**APPENDIX A – WORKING PAPER LITERATURE REVIEW**

This appendix provides an early draft of a working paper literature review focused on Urban Heat Mitigation Techniques. We provide this draft paper as documentation for the report. As of publishing this manuscript, a latter version of this text was revised and submitted for review at a journal. Before citing this appendix, please reach out to the authors to inquire whether an updated version of the paper is available or has been published.

**Urban Heat Mitigation Techniques in Transportation Planning:**

**A Look at the Literature**

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As the impacts of climate change continue to increase, heat risk has become a more significant health and safety threat. Despite the transportation sector’s role in contributing to both climate change and the urban heat island (UHI) effect, little attention has been paid to how the transportation sector can mitigate urban heat. This is particularly relevant as heat disproportionally impacts low-income, marginalized, and minority communities as well as those who engage in active and public transport. This is due, in part, to a higher ratio of impervious surfaces, such as transportation infrastructure, to vegetation.

This scoping literature review draws from over 200 articles that investigated heat mitigation strategies along roadways. The analysis highlights the importance of four overarching heat mitigation strategies at the human-level scale: cool pavements, urban greening, street and building morphology, and leveraging water for evaporative cooling. These heat mitigation strategies support safer and healthier multi-modal environments by increasing human thermal comfort for pedestrians, bicyclists, and transit users. In addition, this review emphasizes the role of transportation planners and engineers in interdisciplinary collaboration that supports planning and implementation processes for cooler corridors and safer communities.

Keywords: extreme heat; transportation systems; climate change; heat mitigation strategies; urban heat island.

**Introduction**

Extreme heat is the leading cause of weather-related deaths in the United States (US). Between 2004 and 2018, approximately 702 people died each year as a result of heat (Vaidyanathan et al., 2020), exceeding the 98 deaths each year from flooding (CDC, 2020). However, the estimated number of heat-related deaths is much higher than vital statistics suggest; some scholars suggest up to 12,000 deaths occurred in the US from 2010 to 2019 (Shindell et al., 2020). Even though heat is the deadliest weather-related event, the sensationalization of more visually dangerous weather events may skew public perceptions around risk. An example of this is the 2021 heatwave in the Pacific Northwest that resulted in the deaths of over 1,000 people (Romanello et al., 2021). This heatwave received far less media attention than the 1,833 deaths caused by Hurricane Katrina (Richard Knabb et al., 2006). Cities with hotter climates can record similar magnitudes of heat deaths as those associated with traffic fatalities. An example of this is Maricopa County, home to Phoenix, Arizona, which reported over 300 heat-related deaths in 2020 (Maricopa County Department of Public Health, 2020) in comparison to 492 traffic deaths (Arizona Department of Transportation, 2020). Heat also causes illness and reduces quality of life, and it increases water and energy needs, faster degradation of infrastructure, harms landscaping and vegetation, and a decrease in overall economic productivity (Ladd Keith & Sara Meerow, 2022).

While travelers are exposed to greater risk of extreme heat, the environment itself also influences heat. For example, in Hoehne et al (Hoehne et al., 2018) the authors review the intersection of transportation and heat with a focus on the street-level built environment in the context of vehicular, active (walking and biking), and transit travel. They find both travel behavior and infrastructure contribute to the rise in urban heat and may also impact travel behavior. In this context, today’s transportation planners and engineers should consider heat in built environment and transportation.

We utilize a scoping review to better understand how transportation planning literature is addressing urban heat mitigation. We demonstrate that while heat strategies are available, understanding the relative tradeoffs and equity impacts of policies in services and infrastructure is lacking. In the next section, we provide background information about *why* heat has become an issue of concern, the differences in heat management and mitigation, and the role of transportation on heat and heat health outcomes. In the following section, we describe our review method and summarize street-level strategies for heat mitigation from that scoping review. We end by providing a broader discussion on future research and implementation needs for heat and transportation-related issues.

**Background**

Urbanization and climate change are intensifying heat in cities across the world and its associated effects. The transportation sector is the leading greenhouse gas (GHG) emitter in the US. Of the 27 percent of US GHG emissions in 2020 attributed to transportation, over half (57 percent) of the CO2 is from light-duty vehicles (United States Environmental Protection Agency, n.d.) Increased severity of the impacts of climate change via GHG emissions has increased the intensity, duration, and likelihood of seasonal extreme heat events and heatwaves (Intergovernmental Panel on Climate Change, 2022). Since 1900, average temperatures in the contiguous US have risen by 1.8˚F (1.0°C) with the estimation that they will continue to rise by 2.5°F (1.4°C) in the next few decades (United States Global Change Research Program, n.d.).

