Urban Heat and Transportation: Human Exposure and Infrastructure

by

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ABSTRACT

Environmental heat is a growing concern in cities as a consequence of rapid urbanization and climate change, threatening human health and urban vitality. The transportation system is naturally embedded in the issue of urban heat and human heat exposure. Research has established how heat poses a threat to urban inhabitants and how urban infrastructure design can lead to increased urban heat. Yet there are gaps in understanding how urban communities accumulate heat exposure, and how significantly the urban transportation system influences or exacerbates the many issues of urban heat. This dissertation focuses on advancing the understanding of how modern urban transportation influences urban heat and human heat exposure through three research objectives: 1) Investigate how human activity results in different outdoor heat exposure; 2) Quantify the growth and extent of urban parking infrastructure; and 3) Model and analyze how pavements and vehicles contribute to urban heat.

In the urban US, traveling outdoors (e.g. biking or walking) is the most frequent activity to cause heat exposure during hot periods. However, outdoor travel durations are often very short, and other longer activities such as outdoor housework and recreation contribute more to cumulative urban heat exposure. In Phoenix, parking and roadway pavement infrastructure contributes significantly to the urban heat balance, especially during summer afternoons, and vehicles only contribute significantly in local areas with high density rush hour vehicle travel. Future development of urban areas (especially those with concerns of extreme heat) should focus on ensuring access and mobility for its inhabitants without sacrificing thermal comfort. This may require urban redesign of transportation systems to be less auto-centric, but without clear pathways to mitigating

impacts of urban heat, it may be difficult to promote transitions to travel modes that inherently necessitate heat exposure. Transportation planners and engineers need to be cognizant of the pathways to increased urban heat and human heat exposure when planning and designing urban transportation systems.

DEDICATION

I dedicate this dissertation to my partner Jazmine, my mother Bonita, and my father Terry. Without their endless support, love, and admiration, this work would not have been possible.

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CHAPTER 1

INTRODUCTION

1.1 Heat and Cities

Concerns are mounting as severe consequences of rapid urbanization and climate change become evident. According to the United Nations, the world's urban population is projected to break six billion by 2045, making up two thirds of global inhabitants (UN, 2015), and over four fifths of all U.S. inhabitants already live in urban areas, accounting for 3% of the U.S. land mass (US CB, 2016). The rapid urbanization and modern industrialization of the past century has driven anthropogenic climate change, threatening human well-being. Consequences of climate change include increased variability and extremes of temperatures and precipitation, sea level rise, worsening air quality, and impacts to water, food, and energy security (Crimmins et al., 2016; Foley et al., 2005; Patz et al., 2005). As a result, large bodies of research have been dedicated to understanding and mitigating negative impacts related to the issues of urbanization and climate change (IPCC, 2015; Madlener & Sunak, 2011; Wall et al., 2007), and adaptation strategies that engage stakeholders have proven beneficial to cities (Hunt & Watkiss, 2011).

A major consequence of urbanization is Urban Heat Island (UHI): a phenomenon where temperatures in urban regions are higher than rural regions due to built infrastructure and anthropogenic waste heat. UHI has been documented in cities across the world, where nighttime urban temperatures can be as high as 12 °C greater than nearby rural areas (TR Oke, 2002). Although UHI is most prominent during the winter and nighttime, increases in urban daytime temperatures are still significant; urban daytime air temperatures are typically 1 to 3 °C higher than rural temperatures, but could be as high as nearly 9 °C (Kolokotroni & Giridharan, 2008). With the additional threat of increasing frequency, severity, and duration of heat waves (Luber & McGeehin, 2008), past research has identified many consequences of urban heat including negative impacts to public health, diminished community well-being, reduced economic activity, increased energy use, and added stress to urban infrastructure (Bondank et al., 2018; Burillo et al., 2019; Kovats & Hajat, 2008; Stamatakis et al., 2013).

Environmental heat is a major threat to human health. The immediate impacts of heat to humans include thermal discomfort, fatigue and exhaustion, cardiovascular and respiratory issues, and heat stroke. Heat stress may require medical attention, especially under extreme temperatures or severe durations, possibly leading to injury or death. As a result, significant numbers of deaths have been attributed to heat across the globe in the past few decades (Berko et al., 2014; Gasparrini et al., 2015; Gosling et al., 2009; Saha et al., 2013), and environmental heat is a leading cause of weather-related fatalities in the United States (CDC, 2012). Additionally, there are significant variations in heat-related health outcomes across socioeconomic status (Harlan et al., 2013; Reid et al., 2009; Uejio et al., 2011). Social and built environment factors that may increase heat vulnerability include: pre-existing medical conditions, poor access to quality housing, limited access to green space, and low access to air-conditioning or cooled spaces (Eisenman et al., 2016; Kovats & Hajat, 2008; O’Neill, 2005). In addition to these direct health-related impacts, heat can disrupt participation in healthy activities which could have adverse effects on the urban populations’ physical and mental health. Increased human heat exposure may reduce and limit productivity, threatening economic development and prosperity

(Kjellstrom et al., 2009). As a result, there is an established but growing focus on understanding human heat exposure to improve public health.

