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A Review of the Geometric Configuration of Urban Arterials and Its Role in Heat Island Intensification: A Thermal Flux Modelling Approach

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ABSTRACT: Urban heat island (UHI) intensification is still one of the most critical environmental issues induced by rapid urbanization and climate change. Urban arterial systems (boulevards, grid networks, radial corridors, multilane transportation canyons) can have a large impact on the modification of the urban thermal balance via changes in the surface energy exchange, anthropogenic heat release, flow obstruction and thermal storage. This review summarizes recent research on the geometric configuration of urban arterials and their contribution to UHI amplification using thermal flux modelling approaches published between 2020 and 2026. The paper investigates the effect of street orientation, canyon aspect ratio, sky-view factor, pavement materials, vegetation distribution and aerodynamic roughness on urban thermal regimes. Focus is on computational fluid dynamics (CFD), ENVI-met, mesoscale weather models, remote sensing techniques and machine-learning-assisted thermal simulations. The review summarizes the major mechanisms by which arterial geometry enhances thermal accumulation, including radiative trapping, suppression of turbulent heat exchange and retention of nighttime heat. Results show that compact canyon geometries, low albedo paving systems and poor ventilation corridors greatly enhance sensible heat flux and thermal discomfort. On the contrary, optimized geometries incorporating green infrastructure, reflective surfaces, permeable materials, and ventilation corridors reduce thermal load dramatically. The paper concludes with recommendations for future integrated urban thermal governance and resilient street design.

KEYWORDS: Urban heat island, urban arterials, street canyon geometry, thermal flux modelling, CFD, ENVI-met, urban morphology, thermal comfort.

1. INTRODUCTION

The urban heat island (UHI) effect refers to the elevated temperatures in urban areas relative to the surrounding rural landscape as a result of changes in the land cover, anthropogenic heat emissions and urban morphology (Santamouris, 2020). The rapid growth of cities has increased their susceptibility to heat. Transportation corridors and arterial road networks have been recognized as important contributors to heat accumulation and changes in urban microclimates (Chen et al., 2022). Urban arterials are geometrically arranged transportation systems with large surfaces of asphalt, high vehicular activity, canyon-like structures and limited capacities of evapotranspiration. Recent studies have demonstrated that geometrical characteristics of arterial systems are of great importance for thermal fluxes via radiation trapping, turbulence modulation and airflow confinement (Xue et al., 2023). The width-to-height ratios of streets, their orientation to prevailing winds, and the properties of the materials of their surfaces all together determine the dynamics of heat exchange in urban canopies (Middel et al., 2021). Therefore, knowledge of the arterial geometry is crucial for designing climate-resilient cities. Thermal flux modelling has become an important tool in the investigation of UHI dynamics at the neighborhood and corridor scales. Numerical methods, such as CFD, ENVI-met, WRF-UCM and large eddy simulation (LES), allow detailed analysis of heat transfer processes in complex urban geometries (Allegrini et al., 2020). These models, along with remote sensing and field observations, provide useful insight into the thermal implications of urban design choices.

This review critically examines contemporary literature concerning geometric configurations of urban arterials and their role in heat island intensification using thermal flux modelling approaches. The study aims to:

1. Review contemporary modelling techniques used for arterial thermal analysis.
2. Examine relationships between urban arterial geometry and thermal flux dynamics.
3. Evaluate the impacts of materials, vegetation, and morphology on UHI intensity.
4. Identify mitigation strategies for thermally resilient transportation corridors.
5. Outline future research directions in urban thermal governance.

2. URBAN ARTERIALS AND URBAN HEAT ISLAND DYNAMICS

Urban arterial systems are among the most thermally influential components of the built environment, owing to their large amount of impervious coverage, localized anthropogenic activity, and direct interaction with processes of energy exchange with the atmosphere. With growing urbanization around the world, transportation corridors are increasingly acting as linear thermal reservoirs changing the local and regional climate by altered radiation balance, heat storage, turbulent exchange and airflow obstruction. In current urban climate studies, arterial networks are recognized as a critical spatial structure controlling the development and transmission of urban heat island (UHI), linking commercial, industrial, and residential districts with high population density via the network of heat-emitting continuous surfaces (Santamouris, 2020; Li et al., 2020). The scale, geometry, traffic density and material make up of urban arterials are not like that of ordinary streets. These corridors generally have high surface temperatures because of large areas of asphalt pavement, medians made of concrete, little vegetation, and high vehicular emissions. Their thermal significance is increased in metropolitan areas with narrow urban canyons and dense building arrangements that hinder atmospheric ventilation and intensify heat retention (Nazarian et al., 2020). Therefore, the architecture of arterial systems impacts urban mobility and micro- and mesoscale climate interactions related to thermal comfort, energy consumption, and public health.

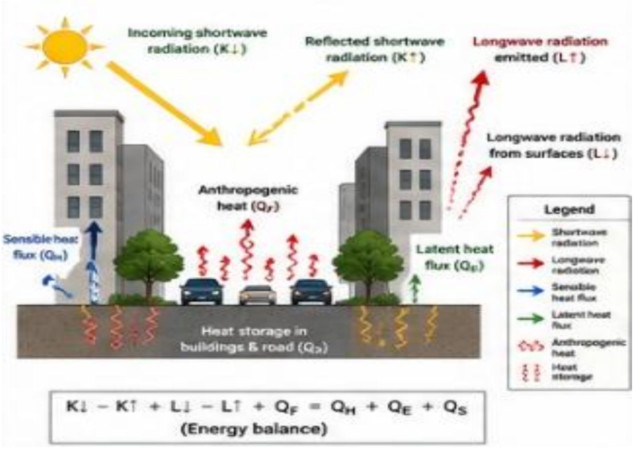

Figure 1. Urban Surface Energy Balance Diagram.

The thermal behavior of urban arterials is primarily controlled by the surface energy balance equation including incoming shortwave radiation, outgoing longwave radiation, sensible heat flux, latent heat flux, and anthropogenic heat release. Changes in street morphology directly modify these elements by influencing solar access, radiative trapping, wind penetration and evaporative cooling potential (Oke et al., 2021. Therefore the geometry of the arteries has become an important parameter in the modelling of urban thermal flux and in climate-sensitive urban planning, as shown in Figure 1.

2.1 Urban Morphology and Thermal Fluxes

Urban morphology has a considerable influence on the thermal performance of cities through modifying energy balance, airflow structure, radiation exchange and surface-atmosphere interactions (Salamanca et al., 2020). The heat absorption, storage and release of urban surfaces over diurnal and seasonal cycles are controlled by morphological characteristics. In dense metropolitan environments, the urban fabric is characterized by impervious materials (Table 1) that create thermally active surfaces with high solar absorptivity and low evapotranspiration capacity.

Table 1. Geometric Variables Affecting UHI

Variable	Thermal Effect	Positive Impact	Negative Impact
H/W Ratio	Radiation trapping	Shading	Reduced ventilation
SVF	Radiative cooling	Night cooling	Solar exposure
Orientation	Solar exposure	Wind access	Heat accumulation

The thermal behavior of arterial systems depends on several interconnected geometric and environmental variables, including:

- Street canyon aspect ratio (H/W)
- Sky-view factor (SVF)
- Building orientation
- Surface roughness
- Road width and pavement composition
- Tree canopy distribution
- Ventilation pathways
- Building density
- Urban compactness
- Surface albedo

- Vegetation coverage ratio

These variables collectively regulate the exchange of momentum, heat, and moisture between urban surfaces and the atmosphere. Morphological complexity influences both the magnitude and temporal evolution of sensible and latent heat fluxes, thereby controlling the intensity of urban heat accumulation.

High aspect ratio compact urban canyons tend to trap outgoing longwave radiation, suppress turbulent ventilation and reduce nocturnal cooling efficiency (Morakinyo et al., 2020). Deep canyons also induce multiple radiative reflections between building facades and pavements, greatly increasing heat storage within the layer of urban canopy. The process is especially severe in highly urbanized districts with dense high-rise developments where sky exposure is limited. On the other hand, broad boulevards and open arterial systems could enhance convective ventilation and promote heat loss by increasing airflow exchange. However, increased openness may also lead to exposure of surfaces to prolonged solar radiation during daytime periods, resulting in elevated surface temperatures and increased pedestrian heat stress (Taleghani, 2021). Thus, the thermal performance of arterial geometry is highly climate-dependent, with differences depending on latitude, solar angle, wind regime, and regional humidity conditions. Building facades, roadside barriers, signage systems and elevated transportation infrastructure are examples of urban roughness elements that further influence atmospheric turbulence and boundary-layer development. Increased roughness may enhance vertical heat exchange through turbulence generation or impede airflow depending on spatial arrangement and wind direction (Nadeau et al., 2020). Thus, urban morphology acts as a multidimensional thermal regulator controlling the spatial heterogeneity of UHI intensity.