Heat intensity in urban areas compared with surrounding rural or natural areas – or the urban heat island (UHI) effect–occurs through a concentration of human activity such as traffic and heat retaining built environments, such as concrete and asphalt roads. During the day, the UHI results in temperatures that are up to 7°F (3.9°C) hotter than the surrounding areas; at night, urban areas are slower to cool off, with temperatures up to 5°F (2.8°C) hotter (Hibbard et al., 2017). The overall magnitude of a metropolitan areas’ UHI effect is a combination of all forms of land use and development. UHI is highly variable within the metro areas, often correlated with ratio of impervious surface to green space. For example, high-density and low-sprawl urban areas which have less volumes of concrete and pavement exposed can exhibit less UHI effect than urban areas that exhibit low-density and high-sprawl (Stone Jr, 2012)

Climate change and urban heat are a dangerous combination, as they expose communities to an increased likelihood of extreme heat events and risk of chronic heat. Demographic, economic, and health vulnerabilities can exploit heat risk. Low-income, minority, and unhoused populations are disproportionately impacted by heat and experience more vulnerability when extreme heat events occur; those with pre-existing conditions, disability, and outdoor jobs face further impacts of extreme heat (Ellena et al., 2020). For example, 94% of historically redlined neighborhoods in the US experience higher temperatures than their counterparts – reaching a difference of as much as 12.6°F (7°C) (Hibbard et al., 2017).

A central purpose of planning is to anticipate changing conditions and coordinate collective action; however, planning’s experience in implementing heat-health interventions is limited. A recent survey of communities within the US found that 73% of planners are at least “somewhat concerned” about the overall impacts of heat, and 84% of planners report that their community has already been affected by heat at some capacity (Keith et al., 2021). Yet heat-focused plans and policies have not been as widely considered or adopted by planners at the same capacity as for other natural disasters and climate risks (Keith et al., 2021) Another assessment of climate preparedness found that only 4% of climate adaptation resources focused on extreme heat (Nordgren et al., 2016). Despite this slow start, heat planning is beginning to see professionalization. The first Chief Heat Officer in the world was named in 2021 within Miami Dade County, with the City of Phoenix following close behind with the establishment of its Office of Heat Management and Response (Keith et al., 2021) and Los Angeles implemented a position in 2022.

Urban heat resilience planning includes, “Proactively managing and mitigating urban heat across the many systems and sectors it affects,” (Keith et al., 2021). Heat mitigation strategies aim to reduce urban heat through land use planning, urban design, urban greening, and waste heat reduction (Ladd Keith & Sara Meerow, 2022). Heat management strategies prepare for and respond to chronic heat risk and extreme heat events which cannot be mitigated (Ladd Keith & Sara Meerow, 2022) These include public health measures, personal heat exposure reduction, emergency preparedness, and access to cool indoor spaces (Ladd Keith & Sara Meerow, 2022). While both heat mitigation and heat management are critical to addressing heat risk, heat mitigation actions are often in the purview of urban planners, civil engineers, architects and landscape architects – those who influence the shape and form of the built environment (Meerow & Keith, 2022).

Although efforts to track, mitigate, and implement heat are increasing, most local governments do not have dedicated roles or offices that address heat, resulting in a lack of ownership of the issue (Keith et al., 2021) Currently, heat planning and mitigation efforts rely heavily on the actions and support of all built environment professionals including transportation planners. Because of this, it is important that all planners and engineers have a general understanding about how policies, decisions, and infrastructures effect heat risk, management, and adaptation. Planning can implement actionable policies that can either mitigate or increase the impacts of UHI. Current and future UHI impacts can be mitigated by implementing transportation systems and infrastructure and land use patterns; this will help reduce greenhouse gas emissions at the local level (Ladd Keith & Sara Meerow, 2022). It is also the responsibility of planners and engineers to rectify the systematic racism embedded in our infrastructure and development patterns in order to promote equity, specifically in relation to the impacts of climate change, and invest in making a truly equitable community (Ladd Keith & Sara Meerow, 2022).

Urban heat resilience planning requires comprehensive and interdisciplinary efforts to be successful. Communities adopt a variety of plans that all influence the form and shape of its future built environment – called a network of plans (Philip R. Berke et al., 2006). This network of plans relevant to heat mitigation efforts includes comprehensive plans, climate action plans, adaptation or resilience plans, hazard mitigation plans, parks and recreation plans, and transportation plans. Transportation-related heat mitigation efforts must be integrated across a community’s network of plan to be effective.

