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Pedestrian Heat Vulnerability and TOD Performance

In the Case of Kendall Square, Cambridge, USA

I. What is TOD

Transit-Oriented Development (TOD) has been recognized for its potential to create sustainable, mixed-use communities centered around public transit systems, thereby reducing reliance on automobiles and mitigating urban sprawl (*What Is TOD?*, 2014). A crucial element for the success of TOD is the enhancement of the multimodal transit experience, with a special emphasis on pedestrian experience.

However, the effectiveness of TOD is now facing increasing threats from climate hazards like heat waves and flooding. These environmental challenges pose significant adverse effects on various modes of transportation, especially on walking. Despite the growing impacts of climate change, many TOD frameworks still lack comprehensive integration of these environmental concerns. For instance, the TOD standards published in 2017 by The Institute for Transportation and Development Policy (ITDP) acknowledge the necessity of creating temperate and comfortable pedestrian environments. The standartds recommend improving walkability by providing shade and shelter from harsh climate conditions through features like street trees, arcades, and awnings, which offer both environmental and psychological benefits (*TOD Standards*, 2017). The ITDP also proposes a methodology for measuring the climate adequacy of walkways, assessing the proportion of walkway segments with adequate shade and shelter amenities (*TOD Standards*, 2017).

Nevertheless, these metrics are often not implemented actively within local TOD frameworks, leaving a gap in performance tracking. This paper addresses this shortfall by examining the impact of climate hazards on pedestrian experiences. It explores how climate challenges can impair the effectiveness of TOD projects, with a specific focus on pedestrian exposure to heat risks in Kendall Square, Cambridge. As for the analysis, this project introduces the Pedestrian Heat Vulnerability Index, a tool designed to systematically evaluate factors such as land surface temperature, access to tree canopy, open spaces, and benches. It will evaluate Kendall square TOD based on the index. Then it moves on to examine the financial implications of such vulnerabilities on TOD projects, highlighting the economic aspect of climate adaptability in urban development.

II. Why Kendall Square?

Building on the need to integrate climate considerations into Transit-Oriented Development (TOD) frameworks, the focus now shifts to Kendall Square in Cambrdige, Massachusetts.

Kendall Square in Cambridge, Massachusetts, has undergone a significant transformation over the last 40 years. Despite not being as centrally located within the regional transit system as downtown Boston,

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Kendall Square has evolved into a model transit-oriented development district(*Actions to Transform Mobility*, 2018). The City of Cambridge has vigorously pursued a multi-modal commuting pattern by adopting progressive parking and transportation demand policies (*Actions to Transform Mobility*, 2018) . Thanks to the efforts, despite the dramatic increases in commercial development already noted, the growth in daily traffic on central roadways with Kendall Square has remained roughly flat since 2000 (*Actions to Transform Mobility*, 2018).

However, even such a rigorous initiative like Kendall Square's TOD does not actively tackle the climate risks faced by pedestrians. This oversight may be attributable to a deficiency in the quantitative assessment of climate impact within the TOD plan, particularly with respect to pedestrian-focused aspects. The lack of such consideration potentially undermines the essential goal of TOD: enhancing walkability.

In this vein, the Pedestrian Heat Vulnerability Index (PHVI) could be useful for projects in Kendall Square. By incorporating the PHVI, such developments can better allocate attention and resources towards improving pedestrian walking conditions. This approach aligns closely with the core principle of TOD to foster walkability. Moreover, a in-depth understanding and documentation of pedestrian heat vulnerability are crucial for accurately projecting the return on investment in TOD projects. This aspect is particularly significant, as the financial viability of these projects can be severely impacted by climate hazards. Therefore, the application of PHVI in Kendall Square serves as an essential step in ensuring that TOD projects achieve their development goals and remain resilient and financially sound in the face of escalating climate challenges.

Kendall Square, 1995

Kendall Square, 2023


III. Developing the Pedestrian Heat Vulnerability Index

As a way to quantify pedestrians' exposure to heat hazards, the Pedestrian Heat Vulnerability Index (PHVI) was developed in this project. It encompasses four elements: land surface temperature, tree canopy, access to open areas (like parks and plazas), and benches. These elements are equally weighted to calculate an aggregate PHVI value. The selection of these components is grounded in their direct impact on pedestrian comfort and safety during hot conditions.

