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Evaluating asphalt pavement surface temperatures using thermal satellite remote sensing

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Abstract

The rapid ageing of asphalt pavement surfaces due to prolonged exposure to intense thermal stresses adversely affects road performance, leading to reduced safety, lower comfort, and higher maintenance costs. Traditionally, the thermal behaviour of asphalt mixtures is investigated under controlled laboratory conditions through thermal cycling to assess performance and predict service life. Although these procedures are efficient and widely adopted, their predictive reliability diminishes under real-world conditions, primarily due to material heterogeneity and non-uniform surface temperature distributions. These challenges are intensified by climate change and the growing impact of urban heat island effects, particularly in heavily urbanised and paved environments. Satellite-based remote sensing platforms equipped with passive sensors provide historical datasets that enable long-term monitoring of land surface temperature at large scales. Multispectral imagery acquired from Landsat-8 Thermal Infrared Sensors (TIRS) and Sentinel-2 Multi-Spectral Instruments (MSI) have proven viable for analysing climate-induced changes in built and natural environments. However, for pavement-scale applications, the spatial resolution of thermal and multispectral imagery, typically ranging from 100 m to 30 m, represents a major limitation. This study proposes an innovative paradigm for high-resolution, large-scale thermal mapping of road pavements based on satellite-derived thermal anomalies. A case study at a toll highway station in the Marche Region, Italy, demonstrates the capability of the proposed methodology to accurately identify pavement surface temperature patterns.

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Keywords: pavement surface temperature, remote sensing monitoring, asphalt ageing, thermal satellite imageries

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1. Introduction

The accelerated degradation of the upper layers of flexible pavements, primarily driven by prolonged exposure to intense thermal stresses, represents a critical challenge in modern road engineering. This degradation adversely affects functional surface properties of highways and urban roads, potentially compromising vehicular safety, reducing driving comfort, and substantially increasing maintenance costs. Laboratory-based thermal cycling tests are commonly employed to assess performance and predict service life of asphalt mixtures. While these methods are accurate, predictive accuracy diminishes in real-world conditions. Moreover, thermal stress to road pavements is intensified by escalating frequency and severity of climate change-related phenomena and urban heat island effects, particularly within densely paved urban environments, as presented by Almeida et al., (2021), Vieira Zezzo et al. (2023), and Jiménez-Muñoz et al. (2014).

Earth Observation (EO) satellites can serve as an additional informative tool for investigating surface temperature variations in urban environments, complementing traditional in-situ temperature measurements. Capability to monitor temperature dynamics over large spatial scales with high temporal resolution offers significant advantages; however, effectively utilising satellite data for urban thermal monitoring remains challenging due to several factors. These include spatial heterogeneity, spatial resolution limitations, and data integration complexities. Temperature variability in urban environments is examined in this study, with particular emphasis on road pavements.

A case study area located in the Marche Region, Italy, is investigated in relation to a specific toll highway station. Subsequent section delineates the potential of satellite-based temperature monitoring and its capacity to address the associated challenges.

2. Satellite-based multispectral monitoring of thermal variability in road pavements

Satellite remote sensing platforms equipped with multispectral sensors represent a valuable source of big data, enabling the analysis of historical time series across various regions of the electromagnetic spectrum, including the thermal domain associated with surface temperature. Among these platforms, Sentinel-2, developed within the framework of the Copernicus Program by the European Space Agency (ESA), is a multispectral mission in polar orbit launched in 2015. It is specifically designed for high-resolution land monitoring, offering detailed imagery of vegetation cover, soil, and water resources, as well as critical information for emergency response. Sentinel-2 provides multiple spectral bands in the visible (VIS) and near-infrared (NIR) ranges, with spatial resolutions reaching up to 10 m. However, it does not include thermal infrared (TIR) bands, which limits its direct applicability for surface temperature retrieval.

Complementing Sentinel-2, Landsat 8 and Landsat 9, jointly developed by NASA and the U.S. Geological Survey (USGS) as part of the longstanding Landsat program, are equipped to acquire both multispectral and thermal imagery. Landsat 8 was launched in 2013, followed by Landsat 9 in 2021, reinforcing the continuity of a satellite archive that now spans over five decades. These missions provide consistent, calibrated, and freely accessible data that support a wide range of scientific, environmental, and urban planning applications.