The transportation sector is naturally embedded in the issue of urban heat and human heat exposure. Some prevalent modes of urban travel, such as walking, biking, and transit use, necessitate exposure to heat in hot climates (Fraser & Chester, 2017). Previous research has identified that socioeconomically disadvantaged groups may be disproportionately affected by travel-related heat exposure, identifying the need for equitable transportation planning that considers heat (Karner et al., 2015). Transportation infrastructure also influences urban heat and human heat exposure, and central to the issue is the dependence on the automobile. Excess solar energy is stored and emitted from urban pavement infrastructure, significantly influencing the urban heat balance. As a result, researchers have thoroughly investigated pavement applications to mitigate UHI and enhance thermal comfort. However, no clear consensus exists on how to best implement pavement technologies such as cool pavements to reduce human heat exposure. Waste heat emitted from internal combustion engines (ICE) during urban vehicle travel is another transportation-related factor that can contribute to urban heat. In some cases, anthropogenic waste heat may be an order of magnitude higher in city centers, indicating that waste heat from human sources (including vehicle use) may be a major factor for localized variations in urban climates (Sailor & Lu, 2004). Urban form is an emergent phenomenon of transportation and city planning and can also affect urban microclimates. Street and neighborhood design can affect the local climate and the prevalence of local cool or heat islands (Johansson, 2006). Previous research spanning many disciplines has investigated mitigation strategies to urban heat and human heat exposure, and it is clear that long-term transportation planning should consider heat impacts on travelers (especially in hot urban climates). Yet gaps exists in understanding the transportation sector's complete role in urban heat and human heat exposure, and to identify ideal solutions for mitigation, the issue of urban human heat exposure as a consequence of the transportation sector should be further explored.

1.1.1 Transportation and Urban Human Heat Exposure

Travel by walking, biking, and transit necessitates exposure to heat especially in hot climates (Fraser & Chester, 2017), posing issues for urban planning towards active and public transit in favor of personal automobile use. Despite clear issues of heat exposure during travel, few studies have assessed heat exposure during travel, and there remains gaps in identifying how travelers accumulate heat and how it can be mitigated. Few studies exist that simulate or quantify heat exposure during urban travel. Swarup et al. (2017) simulated heat exposure in an urban traveler population by modeling travel in a synthetic Alabama population. Their results indicate that this approach is valuable to examine heat exposure through travel at the population level, and could even be used to evaluate different mitigation strategies or policies. Karner et al. (2015) examined heat exposure and travel data in the San Francisco Bay Area and found that because disadvantaged groups more commonly walked and biked, targeting heat exposure mitigation through active travel could have disproportionate benefits to vulnerable groups. Similarly, Taylor and Morris (2015) highlight that public transit serves lower income individuals most, but transit agencies often focus on appealing to more affluent demographics rather than improve transit quality in low income areas. As previous research has established that disadvantaged populations are more vulnerable to heat and more often rely on active and public transit, there is significant value to improving understanding of heat exposure during travel. Research has also shown that transportation system design could influence heat exposure. Fraser & Chester (2016) found that because transit system design focuses on constraints not including heat exposure, certain travelers could be adversely impacted and vulnerable during extreme heat. Other research has investigated heat exposure at smaller sample sizes through case study approaches, identifying that significant heterogeneity in exposure profiles exist between individuals in similar climates (Bernhard et al., 2015; Kuras et al., 2015). These studies identify the need for city and transportation system planners to strengthen adaptive capacity to ensure travelers can be better protected during periods of extreme heat.

Although heat exposure during active travel has been researched, it is unclear how travel behavior is influenced by extreme heat conditions. In general, research has shown that weather influences travel patterns (Cools et al., 2010). Several studies have shown that weather impacts transit ridership with positive and linear correlations between temperature and outdoor travel frequency, indicating temperate weather is most desirable for outdoor travel (Arana et al., 2014; Kalkstein et al., 2009; Singhal et al., 2014). Some research has been identified that pedestrians may walk faster under higher temperatures (Rotton et al., 1990), but there is limited research and data that documents travel behavior in extreme heat periods as weather rarely reaches extremes. As a result, there is no research that asserts the effects of extreme heat on travel patterns, although it is intuitively expected that heat will dissuade or alter travel in some way. Climates shifting towards more temperate weather year-round may also attract more tourism (Gössling et al., 2012; Maddison, 2001), but no research has estimated at what point cities might lose inhabitants due to increased thermal conditions. If the threat of heat stress or diminished thermal comfort during extreme heat periods limits travel mobility and accessibility, there is potentially many negative impacts to the urban community, especially if individuals of lower socioeconomic status are the first to change or avoid travel. Consequences of heat-caused behavior shifts could have downstream impacts on public transit ridership and solvency, tourism, commerce, and other sectors. Reduced mobility and accessibility during hot periods could decrease economic output and prevent those who rely on walking, biking, and transit to access jobs, health care, and other important services. Furthermore, reduced time spent outdoors could reduce health-related benefits. In the US, researchers have found high temperatures may deter or constrain outdoor physical activity (Graff Zivin & Neidell, 2014; Obradovich & Fowler, 2017), leading to decreases in total physical activity. As physical activity has been widely shown to have positive physical (Sallis et al., 1998) and mental (Frumkin et al., 2017) health benefits, community health could be affected by more than just direct heat stress. With potential of increased heat waves, average temperatures, and frequency of extremely hot days, mitigation of heat exposure during walking, biking, and transit should be important to communities to promote healthy lifestyles, social equity, and a strong, resilient economy.

