A framework for a comprehensive mobile data acquisition setting for the assessment of Urban Heat Island phenomenon

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Abstract –
The debates around the Urban Heat Island phenomenon (UHI) have gained momentum in the context of smart cities and sustainable development. It is crucial to understand the complex interaction between urban features and temperature variation in the city based on reliable and detailed data. Yet, the complex interaction between the UHI of the canopy layer, paved surfaces and urban geometries (e.g., buildings, vegetation, and urban elements) has not been intensively explored to accurately capture their interplay. This is mainly caused by the palpable absence of comprehensive data that can support this type of correlational analysis. This paper proposes a comprehensive data acquisition framework to guide the collection of the requited data for the development of a data-driven UHI assessment model, with a specific focus on the contributions of paved roads to UHI.
The framework was tested with a case study in Apeldoorn, the Netherlands, during a period of six months. The data collected, highlights the useability of the proposed framework for collecting high-resolution urban data required to assist local governments and urban planners to make informed decisions. To the best of authors' knowledge, this is the first time the interplay between urban feature, surface and air temperatures has been measured via mobile transects.

Keywords
Data-driven methods; data collection; smart and sustainable cities; mobile sensing systems; urban heat island

1 Introduction

The extreme weather conditions caused by climate change are reshaping the world. There were 38 heat waves in Europe in the last century, 17 of them in the last decade. Only the heat wave of 2003 caused 70,000 excess deaths over 4 months in Central and Western Europe [1]. In urban areas, the negative effects of climate change are greater. This is because changes in the natural environment, render urban areas more prone to store solar radiation [2]. 75% of the world's population is living in fast growing urban areas, and this number is projected to continue to increase in the years to come [3]. While global efforts are focused on climate adaptation and smart, sustainable urban development, climate policies and actions are often based on subjective knowledge due to the absence of sound and comprehensive data [4].

UHI phenomenon is defined as the temperature difference between the suburbs and the inner city. To measure the UHI effects, two main approaches have been widely adopted: (1) air temperatures, which refers to the UHI of the canopy layer (CUHI), and (2) the surface UHI (SUHI), which refers to the thermal emissivity of land surfaces [5]. CUHIs are usually studied by measuring air temperatures, typically at about 2 m above the ground via fixed or mobile weather stations. SUHI, on the other hand, are monitored via remote sensing data. Although techniques to measure and explain both CUHI and SUHI have been successful in explaining these phenomena, they possess a few limitations. First, commonly fixed weather stations are used to continuously measure air temperatures. While weather stations collect the data with a high frequency, the ability of the data coming from limited fixed locations to represent the temperature variability in the city (from the city center to the outskirts) is questionable. Moreover, weather stations are often located in open areas to avoid interference from shading or urban factors [6]. As such, they do not capture the effects of drivers that intensify the UHI phenomena. Remote sensing technologies, on the other hand, do provide sufficient data resolution to characterize inner urban centers and rural surroundings. However, they do not account for temperature differential above the ground.

To overcome these limitations, researchers worldwide have modeled the spatial variability of urban temperatures by applying sensing technologies and spatial and numerical models that integrate data from multiple sources [7]. In addition, the technological advances of recent years have made it possible to deploy mobile weather stations to map the temperature variation in the city at a higher resolution. The emphasis, however, has been placed on the relationship between urban geometries (e.g., Sky View Factor (SVF), height to width ratio (H/W)) and air temperature [8, 9]. Other studies have looked at the relationship between geographic characteristics, such as proximity to the coast, rivers, and land cover [10, 11]. Nevertheless, the relationship between paved roads and temperature variation in the city has not received much attention. This is a major oversight because paved surface has been commonly identified as one of the main drivers of UHI.

Between 2016 and 2021, a considerable amount of literature was published on the different field campaigns for the collection temperature data via mobile measurements [6, 8, 12-16]. While the majority targeted CUHI temperatures, a few studies focused on air temperatures and thermal comfort, the relation between air temperatures and evapotranspiration, and the interaction between air and surface temperatures.