**Data & Methods**

This manuscript aims to provide additional context to the challenges described above by outlining strategies that transportation planners and engineers may consider to mitigate urban heat. For this paper, we performed a scoping review of the academic literature that examined street-level mitigation strategies that consider or improve various types of “heat” outcomes. Scopus and TRID were searched for the following terms: (“extreme heat” OR “urban heat island” OR “heat exposure” OR “thermal comfort”) AND (“transportation” OR “pedestrian” OR “bicycle” OR “public transit”). After restricting to post-2010 articles, searching both Scopus and TRID resulted in 637 and 212 items respectively through September 2021.

Each item was further screened by both a student and faculty member reading abstracts using Rayyan (Ouzzani et al., 2016), a free bibliography software that allows for blind screening. For inclusion, articles were required to engage heat as a primary topic area and discuss transportation infrastructure that would feasibly support multiple modes along a streetscape within urban areas. For example, we tried to exclude pedestrian-only or bike-ped paths within parks, in part because parks as respite from heat is a large and well-studied heat-adaptation area. We focused on the street scale rather than regional-only treatment of heat for UHI effects. UHI topics were included only if the article also addressed street-level framing or study. We did not include indoor applications such as in-cabin vehicular thermal comfort or conditions within indoor transit/rail stations. Finally, we also excluded articles focused on athletic performance for cyclists, although we do acknowledge that lessons learned about managing heat exposure in extreme conditions documented in exercise science could be applicable here. When disagreements in inclusion status were different between the reviewers, both re-reviewed the abstract and discussed until reaching consensus. After screening, 233 articles remained. Articles were tagged with themes in an inductive manner during the screening exercise, allowing the research team to identify broad research areas within the literature (summarized in Table 1).

Table 1: List of Themes Identified in Review, Common Terms in Searches, and Frequency of Articles Identified

|  |  |  |  |
| --- | --- | --- | --- |
| **Theme** | **Term** | **Frequency** | **Definition** |
| Framing of Heat | Urban Heat Island | 88 | Study is framed around or involves the Urban Heat Island, usually by de-scaling the regional to the local. |
| Pedestrian Thermal Comfort | 82 | Discusses heat at the “pedestrian” level. Articles were screened to exclude “pedestrian” as shorthand for weather measurements 1-2m high in outdoor spaces, instead, focusing on those that engaged pedestrian facilities.  |
| Microclimate | 56 | A localized climate that differs to that of the surrounding area |
| Heat Mitigation Strategies | Cool pavement | 76 | Article engages engineered pavement (streets and sidewalks) as a primary way to adapt to heat. Most articles are discussing “cool” pavements but some pervious solutions are also included. |
| Urban greening | 61 | Article engages greening as a primary way to adapt to heat. This includes both tree canopy and greening strategies along roads. |
| Street and building morphology | 59 | Discussion of road segment level characteristics such as orientation, wind, and building height as shade. |
| Water | 12 | Use of water or evaporative cooling is discussed as an adaptive measure along roads. |
| Heat Management Strategies | Health & Emergency Transport | 22 | Article engages health outcomes, usually emergency transport by ambulance, as a transportation and heat health outcome. |
| Air quality | 32 | Article investigates the co-occurrence of heat and air quality challenges. |
| Extreme heat event | 12 | Primary focus is on extreme heat event(s). |

**Results**

In addition to documenting general distribution of topics among the 233 articles, several research themes appeared. Before addressing these themes, we also want to acknowledge that due to the interdisciplinary nature of this topic, there are many different heat-related terms. We have defined some relevant terms in Table 2 to assist in this discussion.