First, Land Surface Temperature (LST) is a key indicator of the heat intensity in an urban area. High surface temperatures can significantly impact pedestrian comfort and health, making it a critical factor in assessing heat vulnerability. Secondly, trees play a vital role in mitigating urban heat through shading and evapotranspiration. Areas with dense tree coverage offer cooler environments, reducing the heat stress on pedestrians. ITDP also acknowledges the importance of street trees in providing shade and shelter to pedestrians (*TOD Standards*, 2017). Finally, open spaces like parks and plazas and benches can offer respite from urban heat. The open spaces often have lower temperatures compared to built-up areas and can serve as cooling zones for pedestrians. And benches and seating areas provide necessary rest spots, especially for vulnerable populations like the elderly or those with health issues.

A. Index Construction

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1. Data Sources

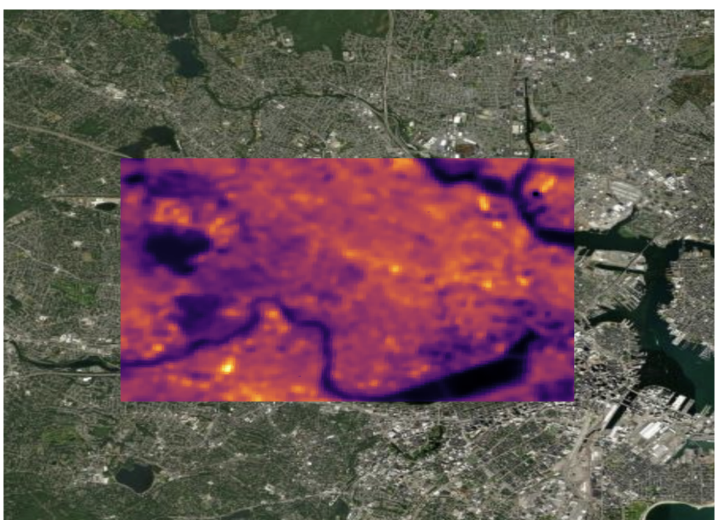
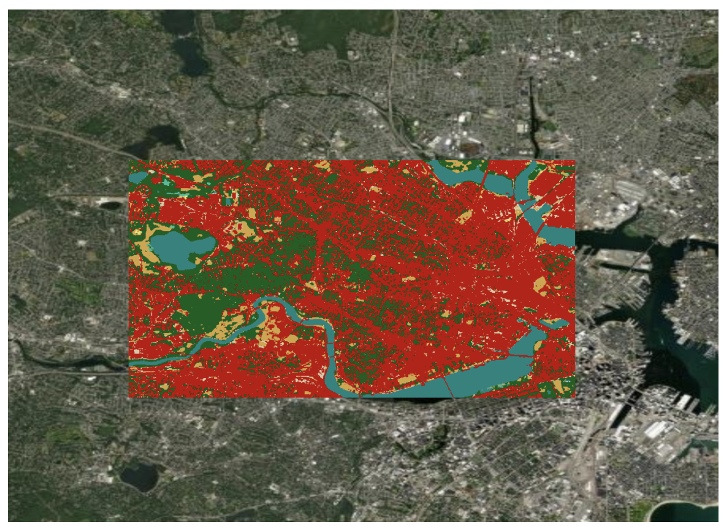
The data source for each element is as follows:

For land surface temperature, the multispectral landsat data from ESRI Living Atlas was used(*Multispectral Landsat - Overview*, n.d.). This Landsat imagery is a collaboration between the U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA), and is streamlined by ESRI for easier access and visualization.

For the tree coverage, the European Space Agency WorldCover 2020 Land Cover from ArcGIS LivingAtlas (*European Space Agency WorldCover 2020 Land Cover - Overview*, n.d.). WorldCover 2020 offers a global land cover map at a 10 m resolution, utilizing Sentinel-1 and 2 data. It includes 11 different land cover classes, with the focus for this study on "10 Tree Cover".

As for the open area and bench access, location data in polygon and point format was retrieved from Cambridge Data github page(*Cambridgegis/Cambridgegis_data*, n.d.).

These components are represented in various formats (Raster for LST and Tree Cover; Vector for Open Space and Benches) and are visualized for the City of Cambridge:

Land Surface Temperature (LST)	Land Cover
 Format: Raster	 Format: Raster
Open Space	Bench

 Format: Vector	 Format: Vector

2. H3 Hexagon Tiles

The data is aggregated into H3 hexagon tiles at resolution 11, a total of 8,648 tiles for Cambridge. This method is chosen over traditional administrative boundaries like zip codes or census tracts for its uniformity in size and shape, allowing for a more consistent and unbiased spatial analysis.