However, the complex interaction between CUHI, paved surfaces and urban geometries (e.g., buildings, vegetation, and urban elements) has not been intensively explored to accurately capture their interplay. This is mainly caused by the palpable absence of comprehensive data that can support this type of correlational analysis. Therefore, a more comprehensive approach towards data collection is required to enable the collection of the data needed to build a more comprehensive temperature profile of urban areas.

Given the above limitation, this paper aims to develop a comprehensive data collection and processing framework to guide the collection, pre-processing and visualization of the data requited for the development of a data-driven UHI assessment model, with a specific focus on the contributions of paved roads to UHI.

The remainder of the paper is structured as follows. First, the proposed framework is presented. This is followed by a brief explanation of a case study that demonstrates the applicability of the framework. The paper ends with conclusions and future work.

2 The framework

To address the research gap presented in Section 1, a comprehensive data collection and processing framework is developed. It encompasses three main steps (Figure 1). The first stage involves the development of a bicycle-based mobile urban data collection station. That is then followed by a data collection campaign. In the last stage, the collected data is pre-processed and visualized.

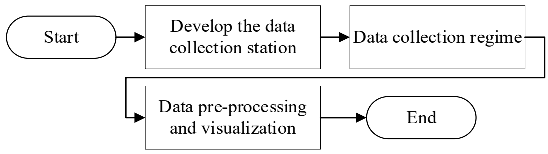


Figure 1: Schematic representation of the proposed framework

2.1 Development of data collection station

The development of the data collection station starts with the analysis of the required data, followed by the analysis of the type of sensor that can meet the data needs, and ends with the assembling of the mobile station.

2.1.1 Data required

The dark materials used to replace natural landscaping in cities store solar radiation during the day and release it when temperatures begin to drop at night. This intrinsic property of the materials used in the built environment is largely responsible for the UHI phenomenon. That has prompted researcher worldwide to devote their efforts to understand the behavior of these materials under different environmental conditions. As highlighted in Section 1, there is an urgent need to expand the body of knowledge on UHI-material interplay based on data that capture as much of the urban environment as possible.

As shown in Figure 2, the urban fabric (i.e., the urban materials) can be categorized in three main groups: building materials, roads (paved or unpaved), and vegetation. Regarding the temperature of buildings, the facade materials are the main concern. Hence, capturing the energy interaction between the building façade and the adjacent urban elements is a key task in the data collection campaign. For instance, the temperature of a building façade next to a green area can be greater or lower than the temperature of a façade in the business district where paved roads are predominant. As such, a thermal camera capable of screening temperatures at a larger distance is best suited for this task. Likewise, there are different types of paved roads, i.e., in terms of function and material type. Hence, a granular measurement of the surface temperature is required.

Finally, the air temperatures at the canopy layer must be taken into account. Air temperature readings should be recorded at the same location that the façade and road surface measurements are taken. This is crucial because the variation of air temperature in relation to the variation of urban geometries and their temperatures can signal the contributions of paved roads to UHI.

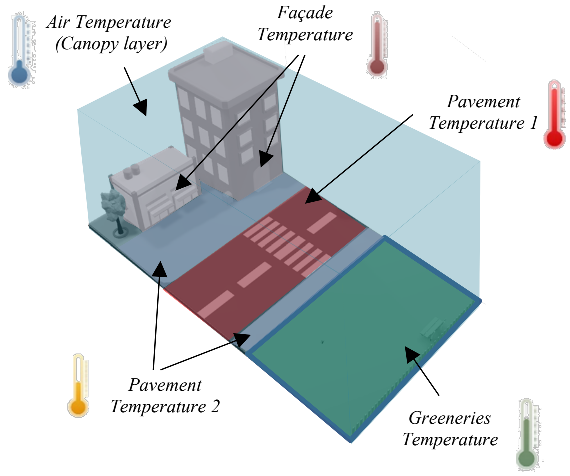


Figure 2: Schematic representation of data required for comprehensive UHI studies

2.1.2 The sensors

A bicycle-based mobile urban data-gathering station is used to roam around the city and collect geo-referenced and time-stamped temperature data at the level of road surfaces and above the ground level. As shown in Figure 3, the sensor kit includes a processing centre, a GPS rover, a mobile weather station, and an infrared camera.