Table 2: Glossary of Heat-Related Terms

|  |  |
| --- | --- |
| Word | **Definition** |
| **Albedo** | Reflectivity of a material, determined by material type and color (Meerow & Keith, 2022). |
| **Ambient Temperature** | Temperature of the ambient air and most commonly matches what people think outdoor temperature with respect to weather (Meerow & Keith, 2022). |
| **Aspect Ratio** | Architectural term that describe height to width (H/W) ratio. In outdoor heat work, a higher aspect ratio creates bigger shadows that can serve as shade. |
| **Cool Corridor** | “Highly shaded streets to serve pedestrians, bicyclists, and vehicles” (Meerow & Keith, 2022). |
| **Cool Pavements** | “Both lighter-colored pavement coatings, which reflect more of the sun’s radiation, and evaporative pavement technologies, which are permeable to water and cool the environment as that water evaporates” (Meerow & Keith, 2022). |
| **Extreme Heat** | Heat that is at the upper level of physiological bound for humans. Can occur in an event or wave (heat wave) or chronically (such as in the summer in the southern portion of the northern hemisphere). |
| **Heat Management Strategies** | “Strategies are those that prepare for and respond to chronic and acute heat risk” (Meerow & Keith, 2022). |
| **Heat Sink** | A concentration of heat, usually based on building materials, that hold in heat and create warmer surroundings as a result. |
| **Heat/Thermal Load** | Amount of heat transferred from one environment to another. In outdoor built environment settings, this often refers to the change in heating or cooling in neighboring building associated with built environment change. |
| **Microclimate** | “The unique climate conditions within a small area, such as a single site or neighborhood. The effect of a particular site design on the microclimate can be different from how it affects the regional UHI effect” (Meerow & Keith, 2022). |
| **Land Surface Temperature** | “Urban heat island maps display areas of higher and lower heat severity within a community. They are usually derived from satellite remote sensing imagery and use reflectivity to estimate land surface temperatures” (Meerow & Keith, 2022). |
| **Pedestrian Thermal Comfort** | Thermal comfort as it relates to the pedestrian experience and perception. |
| **Radiant Temperature** | “primarily comes from thermal radiation from the sun, but it can also come from other surrounding objects that radiate heat, such as machinery or pavement” (*7*). |
| **Smart Wetting** | The use of water and mist to purposely cool surfaces and air via evaporative cooling (Meerow & Keith, 2022). Draws from or is similar to *uchimizu*, a 17th Century Japanese practice of using water for exactly this purpose (Fukusaka & Matsubara, 2014). |
| **Solar Radiation** | Thermal energy from the sun (Meerow & Keith, 2022). |
| **Standard Effective Temperature** | “equivalent dry bulb air temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for the activity concerned would have the same skin temperature and skin wetness as in the actual environment” (Y. Zhang et al., 2017). |
| **Street Canyons** | “Ventilation corridors are air passages in an urban area that decrease the UHI effect and improve human thermal” (Meerow & Keith, 2022). |
| **Street Morphology** | Refers to the physical 3-D spatial aspects of a street including street orientation, building mass and shaping, ventilation corridors. |
| **Thermal Comfort** | How humans experience and perceive heat, determined by air temperature, humidity, radiant heat, and wind speed. (Meerow & Keith, 2022). |
| **Thermal Peaks** | High point of temperature and/or thermal load. |
| **Urban Greening** | *“*strategies such as urban forestry, green stormwater infrastructure, green roofs, parks, and greenways can help mitigate the UHI effect and cool microclimates.” (Meerow & Keith, 2022). |
| **Urban Heat** | Heat as a result of the form and function of the built environment (Meerow & Keith, 2022). |
| **Urban Heat Resilience** | Proactively mitigating and managing urban heat across the many systems and sectors it affects (Meerow & Keith, 2022). |
| **Vehicle Waste Heat** | “Waste heat from vehicles is a component of urban waste heat that increases the UHI effect” (Meerow & Keith, 2022). |
| **Wet Bulb Globe Temperature** | “The wet bulb globe temperature (WBGT) is a more comprehensive way to approximate human thermal comfort through the use of portable devices that record ambient air temperature, humidity, wind speed, and radiant heat” (Meerow & Keith, 2022). |

First, there are two distinct scales at which transportation-related personal heat exposure impacts are framed. The first is a region-wide scale, consistent with UHI literature. Some studies use UHI to inform why transportation and heat are linked; other studies discuss the spatial variability within a region as it related to transportation and land use systems. Another common region-wide application was high heat transportation management strategies which are not the focus of this paper. For example, 22 articles used emergency vehicle use during heat waves to understand the human impact of heat, including on transportation services. One of the studies found that during an extreme heat event, ambulance calls increased by 14% and overall mortalities increased by 13%; one can infer that this event had an impact on the response rate of emergency services and associated mortality displacement as a result of heat (Schaffer et al., 2012). We also found that this regional scale of analysis often links vehicular travel to air quality (n=32) including GHG emissions. For example, a simulated study found that redesigning streets to prioritize active transport, light rail systems, and open space resulted in better air quality through up to a 60% reduction of nitrogen oxides emissions (Liu et al., 2019).