H3 hexagon tiles
 H3 hexagon tiles at resolution 11 Total of 8,648 tiles were generated to cover the extent of the City of Cambridge.

Zoomed-in H3 hexagon tiles

B. Index Construction

The PHVI formula is as follows:

$$PHVI = (W\ temp \times Temp) + (W\ tree \times Tree) + (W\ open \times Open) + (W\ bench \times Bench)$$

Where:

- *Temp* is the standardized temperature value.
- *Tree* is the standardized tree cover deficit value.
- *Open* is the inverted standardized value of open space access.
- *Bench* is the inverted standardized value of bench access.
- $W\ temp$, $W\ tree$, $W\ open$, $W\ bench$ are the respective weights of these standardized values.

1. Feature Calculation

- For *Temp*, the maximum average land surface temperature (LST) within each hexagon tile was calculated using Band 10 Surface Temperature in Celsius . This involves aggregating the LST data from the Landsat imagery for all pixels within each hexagon.

Histogram: Max Average LST Aggregated to Hexagon Tiles	Plot: Max Average LST Aggregated to Hexagon Tiles

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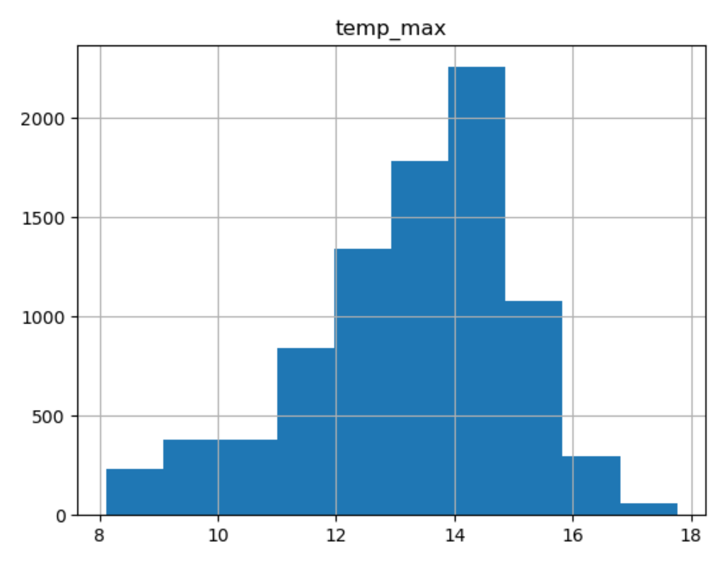
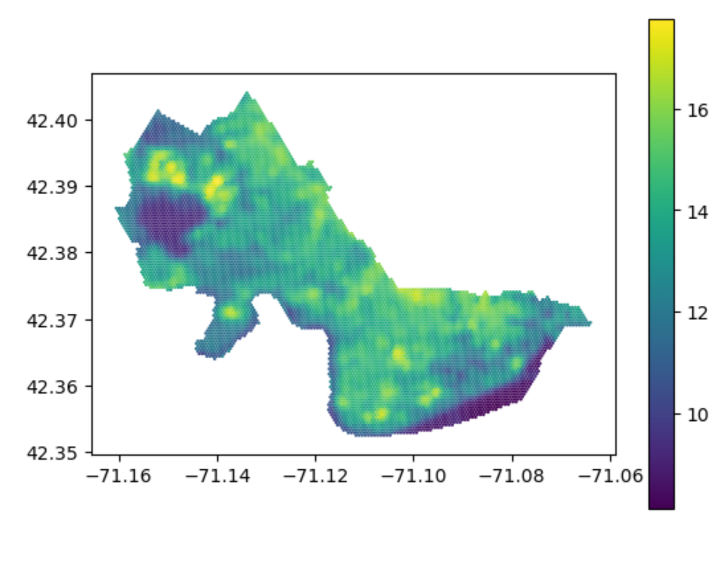
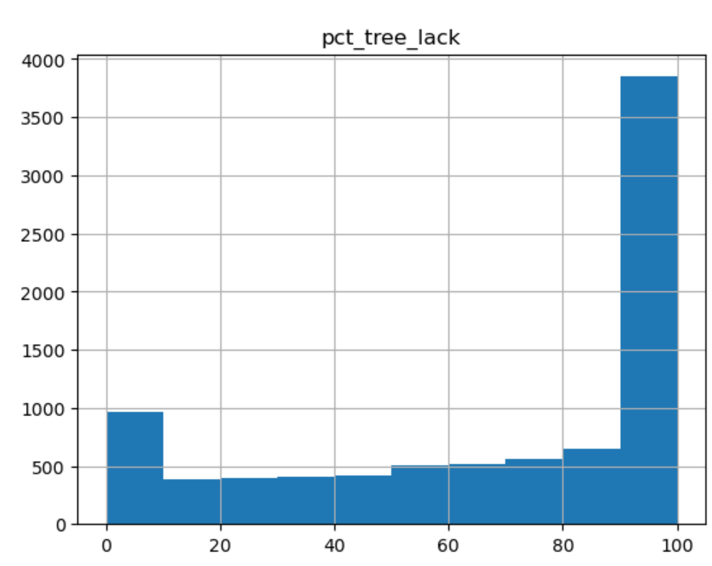
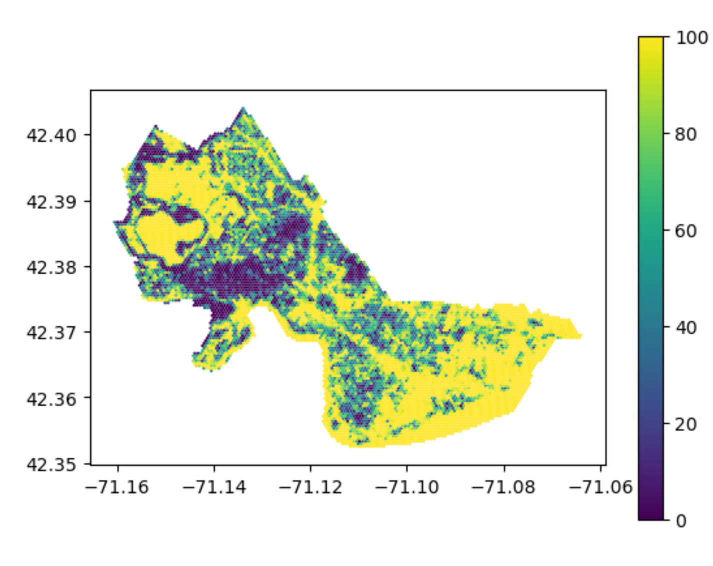