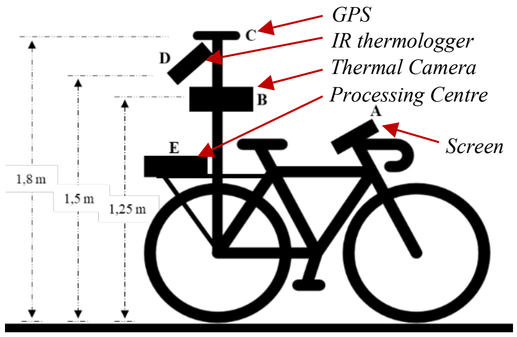


Figure 3: Schematic representation of the bicycle-based mobile urban data-gathering station

To record accurate locations, a GPS antenna is used. A dedicated GPS antenna is chosen instead of a smartphone because the latter do not provide the accurate and frequent enough data needed for the high-resolution data collection campaigns.

A Thermal imaging temperature sensor is used to read thermal images of the surrounding building façades. Thermal imaging cameras are widely used for building inspections, body temperature screening, etc. They are suited to read measurements at a distance without compromising the capabilities of capturing temperature variations with high accuracy. Figure 4 presents a sample of an image taken from the thermal imaging sensor. Each frame contains temperatures for every pixel in the image. In this research, the average temperature along the horizontal line (as shown in Figure 4) of the middle of the frame was stored. This is because the middle of the image has a higher chance of providing unobstructed view of the façade (no leaves or cars).

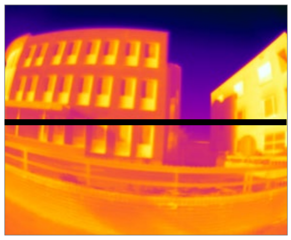


Figure 4: Sample image from the thermal camera

To capture the surface temperature, an infrared sensor is best suited. As shown in Figure 3, an InfraRed Thermometer (D), coupled with an environmental sensor, is placed 1.5 m above ground to read air temperature, relative humidity, and wet bulb.

All the sensors are connected to a dedicated processing centre. This processing centre runs a windows-based application developed to record, synchronize, and store the readings from the sensors in real-time. The data is stored in a comma-separated values (CSV) file format as follows: *Row ID, GPS time, Latitude, Longitude, Altitude, Thermal camera readings, Canopy air temperature, Wet bulb, Relative Humidity, Surface temperature, and time*. In addition, for each row of recorded data, a digital image, similar to Figure 4, is stored in a JPG format. The architecture of the processing centre is shown in Figure 5.

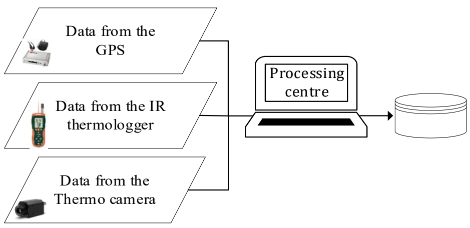


Figure 5: Illustration of the data storage process

2.2 Data collection campaign

Since the objective of the field campaign is to reveal the interplay between urban morphologies and the UHI, the time of day when field campaigns are conducted is critical. In a nutshell, the proposed campaign seeks to capture the variation of temperatures during the day and across the targeted city as much as possible. Therefore, it is recommended to create three different temperature profiles per day (i.e. morning, afternoon, and evening UHI profiles). The reason for this lies in the process by which solar energy is absorbed and released by the urban fabric, which follows the solar pattern of dawn and dusk. A morning shift (a few hours after sunrise) is required to capture the temperatures of the urban fabric before solar radiation is absorbed. Another shift must be carried out during the hours in the day when the intensity of the sunlight is highest. Finally, another shift during the sunset is required.