When addressing smaller scales of urban heat, the literature focuses on several concepts. First is the notion of a microclimate (n=56) to describe the site level effects of urban heat. Many microclimate studies (n=82) specifically look at pedestrian-scale thermal comfort to capture the human experience at a street-level (Gaber et al., 2020) through measuring and modifying aspects of street morphology such as building height, street width, and orientation. It is also useful to know that the word pedestrian is used multiple ways. For example, pedestrian is often shorthand in the street morphology and meteorology world for measures taken approximately two meters off the ground but has nothing to do with the act of walking (Chew & Norford, 2019); we largely excluded studies that had no other transportation aspect besides “pedestrian-level” measures on a street. Researchers investigating personal heat exposure during walking and biking modes are much less common. There are a few notable exceptions (Caprì et al., 2016; Karner et al., 2015; Kim et al., 2018b; J. M. Lee, 2020; Ma et al., 2021; Vasilikou & Nikolopoulou, 2020).

We identified some surprising omissions given the role of vehicles in generating heat and impervious surface infrastructure that exacerbate the UHI effect. For example, there is very little within the literature about vehicular waste heat with some notable exceptions (X. Chen et al., 2021; Teufel et al., 2021; Wong, 2020). There is a small, but well-reasoned, body of literature grappling with the need to reduce pavement across the landscape at large to mitigate urban heat. These kinds of studies might evaluate the implementation of reflective pavements within parking lots to reduce the large level of pavement adding to the UHI (Sen et al., 2020), or the greening of paved areas to reduce pavement and increase shade all together (Martini et al., 2020).

Street-level transportation adaptation strategies within the articles reviewed generally mirror that of the greater heat adaptation and urban design literature. Articles specific to this more human-level scale were categorized as shown in Table 1 into four large strategies: cooling pavement, urban greening, using street morphology and design, and water-based solutions. Cool pavement (n=76) and urban greening (n=61) were most prevalent. Street morphology studies (n=59) tended to focus on shading to reduce heat with some attention to wind levels that often occur in street canyons created in urban areas with higher buildings. Water and misting strategies that leveraged evaporative cooling of water to reduce temperatures and improve comfort were less common (n=12), perhaps because many places dealing with extreme heat are also in arid climates with concerns about water use. We discuss each of these categories in more detail below.

***Cool Pavement***

We identified 76 articles looking at “cool pavement” strategies—evaluating the efficacy of reflective and permeable pavements, both alone and in comparison, with other traditional and cool pavement types. The studies are largely written from a materials engineering point of view, borrowing concepts from both increasing albedo using cool roofs and leveraging lessons learned from asphalt performance in higher heat (Mallick, R., et al., 2015). Most cool pavement studies discussed theoretical or lab-based performance; fewer evaluated cool pavements in the field.

In general, studies suggest reflective and permeable pavements can reduce surface temperature by 4-6°C (39.2-42.8°F) (Middel et al., 2020). However, the impact on the ambient temperature of the surrounding area and users is less clear. For example, cool pavements do not appear to be effective at reducing mean radiant temperatures, increasing thermal discomfort (Middel et al., 2020; Salman & Saleem, 2021). This may be because reflective pavements with higher albedo are more likely to reflect onto other surfaces, which can cause an increase in surrounding surface temperatures by 1-3°C (33.8-37.4°F) within the surrounding area (Ferrari et al., 2019). Middel also clarifies that the efficacy of reflective pavements depend on the context of the climate and built environment in which they are used (Middel et al., 2020). Other researchers are also concerned that reflecting light and heat from surfaces may result in negatively impacting pedestrian thermal comfort during colder periods, (Li et al., 2016).

Articles also explored the design details of cool pavements. For example, one article compared pigmentation of cool pavements; finding that white and yellow bricks had the greatest ability to reduce surface temperature by 10.2°C (50.4°F) and 8.2°C (46.8° F), respectively (Mun-soo et al., 2021). However, greening blocks – paver with embedded grass – still had the most potential to help promote pedestrian thermal comfort, reducing the surface temperature by 22.6°C (72.7°F) (Mun-soo et al., 2021). Most articles that assessed the efficacy of pedestrian thermal comfort via cool pavements suggested that they should be used in combination with vegetation and other cooling techniques (Cuculic et al., 2012). However, only a few articles compared the strategies. For those that did, urban greening is about 5°C (41°F) more effective at reducing the air temperature at the pedestrian level than cool pavements even though the increased humidity from greening may decrease thermal comfort in some climates (Maggiotto et al., 2021).