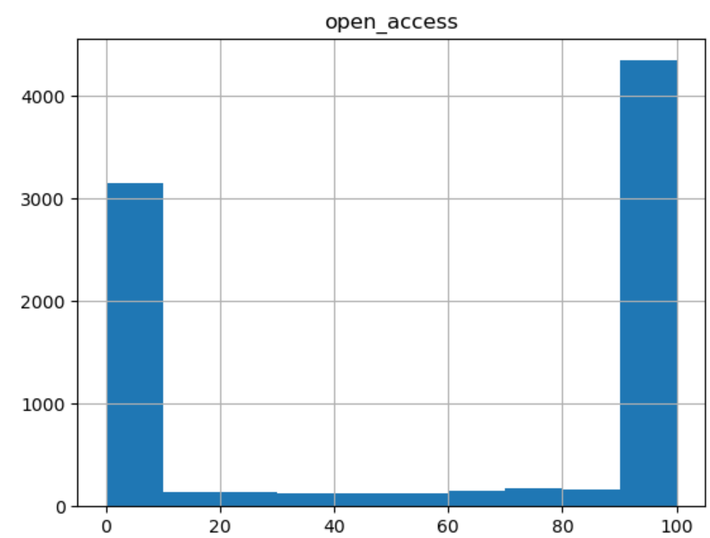
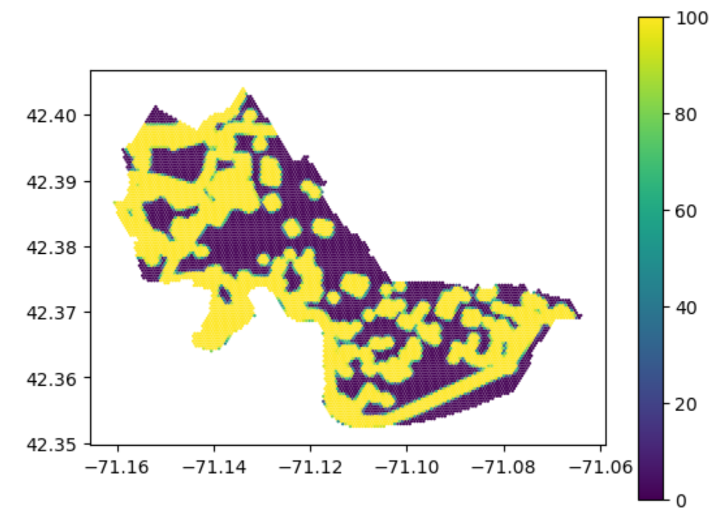
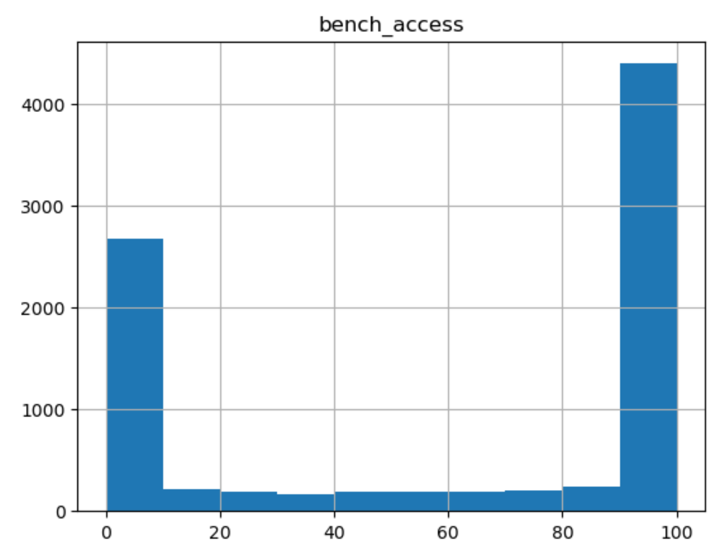
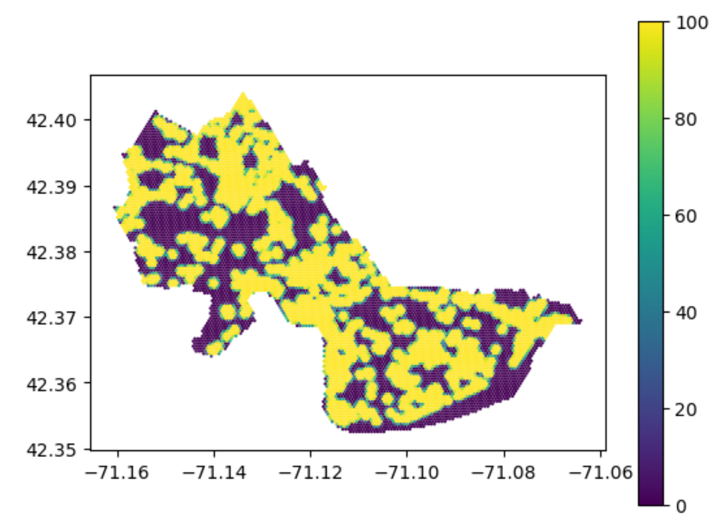