1.1.2 Transportation Infrastructure’s Influence on Urban Heat

Paved surfaces, the largest component of transportation infrastructure in most urban regions, strongly affect the local heat balance by reflecting, absorbing, and emitting energy, influencing urban heat and human heat exposure. In the urban US, asphalt and concrete travel ways, parking lots, and sidewalks account for approximately 30-40% of land cover (Akbari et al., 2003; Rose et al., 2003), and may reach as high as 40-66% in non-residential areas (Akbari & Rose, 2001a, 2001b). Asphalt pavement, the dominant type of urban surface pavement, has low ratios of irradiance reflected to absorbed (albedo). Paved surfaces with high albedo (often referred to as 'cool' pavements) absorb less solar energy by instead reflecting it, reducing the heat emitted into the local environment. Previous research has established that increasing pavement albedo reduces the pavement surface temperature (Asaeda et al., 1996; Gui et al., 2007) and may lower nearby peak ambient temperatures by 1-2 °C (Carnielo & Zinzi, 2013; Santamouris et al., 2012). However, increasing pavement albedo may increase the radiant load on nearby pedestrians, thereby decreasing their thermal comfort (Erell et al., 2014; Li et al., 2016; Taleghani et al., 2016). As a result, ambient air temperature reductions from cool pavements may be ineffective at increasing human thermal comfort. Although many pavement designs are promoted to mitigate heat, it is not yet clear what designs in which situations would be most effective in reducing urban heat and improving human thermal comfort.

Although cool pavements are often promoted as a strategy to reduce urban heat, there is evidence that high pavement albedos may compromise local pedestrian thermal comfort. Due to increases in reflected solar radiation, cool pavements can increase mean radiant temperature (MRT) and physiological equivalent temperature (PET), two important metrics in measuring human thermal comfort. MRT measures the net radiant heat exchange in an environment, and in turn impacts PET, a thermophysiological comfort index. Erell et al. (2014) found that small decreases in air temperature only partially offset the increased radiant burden to pedestrians near cool pavements. They estimated an increased thermal load on pedestrians of up to approximately 30 W per 0.1

increase in albedo, with the highest thermal loads occurring in the afternoon. They also find that after a certain level of urban compactness (high ratios of building height to street width), the effects of increased albedos on pedestrian thermal loads are negligible. Taleghani et al. (2016) simulated changes in microenvironments in a neighborhood in Los Angeles, CA and found that increased reflected solar energy from cool pavements may increase PET by 2.2 °C and MRT by 7.8 °C. No research has monitored the before and after ambient air temperatures from cool pavement implementation, indicating a gap in understanding direct in-situ benefits.

Parking lots in urban regions contribute to a significant fraction of urban paved surfaces, are an important factor in urban design, and their influence on urban heat is understudied. Parking lots often consist of impervious, low albedo asphalts, and have been identified as miniature heat islands (Aniello et al., 1995; Scott et al., 1999). Parking lot use also necessitates heat exposure by means of access and egress to automobiles. The extent of available parking and minimum parking requirements in the US has often been lamented by researchers as constraining urban design, encouraging automobile dependency, and driving urban sprawl (Amélie Y. Davis et al., 2010; Shoup, 1997). Despite the fact that abundant parking exists, little research has quantified the magnitudes of available parking in urban regions (Chester et al., 2015). All these factors may indirectly affect the urban climate; reduced ICE vehicle use could reduce vehicle waste heat, and urban design not devoted to the automobile could reduce sprawl and pavement land cover. Most research on the thermal performance of pavements does not mention or quantify the contribution of parking compared to travel ways. Additionally, parking lots can have negative impacts to co-located vegetation, which can provide localized cooling benefits. Celestian and Martin (2004) found that soils adjacent to or under asphalt parking lots were warmest compared to other types of landscapes in Phoenix, AZ. The authors indicate this to be an important factor explaining why parking lot trees in hot desert climates grow poorly compared to trees not near asphalt surfaces. Given the high amount of urban land dedicated to pavements, more research could investigate the role of parking infrastructure on urban heat island to identify additional mitigation opportunities through urban design.

Urban form also influences the urban climate (Hart & Sailor, 2009; Middel et al., 2014; Stewart & Oke, 2012), and urban form is a major consequence of transportation planning. Properties of urban form such as street orientation, path shading, and building heights can all influence the thermal comfort of outdoor travelers. Streets within deep building canyons are preferable due to increased shading and protection from incident solar radiation, especially in dry hot climates (Johansson, 2006). Orientation of street canyons also affects the amount of solar exposure, such that east-west oriented streets are exposed to higher amounts of solar radiation (Andreou & Axarli, 2012; Bourbia & Awbi, 2004; Bourbia & Boucheriba, 2010; Erell et al., 2014). Urban form may also influence the prevalence of extreme heat events; Stone et al. (2010) found that sprawled metropolitan regions had twice the rate of extreme heat events compared to more dense metropolitan regions. Promoting dense urban form has been associated with local cool islands during mid-afternoons due to high shade and decreased surface absorption of solar radiation (Middel et al., 2014). Given these findings, it is clear that intelligent city and transportation planning could play a role in mitigating heat exposure to urban inhabitants.