While our review focused on the transportation right-of-way, the ratio of parking lots is quite high in most urban areas, with one study of the Phoenix metropolitan area finding that 10% of the total urban land use are parking lots (Hoehne et al., 2019). Applying cool pavements and other cooling methods to surface parking lots may be a way to better study and extend the life of cool pavements which are often surface level treatments that can wear away quickly on high traffic roads (Maggiotto et al., 2021). Parking lots with higher albedo have been found to reduce the air temperature by about 1°C (33.8°F) (Sen et al., 2020). The implementation of reflective parking lots create microclimate scenarios in which there is no thermal stress for pedestrians, which is not achieved by typical parking lot scenarios (Sen et al., 2020).

***Urban Greening***

Urban greening and vegetation strategies for reducing localized heat, including along the roadway, are well represented in the literature we reviewed (n=61). Many of these articles (n=19) specifically refer to vegetation as shade provision to promote pedestrian thermal comfort while limiting associated solar radiation reflected by sidewalks (Kim et al., 2018). Many studies focused on urban greening incorporate additional co-benefits such as the ability to “diminish noise pollution, capture airborne pollutants, sequester carbon dioxide, and reduce stormwater runoff” (Lanza & Durand, 2021). Although artificial and natural shading produced the same thermal benefits (Middel et al., 2016), one study noted that vegetation as shading provides aesthetic benefits that promote outdoor activity and active transportation (Piselli et al., 2018).

The literature also grapples with variability in urban greening strategies. For example, trees with large crowns (T. Chen et al., 2021) typically provide the best pedestrian thermal comfort benefits and UHI mitigation when compared to other types of vegetation (Middel et al., 2021; Tiwari et al., 2021). Many of these studies also compared urban greening to other UHI mitigation strategies with wide consensus that vegetation was the best performing UHI mitigation strategy. For example, when compared with permeable pavements, greening pavements outperform in mitigating UHI by about 13°C (55.4°F) (Mun-soo et al., 2021).

Some challenges to urban greening along streets also appear in the literature; however, it is important to state most are context specific. For example, one study found that trees could be effective at promoting pedestrian thermal comfort during warmer seasons, however, increased shade could be hazardous during the winter months (Azcarate et al., 2021). Similarly other studies found that an increase of trees helps to cool during the day and create warmth at night, as larger canopies retain heat (Razzaghmanesh et al., 2021). These findings point to the importance of choice of species and orientations of the vegetation within the street to achieve the maximum UHI mitigation and pedestrian thermal comfort benefits (Lobaccaro et al., 2019).

***Street and Building Morphology***

The articles that discuss street morphology typically focus on the efficacy of street orientation and building design in creating shade in the context of street canyons. Many of these articles specifically look at the impact of the various street morphology aspects upon pedestrian thermal comfort (n=35) and how urban vegetation can be implemented within existing street design to support heat mitigation efforts (n=24). Other studies show that there is a very clear connection between the available urban landscape designs and travel behaviors of pedestrians (H. Lee et al., 2020; Masoud et al., 2020).

Street orientation and the related height-width aspect ratios heavily affect the intensity of thermal peaks and their overall duration (Lobaccaro et al., 2019). Because the built form and street orientation of buildings are not easily changed, much of the literature focuses on appropriately matching other heat reduction strategies to the existing environment (Morakinyo et al., 2019). For example, East-West oriented streets see better heat mitigation through vegetation (reduction in air temperature by 2.1°C, or 35.8°F) than North-South oriented streets (reduction in air temperature by 0.9°C, or 33.6°F) (Sanusi et al., 2016). Another study examined how the orientation and aspect ratio of green walls were significant in determining the efficacy of the technique’s thermal reduction (Morakinyo et al., 2019). In a simulated study, results showed that street orientation accounted for the largest contribution to the standard effective temperature at an average of about 54%; aspect ratio accounted for about 20% of the contribution to the standard effective temperature; while vegetation accounted for about 9% and surface albedo had about 6% contribution (Y. Zhang et al., 2017). Finally, some studies acknowledge that street design that prioritizes “mixed-land use, connected road network equipped with dedicated walking and cycling infrastructures” in conjunction with green spaces to significantly increase pedestrian thermal comfort and air quality can help reduce GHG emission and thus support a reduced UHI over time (T. Chen et al., 2021).

***Water***

We found several papers focused exclusively on water, including evaporative cooling and different permeable pavement types. As expected, some framed the heat reduction qualities as a co-benefit of localized stormwater infrastructure (Henderson & Tighe, 2011). For example, smaller manmade wetlands, or biobasins, can be integrated into the urban environment to store rainwater, provide increased pedestrian thermal comfort, and curb superficial flooding (McPhearson et al., 2016).