- For *Tree*, pixels within each hexagon tile classified as 'Tree Cover' were counted to determine the total tree presence. The percentage of the tile covered by trees was then calculated by dividing the tree pixel count by the total number of pixels in the tile. Finally the value was subtracted from 100 to obtain the tree cover deficit value. The calculated tree cover deficit is considered additive to the PHVI, meaning that a higher tree cover deficit score, indicating less tree coverage, contributes to a higher vulnerability score in the index.

Histogram: Percentage of Tree Deficit	Plot: Percentage of Tree Deficit
	

- For *Open* and *Bench,* a 100-meter buffer was created around all open space polygons and bench locations. The overlapping area between these buffers and each hexagon tile was calculated. The percentage of each tile covered by these buffers was then inverted to reflect inaccessibility.

Therefore, Open and Bench are additive to PHVI.e inaccessibility to such facilities. Therefore, *Open* and *Bench* are additive to PHVI.

Histogram: Open Space Access	Plot: Open Space Access
	
Histogram: Bench Access	**Plot: Bench Access**
	

2. Feature Standardization

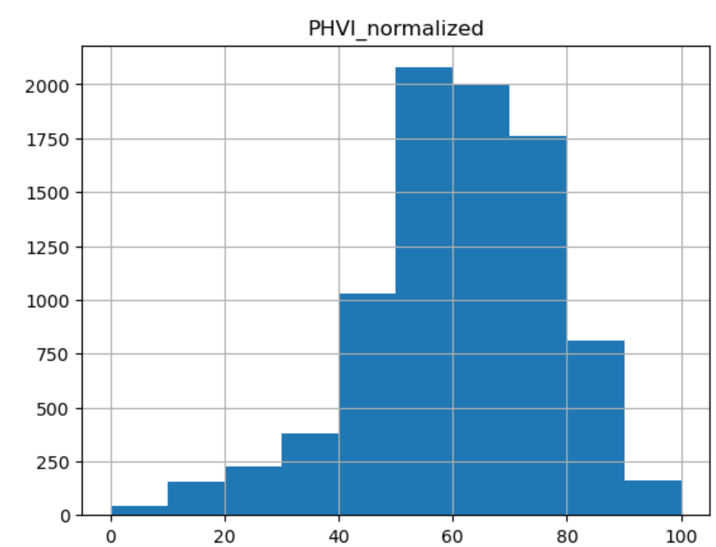
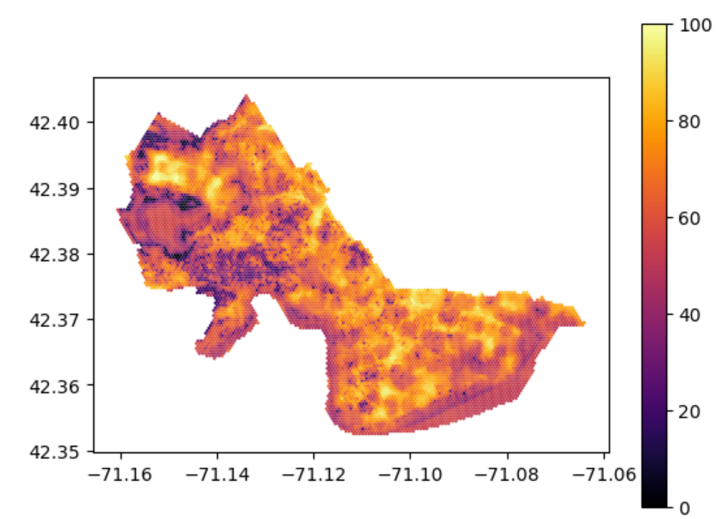
Each component was then standardized to ensure comparability and uniformity in measurement scales. The standardization method for each feature was chosen based on its distribution characteristics, as observed in the histograms. Generally speaking, the goal of standardization is to scale the features to a common range without distorting differences in the ranges of values or losing information.

Looking at the histograms provided:

- *temp_max*: The histogram indicated a normal distribution. Given this distribution, z-score standardization was deemed appropriate. This method involves subtracting the mean value from each data point and dividing the result by the standard deviation, effectively normalizing the data around a mean of zero and a standard deviation of one.
- *pct_tree_lack*: This feature displayed a heavy leftward skew in its distribution. To address this skewness, a logarithmic transformation was first applied to normalize the distribution. Following this, min-max scaling was used to bring the transformed data onto a 0 to 100 scale.
- *open_access and bench_access*: Both features showed a binary-like distribution, with variations being percentages. Min-max scaling was the chosen method for these variables. This technique adjusts the values so that they fall within a 0 to 100

3. Weight Average

The standardized features were equally weight averaged to obtain the final value PHVI. Original PHVI was in the range of [-1.281673, 1.157608]. Thus, it was adjusted to 0 to 100 range using min-max scaling. The final distribution is as follows:

Histogram: Normalized PHVI Values	Plot: Normalized PHVI Values
	

C. Analysis

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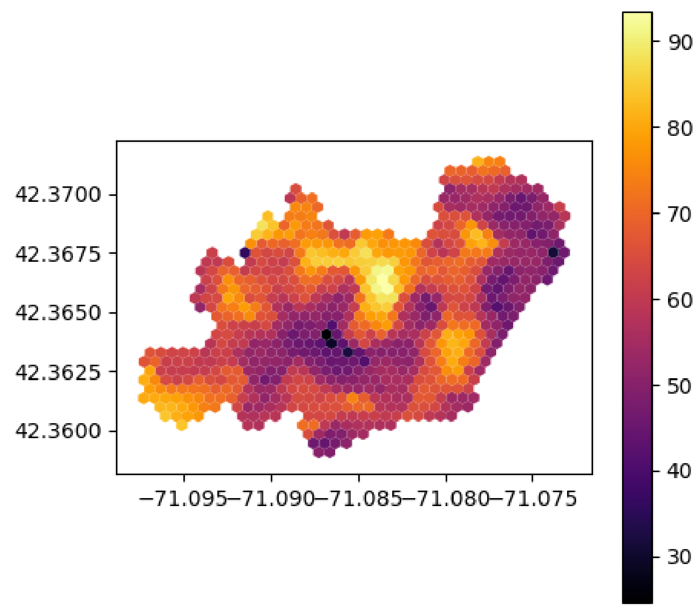
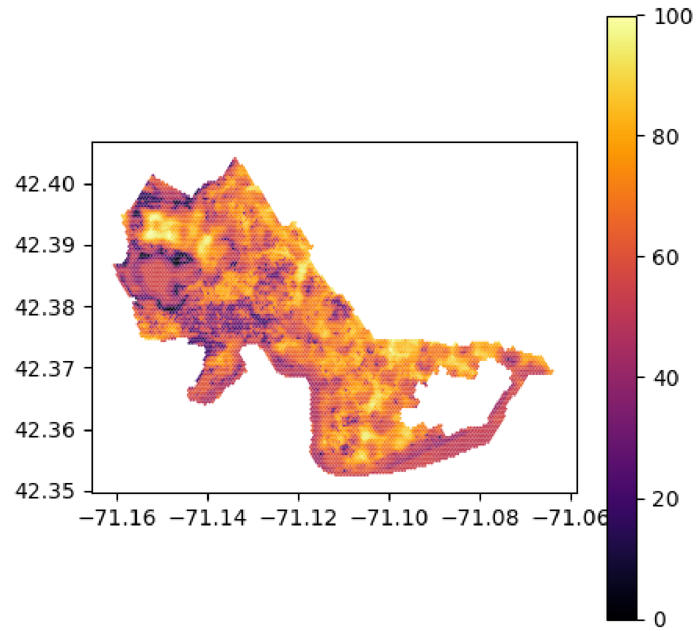
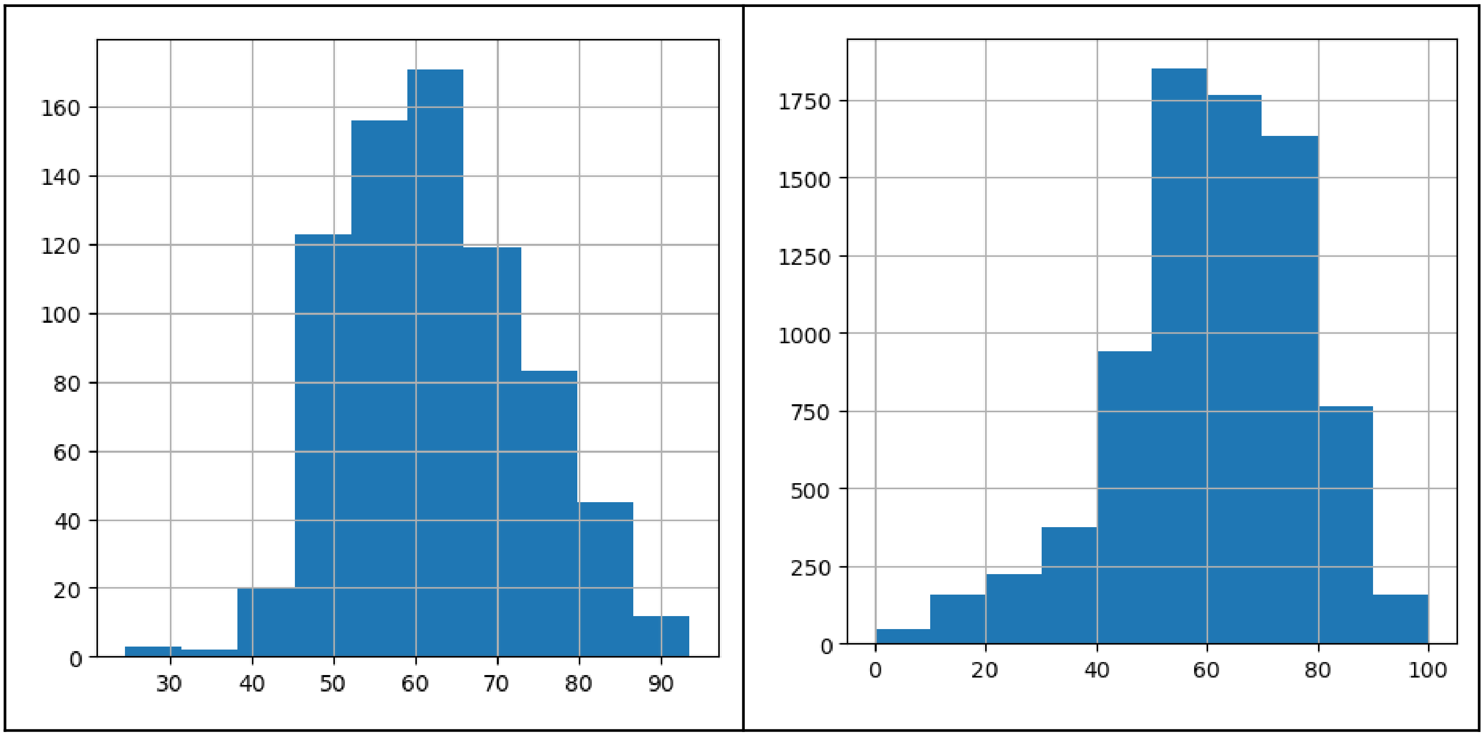
The PHVI provides an insight into the heat vulnerability of Kendall Square, particularly in relation to the rest of Cambridge. Kendall Square's mean PHVI is calculated at 62.41, which is marginally higher than the Cambridge average of 60.91. However, the difference is solely raised by the lack of vegetation, particularly tree canopy. The area's mean value for standardized tree cover deficit stands at 0.52, in contrast to -0.048 for the rest of Cambridge (total range is [-3.126627, 0.617083]). This highlights an area where Kendall Square lags behind – the provision of natural shade and cooling through tree coverage. In terms of land surface temperature (LST), open space access, and bench access, Kendall Square performs slightly better than the broader Cambridge area. However, again, these positive aspects are overshadowed by the deficit in tree canopy.