Due to high volumes of travel and inefficiencies from ICE vehicles in urban regions, anthropogenic waste heat from urban vehicle travel may be a notable contributor to the urban heat balance. Even with continuing improvements to engine efficiencies, modern ICE automobiles still waste significant amounts of fuel energy as heat. Typically, around two-thirds of fuel energy in ICE vehicles is lost as waste heat through exhaust and coolant (Endo et al., 2007; Hsiao et al., 2010; Saidur et al., 2009; Yu & Chau, 2009), and as much as 80% of fuel energy can be lost to waste heat under very poor conditions (Orr et al., 2016). In addition, combustion of fuel generates water vapor and air pollution which may also affect the urban climate. Therefore, waste heat from vehicle travel is an important factor to consider when assessing urban heat.

Some research exists that quantifies the influence of vehicle travel on urban anthropogenic waste heat, however, there is limited research that quantifies and explores how changes in vehicle travel may influence local climate and human heat exposure. According to Sailor and Lu (2004), most cities have peak anthropogenic waste heat values between 30 and 60 W m^{-2} (city-wide averages) and heating from vehicles could make up as much as 62% of the total in summer months. In another study, Hart & Sailor (2009) used in-situ measurements in Portland, OR to evaluate spatial variability of air temperatures over urban roadways. They found that air masses near major roadways are some of the warmest in the region. Although some of the warming is attributed to the pavement, an average increase of 1.3 °C was observed on weekdays relative to weekends along roadways. The authors offer increased waste heat via weekday traffic and building use as the likely contributors to this discrepancy. In Smith et al. (2009), vehicle waste heat was estimated to account for 32% of anthropogenic heat fluxes in Manchester, UK.

These previous studies indicate that vehicle related waste heat is an important factor in the urban energy balance. There may exist viable strategies to reduce anthropogenic waste heat from urban vehicle travel by increasing the fleet fuel economy and shifting to electric vehicles. This could offer cooling in urban areas around roadways were pedestrians are often found.

1.2 Research Objectives

Some aspects of how urban transportation affects urban heat and human heat exposure are underexplored. There are few studies that model or quantify heat exposure during activities, especially across whole urban populations, making it difficult to understand how engaging in various activities contributes to exposure, vulnerability, and opportunities for mitigation. There are also gaps in understanding how transportation infrastructure and transportation planning can influence urban heat exposure. One specific element of transportation infrastructure is also understudied in the context of urban heat: few studies have quantified the extent of urban parking infrastructure, and as a result, it is difficult to quantify the influence of parking infrastructure on UHI. Finally, previous research has established that pavement infrastructure and vehicle travel may significantly contribute to urban heat, yet little research examined the nexus of pavement and vehicle heat contributions to the urban heat balance. To fully understand the transportation systems impact on urban heat and human heat exposure, this dissertation seeks to address these highlighted research gaps through three primary research objectives:

I. Investigate how human activity results in different outdoor heat exposure
II. Quantify the growth and extent of urban parking infrastructure

III. Model and analyze how pavements and vehicles contribute to urban heat

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CHAPTER 2

HEAT EXPOSURE DURING OUTDOOR ACTIVITIES IN THE US VARIES SIGNIFICANTLY BY CITY, DEMOGRAPHY, AND ACTIVITY

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2.1 Introduction

Cities face warmer futures as a consequence of continued urbanization and global-scale climate change, and health needs related to heat may grow independently of projected warming as urban populations grow and age (McCarthy et al., 2010). Heat already ranks as a leading weather-related cause of human mortality and morbidity in the US (Berko et al., 2014), and improved planning, preparedness, and response strategies are required now and into the coming decades.

The immediate impacts of heat on human health and well-being span a wide range of events and outcomes, including thermal discomfort, fatigue and exhaustion, cardiovascular and respiratory distress, and heat stroke. Beyond these immediate effects, heat has the potential to disrupt other health-promoting activities. In some regions, heat may deter or constrain outdoor physical activity (Graff Zivin & Neidell, 2014; Obradovich & Fowler, 2017), which has been widely linked to physical (Sallis et al.,

1998) and mental health benefits (Frumkin et al., 2017). Furthermore, if heat affects how and where people choose to spend their time, downstream impacts on public transportation, tourism, commerce, and other sectors could occur. Thus, there should be wide interest in understanding more precisely the nature of people's experiences with heat in cities, not only to reduce adverse health events, but also to help cities achieve other goals related to economic growth, efficiency, equity, and overall quality of life.