As for the speed of the cycling, given that data are stored every second, a constant cycling speed of 8 km/h is recommended to collect data with a spatial resolution of 2 m.

2.3 Data pre-processing and visualization

The goal of this steps is to organize the collected datasets in such a way that they can later be used for data-driven modeling. As illustrated in Figure 6, data pre-processing and visualization involves five main steps. First, all collected field measurements must be assembled and arranged in a data frame.

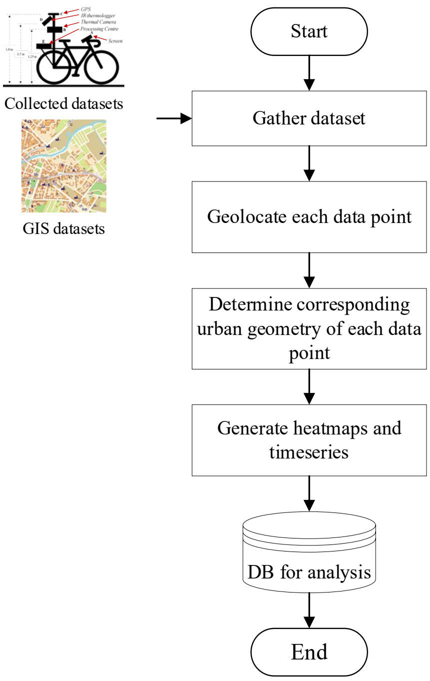


Figure 6: Flow chart of data processing and visualization

Since each measurement point is stored with a corresponding latitude and longitude, it can be geolocated using a GIS software, from where the routes can be examined and compared spatially. Once the data points are georeferenced, it is possible to map each measurement with its corresponding geometry. This is a two-step process. First, the measurements corresponding to the surface temperature are assigned to its corresponding road. In the second step, the readings from the thermal camera are assigned to each corresponding façade. The proposed method is illustrated in Figure 7. In this method, a line perpendicular to the movement direction of the bike is drawn at each point. If the point intersects with the footprint of the building, the reading is considered to be of the façade. For each façade, the final temperature is taken as the average of all the readings associated with that façade.

Figure 7: Example of the temperature readings for a given façade

Next, the geolocated datasets for each day and temperature profile (i.e., morning, afternoon, and evening) are consolidated into a single data frame where each road has the following attributes: *Road ID, Temperature profile, Surface temperature, Canopy air temperature, Façade temperature, Wet bulb, Relative Humidity.*

3 Case study

To evaluate the applicability of the proposed framework, a case study was conducted in the city of Apeldoorn, the Netherlands. Apeldoorn (52.2112° N, 5.9699° E) is a medium-sized city, located in the middle of the countryside and the De Hoge Veluwe nature reserve. The average elevation of the city is 39 m above sea level, and it has a moderate oceanic climate. It is the 11th largest municipality in the Netherlands, with 165,525 inhabitants (2021), which make it a good example of a midsize city in the Netherlands. However, due to its geographic location, it presents a unique combination of vegetation and built environment, which offers the basis for an interesting analysis of the UHI. In terms of infrastructure, the heights of buildings are between 10 and 15 meters, and the city center is densely built up. The construction materials of the building facades are homogeneous, varying from dark to light traditional Dutch bricks.

Given the importance of having a comprehensive sample of urban features, an 8 km-long urban circuit was selected to sample the urban area from the center of the city, passing through commercial, recreational, and residential areas (Figure 8).