Some of the studies investigated the evaporative cooling function of permeable pavements, finding that permeable pavements are most effective as a tool for thermal comfort and UHI reduction if they have a constant source of water (Li et al., 2013). Although permeable pavements at full efficacy do not significantly impact air temperature or humidity, they exhibit more solar reflection and less infrared radiation (Shimazaki et al., 2021).This level of efficacy also has the potential to reduce the heat loads of both buildings and vehicles (Li et al., 2013).

Application of supplemental water was also considered. For example, smart wetting could be used to leverage permeable pavements and decrease surface temperature by about 20°C (68°F) at the most advantageous/hottest times of day, typically around 2-3PM (Kubilay et al., 2019). Another study assessed misting systems at an outdoor bus stop, finding that they are effective, especially at promoting thermal comfort for pedestrians who are momentarily stationary (M. Zhang et al., 2021). This study also noted that misting systems increase thermal comfort levels for women and those who are obese (M. Zhang et al., 2021).

**Discussion**

The primary purpose of transportation systems is to move people and goods. Yet the very act of travel exposes the user and non-users to environmental conditions – including heat - that impact their health and wellness (Poom et al., 2021). The transportation infrastructure enabling movement is also a primary contributor to GHG emissions and UHI. This scoping review demonstrated that transportation planning and engineering can help mitigate urban heat. There are a wide range of transportation planning and design techniques that can reduce the overall UHI and more localized impacts of heat. The promotion of pedestrian, bicyclist, and transit user comfort, specifically thermal comfort, can help make active travel modes more comfortable, leading to decreased GHG emissions contributing to climate change.

As urban heat increases the dangers posed by climate change, heat mitigation techniques must be integrated into all parts of planning. Transportation planners may be tempted to conceptualize heat as a hazard similar to flooding, but this may inappropriately restrict attention to extreme heat events. We argue that increasing chronic heat risk during the lengthening and intensifying summer season is also a growing concern. Outdoor activities–particularly those between mid-day and late afternoon– will become riskier, even with steadily rising average temperatures. Travel activities are no exception. An older adult waiting for transit in the afternoon will be at higher risk than those traveling in an air-conditioned vehicle; possibly indicating a need for shorter bus headway times, even during off-peak hours, during particularly hot times of the year. Similarly, tweens and teens in lower-income neighborhoods often seek shelter and activities at an air-conditioned community center mid-day during the summer, usually walking through built environments with fewer trees and shading during the midday heat. Safe Routes to Schools–arguably one of the most successful modern active travel campaigns–typically view trees as making the walk pleasant. Reframing greening as a safety need would reduce heat risk during afternoon travel while also likely increasing active travel.

The selected articles represented a breadth of locations; however, the majority of studies took place in locations that are more likely to face extreme heat events. Within the United States, most of the studies focused on places with arid climates, specifically Arizona and California. For example, there were 7 studies focused on water that took place within the US, the majority seemed to take place within areas that experience regular extreme heat events–including Arizona, California, and South Carolina. It seems that there is a larger focus on studying heat mitigation techniques in places that are/will face the most acute thermal discomfort and depletion of natural resources through climate change. From a global perspective, this trend is also apparent. Many of the studies are in countries and cities that face growing thermal discomfort and extreme heat events, reflecting a current and future need to implement the studied strategies. Additionally, as each microclimate will have different heat mitigation needs, it will be crucial to increase studies in places that are not used to extreme heat events to prepare for increasing impacts of climate change.

Although transportation systems contribute to and are impacted by heat, viable solutions will require an interdisciplinary approach. Transportation planners must work with a variety of professions to ensure that proposed transportation-focused heat resilience solutions do not cause more harm to the environment, disenfranchised communities, and public health. Planners can assess how different techniques can impact overall health via pedestrian thermal comfort through a public health lens. Architecture and landscape architecture can help to design sustainable and resilient buildings and landscapes that can optimize thermal comfort and UHI mitigation at the site level, contributing to increased thermal comfort at the city-scale. Politicians and activists can help develop equitable and achievable policies that support heat mitigation techniques that best serve the community. Additionally, urban forestry efforts can assist in providing the native vegetation that achieve the location’s desired effects. Finally, transportation planners can provide their expertise to implement the most effective solutions in reducing GHG emissions and mitigate urban heat while providing increased pedestrian thermal comfort and streets that support safe active transport.