Vulnerability to heat and other hazards is often defined as a function of exposure, sensitivity, and adaptive capacity (Eisenman et al., 2016; Turner et al., 2003). Regardless of the specific framing used to define risk or vulnerability, *exposure* is a critical link in the causal pathway that connects environmental heat to societal outcomes of interest. At the population scale, there have been significant advances over the past several decades in understanding how weather conditions contribute to mortality and morbidity in cities (Anderson & Bell, 2009; Eisenman et al., 2016; Gasparrini et al., 2015; Saha et al., 2013). The repeated identification of temperature-mortality and temperature-morbidity associations across the world points to the obvious importance of exposure. Previous literature has widely established the link between lower socioeconomic status and increased risk of negative heat-related health outcomes (Eisenman et al., 2016; Harlan et al., 2013; Pickett & Pearl, 2001; Reid et al., 2009; Uejio et al., 2011). Characteristics such as higher rates of pre-existing health conditions, lower quality housing, less access to cooling resources, and low surrounding vegetation are common determinants of increased risk. Individuals living in poverty have higher rates of pre-existing health conditions (Joseph et al., 2007; Phelan et al., 2010) and decreased ability to access necessary medical care or cooling resources (Balbus & Malina, 2009), leading to increased risk (Kovats & Hajat, 2008). However, the specifics of population heat exposure—necessitating contact between individuals and the environment—has rarely been considered in heat-health risk assessments as it has been in other environmental topics such as pollution exposure (Ott, 1985). Understanding the circumstances by which people are exposed to heat and how this exposure varies at scales ranging from person-to-person to city-to-city may offer new insights into the risk mitigation and adaptation strategies that might be most efficient or beneficial.

Assessment of heat exposure at the individual level can be difficult, and consequently much research focuses on place-based rather than person-based assessments. Personal heat exposure is defined as contact between an individual and an indoor or outdoor environment that poses a risk of thermal discomfort and/or an increase in core body temperature (Kuras et al., 2017). Thus, assessment of personal heat exposure requires not only information about environmental conditions, but also information about people and their time-activity patterns. Although observational and simulation data related to human time-activity patterns are at the core of exposure assessment for other hazards such as air pollutants (Jerrett et al., 2005; Park & Kwan, 2017), such data have infrequently been collected or examined to understand the nature of health risks associated with heat. The research that does exist spans case study approaches using wearable sensors (Bernhard et al., 2015; Kuras et al., 2015); city-scale assessments using simulation tools (Glass et al., 2015; Karner et al., 2015; Swarup et al., 2017), and analysis of national-scale survey data (Graff Zivin & Neidell, 2014; Obradovich & Fowler, 2017). In addition to heat exposure, activity intensity can also influence heat stress; higher physical exertion (i.e. increased metabolic rates) can accelerate heat exhaustion

(Armstrong et al., 2007; Havenith et al., 1998). However, heat exposure research lacks quantification of the intensity of physical activity during hot weather despite clear guidelines to avoid high intensity physical activity when heat stress is possible (OSHA, 2017). As a result, there is opportunity to evaluate activity intensity alongside heat exposure to identify if activity intensity is an overlooked factor when evaluating heat exposure.

To address these research gaps, we focus on two main research questions: 1) How does human activity lead to different levels of outdoor heat exposure in the US urban population? and, 2) How does accumulated heat exposure vary amongst population subgroups in US urban areas?

2.2 Methodology

To evaluate the relationship of heat exposure with activity, urban location, and demography across the contiguous US, individual-level time-activity data from the American Time Use Survey (ATUS, years 2004 to 2015) are combined with weather data for major metropolitan statistical areas (MSAs) in the US. Heat exposure during activities is assessed using measures of metabolic intensity, activity duration, and regional apparent temperature.

2.1.1 Activity Data

Administered by the Bureau of Labor Statistics (BLS), the ATUS is an annual and ongoing survey that estimates national trends in labor, health, and social activity. Time use data from the ATUS are compiled to identify historical activity patterns in the urban US Individuals age 15 or older are eligible, and questions are asked via computer-assisted telephone interviewing about time use, socioeconomic status, and characteristics of their household (BLS & US Census Bureau, 2016). The survey of respondent's time use encompasses all activities during a pre-determined 24-hour date. We choose the ATUS to evaluate individual heat exposure because it comprehensively documents daily personal time use over a long period for many individuals living in different cities. Activity records are temporally explicit, allowing regional temperatures to be matched with each activity to estimate heat exposure for activities that occur outdoors. We focus on aggregation of ATUS records at the MSA level to compare regional patterns in exposure. This is the smallest spatial scale at which sufficient sample sizes exist for a multi-city analysis, allowing for comparisons across activity times and types, demographic groups, and MSAs. The ATUS has been conducted since 2003, but data utilized is from July 2004 to December 2015 due to significant changes in the survey in mid-2004.

To identify geographic locations of activities, ATUS records are matched to records from the Current Population Survey (CPS) to identify the corresponding MSA of residence for each household (Flood et al., 2015). We choose 50 of the most populous MSAs for evaluation such that a high sample of outdoor activities during hot weather across multiple climates could be assessed. Appendix **Tables A1** and **A2** summarize the MSAs included, and **Figure 1** displays a US map with climate zone classifications and MSAs locations. We group MSAs according to the US Department of Energy climate zone classifications (Baecheler et al., 2010) to compare urban heat exposure patterns across contiguous US climates. As this classification system is at the county level, we aggregate up to the MSA level. Of the MSAs in this analysis, 12 have inter-county, intra-MSA climate zone classifications. In these cases, the dominant climate zone by population cover is chosen (see Appendix **Table A3** for details).