Figure 8: 8 km-long urban circuit selected for the case study

3.1 The prototype

A bicycle was equipped as described in section 2.1.3 and shown in Figure 9. It features (1) an ANN-MS high performance active GPS antenna, (2) a thermologger (Extech HD500) equipped with air temperature, relative humidity and wet bulb sensors, (3) an infrared thermometer with an accuracy of 30:1 distance to target ratio, and (4) a thermal camera (FLIR A45 FOV 69). As for the processing center, a windows tablet was installed to facilitate on-the-fly access to the data being recorded. Table 2 summarizes the installed equipment.

3.2 Preliminary results

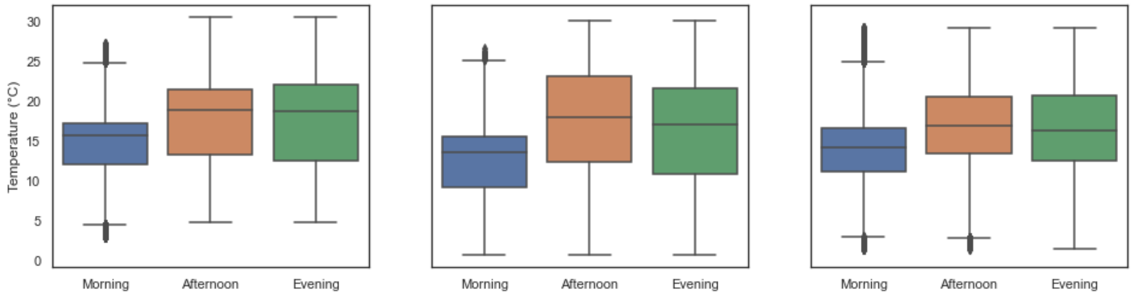
Field campaigns were conducted between 25th of March and 30th of August, 2021, two times per week. For each time the field measurements were undertaken, it started and ended at the same point to make the measurements as consistent as possible. Under heavy weather conditions the field campaigns were not conducted.

Figure 9: Developed mobile data collection unit

Table 2: Summary of measurement equipment installed on the bicycle

Sensor	Reference in Fig. 3	Function	Model	Measured parameter
 GPS	A	Localization	ANN-MS, GPS antenna	Longitude and Latitude
 Thermologger	B	Surface temperature monitoring and weather station	Extech HD500	Surface Air Temperature, Relative Humidity, Wet Bulb
 IR Camera	C	Façade temperature monitoring	FLIR A45 FOV 69	Urban morphology temperatures
 Processing Centre	D	Data Processing	Microsoft surface pro-2	N/A

The processing of the data started with the detection of outliers to identify measurements that deviated substantially from others. This was done by the interquartile range (IQR) method per street. After removing the outliers, the dataset was assembled, as described in section 2.3. As specified in section 2.2, three temperature profiles were collected. Figure 10 presents the summary of the temperatures for the complete dataset in the three profiles measured by the mobile station. The mean morning air temperature was 14.8 °C, while the surface temperature reading was 2.8 degrees lower (12.0 °C). The average temperature reading from the thermal camera in the morning was 13.8 °C with a maximum temperature reading of 29.3 °C, while the maximum morning surface temperature and air temperature were 26.6 °C and 27.2 °C, respectively. In the afternoon the maximum temperatures oscillated between 29.2°C and 30.6 °C. In turn, in the evening the



(a) (b) (c)

Figure 10: Distribution of the temperature measurements recorded during the field campaigns: a) air temperature; b) surface temperature; and c) façade temperature.

maximum air temperature and surface temperature were 30.6°C and 30.1 °C, respectively. The thermal camera readings were approximately one degree lower (29.2 °C). Figures 11 compares the three different temperature profiles recorded by the mobile station during the six months of data campaign with the air temperature recorded by an on-site weather station located on the surroundings of the city. The air measurements remain constant, while the surface measurements are low in the morning, increased in the afternoon and remain high in the evening. Further, the surface temperatures were highest in the afternoon and decreased during the evening. While this paper concerns mainly with a detailed explanation of the framework for a comprehensive mobile data acquisition regime, the preliminary analysis of the data indicates a pattern of increasing temperatures in the inner city throughout the day. In particular, the surface temperature, which starts with a relatively low temperature in the morning, almost doubles by noon, and stays high until sunset. It is this thermal energy that is released during the night and thus increasing the temperatures in the city.