Each Landsat satellite carries two primary instruments: the Operational Land Imager (OLI), which captures data in the VIS, NIR, and shortwave infrared (SWIR) regions, and the Thermal Infrared Sensor (TIRS), which detects thermal radiation in two longwave infrared bands centered at 10.9 μm and 12.0 μm. These thermal bands are specifically designed to estimate Land Surface Temperature (LST), supporting applications such as urban heat island analysis, evapotranspiration monitoring, and thermal characterisation of built environments.

The OLI instrument offers a spatial resolution of 30 m for multispectral bands and 15 m for the panchromatic band, while the TIRS thermal bands have a native resolution of 100 m, typically resampled to 30 m. This relatively coarse resolution represents a significant constraint for local-scale analyses, particularly in urban contexts and for road pavement-related investigations. In this regard, multispectral imagery from Landsat-8's TIRS has been effectively employed to study climate change-induced transformations in both built and natural environments. Nonetheless, the spatial resolution of thermal datasets, nominally 100 m and interpolated to 30 m, remains a limiting factor for detailed urban assessments.

Table 1. Description of the spectral bands of the Sentinel-2 mission (Copernicus), adapted from European Space Agency - Sentinel-2 User Handbook (2015).

Sentinel-2 Band	Description	Central Wavelength (nm)	Bandwidth (nm)	Spatial Resolution (m)
B1	Coastal Aerosol	443	20	60
B2	Blue	490	65	10
B3	Green	560	35	10
B4	Red	665	30	10
B5	Red Edge 1	705	15	20
B6	Red Edge 2	740	15	20
B7	Red Edge 3	783	20	20
B8	Near Infrared (NIR)	842	115	10
B8A	Narrow NIR	865	20	20
B9	Water Vapor	945	20	60
B10	Short-Wave Infrared (SWIR)	1375	30	60
B11	SWIR 1	1610	90	20
B12	SWIR 2	2190	180	20

Table 2. Description of the spectral bands of Landsat 8/9, adapted from the Landsat Official Website (USGS).

Band Landsat 8/9	Description	Central Wavelength (nm)	Bandwidth (nm)	Spatial Resolution (m)
B1	Coastal Aerosol	443	20	30
B2	Blue	482	65	30
B3	Green	561	57	30
B4	Red	655	37	30
B5	Near Infrared (NIR)	865	28	30
B6	SWIR 1	1,610	85	30
B7	SWIR 2	2,200	190	30
B8	Panchromatic	590	180	15
B9	Cirrus	1,375	20	30
B10	Thermal Infrared (TIRS 1)	10,895	590	100 (resampled to 30)
B11	Thermal Infrared (TIRS 2)	12,005	980	100 (resampled to 30)

3. Methodology

TIR satellite imagery acquired by multispectral sensors plays a pivotal role in LST across global and regional scales. Nevertheless, TIR bands typically exhibit coarser spatial resolution than shorter-wavelength multispectral bands, which constrains the level of spatial detail in LST products, such as those derived from the Landsat mission, to approximately 100 m. Although these data are frequently resampled to 30 m to improve usability, the native resolution remains a limiting factor for applications requiring fine-scale thermal characterisation. Such resolution is generally adequate for broad-scale thermal assessments and long-term environmental monitoring. To complement these thermal datasets, Sentinel-2 MSI Level-2A imagery offers higher-resolution multispectral data (up to 10 m) in the VIS and NIR ranges, with a revisit time of approximately 5 - 12 days. Although Sentinel-2 lacks thermal sensing capabilities, its fine spatial resolution and frequent temporal coverage make it a valuable asset when integrated with Landsat thermal data. For example, the Landsat-8 surface reflectance product has been widely used to generate spectral indices at 30 m resolution, facilitating the derivation of land cover characteristics relevant to surface temperature dynamics. This complementary relationship between Sentinel-2 and Landsat missions has motivated the development of downscaling methodologies aimed at enhancing the spatial resolution of LST products. An effective approach involves the use of regression-based algorithms that combine the high spatial detail of Sentinel-2 with the thermal information from Landsat's TIRS. Despite notable advancements, the integration of these heterogeneous datasets to produce accurate, high-resolution LST remains a methodological challenge due to differences in spectral coverage, spatial resolution, and acquisition timing.

Recent studies, including Onačillová et al. (2022), have introduced innovative downscaling techniques designed to estimate LST at a refined 10 m resolution. These methods are grounded in multilinear regression frameworks that exploit spectral correspondences between Landsat and Sentinel-2 bands, particularly through the use of multispectral indices.