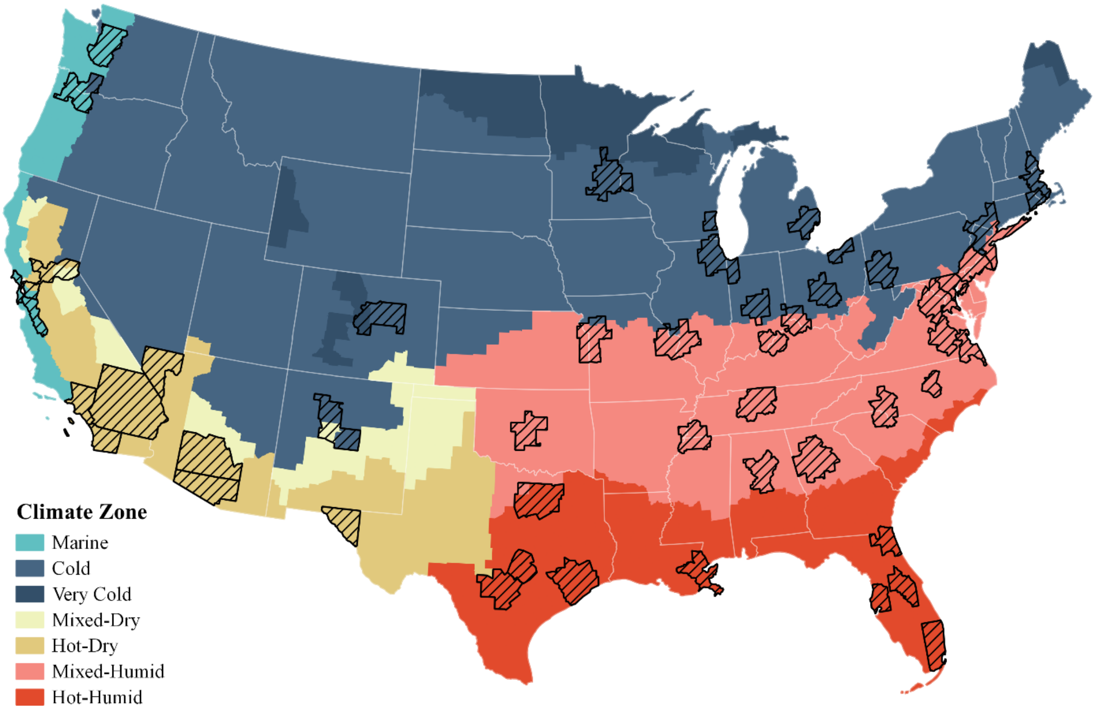

Figure 1. Metropolitan Statistical Areas Studied with Climate Zones Classifications. MSAs included in this analysis are hatched in black. For a list of the MSAs, please see the SI. Note that the 'Very Cold' climate zone is not represented as a dominant climate zone for any MSA studied.

2.1.2 Classifying Outdoor Activities

This analysis focuses on outdoor activity and its associated heat exposure and metabolic intensity. ATUS activity types and location codes were reviewed to determine which activities occur indoors, outdoors, or at an unknown location, following a similar approach to Zivin and Neidell (2014). As this classification scheme is conservative with marking activities as occurring outdoors, actual time spent outdoors by ATUS respondents may be underestimated.

Activities (ATUS variable TRCODEP) are coded as occurring outdoors or elsewhere (inside or unknown) based on the activity description. Activities are coded as occurring indoors or outdoors if they are explicitly described as such or are highly probable to occur indoors ($P_{indoor} \gg P_{outdoor}$) or outdoors ($P_{indoor} \ll P_{outdoor}$). Note that probabilities for these activities to occur indoors or outdoors are not explicit but used as examples for context. For activities that usually occur indoors but may occur outdoors depending on circumstance ($P_{indoor} > P_{outdoor}$), a classification of 'indoors' is chosen. For remaining cases, such as activities that could reasonably occur either indoors or outdoors ($P_{indoor} \cong P_{outdoor}$), or locations with vague descriptions, a classification of unknown is chosen. The distinction between indoor activities and activities with an unknown location is trivial for this analysis because only outdoor heat exposure is being investigated, but indoor and unknown activity locations are still differentiated for clarity. Examples of probable indoor activities are "laundry", "bowling", and "computer use;" examples of probable outdoor activities are "exterior [household] cleaning", "hiking," and "golfing;" examples of activities with unknown indoor/outdoor classifications are "traveling", "tobacco and drug use", and "playing basketball". Some examples of activities that are coded as indoors under the assumption the activity usually occurs indoors are "eating and drinking", "watching football", and "playing with children (not sports)." For a full list of how ATUS activities are classified, see SI Section 1.2.