Recent studies on thermal flux emphasize the importance of considering urban morphology not only as a physical planning feature but also as a dynamic climatic factor influencing urban resilience under climate change scenarios (Emmanuel & Krüger, 2021). Therefore, the use of morphology sensitive thermal models in transportation planning is important to the sustainable development of the cities.

2.2 Street Canyon Geometry

Street canyons are one of the most investigated urban configurations in UHI research, as they have a direct impact on air flow patterns, radiative exchange processes and thermal storage dynamics. A street canyon is generally defined as a street flanked on both sides by continuous rows of buildings forming a semi-enclosed atmospheric channel. The geometric characteristics of these canyons play a significant role in controlling the urban microclimate and the thermal conditions experienced by pedestrians. Research shows that the orientation of canyons relative to solar trajectories and prevailing wind directions has a significant impact on thermal accumulation and energy redistribution (Lin et al., 2021). The orientation of arterial streets affects how long and how intense solar exposure is on pavements and building facades. East-west canyons often have extended solar heating in the afternoon, whereas north-south corridors are sometimes shaded intermittently, with the pattern depending on building height and latitude (Qaid & Ossen, 2020). Street canyon aspect ratio (H/W), a ratio between building height and street width, is one of the most important parameters in thermal flux modelling. High aspect-ratio canyons tend to have lower sky-view factors, less wind penetration and more longwave radiation trapping. These characteristics enhance nocturnal warming and inhibit thermal recovery after sunset (Chatzidimitriou & Yannas, 2021).

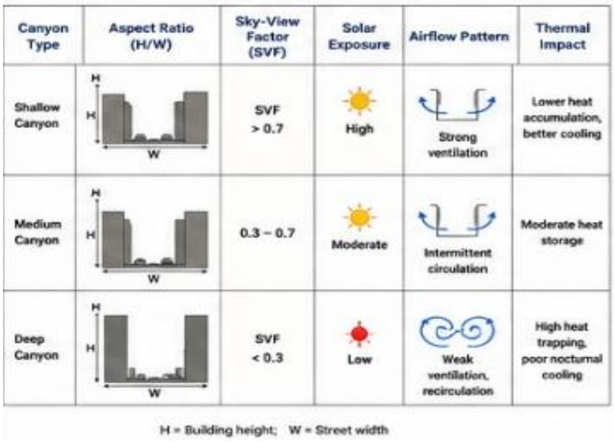

Figure 2. Typical Urban Street Canyon Geometries.

ENVI-met and CFD simulations show that the aspect ratio of the canyon between 1.0 and 2.0 can greatly alter the thermal comfort of pedestrians, sensible heat flux distribution and the air circulation efficiency (Park et al., 2024). In hot-arid climates, moderately compact canyons may offer beneficial shading effects that reduce thermal stress during the day. In humid tropical climates, however, an excess of compactness can frequently hinder ventilation and increase humidity levels, making the outdoor environment even less comfortable (see Figure 2). Another important geometric factor is the sky-view factor (SVF) that measures the ratio of visible sky from the street level. Lower SVF values are frequently observed in regions with higher nighttime temperatures, since lower SVF values are related to less sky exposure, which restricts the radiative heat loss to the atmosphere (Chen et al., 2022). Therefore, urban arterials with very low SVF values act as heat-retention corridors at night, which amplify the local UHI intensity. In addition, the dynamics of flow in street canyons is governed by the formation of vortices and turbulence structures. Recirculating eddies in canyon spaces are caused by wind flow over buildings and affect pollutant transport, heat accumulation and thermal stratification (Xue et al., 2023). Poor ventilation in narrow canyons often creates dead thermal zones where sensible heat is stored up to pedestrian levels. Wider canyons can allow more mixing in the atmosphere, but they can also allow more penetration of solar radiation and heating of the surface.

The thermal behavior is further complicated by the complex interaction of canyon geometry and vegetation. Street trees can provide substantial shading and evaporative cooling benefits. However, dense vegetation may impede the airflow and reduce the ventilation efficiency in the already cramped canyon (He et al., 2023). Thus, thermal optimization of arterial systems requires a balanced integration between geometry, vegetation and ventilation pathways.

In recent works, coupled CFD-radiation simulations were more and more used in thermal modelling in order to study the mechanisms of heat transfer at the canyon scale. These integrated approaches allow for high resolution representations of the airflow, radiation exchange, turbulence intensity and thermal comfort indicators for different urban configurations (Allegrini et al., 2020). Such techniques have become invaluable tools for climate responsive urban design.

2.3 Surface Materials and Thermal Storage

Properties of the surface materials are strong determinants of urban thermal dynamics as they govern the ability of urban surfaces to absorb, conduct, store and release heat energy. Urban arterial corridors are mainly composed of asphalt pavements, concrete sidewalks, metallic infrastructure, and dark roofing materials, which are characterized by high thermal admittance and low albedo (Sailor et al., 2021). These material properties are important in urban heat storage and nocturnal intensification of the UHI. Asphalt pavements are among the most thermally active of urban surfaces because of their dark color, high heat capacity, and high solar absorptivity. The surface temperature of asphalt reaches more than 60°C during the daytime under intense solar radiation of summer. The heat absorbed during the day is released slowly at night, prolonging the period of elevated urban temperatures and energy demand (Mohajerani et al., 2020). The thermal performance of urban materials is governed by several physical properties, including:

- Albedo
- Thermal conductivity
- Specific heat capacity
- Emissivity
- Moisture permeability
- Surface roughness
- Thermal diffusivity

Low-albedo surfaces absorb greater quantities of shortwave solar radiation, thereby intensifying sensible heat flux within urban canopies. High-conductivity materials facilitate rapid heat transfer into deeper pavement layers, while high thermal mass materials prolong nocturnal heat release, as shown in Table 2.

Table 2. Thermal Properties of Urban Materials

Material	Albedo	Thermal Conductivity	UHI Contribution
Asphalt	Low	High	Very high
Concrete	Moderate	High	High
Permeable pavement	Moderate	Moderate	Lower

Reflective pavements and cool materials have emerged as promising strategies to lower arterial surface temperatures. Studies have shown that high-albedo coatings and reflective aggregates can lower pavement temperatures by approximately 5-12 °C, depending on climate and solar intensity (Schneider et al., 2023). However, high reflectivity may increase radiant temperature and pedestrian discomfort if reflective surfaces are not combined with appropriate shading systems and vegetation cover. Permeable pavements are another important thermal adaptation strategy as they provide evaporative cooling through moisture retention and infiltration. Water stored in porous pavement structures increases latent heat flux and reduces sensible heat accumulation, and therefore moderates the daytime surface temperature (Wang et al., 2020). Permeable materials also enhance stormwater management and reduce surface runoff during extreme precipitation events.

Urban materials have also a dynamic interaction with anthropogenic heat sources such as vehicle emissions, industrial exhaust and air-conditioning systems. Metallic surfaces and dark pavements add to the thermal accumulation around transportation corridors especially during peak traffic times when sensible heat emissions are high (Salvati et al., 2021). Thermal behavior of arterial materials also depends on climatic region, maintenance conditions and aging processes. Dust accumulation and material degradation often lower albedo and increase thermal absorption on weathered pavements. Thus, the lifecycle thermal assessment of urban materials has become an emerging research area in sustainable transportation infrastructure planning. More sophisticated thermal flux modelling methods are increasingly incorporating material-specific heat transfer properties into urban climate simulations. Coupled energy balance models now allow detailed modeling of conductive, convective and radiative heat transfer over complex arterial systems (Fonseca & Schlueter, 2021). These approaches provide useful insights into the role of material selection for long-term urban thermal resilience and climate adaptation strategies.

3. THERMAL FLUX MODELLING APPROACHES

Thermal flux modelling has emerged as an important analytical tool to understand the complex interactions between urban geometry, atmospheric processes and heat island intensification. Nowadays, the urban thermal environment studies are more and more based on numerical simulations, remote sensing techniques and data-driven modelling systems to quantify the exchange of heat, momentum and radiation in urban arterial environments. Such modelling approaches also allow us to describe in detail how urban forms change the thermal energy transport mechanisms at different spatial and temporal scales (see Figure 3).