Specifically, the approach uses established relationships between LST and key land cover indicators, such as the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Built-up Index (NDBI), and the Normalized Difference Water Index (NDWI). By integrating these indices, derived from Sentinel-2 imagery, with LST values obtained from Landsat 8 (L8) thermal bands, a multiple linear regression model is constructed to enhance the spatial resolution of temperature estimates (Fig. 1). The formulation of this model is expressed in Equation (1) and the methodology presented in Onačillová et al. (2022). The downscaling approach is based on fitting a linear relation using three spectral indices (NDVI, NDBI, NDWI) derived from L8, acting together as predictors with LST as the predicted variable. All input raster layers were in 30 m resolution. Then, the equation for the LST calculation from L8 imagery was derived using the output coefficients ($a_0 - a_3$) to calculate the LST_{30m}.

The LST at the 10-m resolution is estimated by applying the model in Eq. (1), where the spectral indices originally derived from Landsat 8 (L8) data are substituted with the corresponding indices obtained from Sentinel-2 (S2) imagery, which provides data at 10 m spatial resolution. The model employed is as follows:

$$LST_{10m} = a_0 + a_1 \times NDVI_{10m} + a_2 \times NDBI_{10m} + a_3 \times NDWI_{10m} + \Delta LST_{10m} \quad (1)$$

where the coefficients (a_0, a_1, a_2, a_3) are the output from the multiple linear regression model, and $NDVI_{10m}$, $NDBI_{10m}$, and $NDWI_{10m}$ are the spectral indices derived from S2 at 10 m resolution. This model is then applied by substituting the Landsat-derived indices with their Sentinel-2 equivalents to predict LST at an enhanced spatial resolution of 10 m. By capitalising on this spectral synergy, the methodology improves the spatial resolution of thermal data and also opens new opportunities to support practical applications such as road pavement condition monitoring.

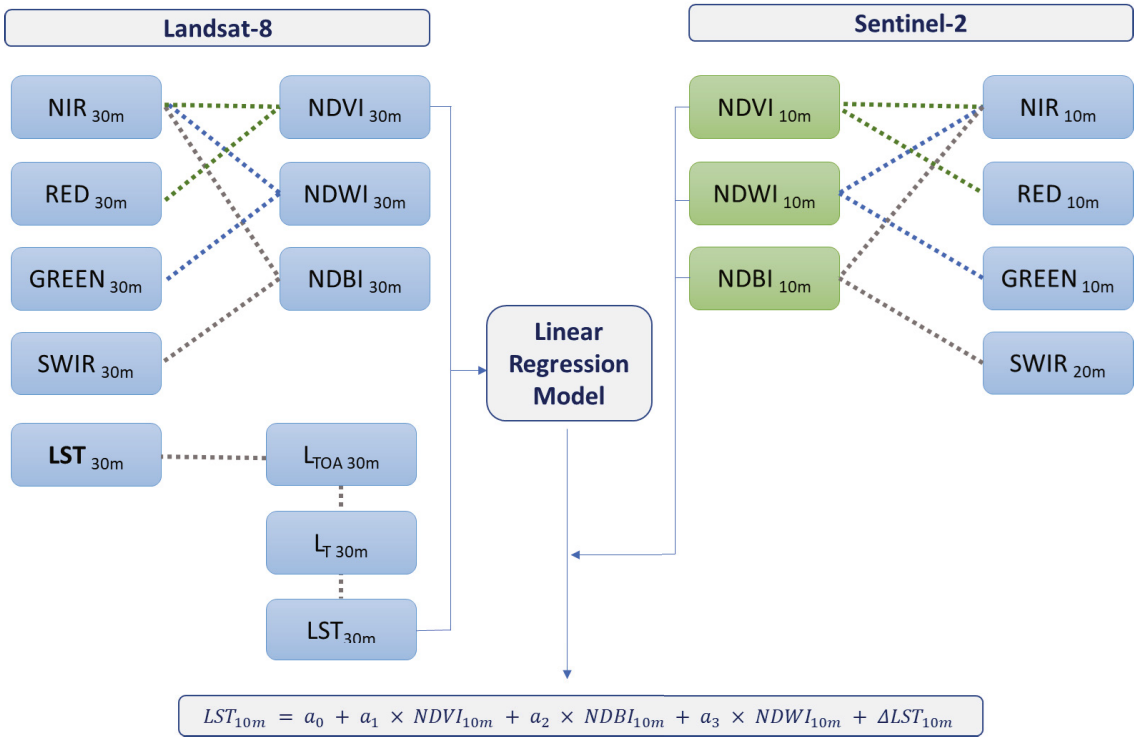


Fig. 1 Downscaling workflow for the Landsat 8 LST with Sentinel-2 spectral indices and linear regression model, modified from Onačillová et al. (2022).