A separate variable, activity *location* (TEWHERE), is also coded as indoors, outdoors, or unknown using the same above classification scheme independent of the activity type. For the given activity locations, only "walking," "biking," "outdoors away from home," and "boat/ferry" are classified as outdoor locations while all other locations are indoors or unknown (e.g. "bus", "library," and "bank" are indoors; "unspecified place" and "other mode of transportation" are unknown). This approach is used so that in cases where the location is unknown based on activity type (e.g. "playing basketball"), the activity can still be marked as indoors or outdoors when the activity location is known (e.g. “outdoors away from home”) and vice versa. In cases where the activity type and location have conflicting indoor/outdoor codes, a code of outdoors is assigned. This is done because the coding is conservative in assigning outdoor activities, therefore an outdoors code is assumed dominant (e.g. “eating and drinking” is coded occurring indoors but would be coded outdoors if it occurs “outdoors away from home”).

Across all work-related activities, less than half a percent occurred “outdoors away from home,” and 72% occurred at “the respondent’s workplace,” the latter of which does not differentiate between indoor and outdoor presence (and thus, were *not* coded as occurring outdoors in our analysis). Therefore, work-related outdoor heat exposure is likely under captured in the ATUS, and this analysis focuses on non-work related activities.

2.1.3 Weather Data

Weather data are obtained from the US National Centers for Environmental Information for each MSA at hourly and sub-hourly times coincident with the ATUS records. Consistent with other multi-city scale assessments of temperature-health risks, meteorological stations are chosen based on completeness of weather records and proximity to MSA population centers with use of one station per MSA.

Outdoor environmental heat is quantified using apparent temperature (T_A). Apparent temperature is commonly used as a combined temperature-humidity index that is intended to represent thermal stress associated with environmental heat as perceived by a human body (Brooke Anderson et al., 2013; Zanobetti & Schwartz, 2008). T_A is estimated using the National Weather Service (NWS) parameterization of the original

Steadman (1979) apparent temperature algorithms (NWS, 2016; Rothfusz, 1990). For more details of apparent temperature estimation via this method, refer to Appendix A.3. For each activity record, all T_A observations occurring during an activity are matched based on date, time, and MSA. For activities occurring during times with gaps in weather observations, the nearest weather observation to the activity time is used if the time difference is under three hours apart. For this approach, only 0.31% (n = 210) of outdoor activities have unavailable weather observations within this window, which are omitted.

2.1.4 Evaluating Individual Exposure and Activity Intensity

The NWS heat index (‘likeliness of heat disorders with prolonged exposure or strenuous activity’) is referenced to evaluate severity of heat exposure for air temperatures above 27 °C (80 °F) with relative humidity above 40% (NWS, 2017). Heat risk and recommended preventative measures elevate with the NWS heat index as follows: 27-33 °C T_A (80-91 °F T_A) require *caution*; 33-39 °C T_A (91-103 °F T_A) require *extreme caution*; and 39°C+ T_A (103 °F+ T_A) are associated with *danger*. Although there is a fourth heat index threshold indicating *extreme danger* (52 °C T_A and above), it is omitted from this analysis because outdoor activity above 39 °C is rarely captured in the ATUS; out of all outdoor activities, only 0.64% (n = 417) occurred above 39 °C, and no activities were observed above 52 °C. To improve the accuracy of exposure estimates for outdoor activities, outdoor exposure is a time-weighted function of all T_A observations for the duration of each activity.

As high physical exertion increases likelihood of heat stress because of internal heat production, metabolic equivalent of task (MET) data for ATUS activity types estimated by Tudor-Locke et al. (2009) are linked to each activity to assess intensity and exposure simultaneously. One MET is defined as the energy to lie or sit quietly and is equivalent to a metabolic rate of consuming 3.5 mL O_2/kg/minute. For example, “relaxing and thinking” is 1.2 MET, “lawn, garden, and houseplant care” is 3.66 MET, and “biking” is 8.0 MET (see SI Section 1.2 for full details). ATUS activities have a range of 0.9 to 10.0 MET. As physical exertion, activity duration, and temperature are important factors when considering heat stress, heat exposure is evaluated as both activity intensity-time (MET-minutes) within NWS heat index levels, and as MET-degree-minutes (MDMs) above 27 °C T_A (80 °F T_A). **Figure 2** demonstrates how activities of varied intensity and duration translate to exposure intensity (MDMs above 27 °C T_A) as T_A increases.