PHVI in Kendall Square	PHVI in Cambridge Except for Kendall Square
	
Distribution of PHVI Values of Kendall Square	Distribution of PHVI Values of Cambridge Except for Kendall Square



V. Discussion

The higher PHVI in Kendall Square, driven largely by inadequate tree coverage, suggests a reduced level of pedestrian comfort and safety, particularly during hotter periods. This could deter pedestrian activity, undermining one of the key objectives of TOD – promoting walkability. The impact does not stop there. The heat vulnerability could discourage the use of non-motorized transportation modes like walking and cycling altogether and public transit to some extent (since taking public transit may involve walking during first/last miles and transfer), which are integral to TOD's sustainable mobility ethos. he increased heat vulnerability could also have financial implications for TOD projects.

Moreover, reduced pedestrian comfort may lead to lower footfall in commercial areas, potentially affecting local businesses. Additionally, the need for increased cooling and shade provisions might require additional investments. If these possible consequences are not considered beforehand, the inadequate funding allocation will surely harm the performance of TOD projects and diminish rhe long-term return on investment.

VI. Limitation

While the research presented provides valuable insights into pedestrian heat vulnerability, particularly in the context of Transit-Oriented Development (TOD), it is important to acknowledge limitations and areas for potential enhancement.

First, the PHVI could be improved significantly by incorporating additional factors. Including data on the thermal capacity of building materials could offer a more nuanced understanding of how urban infrastructure contributes to ambient heat. Also, beyond tree canopies, the shades offered by buildings and other structures could be incorporated. Furthermore, the dimensions of pedestrian pathways influence wind flow and circulation, which in turn affects thermal comfort. Analyzing the width of sidewalks and alleys could refine the PHVI. Finally, different land uses, such as office or commercial spaces, have varying impacts on heat vulnerability. They may contribute to higher pedestrian density and traffic, thus increasing local heat levels. Including land use as a predictor in the PHVI could enhance its descriptive power of heat vulnerability.

Another area of improvement in this study is the link between PHVI and financial metrics. Although this part was one of the major goals of this research, not enough attention was given to it. I suggest cost-benefir analysis in future research. Meaning, understanding the financial implications of different urban planning interventions to lower PHVI scores. This could involve comparing the costs of various cooling and shading solutions against their potential benefits in terms of increased pedestrian comfort and safety.

VIII. References

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