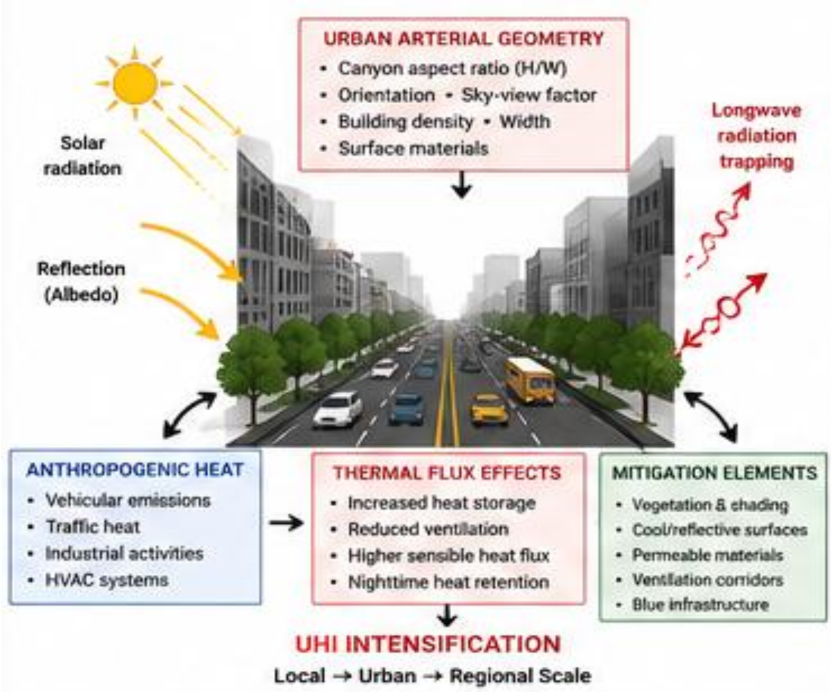

Figure 3. Conceptual Framework of Urban Heat Island Intensification Along Urban Arterials.

Urban arterials are highly dynamic thermodynamic systems. Nonlinear interactions between solar radiation, anthropogenic heat emissions, airflow turbulence, moisture transport and material heat storage are present. Such multidimensional interactions cannot be fully captured by direct field measurements alone and thermal flux modelling has therefore become an important scientific methodology to evaluate the urban heat processes and test mitigation strategies under different environmental conditions (Fonseca & Schlueter, 2021). Modern thermal models are progressively more realistic in terms of atmospheric physics, computational fluid dynamics, land-surface processes, vegetation interactions, and energy balance equations for simulating urban microclimates. Depending on the scale of analysis, modelling approaches may focus on individual street canyons, neighbourhood districts or entire metropolitan regions.

The principal modelling approaches commonly applied in UHI and arterial thermal research include:

- Computational Fluid Dynamics (CFD)
- ENVI-met microscale simulations
- Mesoscale atmospheric models
- Remote sensing analysis
- Machine learning and artificial intelligence techniques
- Coupled urban canopy models
- Large eddy simulation (LES)
- Hybrid physics-data-driven models

These methods collectively contribute to a more comprehensive understanding of the thermal behavior of urban arterial systems and their role in heat island intensification.

3.1 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) is now one of the dominant numerical approaches for studying urban thermal environments, because it can resolve airflow, turbulence, buoyancy effects and heat exchange processes at an extremely high spatial resolution. CFD allows detailed analysis of the complex aerodynamic and thermodynamic interactions taking place within urban street canyons, arterial intersections and densely built-up metropolitan environments (Nazarian et al., 2020). Thermal and aerodynamic conditions in urban arterial systems are highly heterogeneous due to irregular geometries, diversity of building heights, turbulence induced by traffic and complex exchange of radiation. These interactions can be simulated using CFD modelling to numerically solve the equations of fluid mechanics and heat transfer that govern atmospheric motion and thermal transport (see Figure 4).

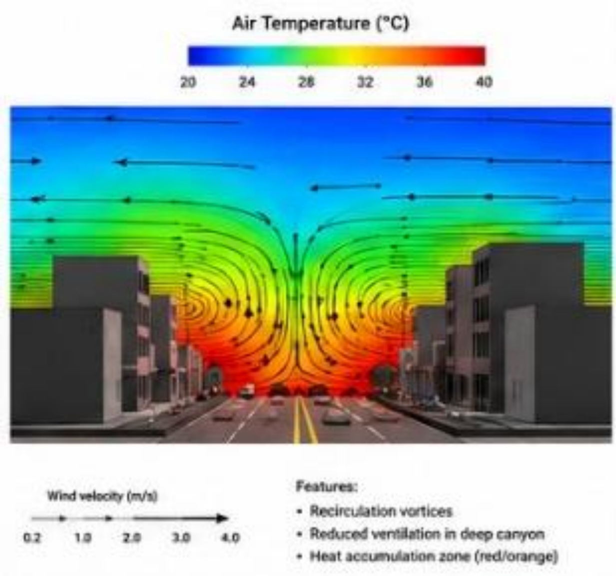

Figure 4. CFD Simulation Visualization

The two most widely applied CFD frameworks in urban climate studies are:

- Reynolds-Averaged Navier-Stokes (RANS)
- Large Eddy Simulation (LES)

RANS models solve the time-averaged equations of turbulent flow with the turbulence closure schemes like the k-ε and k-ω models. These methods are computationally efficient and are widely used in urban-scale airflow and thermal studies. However, the RANS approaches are likely to oversimplify the transient turbulence structures and local vortex dynamics in highly complex urban canopies. LES models, on the other hand, explicitly resolve larger turbulent eddies and parameterize the smaller scales. The LES allows for much more accuracy in capturing transient airflow behavior, recirculation and thermal stratification within the street canyons but requires much more computational resources (Allegrini et al., 2020). CFD simulations solve the governing equations for:

- Mass conservation
- Momentum transport
- Energy balance
- Turbulence dynamics
- Radiative heat transfer
- Moisture transport
- Pollutant dispersion

The conservation of momentum for incompressible urban airflow can be expressed using the Navier-Stokes equations:

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)=-\nabla p+\mu\nabla^2\mathbf{u}+\mathbf{F}$$

where $\rho$is the fluid density, $\mathbf{u}$is the velocity vector, $p$is pressure, $\mu$is the dynamic viscosity, and $\mathbf{F}$represents external body forces, such as buoyancy and gravitational forces. Similarly, urban heat transport can be described by the energy equation:

$$\rho c_p\left(\frac{\partial T}{\partial t}+\mathbf{u}\cdot\nabla T\right)=k\nabla^2 T+Q$$

where $T$is temperature, $c_p$is the specific heat capacity, $k$is the thermal conductivity, and Qdenotes internal heat sources, including anthropogenic heat emissions.

Important correction: for incompressible flow, you should also include the continuity equation:

$$\nabla\cdot\mathbf{u}=0$$

This condition is necessary because the Navier-Stokes equations alone do not fully define incompressible airflow. CFD approaches enable detailed evaluation of:

- Heat advection mechanisms
- Buoyancy-induced circulation
- Thermal plume development
- Canyon vortex formation
- Surface-atmosphere heat exchange
- Pollutant transport pathways
- Pedestrian thermal comfort

- Ventilation efficiency

Research repeatedly shows that the geometry of urban streets can dramatically alter turbulent air flow patterns. In particular, narrow canyons tend to produce isolated recirculation vortices that trap heat and pollutants at pedestrian levels, while wider corridors tend to benefit ventilation and heat removal (Xue et al., 2023). Recent progress in CFD modelling involves the increasingly integration of radiative transfer models, vegetation aerodynamics and anthropogenic heat sources in fully coupled urban climate simulations. Very realistic representations of urban heat fluxes under changing climatic conditions are now possible with hybrid CFD-energy balance models (Fonseca & Schlueter, 2021). CFD modelling, although advantageous, has several limitations. Some of the limitations include high computational demand, sensitivity to boundary conditions and uncertainties in turbulence parameterization. However CFD remains one of the most powerful tools for analyzing urban thermal dynamics and for evaluating climate sensitive arterial design strategies.

3.2 ENVI-met Simulations

ENVI-met is one of the most applied microscale urban climate models for exploring thermal comfort, airflow interactions, vegetation performance and urban heat island dynamics. ENVI-met is a 3D-modelling system which integrates atmospheric physics, vegetation processes, surface heat transfer and radiation exchange to simulate urban environments. It was developed specifically for urban environmental simulations and is able to represent complex urban environments at fine spatial scales (see Figure 5).

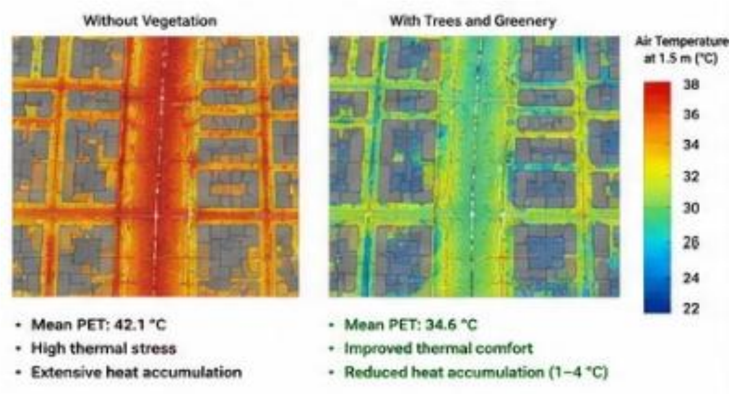

Figure 5. ENVI-met Thermal Comfort Simulation.

Unlike conventional atmospheric models that primarily focus on regional climate behavior, ENVI-met emphasizes microscale interactions occurring within urban neighborhoods, street canyons, pedestrian zones, and arterial corridors. The model has therefore become particularly valuable for evaluating the thermal implications of urban design and landscape architecture interventions.