4. Experimental application and results

In this study, temperature data acquired from Landsat 8 were downscaled using Sentinel-2 data, following the methodology described by Onačillová et al. (2022). The aim was to assess the capability of satellite-based approaches to detect surface changes at the urban scale, with an emphasis on road pavements. The case study focuses on a highway section near Civitanova Marche, Italy, characterised by a dense-graded asphalt concrete (DGAC) wearing course. The methodology was initially applied to a broader area encompassing both urban and vegetated zones to calibrate the relevant coefficients of the downscaling algorithm. Subsequently, the analysis was refined to concentrate on the vicinity of the A14 highway, with particular attention to the toll highway station. The temperature assessment spans a six-year period, emphasising the month of July, when temperatures are notably higher than in other months, covering consecutive years from 2018 to 2024. The coefficients in Eq. (1) (a_0=32.99, a_1=1.29, a_2=10.47, a_3=4.39), were derived from the multiple linear regression model, in which $NDVI_{10m}$, $NDBI_{10m}$, and $NDWI_{10m}$, represent spectral indices obtained from Sentinel-2 imagery at 10 m spatial resolution. The downscaling process yielded thermal values at a spatial resolution of 10 m for each pixel, aligning with the spatial resolution of the S2 spectral bands.

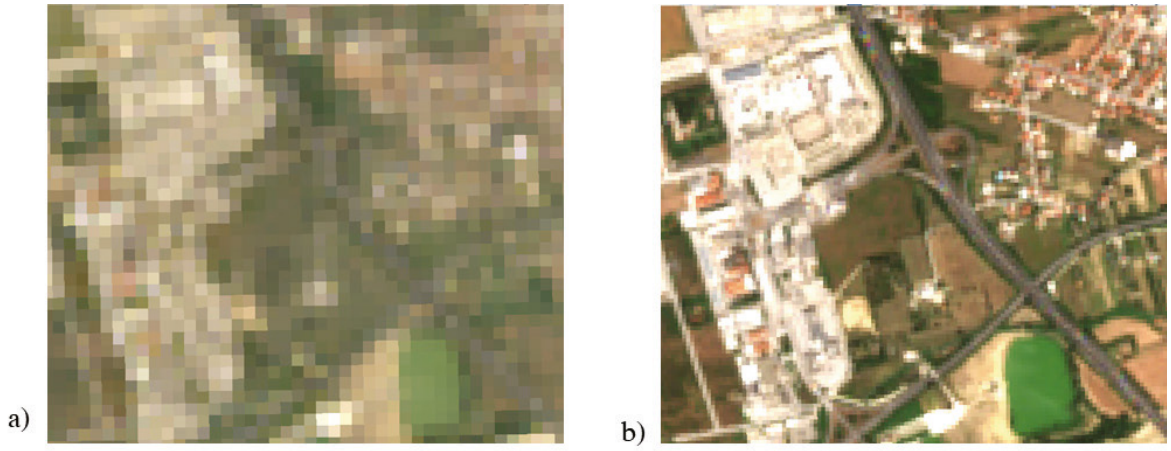


Fig. 2. Visualisation of the RGB optical imagery illustrating varying spatial resolutions: (a) Landsat (30 m), (b) Sentinel-2 (10 m), in the areas selected for applying the downscaling model.