4 Discussion and future work

The results of this study highlight the variation of temperatures during the day across the city. The granularity of the data collected by the mobile station allows to perform different type of analysis at different scales (i.e., city, urban canyon, street, material level). For example, Figure 12a presents an example of an urban canyon and Figure 12b illustrates the data collected for that part of the city. Figure 12c shows an example of a thermal image at this canyon. Figure 12d summarizes the temperature variation for that urban canyon on the morning of Jun 14th. This level of detail in the data makes it possible to evaluate the different characteristics of the urban materials in conjunction with the different geometric configurations of the city at a very detailed level. Moreover, as shown in Figure 13, the specific behavior of the paved surfaces themselves can be studied. In the specific example of Figure 13, the surface temperature went from 13 °C in the morning to 48.5 °C in the afternoon, finding a more or less constant temperature in the evening at 31 °C. This is a difference of 18 °C between the morning and evening UHI temperature profiles at that given location. Figure 13 also shows the behavior of different road materials; brick shows a lower temperature in the afternoon profile than asphalt concrete.

With these data at hand, different analyses can be performed, at different scales, and at different times of day (e.g., cooling/warming effects of different types of materials at different locations over different time periods), as well as different urban elements (e.g., vegetation, buildings, cold sinks, roads) on the UHI. Furthermore, the intricate interplay between these decision variables and how the combination of these urban elements could result in optimum context specific design for the built environment. In addition, the authors see great potential for this data collection regime because, once the bicycle is up and running, data collection and analysis do not require a large capital investment. Moreover, since the configuration of the bicycle is quite straightforward, it can be envisaged that larger municipalities could implement this green solution of city bikes. A similar initiative has already been launched in the province of Utrecht with a less sensorized bike that aims to map air quality [17].

Future studies based on the data collected will involve the development of a data-driven approach to study the contribution of paved surfaces to temperature variation in the city. To this end, the authors are already busy analyzing the data collected for the city of Apeldoorn to investigate the impact of pavement material and road design on UHI. Finally, other data collection campaigns will be carried out in other urban areas with different climatic locations.

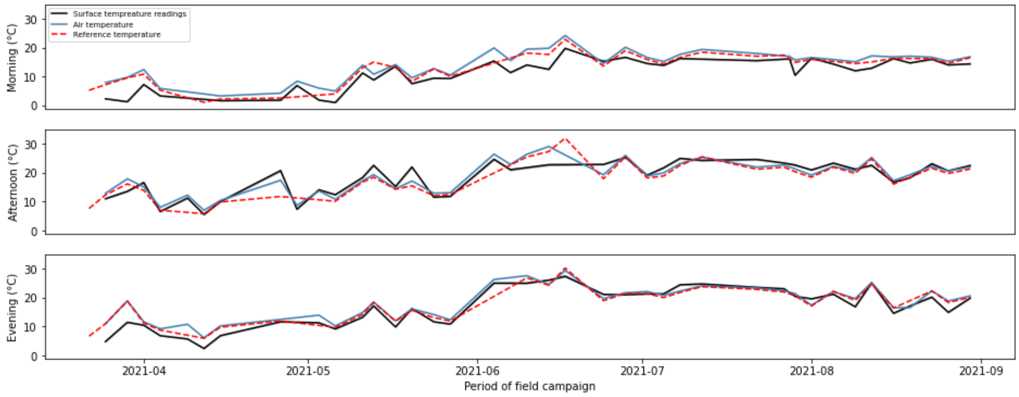


Figure 11: Plots of the three different air temperature profiles obtained with the bicycle-based mobile urban data-gathering station