ENVI-met integrates several critical physical processes including:

- Radiation exchange
- Surface heat transfer
- Vegetation interactions
- Soil moisture dynamics
- Airflow simulations
- Turbulence generation
- Evapotranspiration
- Anthropogenic heat emissions

The model calculates shortwave and longwave radiation exchanges between urban surfaces, buildings, vegetation canopies, and the atmosphere. This allows for a detailed assessment of shading effects, thermal storage behavior and radiant temperature distribution in arterial environments. One of ENVI-met's big strengths is the vegetation modelling. The model simulates transpiration, shading, aerodynamic drag and latent heat exchange associated with trees, shrubs, and green infrastructure systems. Several studies show that tree-lined boulevards and vegetated transportation corridors greatly contribute to improving thermal comfort by reducing solar exposure and increasing evaporative cooling (Tsoka et al., 2021). The ENVI-met simulations have repeatedly demonstrated the strong influence of the spatial configuration of urban greenery and canyon geometry on local thermal conditions. Research shows that strategically placed roadside vegetation may reduce pedestrian-level air temperatures by about 1-4°C during extreme summer conditions, while at the same time lowering mean radiant temperature and improving outdoor comfort indices (He et al., 2023).

The model is particularly effective for evaluating:

- Pedestrian thermal comfort
- Urban greening strategies
- Heat mitigation interventions
- Street canyon microclimates
- Surface temperature distribution
- Solar radiation exposure

- Ventilation pathways

Thermal comfort indices commonly calculated using ENVI-met include:

- Physiological Equivalent Temperature (PET)
- Universal Thermal Climate Index (UTCI)
- Predicted Mean Vote (PMV)

These indices help quantify the human physiological response to urban heat exposure under varying geometric and climatic conditions.

Further ENVI-met studies reveal a significant influence of the urban geometry on the recirculation of the airflow and thermal stratification . Deep street canyons often have stagnant thermal zones with high temperature and low ventilation, and moderate canyon openness improves the efficiency of convective cooling (Yang et al., 2021). ENVI-met has been widely used, but it has some limitations too. Simulations can be computationally expensive, particularly for large urban areas or high resolution scenarios. The model accuracy also depends on accurate specification of the boundary conditions and calibration with field observations. Still, ENVI-met is one of the most reliable and widely used tools for microscale urban thermal analysis.

3.3 Mesoscale Models

The mesoscale atmospheric models are intended to simulate the urban climate interactions at the spatial scales of a city and a region. These models are critical tools for exploring the wider climatic effects of urbanization, such as heatwave amplification, atmospheric circulation modifications, and large-scale urban heat island development. One of the most widely used mesoscale system is the Weather Research and Forecasting Model coupled with Urban Canopy Models (WRF-UCM). This coupled framework couples atmospheric dynamics with urban land-surface parameterizations to capture interactions between urban morphology and meteorological processes (Li et al., 2020).

WRF-UCM simulations incorporate multiple urban processes including:

- Surface energy balance
- Anthropogenic heat release
- Urban roughness effects
- Radiation trapping
- Building heat storage
- Boundary-layer development
- Moisture exchange
- Urban canopy turbulence

Urban canopy models embedded within WRF represent buildings, streets, and urban materials as thermally active elements that exchange energy with the atmosphere. These parameterizations allow simulation of how urban arterial systems influence city-scale temperature patterns and atmospheric circulation.

Mesoscale models are particularly valuable for investigating:

- Heatwave amplification
- Regional thermal gradients
- Urban expansion impacts
- Nocturnal heat retention
- Climate change interactions
- Air pollution transport
- Urban ventilation systems

Studies with WRF-UCM show that transportation infrastructure strongly enhances the nocturnal UHI, due to the delayed heat release from pavements and the continuous anthropogenic heat emissions. Urban arterials are often linked thermal corridors between industrial districts, commercial centers and densely populated neighborhoods (Krayenhoff et al., 2021). Additional mesoscale modeling suggests urban expansion affects regional atmospheric stability and could contribute to extreme heat events via positive feedbacks. The dense transportation networks increase the thermal roughness and decrease evapotranspiration, thus exacerbating the urban warming (Salamanca et al., 2020). Recently, there has been an increasing coupling of mesoscale models with microscale CFD frameworks for multiscale representation of urban climate. Coupled systems of this type allow for the simultaneous simulation of regional meteorological processes and local street canyon processes, and thus improve the accuracy of thermal flux predictions. However, mesoscale models are still limited in their capability to fully resolve highly localized airflow structures in individual street canyons due to grid resolution limitations. Thus, the combination of mesoscale and microscale approaches is still an active field of research in urban climate.

3.4 Remote Sensing and Machine Learning

Remote sensing technologies have transformed urban thermal analysis by enabling large-scale spatial mapping of surface temperature distributions and urban heat island intensity. Satellite-derived land surface temperature (LST) datasets provide continuous thermal observations across entire metropolitan regions, allowing researchers to identify spatial heat patterns associated with urban arterial systems, land-use configurations, and surface materials (Yao et al., 2022). Frequently utilized satellite platforms in urban thermal studies include:

- Landsat
- MODIS
- Sentinel

- ASTER
- ECOSTRESS

These systems provide multispectral and thermal infrared images that can detect urban surface temperature variations at a high spatial and temporal resolution. Remote sensing techniques are especially effective for the detection of thermally active transport corridors, industrial heat clusters and vegetation cooling effects. Thermal satellite images reveal that the surface temperature of large arterial roads is often significantly higher than the urban environment because of the concentrated coverage of asphalt and anthropogenic heat emissions. Thermal anomalies may persist into night periods due to delayed heat release from pavement materials (Wang et al., 2021). Increasingly, remote sensing data are being integrated with geographic information systems (GIS), databases of urban morphology, and models of thermal flux, to evaluate the impact of geometric configurations on UHI intensity. Remote sensing studies generally derive parameters such as:

- Land surface temperature (LST)
- Normalized Difference Vegetation Index (NDVI)
- Surface albedo
- Impervious surface fraction
- Urban density
- Sky-view factor
- Surface emissivity

Recent advancements in machine learning and artificial intelligence have further revolutionized urban climate modelling. Machine learning algorithms now combine thermal imagery, urban morphology datasets, meteorological observations, and socioeconomic variables to predict UHI intensity under varying geometric and climatic conditions (Reinbigler et al., 2026).

Common machine learning techniques applied in urban thermal studies include:

- Artificial Neural Networks (ANN)
- Random Forests (RF)
- Support Vector Machines (SVM)
- Deep Learning Models
- Gradient Boosting Algorithms

These approaches improve predictive performance while reducing computational costs associated with conventional physics-based simulations. AI-driven models are particularly effective for identifying nonlinear relationships between urban geometry and thermal behavior.

Machine learning applications additionally support:

- Real-time heat forecasting
- Urban heat vulnerability mapping
- Thermal anomaly detection
- Climate adaptation planning
- Smart-city thermal management systems

Deep learning techniques are becoming increasingly promising for automatically extracting urban morphology features directly from high-resolution imagery, and thus for improving the integration of spatial urban features into thermal simulations. While the benefits are significant, remote sensing and AI-based methods are limited by data quality, temporal coverage, cloud contamination, and model interpretability. Hence, recent studies increasingly propose the use of hybrid modelling systems combining physics-based simulations with machine learning optimization to improve both accuracy and computational efficiency, as shown in Figure 6.

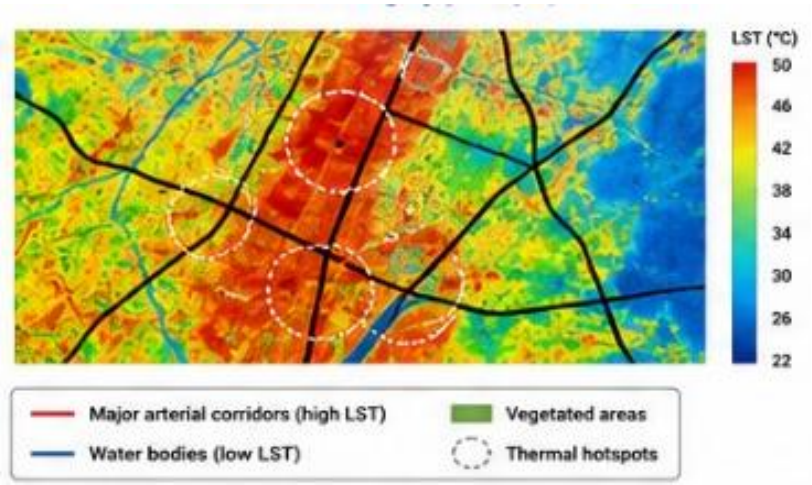

Figure 6. Remote Sensing Thermal Map

The integration of remote sensing, CFD, mesoscale atmospheric models, and artificial intelligence represents a major advancement in urban thermal science and offers substantial potential for climate-responsive transportation planning and sustainable urban governance.