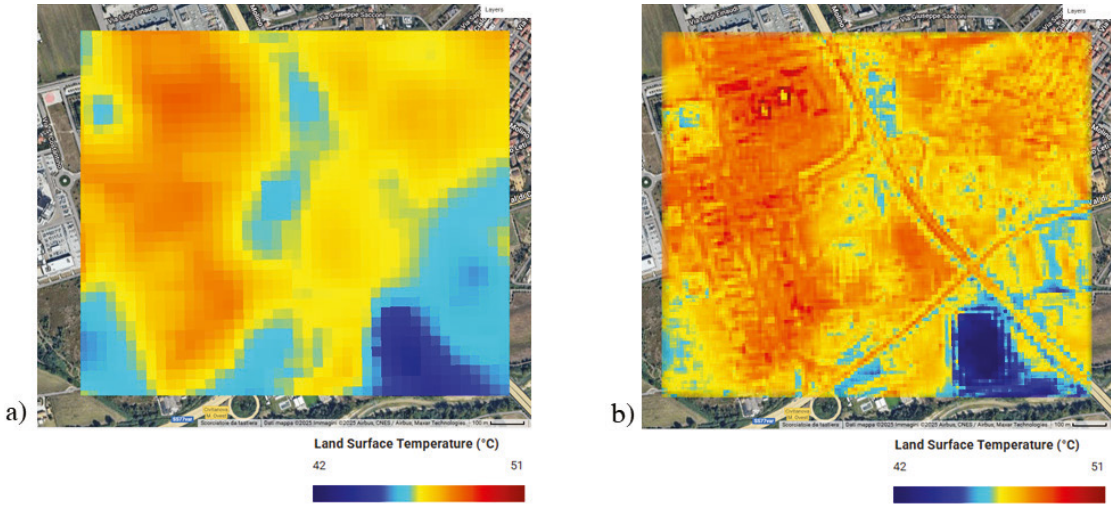


Fig 3. Land Surface Temperature (LST) analysis for July 2024: (a) original Landsat imagery at 30 m resolution, and (b) Landsat imagery after downscaling to 10 m resolution. Each pixel represents a temperature value expressed in °C. The downscaling procedure integrates Landsat thermal data with a multiple regression model informed by Sentinel-2 parameters.

In addition, Figure 3b illustrates how the 3 m temperature resolution enables the categorisation of transport infrastructures and the assignment of specific temperature values to them, clearly delineating the presence of a highway that is not discernible at lower spatial resolutions (i.e., in Fig. 3a). The second phase of the study focused on a more detailed analysis of two specific exit zones of the highway toll station. For each identified area, representative pixels and their corresponding temperature values were selected over multiple years, allowing for the assessment of thermal trends over a six-year period. The satellite dataset was preliminarily investigated, revealing a regularly repeated orbit with acquisitions around 10:00 UTC on multiple dates. July data from Sentinel-2 and Landsat, both operating in the same time window, allow for comparison between the two areas. To minimise decorrelation effects, the adopted strategy was to reduce the temporal gap between Sentinel-2 and Landsat acquisitions, selecting the Sentinel-2 L2A products, which are already corrected for the atmospheric effects. Following the approach of Onačillová et al. (2022), NDVI, NDBI, and NDWI were applied to develop the multiple regression model for temperature estimation. These indices can also be extended to asphalt surfaces, as their values correlate with physical properties and thereby contribute to the characterisation of different material typologies and their associated temperatures. Pixel-level temperature values can be compared across different dates, with variations potentially linked to material composition and surface reflectance. Figure 4 presents the historical time series of temperature data associated with the eastbound and westbound exits. Each line represents the temperature value (°C) of an individual pixel, downscaled to a spatial resolution of 10 m. The black line indicates the mean temperature value, serving as a reliable indicator of thermal behaviour while reducing the influence of noise and potential local anomalies.