Figure 12a: Urban canyon

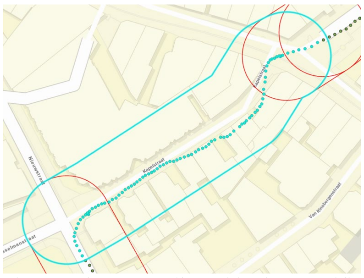


Figure 12b: Data collected in that specific urban canyon

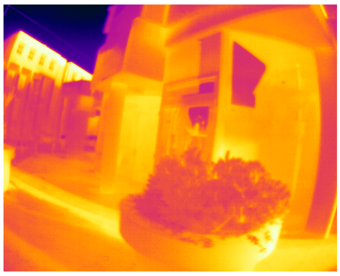


Figure 12c: Example of façade temperature

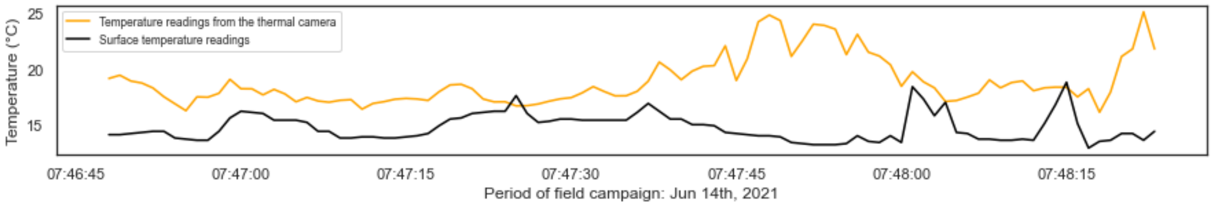


Figure 12d: Surface temperatures and thermal readings in that urban canyon on the morning of Jun 14th, 2021

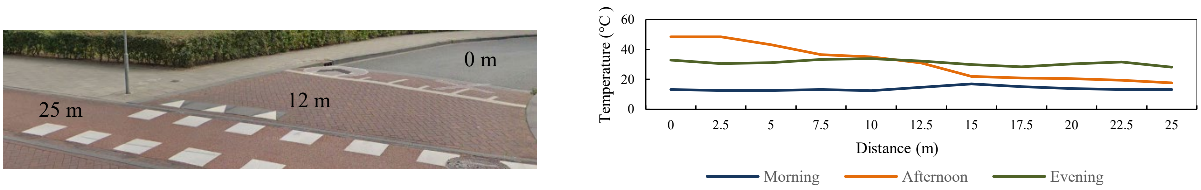


Figure 13: Example of surface temperature measurement taken on the 14th of June 2021. The temperature variation ranges from 13 °C in the morning to 48.5 °C in the afternoon across the different road materials.

5 Conclusions

The aim of this research work was to present a framework for a comprehensive mobile data acquisition regime to assist the understanding of the UHI with particular interest in paved surfaces. The framework was tested in a case study in Apeldoorn, the Netherlands, during a period of six months. It is shown that the proposed mobile surveying unit provides high-resolution urban data. Further, the case study demonstrated that the mobile unit enables the acquisition of the data required to build a more comprehensive temperature profile of a given urban area. This level of detail in the data makes it possible to evaluate the different characteristics of urban materials along with the different geometric configurations of the city at a different levels of detail.

The granularity of the data collected by the mobile unit enables the quantitative analysis of the interaction between the UHI, paved surfaces and urban geometries. These quantitative measurements can be useful tools to assist local governments and urban planners to make informed decisions. Moreover, the framework presented in this research offers a clear pathway to feed mobile transect data streams into the UHI discussion with emphasis in urban road infrastructure. This could allow accurate correlations, develop regression models, identify key features by location, and ultimately the development of a data-driven models for comprehensive assessment of Urban Heat Island phenomenon.

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