4. MECHANISMS OF HEAT ISLAND INTENSIFICATION ALONG URBAN ARTERIALS

Urban arterial systems are some of the most thermally active elements of modern metropolitan environments. Several interlinked physical processes exacerbate the effects of the urban heat island (UHI), including high impervious coverage, vehicular density, limited ventilation, and complex geometric configurations. Arterial corridors, unlike isolated urban structures, are continuous thermodynamic pathways redistributing heat, moisture and pollutants across urban canopies. These thermal pathways have a strong influence on local energy balance, atmospheric stability and nocturnal heat retention. The enhancement of heat islands along transportation corridors is driven by the interaction of a number of dominant mechanisms such as radiative trapping, anthropogenic heat emissions, ventilation suppression and thermal storage processes. The magnitudes of these processes depend on the urban morphology, the climatic conditions, the traffic intensity, the material composition and the distribution of vegetation. Current thermal flux modelling suggests that arterial systems tend to be persistent heat reservoirs enhancing urban warming even when the surrounding rural environment is cooling down rapidly during night time (Santamouris, 2020). Moreover, urban arterials affect the micro- and mesoscale atmospheric circulation. The accumulation of heat in these corridors changes the turbulent energy exchange and helps to create localized thermal anomalies that can span whole metropolitan areas. Therefore, understanding the mechanisms that drive heat intensification along arteriolar systems is critical for the development of climate-responsive urban planning and sustainable transportation infrastructure.

4.1 Radiative Trapping

One of the primary mechanisms that cause urban arterial corridors to experience intensified heat islands is radiative trapping. Multiple reflections between building facades, road pavements and other urban surfaces in dense street canyons reduce outgoing longwave radiation. This repeated radiation exchange strongly enhances the heat retention in the urban canopy layer and increases the air temperature at night (Allegrini et al., 2020). Urban surfaces absorb incoming shortwave solar radiation during the day and emit longwave radiation after sunset. In open country much of this outgoing radiation is lost directly to the atmosphere. But in dense urban canyons, geometrical constraints of streets and high-rise buildings limit the radiative escape pathways. Longwave radiation emitted by one surface is reflected back and forth and reabsorbed by adjacent surfaces, which improves thermal storage and increases the length of time that heat is retained. The intensity of radiative trapping is strongly controlled by street canyon geometry , building height and sky-view factor (SVF). The geometry of high-rise canyons increases the absorption of radiation and at the same time limits the exposure to the sky. Reduced sky view factor inhibits nocturnal cooling and prolongs thermal discomfort, particularly on heatwave conditions. Urban canyons with low SVF values commonly have higher temperatures at night because of the severely limited radiative heat loss to the upper atmosphere (Chen et al., 2022). Surface optical properties (albedo, emissivity) also affect radiative trapping. Dark pavements and building materials absorb more solar radiation and retain high thermal energy during the day. These surfaces then re-radiate heat by longwave emission during the nighttime period thus increasing the urban heat island effect.

The net urban radiation balance can be expressed as:

$$Q^{*} = K_{\downarrow} - K_{\uparrow} + L_{\downarrow} - L_{\uparrow}$$

where Q^{*}represents the net all-wave radiation flux, $K_{\downarrow}$and $K_{\uparrow}$denote the incoming and reflected shortwave radiation, respectively, while $L_{\downarrow}$and $L_{\uparrow}$represent the incoming atmospheric longwave radiation and outgoing terrestrial longwave radiation, respectively.

This equation characterizes the total radiative energy exchange in the urban surface-atmosphere system and constitutes a basic element of the urban surface energy balance. Positive values of Q^*indicate net gain of radiative energy on the urban surface, whereas negative values indicate net radiative loss. In dense urban canopies, outgoing longwave radiation is trapped to some extent by repeated surface interactions, thus increasing net heat storage.

CFD and ENVI-met simulation results show that this process is exacerbated in compact arterial geometries due to the decreased efficiency of radiative exchange and the increased mean radiant temperature at pedestrian level (Yang et al., 2021). In addition, reflective street canyon surfaces can create local thermal hot spots by redirecting radiation to pedestrians and adjacent facades. Thus, thermal mitigation strategies must weigh the cooling benefits of reflective against human thermal comfort considerations.

4.2 Anthropogenic Heat Emissions

Anthropogenic heat emissions constitute another major driver of heat island intensification along urban arterials. Transportation corridors concentrate human activities, mechanical energy consumption, and industrial processes that collectively generate substantial sensible heat release into the urban atmosphere.

Major sources of anthropogenic heat within arterial systems include:

- Vehicle engines
- Air-conditioning exhaust
- Industrial activities
- Human metabolism
- Lighting systems
- Public transportation infrastructure
- Commercial activities
- Construction operations

Vehicular traffic continues to be among the dominant sources of anthropogenic heat in urban corridors. The conversion of the energy in the fuel to mechanical motion is not very efficient in an internal combustion engine; most of the energy is lost as heat through the exhaust system, engine parts, and frictional processes. The levels of traffic congestion can significantly increase the sensible heat build-up due to prolonged idling and decreased airflow around vehicles (Sailor et al., 2021). Indoor air-conditioning systems also contribute to urban warming by moving indoor heat to outdoor environments. Commercial areas with dense building stock and significant cooling loads tend to have elevated night-time temperatures as the air-conditioning exhausts are maintained after dark.

Anthropogenic heat flux can be represented as:

$$Q_F = Q_V + Q_B + Q_M$$

where $Q_F$denotes the total anthropogenic heat flux, $Q_V$represents heat emissions associated with vehicular transportation, $Q_B$corresponds to building-related heat release resulting from heating, cooling, and energy consumption, and $Q_M$reflects metabolic heat generated by human activities.

This relationship is often used in urban energy balance and urban climate models to quantify the contribution of human activities to the urban heat island effect. Typically, building energy use and transportation systems constitute the majority of anthropogenic heat emissions in the dense urban areas. Research has shown that in highly urbanized transportation corridors that have peak activity periods, anthropogenic heat contributions could exceed 50–100 W/m^2 (Salamanca et al., 2020). In megacities, this excess heat input substantially changes atmospheric stability and augments the nighttime UHI effects.

Transportation infrastructure also serves as a spatial conduit for redistribution of anthropogenic heat. Urban arterials are continuous thermal corridors connecting industrial districts, commercial centers and densely populated neighborhoods. Hence, thermal anomalies generated in one district can be transported along arterial pathways and influence the temperature distribution of larger metropolitan areas. More recent studies show that electric mobility systems, although environmentally friendly in terms of emission reductions, may still contribute to local heat build-up through battery operation, charging infrastructure and electrical dissipation processes. Therefore, the future transportation planning should include not only decarbonization but also integrated thermal management.

4.3 Turbulence Suppression and Ventilation Constraints

Urban canyon geometry strongly influences air flow patterns, turbulent mixing, and atmospheric ventilation efficiency. In many densely built arterial systems, geometric confinement suppresses natural ventilation and reduces the dissipation of accumulated heat, thereby intensifying urban thermal stress.

Air flow within street canyons depends on several geometric and climatic variables including:

- Building height
- Street width
- Aspect ratio
- Wind direction
- Surface roughness
- Canyon orientation
- Vegetation density

Narrow canyons with poor orientation relative to prevailing winds often reduce ventilation efficiency and heat dissipation (Xue et al., 2023). Stagnant thermal microclimates are created under weak air flow conditions where the removal of sensible heat and pollutants from street-level environments is constrained. Compact street canyons are characterized by recirculating vortices. Such vortices arise from the interaction of ambient wind flow with turbulence induced by buildings. These vortex structures trap heat and pollutants at pedestrian level and, hence, increase thermal discomfort and decrease urban air quality. The Reynolds number for urban air flow can be written as:

$$Re = \frac{\rho u L}{\mu}$$

where Rerepresents the Reynolds number, $\rho$is the fluid density, $u$denotes the characteristic flow velocity, $L$is the characteristic length scale, and μrepresents the dynamic viscosity of the fluid.

The Reynolds number is a dimensionless parameter that characterizes the flow regime by comparing inertial forces to viscous forces. In urban aerodynamics, the high Reynolds number regimes are usually related to turbulent flow, increased mixing and complex vortex formation around buildings and street canyons.

Vortex intensity and circulation patterns are highly dependent on urban canyon geometry, building arrangement and wind direction. Deep narrow canyons tend to establish stable recirculation zones that can impede pollutant dispersion and contribute to localized heat buildup in dense urban settings. The presence of urban roughness elements, such as buildings, overpasses, roadside barriers and dense vegetation, further complicates the structures of airflow. Increased roughness can cause local turbulence but can also, depending on the spatial arrangement, block large-scale ventilation pathways. CFD simulations reveal that isolated recirculation zones are often created in compact canyons with severely limited air exchange with the overlying atmosphere. These stagnant areas allow for heat to build up, pollution and high humidity levels to concentrate. The street's orientation also influences the efficiency of ventilation. Arterials that are perpendicular to prevailing winds tend to have less penetration of airflow than corridors that are parallel to the dominant wind directions (Lee et al., 2021). As a result, the problem of keeping ventilation corridors in congested metropolitan areas for the purpose of atmospheric cooling has become more and more significant for urban planners. Vegetation interactions further complicate the dynamics of urban airflow. Trees provide shading and evapotranspiration benefits, but overly dense canopies may block ventilation and promote thermal stagnation in already confined street canyons. Thus, vegetation design should take into account the trade-off between cooling performance and airflow preservation.

