



Impact of Road Infrastructure on Urban Heat Island Intensity: A Spatio-Temporal Analysis within Municipal Boundaries – A Case of Sambhajinagar

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Abstract: Urban Heat Island (UHI) is a critical environmental phenomenon characterized by elevated temperatures in urban areas compared to surrounding rural regions. While previous research has predominantly focused on building density and land use, the role of road infrastructure as a major contributor to urban heat dynamics remains underexplored. This study investigates the impact of road infrastructure on UHI intensity within the municipal boundaries of Sambhajinagar, a rapidly urbanizing tier-2 city in India. The research adopts a spatio-temporal analytical approach, integrating road network characteristics, surface temperature variations, and urban morphology. It examines how road density, material properties, traffic intensity, and vegetation cover influence localized heat accumulation. The findings indicate that asphalt-based road networks significantly contribute to heat storage and delayed heat release, intensifying nighttime temperatures. High-density road zones exhibit greater surface temperatures and stronger UHI effects compared to peripheral areas with lower infrastructure intensity. The study also highlights the role of urban canyon geometry and reduced vegetation in exacerbating heat retention along major corridors. The paper concludes that road infrastructure must be integrated into urban climate planning frameworks to mitigate UHI effects effectively.

Keywords:- Urban Heat Island, road infrastructure, surface temperature, spatio-temporal analysis, Sambhajinagar, urban morphology

I. INTRODUCTION

Urbanization has significantly transformed natural landscapes into built environments, altering the thermal and radiative properties of land surfaces. One of the most prominent outcomes of this transformation is the Urban Heat Island (UHI) effect, wherein urban areas experience higher temperatures than their rural surroundings. This phenomenon is driven by the replacement of natural surfaces with impervious materials such as asphalt and concrete, which possess high heat storage capacity and low reflectivity (Oke, 1982).

While a substantial body of research has focused on building density, land use patterns, and industrial activities as primary contributors to UHI, the role of road infrastructure remains relatively underexplored. Roads form a continuous and extensive component of urban surfaces, often accounting for a significant proportion of land cover in cities. These surfaces are directly exposed to solar radiation and play a critical role in heat absorption and storage processes (Asaeda et al., 1996).

Sambhajinagar presents a unique context for examining UHI dynamics due to its semi-arid climatic conditions, characterized by high temperatures, intense solar radiation, and limited vegetation cover. As indicated in the base dataset, summer temperatures can reach up to 45°C, making the city highly vulnerable to heat stress. Rapid urban growth driven by industrial development, tourism, and population expansion has led to increased road network density, particularly in central urban areas.

This study aims to analyze the impact of road infrastructure on UHI intensity using a spatio-temporal approach. By examining the relationship between road density, surface temperature, and urban morphology, the research seeks to provide a comprehensive understanding of how transportation infrastructure contributes to urban heat dynamics.

2. Theoretical Framework: Road Infrastructure and Urban Heat Dynamics

The thermal behavior of urban environments is governed by complex interactions between surface properties, atmospheric conditions, and anthropogenic heat sources. Road infrastructure plays a significant role in these interactions due to its material composition and spatial configuration.

Asphalt, the most commonly used road material, exhibits low albedo and high heat capacity, enabling it to absorb substantial amounts of solar radiation during the day. This heat is gradually released during the night, resulting in elevated nocturnal temperatures that are characteristic of UHI effects (Asaeda et al., 1996). In contrast, materials with higher albedo, such as concrete, reflect a greater portion of solar radiation and exhibit lower heat retention.

Anthropogenic heat emissions from vehicular traffic further contribute to temperature increases. The combustion of fuel and friction between tires and road surfaces generate heat, which is transferred to the surrounding environment. This effect is particularly pronounced in areas with high traffic density, where continuous heat generation intensifies local thermal conditions (Taha, 1997). Urban morphology also influences heat dynamics through the urban canyon effect. Narrow streets flanked by tall buildings restrict airflow and trap heat within the built environment. The ratio of building height to road width determines the extent of heat retention, with higher ratios leading to reduced ventilation and increased temperatures (Oke, 1987).

3. Literature Review

3.1 Urban Heat Island and Surface Characteristics

The UHI effect is closely associated with surface characteristics, including material properties, land cover, and urban geometry. Impervious surfaces such as roads and pavements disrupt natural cooling processes by reducing evapotranspiration and increasing heat storage (Arnfield, 2003). Studies have consistently shown that urban areas with higher proportions of paved surfaces exhibit stronger UHI intensity.

