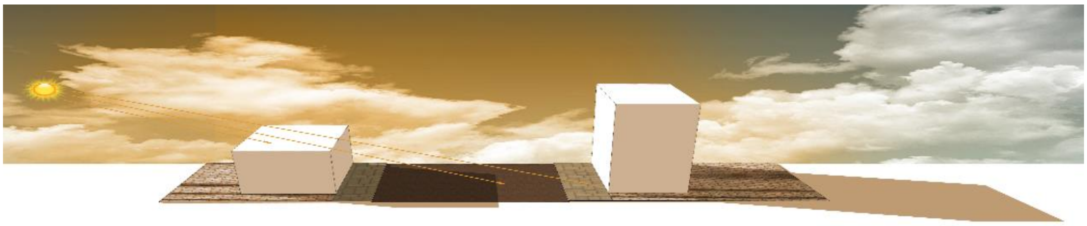


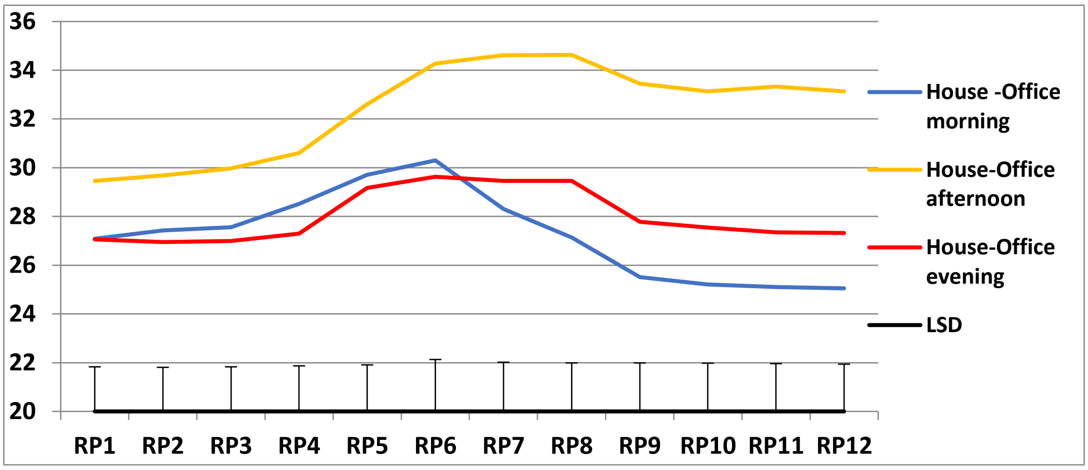
2- Examples of physical and environmental properties and their influences in ST

2.1. Images of two locations with (House-Office) road side characteristics located at 15 Regent Terrace and Canning (Top), Sun positions at three times measurements (Middle), Mean of ST at 3 times and, SVF for two sites at 3 locations (Bottom)








36
34
32
30
28
26
24
22
20
RP1 RP2 RP3 RP4 RP5 RP6 RP7 RP8 RP9 RP10 RP11 RP12
House -Office morning
House-Office afternoon
House-Office evening
LSD