4.4 Thermal Storage and Nocturnal Release

Urban heat island amplification is defined by thermal storage and delayed nocturnal heat release. Impervious pavement systems, concrete structures, and dense urban materials are capable of absorbing large quantities of solar energy during the day and radiating this heat into the atmosphere over an extended period after sunset. This thermal inertia increases night temperatures and extends the exposure to the urban heat (Santamouris, 2020). The urban arterial corridors are very sensitive to thermal storage because of the large area of asphalt pavements and concrete surfaces with high heat capacity and thermal conductivity. On exposure to the sun during the day, these materials get heated in the inner layers. After sunset the stored heat is slowly lost by conduction, convection and longwave radiation.

The conductive heat transfer process can be expressed using Fourier's law:

$$q = -k\frac{dT}{dx}$$

where $q$denotes the conductive heat flux, $k$represents the thermal conductivity of the material, and $\frac{dT}{dx}$corresponds to the temperature gradient in the direction of heat transfer.

The negative sign indicates that heat flows from regions of higher temperature toward regions of lower temperature. In urban heat transfer studies, Fourier's law is widely applied to evaluate conductive heat exchange through building envelopes, pavements, and urban construction materials. Thermal storage capacity depends on several material and environmental characteristics including:

- Material conductivity
- Surface albedo
- Moisture content
- Pavement thickness
- Surface roughness
- Specific heat capacity
- Thermal diffusivity

The dark asphalt pavements have very high heat absorption due to their low albedo values. This material can slowly release its stored heat for hours after sunset, thus reducing nocturnal cooling and enhancing nighttime UHI effects. Nighttime heat release also increases urban energy demand because lower efficiency of building cooling leads to greater reliance on air-conditioning systems due to higher nighttime temperatures. This feedback loop further amplifies anthropogenic heat emissions and contributes to persistent thermal stress.

Thermal storage behavior is also affected by moisture conditions. Dry impervious surfaces tend to accumulate more heat than moist or permeable materials where evaporative cooling takes place. Conversely, permeable pavements and vegetated surfaces dissipate heat more efficiently through latent heat flux processes as shown in Table 3.

Table 3. Comparison of Thermal Flux Modelling Approaches

Model	Scale	Strengths	Limitations
CFD	Microscale	High resolution	Computationally expensive
ENVI-met	Microscale	Vegetation modelling	Long simulation time
WRF-UCM	Mesoscale	Regional analysis	Lower resolution
Remote sensing	Regional	Large spatial coverage	Limited temporal resolution

Recent thermal flux modelling studies demonstrate that urban arterials with high thermal inertia frequently maintain elevated surface temperatures even during pre-dawn periods. This delayed thermal recovery significantly affects human health, sleep quality, and cardiovascular stress during prolonged heatwave events.

Consequently, reducing thermal storage capacity through cool pavements, reflective materials, permeable surfaces, and vegetated infrastructure has become a central objective of climate-sensitive transportation planning.

5. INFLUENCE OF GEOMETRIC VARIABLES

The geometric arrangement of urban arterials determines the urban thermal behavior and the heat island intensity. The radiation exchange, airflow distribution, thermal storage and the ventilation efficiency are collectively controlled by the street sizes, building distributions, orientations and density of the city. The geometric variables govern the interaction of the urban surfaces with the atmospheric processes, affecting the heat accumulation during the day and the cooling performance during the night. Urban thermal studies increasingly reveal the spatially heterogenous effects of geometric characteristics on thermal comfort and energy balance. The thermal impact of the geometry is a function of climatic zone, season, sun angles and local meteorology. Therefore, geometry-sensitive urban planning has been recognized as an important approach to mitigate heat island effects in fast-urbanizing areas.

5.1 Aspect Ratio (H/W)

Street canyon aspect ratio, commonly expressed as the ratio between building height and street width (H/W), strongly influences solar exposure, wind penetration, radiative exchange, and airflow circulation within urban arterials.

$$H/W = \frac{\text{Building Height}}{\text{Street Width}}$$

A higher H/Wratio generally indicates deeper urban canyons, which tend to reduce solar access at street level, limit ventilation efficiency, and enhance heat trapping due to restricted airflow and multiple reflections of radiation between building surfaces. In contrast, lower H/Wratios tend to allow for greater wind penetration and enhanced thermal ventilation in the urban setting.

High-aspect ratio deep canyons often have a low sky-view factor and poor ventilation, which results in higher night-time temperatures and increased heat storage (Park et al., 2024). These small-scale geometries limit outgoing longwave radiation and trap heat in the urban canopy layer.

By contrast, shallow canyons with low aspect ratios allow more solar penetration and may experience increased daytime surface heating. They do, however, tend to have better ventilation and to be more effective in cooling at night. The thermal effects of aspect ratio are strongly climate-type dependent. In hot-arid climates, moderately compact canyons may provide beneficial shading and reduce daytime thermal stress. Too much compactness often limits air flow and increases humidity accumulation in humid tropical climates thus worsening thermal discomfort. CFD and ENVI-met studies also consistently show that the optimal aspect ratios are a compromise between shading performance and ventilation efficiency. Therefore, climate responsive urban design should be adapted carefully to the regional environmental conditions in terms of canyon geometry.

5.2 Orientation

Street orientation strongly affects solar penetration, wind accessibility and thermal exposure within arterial systems. The orientation of streets with respect to the solar paths influences the length and the intensity of the radiation received by urban surfaces during a day. Afternoon temperatures in east-west canyons are often high, since during the warmest part of the day the sun shines on them directly. These orientations tend to raise the temperature of the pavement and the heat stress experienced by pedestrians. In general, north-south orientations tend to have a better shading performance for many climates since buildings periodically shade street surfaces as the solar angles change during the day (Qaid & Ossen, 2020). Thus, north-south corridors tend to reduce daytime temperatures and enhance thermal comfort. Street orientation also affects urban ventilation patterns. Corridors parallel to prevailing winds are more likely to have increased airflow penetration and better heat dissipation than corridors perpendicular to prevailing winds that obstruct atmospheric circulation. Modelling of thermal flux suggests that the optimum street orientation should take into account solar access, prevailing wind patterns and local climatic characteristics in order to maximise thermal resilience.

5.3 Sky-View Factor

Sky-view factor (SVF) represents the proportion of visible sky observed from a given point at street level and serves as a critical indicator of urban radiative exchange efficiency.

$$SVF = \frac{\text{Visible Sky Area}}{\text{Total Hemispherical Sky Area}}$$

Lower values of SVF are usually associated with less nocturnal cooling and higher thermal stress because of the limited exposure to the sky that restricts the outgoing longwave radiation. Consequently, dense urban canopies with low SVF tend to store more heat at night, resulting in a stronger urban heat island effect. The Solar Variability Factor (SVF) is a commonly used approach in urban climatology and environmental design to estimate the impact of urban geometry on thermal comfort, radiation balance and microclimatic behavior within street canyons and highly built-up environments. High SVF values improve radiative cooling performance, but they can also increase solar exposure during the daytime. Therefore, thermal optimisation is a trade-off between sky exposure and shading and ventilation performance.

Recent studies on urban climate have included more and more the Sky View Factor (SVF) in the assessment of thermal comfort and heat mitigation planning. This is because the SVF provides a quantitative measure of the geometric openness of urban environments.

5.4 Urban Density

Urban density has a strong impact on the heat accumulation due to changes in the surface roughness, building compactness, anthropogenic activity and the availability of vegetation. High density urban districts tend to have high thermal storage and low evapotranspiration because of the dominance of impervious surfaces in the landscape. Dense metropolitan areas also create stronger radiative trapping effects and more complex airflow obstructions. However, a strategic compactness combined with preserved ventilation corridors can enhance the thermal resilience by reducing transportation demand, and enabling efficient shading (Martilli et al., 2020). The relationship of density to UHI intensity is still highly context dependent. Excessive sprawl may increase surface exposure and heat emission associated with transportation, while excessive compactness may suppress ventilation and enhance night-time warming. Hence, sustainable urban planning is increasingly advocating balanced density configurations integrated with green infrastructure, reflective materials and ventilation networks to optimize urban thermal performance.