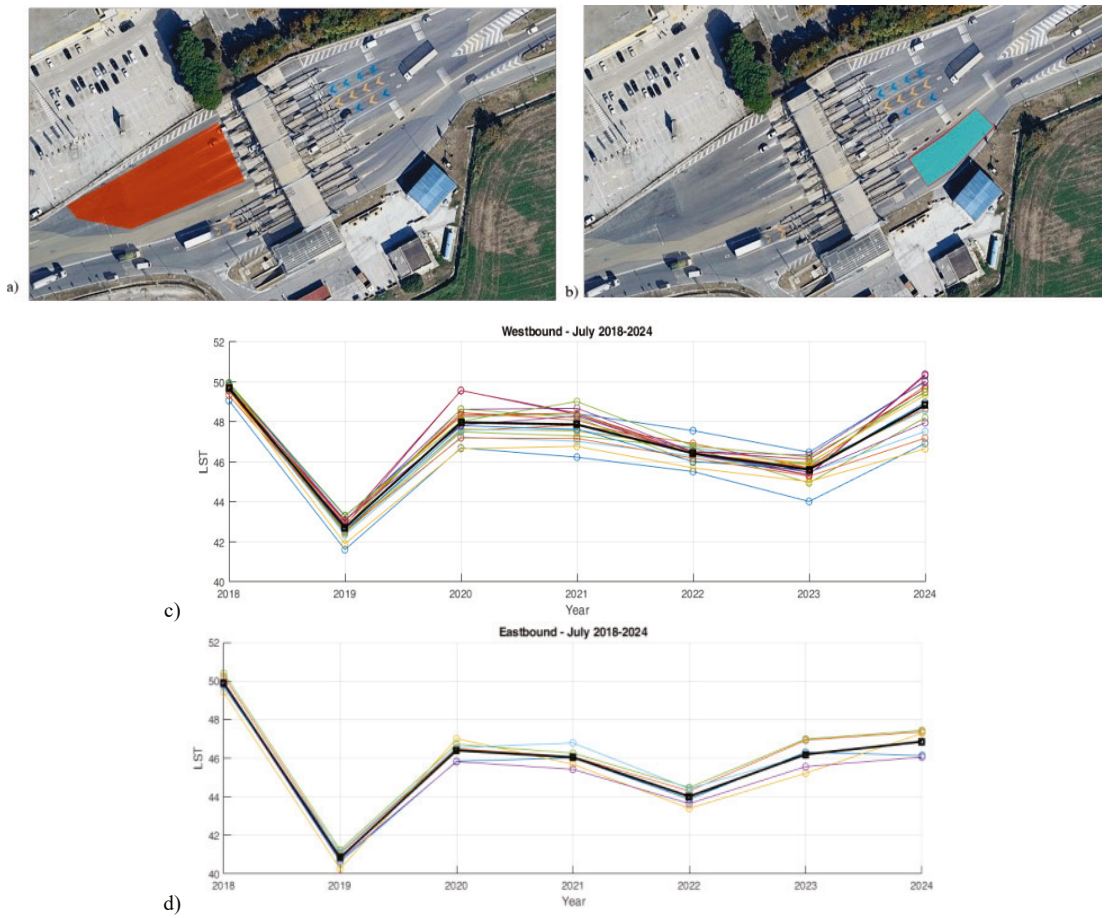


Fig. 4. Sub-area localisation: (a) westbound and (b) eastbound highway toll exits. These zones were analysed through pixel-based temperature time series (°C). Temperature time-series profiles in (c) and (d) illustrate the trends for the westbound (red) and eastbound (cyan) areas, respectively, with the black line indicating the mean value.

This pixel-level analysis reveals notable spatial variability within the study areas, highlighting subtle temperature differences that may otherwise be overlooked. Temperature values ranged from 44 °C to 50 °C in both selected areas, reflecting a consistent thermal pattern between the two zones. The persistence of consistent thermal patterns across multiple years indicates stable underlying surface properties. Furthermore, downscaling to a 10 m resolution significantly improves the ability to detect localised variations in surface temperature that correspond to specific pavement conditions or repair activities. Such enhanced spatial detail enables a more comprehensive understanding of urban heat dynamics, which is essential for more targeted and effective infrastructure management. The temporal dimension of the dataset also facilitates the monitoring of seasonal and interannual variations, thereby offering a comprehensive perspective on thermal behaviour within these critical transportation corridors. Collectively, these findings highlight the potential of satellite-based downscaling techniques to support high-resolution pavement monitoring and to inform data-driven maintenance decision-making at the urban scale.

5. Conclusions and future perspectives

At this stage of the research, no historical pavement temperature data are available for the reference period. Nevertheless, the methodology presents promising prospects for future application, calibration, and validation in conjunction with additional sensor systems, which can be employed in forthcoming studies and for broader future research. This analysis provided insights into how satellite-derived temperature data can be utilised to assess variations influencing spectral responses, thereby facilitating more effective infrastructure management and monitoring strategies. The key innovation of this approach lies in its potential to integrate satellite-based techniques with existing monitoring methods. However, it is important to acknowledge that spatial resolution remains the primary limitation for extending this approach to narrower roadways, such as single- or dual-lane carriageways, particularly within densely built urban environments. The deployment of complementary sensors is planned in future phases of the research to improve validation and enhance operational applicability.

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