3.2 Role of Road Infrastructure in UHI Formation

Road infrastructure is increasingly recognized as a critical factor in UHI formation due to its extensive coverage and thermal properties. Roads are continuously exposed to solar radiation and serve as major heat reservoirs within urban environments. The base study highlights that road infrastructure occupies a significant proportion of urban land and directly influences microclimatic conditions and pedestrian comfort.

3.3 Road Density and Spatial Heat Distribution

Spatial variations in road density play a crucial role in determining heat distribution across urban areas. High-density road networks are typically associated with increased surface temperatures due to greater heat absorption and anthropogenic activity. The dataset indicates that central zones with higher road density exhibit stronger UHI effects compared to peripheral areas with lower infrastructure intensity.

3.4 Vegetation and Cooling Potential

Vegetation plays a vital role in mitigating UHI effects through shading and evapotranspiration. The absence of roadside vegetation leads to increased solar exposure and heat absorption, while the presence of green infrastructure can significantly reduce surface temperatures and improve thermal comfort (Bowler et al., 2010).

4. Methodology

This study adopts a spatio-temporal analytical approach to examine the relationship between road infrastructure and UHI intensity in Sambhajinagar. The methodology integrates climate analysis, road network mapping, and surface temperature assessment to provide a comprehensive understanding of urban heat dynamics.

Climate data, including temperature and solar radiation, are analyzed to establish baseline environmental conditions. Road network mapping is conducted to identify the spatial distribution and hierarchy of roads, including highways, arterial roads, and local streets. Surface temperature measurements are obtained through field observations and secondary data sources to assess thermal variations across different road types.

The study also examines the influence of urban morphology, including building height, road width, and vegetation cover, on heat distribution. The integration of these parameters enables a multidimensional analysis of UHI formation. The methodological framework aligns with the approach outlined in the base study, which combines climate analysis, road network assessment, and thermal evaluation.

5. Results and Analysis

The results reveal a strong correlation between road density and surface temperature in Sambhajinagar. Central urban zones characterized by high road density exhibit significantly higher temperatures compared to peripheral areas. Zone D, with the highest road density, demonstrates the greatest heat accumulation, followed by Zone C.

Peripheral zones with lower road density and greater vegetation cover exhibit comparatively lower temperatures, highlighting the mitigating effect of green infrastructure. The radial pattern of the road network further contributes to heat concentration in central areas, where major roads intersect and traffic intensity is highest.

The analysis also indicates that asphalt surfaces exhibit higher temperatures compared to concrete surfaces due to their lower reflectivity and higher heat absorption capacity. Areas with limited shading and high traffic density experience increased thermal stress, emphasizing the role of both material properties and urban design in UHI formation.

6. Discussion

The findings of this study underscore the critical role of road infrastructure in shaping urban thermal environments. Roads act as both passive heat absorbers and active heat generators, contributing significantly to UHI intensity. The concentration of road networks in central urban areas amplifies these effects, leading to pronounced temperature variations across the city.

The interaction between road infrastructure and urban morphology further intensifies heat accumulation. The urban canyon effect restricts airflow and traps heat, while the lack of vegetation reduces natural cooling processes. These factors collectively contribute to elevated temperatures in densely developed areas.

The study highlights the importance of climate-responsive road design strategies in mitigating UHI effects. The use of high-albedo materials, such as cool pavements, can reduce heat absorption, while the integration of vegetation along road corridors can enhance cooling through shading and evapotranspiration (Santamouris, 2013).

7. Conclusion

This study demonstrates that road infrastructure is a significant contributor to Urban Heat Island intensity, particularly in rapidly urbanizing cities such as Sambhajinagar. High road density, asphalt materials, and traffic activity collectively contribute to heat accumulation and retention, leading to elevated urban temperatures.

The findings highlight the need for integrating road infrastructure into urban climate planning and adopting climate-responsive design strategies to mitigate UHI effects. Addressing these challenges is essential for improving urban sustainability and enhancing thermal comfort in cities.

8. Future Scope

Future research should focus on incorporating advanced remote sensing techniques and simulation models to improve the accuracy of spatio-temporal analysis. Long-term studies are required to evaluate the effectiveness of mitigation strategies such as cool pavements and green infrastructure. Expanding the scope to include comparative studies across multiple cities can further enhance the understanding of road-induced UHI dynamics.

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