6. VEGETATION AND BLUE INFRASTRUCTURE

Vegetation and Blue Infrastructure have been identified as some of the most effective nature-based solutions to reduce the intensification of Urban Heat Islands (UHI) in arterial transportation corridors. Urban green space has a significant impact on the thermal environment via shade, evapotranspiration, surface cooling, aerodynamic regulation and carbon sequestration. Water-based systems enhance at the same time evaporative cooling, atmospheric moisture balance and power fluctuations in densely urbanized districts. Collectively, these ecological interventions provide critical mechanisms of climatic regulation, can mitigate thermal stress and improve pedestrian comfort and urban resilience in climate change scenarios. Urban arterial systems are susceptible to excessive heat build-up due to the high percentage of impervious surfaces, such as asphalt pavements and concrete infrastructure. These corridors are often characterized by sparse natural vegetation and thus lower evapotranspiration and higher sensible heat fluxes. Hence, the integration of green and blue infrastructure into transport networks has become a key objective of climate-sensitive urban planning. Urban vegetation plays an important role in mitigating UHI intensity through several interconnected mechanisms, including:

- Shading
- Evapotranspiration
- Surface cooling
- Wind modification
- Radiation interception
- Carbon absorption
- Moisture retention

- Pollutant filtration

Tree-lined arterials improve pedestrian thermal comfort and reduce pavement surface temperatures by intercepting incident solar radiation. It has been reported that the pavement temperature can be lowered by more than 10°C when there is continuous canopy coverage during extreme summer conditions (Morakinyo et al., 2020). Vegetation also reduces mean radiant temperature (MRT), which is one of the most important variables affecting outdoor thermal comfort . The cooling potential of vegetation is strongly related to the evapotranspiration processes, which occur when plants absorb thermal energy by water evaporation from leaf surfaces and surrounding soils. Table 4. Evapotranspiration also leads to latent heat exchange that reduces the accumulation of sensible heat and helps to moderate the temperature of urban air.

Table 4. Cooling Performance of Mitigation Strategies

Strategy	Temperature Reduction	Advantages	Limitations
Green roofs	1-3°C	Evapotranspiration	Maintenance
Tree canopy	2-10°C	Shade	Airflow obstruction
Cool pavements	5-12°C	Reduced heat storage	Glare risk

The latent heat flux can be expressed as:

$$Q_E = L_v E$$

where $Q_E$denotes the latent heat flux, $L_v$represents the latent heat of vaporization, and Ecorresponds to the evapotranspiration rate.

This relationship implies that a fraction of the available surface energy is used up in the phase change of water from liquid to vapor which, in turn, limits surface and atmospheric warming. Vegetation with high evapotranspiration capacity can significantly reduce surface temperatures, improve outdoor thermal comfort and mitigate urban heat island intensity in urban regions. Therefore, urban green infrastructure including parks, green roofs, street trees, vegetated corridors is critical for improving urban thermal resilience and environmental sustainability. Street trees also affect urban airflow structures through altering wind velocity and turbulence characteristics. Well-designed vegetation systems can alter the flow of air and reduce thermal stagnation in street canyons. However, dense canopies can limit ventilation and promote humidity accumulation, especially in humid tropical climates where natural airflow is critical for thermal dissipation (He et al., 2023). Hence, species selection is important for the thermal mitigation performance. Broadleaf deciduous trees tend to provide better summer shade, but allow solar penetration in the winter. Drought resistant species are also important in dry areas where the availability of water limits the long-term viability of vegetation. Beyond street trees, urban green infrastructure systems include:

- Green roofs
- Vertical Greenery Systems
- Bioswales
- Urban parks
- Vegetated medians
- Rain gardens
- Green buffers
- Ecological corridors

These systems collectively improve urban thermal regulation while simultaneously enhancing biodiversity, stormwater management, and air quality. Blue infrastructure is also a major contributor to urban cooling via processes of evaporative and convective heat exchange. Water bodies have a high specific heat capacity and are able to absorb and transfer thermal energy more slowly than impermeable surfaces. Features like fountains, canals, retention ponds, permeable water systems, and artificial wetlands create localized cooling zones that can reduce air temperatures in the surrounding area. The thermal moderation capacity of water systems can be expressed by the heat balance relationship:

$$Q = mc\Delta T$$

where Qrepresents the heat energy transferred, $m$is the mass of the substance, $c$denotes the specific heat capacity, and ΔTrepresents the temperature change.

This relationship shows that because of the high specific heat capacity of water, bodies of water can absorb or release large quantities of thermal energy with relatively small changes in temperature. As a result, urban lakes, rivers, fountains and other elements of blue infrastructure play a role in temperature regulation through moderating daytime heating and reducing temperature fluctuations in the surrounding urban environment. This principle is often used in urban climate and environmental engineering studies to assess the cooling performance of water-based mitigation strategies and their contribution to mitigating urban heat island intensity. Urban water systems also provide evaporative cooling which reduces ambient temperatures during the day. As a result, integrated blue-green infrastructure networks have been found to be highly efficient strategies to mitigate arterial heat build-up and improve urban climate resilience. But badly designed vegetation and water systems may have unintended thermal effects. In tropical and subtropical climates, high vegetation density can block ventilation paths and raise humidity levels. Similarly, water system deterioration can result in stagnation, water pollution, and vector-borne health problems. Thus, successful implementation requires climate-sensitive design, species optimization, hydrological integration, and long-term maintenance planning.

7. HUMAN THERMAL COMFORT AND PUBLIC HEALTH

Urban heat island intensification directly impacts human thermal comfort, physiological health, social equity, and urban livability. High temperatures in arterial transportation corridors lead to increased human exposure to thermal stress, particularly during extreme heat events and extended heatwaves. Urban arterials are heavily used by pedestrians, cyclists, commuters and outdoor workers and therefore thermal performance is an important factor affecting public health outcomes in metropolitan areas. UHI intensification contributes to numerous health and environmental risks including:

- Heat stress
- Cardiovascular diseases
- Respiratory illnesses
- Heat-related mortality
- Dehydration
- Reduced labor productivity
- Sleep disruption
- Increased energy consumption

Heat stress occurs when the human body is unable to shed heat through sweating and convection effectively. High humidity and little air movement combined with increased ambient temperatures result in a marked rise in physiological strain. Urban arterial systems with large asphalt surfaces, lack of shading, and limited ventilation are often thermal hotspots that subject pedestrians to dangerous thermal conditions. Human thermal comfort depends on the balance between metabolic heat production and environmental heat exchange. This balance is strongly influenced by:

- Air temperature
- Relative humidity
- Wind speed
- Solar radiation
- Mean radiant temperature
- Clothing insulation
- Metabolic activity

To quantify thermal comfort within urban environments, researchers commonly employ several biometeorological indices including:

- Physiological Equivalent Temperature (PET)
- Universal Thermal Climate Index (UTCI)
- Predicted Mean Vote (PMV)

The Physiological Equivalent Temperature (PET) index evaluates thermal stress by integrating air temperature, radiation exposure, humidity, and wind conditions. Similarly, UTCI provides a standardized assessment of outdoor thermal stress under varying climatic conditions. These indices are widely applied in ENVI-met and CFD simulations to evaluate the thermal impacts of arterial heat accumulation (Middel et al., 2021).

The human heat balance equation can be expressed as:

$$M - W = C + R + E + S$$

where Mrepresents metabolic heat production, Wdenotes external mechanical work performed by the body, Ccorresponds to convective heat exchange, Rrepresents radiative heat transfer, Eindicates evaporative heat loss through perspiration and respiration, and Sdenotes heat storage within the human body.

This equation describes the thermal equilibrium between the heat generation inside and the heat exchange with the environment. If the amount of heat gained is more than the amount of heat dissipated, then there is a positive storage of heat (S>0), which may lead to thermal discomfort or heat stress. In contrast, negatively stored heat means the body is cooling down.

The human heat balance model is widely used in urban climatology, biometeorology, occupational health and outdoor thermal comfort research for the assessment of the physiological effects of urban microclimates on pedestrians and sensitive groups.

Think about it, this is a lot of stress on your cardiovascular system, which has to work harder to maintain a balance between heat and cool. In addition, the exposure to heat exacerbates respiratory diseases by increasing the formation of ozone and the level of pollutants in poorly ventilated street canyons. Thermally uncomfortable corridors disproportionately affect vulnerable populations including:

- Elderly individuals
- Children
- Outdoor workers
- Low-income communities
- Individuals with chronic illnesses
- Pedestrians dependent on public transportation

Low-income populations are more thermally vulnerable as they tend to have less green infrastructure, more impervious surfaces, and less access to cooling systems in economically disadvantaged neighborhoods . Thus, urban heat island effects are also important issues of environmental justice and social equity. Globally, climate change and urban warming have led to a significant increase in heat-related mortality in many cities. The extended exposure to heat during the night is particularly dangerous because the reduced cooling at night limits physiological recovery during sleep periods. Urban arterials with high thermal storage and anthropogenic heat emissions contribute in turn greatly to the thermal stress during nighttime. In addition, increased temperatures in cities raise the demand for air conditioning and therefore anthropogenic heat emissions, establishing positive feedback loops that intensify UHI. Thus, sustainable thermal mitigation strategies are essential for protecting public health and reducing climate-related urban vulnerabilities.