We argue the corridor should be leveraged as an appropriate scale of planning for implementing urban heat resilience strategies. While site level decisions are important, conceptualizing more holistic “cool corridors” provides an umbrella for synergies while matching strategies to built environment variation within a region(Ladd Keith & Sara Meerow, 2022). This includes a context-relevant combination of mitigation strategies such as cool pavement, urban greening, street and building morphology, and water use. Transportation professionals can also employ heat management strategies, such as closer transit headways during summer, public awareness and education campaigns, and training transit employees to be aware of heat illness symptoms. These cool corridor strategies should be selected by matching strategies to modal risk. For example, cool corridors along high frequency transit routes could emphasize bus shelters designed for shade while bikeways or greenways could focus on urban greening.

The cooling effect magnitude by urban heat mitigation strategy was difficult to ascertain from the literature. Many of these strategies are emergent and variations in climatological, meteorological, and built environment context and in measures makes accurate comparison of strategies difficult. For example, cool pavements leverage surface temperatures, street morphology is highly sensitive to wind, and water and greening strategies are highly sensitive to humidity. Transportation funders and researchers could better support municipalities through study designs that simultaneously compare two different strategies (i.e. cool pavements and shade).

Shade from urban greening, buildings, and built structures often outperform other heat mitigation techniques when considering human thermal comfort. Urban greening and heat mitigation have been the most scientifically developed, which supports the current understanding of this technique’s efficacy. As urban greening is in the quasi-purview of transportation professionals, they can be directly implemented within transportation plans. In addition to heat mitigation, urban greening can promote aesthetic appeal of a given area. This makes it imperative for trees and other vegetation to be better integrated into streetscapes. Urban greening needs to be forward looking, matching plant species to our hotter – and when applicable, more arid – future. Our own experience with local governments is that urban greening in dense areas can often be difficult because of tensions around right of ways, utilities, early watering during establishment, and ongoing maintenance plans. This, again, speaks to the need for a multi-disciplinary approach to our streets.

When vegetation is not a viable option, built shade structures and engineered cool materials can help. Maximizing these strategies requires more study including evaluation in real-world conditions. Pavement choices are within transportation professionals’ control and there are many opportunities for cool pavement implementation. However, this is an emerging field of study and more study is required to understand how and when to best use cool materials in conjunction with other heat mitigation techniques. Cool pavements also add expense to already stretched paving budgets. Studies including cost-benefit analysis of cool pavements would be helpful.

Although urban design does not exclusively fall into the realm of the transportation professional, street and building morphology should be considered. Building orientation and resulting street canyons can provide shade and increased winds that can promote pedestrian thermal comfort. However, the implementation of this technique requires an interdisciplinary effort that may be difficult to coordinate: zoning, land-use, private developers, transportation, urban forestry and more would need to work together. It may be more realistic to consider street orientation and aspect ratio as an existing factor rather than a heat mitigation strategy.

The use of water also proves to be a useful heat mitigation technique, particularly in less humid environments. However, many regions facing the impacts of extreme heat and UHI have finite water available. These strategies may be unsustainable for arid environments or regions experiencing severe water shortages. Cities in these regions might be better off forgoing pavement wetting or misting in favor of reserving water to support current urban tree canopy and establish young, drought-resistant trees, planted in areas with the highest shade creation for pedestrians.

Transportation planners have the ability to mitigate urban heat, reduce GHG, and address the increasing impacts of climate change to help create more heat resilient communities. As urban heat mitigation strategies become increasingly well-known and more commonly used, implementation must incorporate the context of local culture, climate, and built environment. There is no silver bullet to address increasing heat across all diverse communities, meaning that it will take research and evaluation to find the optimal combination of urban heat resilience techniques that ensure the best thermal comfort. With climate change and UHI continuing to increase, we call for action to address and reform our transportation needs and behaviors. It is imperative that active and public transportation receives necessary investment in design, planning, and implementation, especially in areas with less access to private vehicles and a heavier heat burden. Actions to mitigate heat will serve to create equitable communities that are more environmentally, socially, and economically sustainable.

**Author Statement**

The authors confirm contribution to the paper as follows: Iroz-Elardo, Keith, Currans, Heath study conception and design; Iroz-Elardo, Heath data collection; Iroz-Elardo, Heath, Keith, Currans analysis and interpretation of results; and Heath, Iroz-Elardo, Keith, Currans manuscript preparation. All authors reviewed the results and approved the final version of the manuscript.

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