8. MITIGATION STRATEGIES

Integrated strategies need to be considered to address urban geometry, surface materials, vegetation systems, airflow pathways and energy consumption patterns to mitigate urban heat island intensification in arterial systems. Recent urban climate research highlights that arterial heat accumulation cannot be fully addressed by a single intervention. Rather, multidimensional climate-sensitive planning approaches are required to achieve long-term thermal resilience. The objective of effective UHI mitigation strategies is to reduce sensible heat storage, increase latent heat exchange and improve ventilation efficiency and reduce anthropogenic heat emissions. Strategies increasingly mix engineering interventions with ecological infrastructure and smart urban governance systems.

8.1 Reflective and Permeable Pavements

Reflective pavements and cool materials are among the most widely implemented engineering strategies for reducing arterial surface temperatures. High-albedo surfaces reflect larger proportions of incoming solar radiation and therefore absorb less thermal energy during daytime periods.
Surface reflectivity is commonly represented by albedo:

$$\alpha = \frac{\text{Reflected Radiation}}{\text{Incoming Radiation}}$$

where αdenotes the surface albedo, representing the fraction of incoming solar radiation reflected by a surface.

Higher albedo values reduce the absorption of solar energy by urban surfaces and thus reduce the heating of the pavement and sensible heat flux into the urban atmosphere. Therefore, the application of high-albedo materials, such as reflective coatings, cool asphalt technologies and light-colored paving materials can significantly reduce the surface temperature during the day and mitigate the intensity of the urban heat island. Albedo is known as an important parameter for the surface energy balance, thermal comfort and building energy performance in urban climate researches.

Permeable pavements offer additional thermal benefits by facilitating evaporative cooling through the infiltration and retention of moisture. The heat stored in porous pavement structures also evaporates to reduce surface temperature, and improve stormwater management at the same time. Permeable systems also reduce the risk of flooding in urban areas and help recharge the groundwater. But the material performance depends on the climate, maintenance conditions and the intensity of traffic. Hence, sustainable deployment requires the assessment of thermal effects on the entire life cycle.

8.2 Green Corridors

Continuous urban green corridors improve air flow, reduce solar exposition and moderate thermal accumulation throughout transportation systems. The combination of street trees, bioswales, green roofs and vegetated medians with vegetation systems yields considerable cooling benefits through shading and evaporative cooling processes. Green corridors also serve as ecological networks, improving both biodiversity and pedestrian comfort. Vegetation placed along the prevailing wind pathways may also add to urban ventilation and atmospheric cooling. The research has shown consistently that the connected urban green spaces outperform the fragmented vegetation patches in terms of the thermal mitigation benefits. The continuous ecological systems improve the large-scale thermal regulation and mitigate the surface temperature heterogeneity (Figure 7).

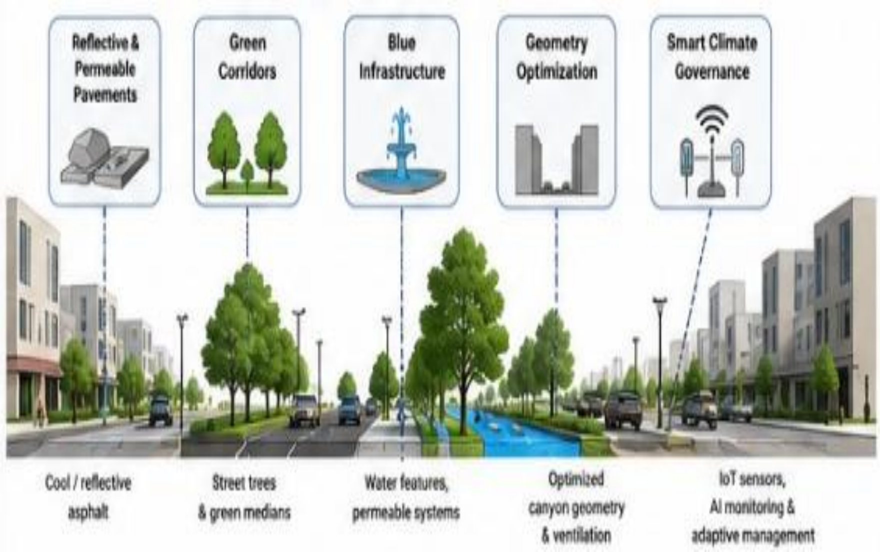

Figure 7. Mitigation Strategies Framework.

8.3 Geometry Optimization

Urban geometry optimization represents one of the most effective long-term strategies for climate-sensitive transportation planning. Thermally responsive urban design should carefully consider:

- Canyon aspect ratios
- Street orientation
- Building space
- Ventilation pathways
- Sky-view factor optimization
- Surface roughness distribution

- Building height variation

Optimized street canyons balance shading performance with ventilation efficiency. In hot-arid climates, moderately compact geometries may reduce daytime heat exposure, whereas humid climates require wider ventilation corridors to facilitate convective cooling.

Urban planners increasingly utilize CFD and ENVI-met simulations to evaluate thermal performance under alternative geometric configurations before implementing infrastructure projects.

8.4 Smart Urban Climate Governance

Future cities require integrated climate-sensitive transportation planning supported by real-time thermal monitoring, artificial intelligence forecasting systems, and adaptive infrastructure management. Smart urban climate governance combines environmental sensing technologies, digital modelling systems, and policy frameworks to improve urban thermal resilience.

Emerging technologies include:

- IoT thermal sensor networks
- AI-based heat forecasting
- Digital twin simulations
- Smart shading systems
- Adaptive pavement technologies
- Urban climate dashboards

These systems enable real-time identification of thermal hotspots and support evidence-based urban planning decisions. AI-driven thermal forecasting additionally enhances emergency response capacity during extreme heat events.

Effective climate governance also requires interdisciplinary collaboration among urban planners, climatologists, engineers, architects, transportation authorities, and public health institutions.

9. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite substantial advances in urban climate modelling and thermal mitigation research, several significant scientific and practical challenges remain unresolved. Current knowledge gaps limit the ability of planners and policymakers to develop fully integrated and climate-resilient arterial systems. Major research gaps include:

1. Limited integration between CFD simulations and urban policy frameworks.
2. Insufficient long-term observational datasets for validating thermal models.
3. Lack of standardized thermal flux metrics across different climatic regions.
4. Limited studies concerning transportation systems in developing countries.
5. Insufficient integration of machine learning with physics-based climate models.
6. Inadequate understanding of nighttime thermal recovery processes.
7. Limited evaluation of compound climate hazards such as heat and air pollution interactions.
8. Uncertainty regarding long-term thermal performance of emerging urban materials.

Future research should prioritize:

- Coupled climate-energy-transport models
- AI-enhanced thermal forecasting
- Nature-based thermal adaptation
- Human-centered urban climate design
- Multi-scale thermal governance systems
- Climate justice and thermal equity studies
- Real-time urban digital twin modelling
- Adaptive urban infrastructure systems

Emerging hybrid modelling frameworks combining CFD, remote sensing, AI, and Internet-of-Things (IoT) technologies offer substantial potential for improving predictive accuracy and supporting evidence-based urban governance. Future investigations should additionally focus on the social dimensions of urban heat vulnerability, particularly among economically disadvantaged populations disproportionately exposed to thermal stress.

CONCLUSION

The geometry of urban arterials is an important factor in the distribution of thermal flux and the intensification of urban heat islands. Street canyon configurations modify radiation balance, turbulent exchange, air flow circulation, anthropogenic heat accumulation and thermal storage processes to create urban microclimates and metropolitan thermal environments. Approaches to modelling thermal flux, including CFD, ENVI-met, WRF-UCM, remote sensing techniques and artificial intelligence systems, have greatly improved scientific knowledge of urban thermal dynamics. These methods show that compact canyon geometries, low-albedo materials, and extensive impervious surfaces and limited ventilation pathways greatly enhance heat accumulation and nocturnal warming. On the other hand, optimized city geometries with vegetation systems, reflective materials, permeable pavements, ventilation corridors and blue infrastructure provide significant cooling benefits and improve thermal resilience. Transportation planning under climate sensitivity thus needs to balance efficiency of mobility with environmental sustainability and health. Nature-based solutions, such as green corridors and urban water systems, are particularly promising pathways for alleviating arterial heat stress, as they can enhance biodiversity, stormwater management, and social well-being at the same time. Similarly, progress in smart urban governance, digital climate monitoring and AI-based forecasting creates new opportunities for adaptive urban thermal management. As global urban warming due to climate change intensifies, future cities will increasingly need to incorporate climate-responsive arterial design principles into the development of transportation infrastructure. Ultimately, sustainable urban resilience will rely on integrated systems of thermal governance that can align engineering innovation, ecological infrastructure, and human-centered climate adaptation strategies. The user uploaded thematic material which has been academically rewritten and developed into the extended discussion.

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