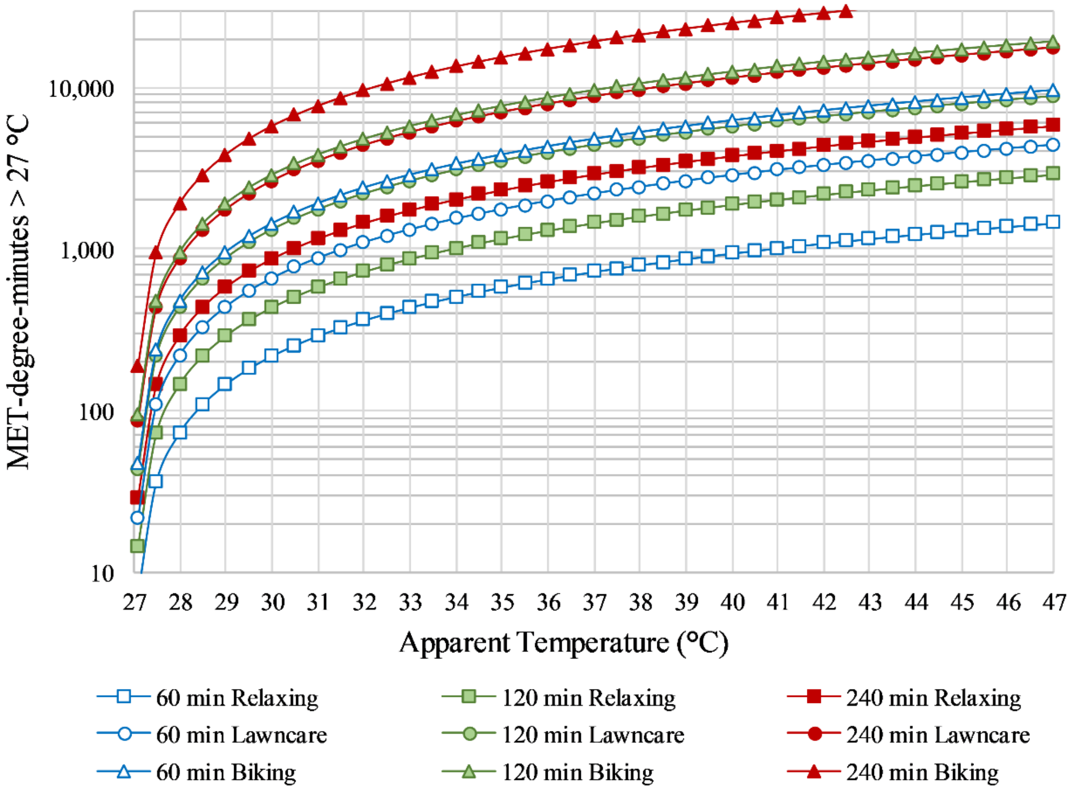

Figure 2. MET-degree-minutes for Sample Activities and Durations. Note that the y-axis scales logarithmically. Relaxing (full description: relaxing and thinking) is 1.21 MET and represents a low intensity activity. Lawn care (full description: lawn, garden, and houseplant care) is 3.66 MET and represents a medium intensity activity. Biking is 8.0 MET and represents a high intensity activity.

We evaluate exposure differences between demographic subgroups to determine if previously established at-risk demographics are more likely to accumulate heat exposure. Socioeconomic status has been widely connected to health outcomes (Pickett & Pearl, 2001), and heat-related social vulnerability has been well documented (Eisenman et al., 2016; Harlan et al., 2013; Reid et al., 2009; Uejio et al., 2011). Lower socioeconomic status is linked to higher rates of pre-existing health conditions, lower quality and higher density housing with less tree cover (Iverson & Cook, 2000; Martin et al., 2004), and lower access to air-conditioning and cooling (Fraser et al., 2016; O'Neill, 2005), all of which can contribute to increased risk of heat stress (Kovats & Hajat, 2008). To ensure income is consistent across years, income levels are adjusted to $2015 based on the BLS monthly historical Cost Price Index for urban US Consumers (US BLS, 2018a). Elderly individuals are often cited as the most vulnerable demographic to heat stress, especially those 65 years of age or older (Gosling et al., 2009; Grundy, 2006; Hondula et al., 2012; Whitman et al., 1997). We therefore define elderly individuals as age 65 and older. Race and heat-related mortality have also been linked in some analyses with those identifying as Black often deemed most at risk (O'Neill, 2005; Whitman et al., 1997), indicating race is an important factor to include in assessments of heat exposure.

To identify significant predictors of exposure intensity at the population level, we empirically model exposure intensity using a fixed effects linear model fitted using weighted least squares. Predictor variables tested focus on demographic, geographic, and temporal influences on activity behavior and climate. Exposure is non-normally distributed; therefore, we choose the best performing model that predicts logarithmic, daily MDMs for ATUS respondents who spent any time outdoors above 27 °C T_A. The relationship of interest focuses on categorical demographic indicators for age group, gender, household income, and race with additional indicator variables to control for climate zone, geographic region (MSA), calendar date, and season. This relationship is modeled as:

$$\begin{aligned} Log(MDM_{i,c,d,m,s}) = \beta_A Age + \beta_G Gender + \beta_I Income + \beta_R Race \\ + \gamma_{c,d,m,s} + \epsilon_{i,c,d,m,s} \end{aligned} \tag{2.1}$$

where i represents the individual, c represents the climate zone, d represents the calendar date, m represents the MSA, and s represents season. The demographic terms (e.g. Age, $Gender$) represent a vector of categorical indicators with corresponding coefficients for each subgroup level (e.g. β_{A1} for age group 1; ages 15 to 24). The Term $\gamma_{c,d,m,s}$ represents a matrix of indicator variables included to control for unobserved effects across the spatiotemporal indicators (climate, date, MSA, and season). To further control for intra-MSA and intra-season correlation, standard errors are clustered on both the MSA and the season. A weighted least squares approach is utilized to incorporate the ATUS individual-level weights to adjust for non-response, strata oversampling, and response variance (US BLS & US CB, 2017).

With time-use data, meteorological data, and activity intensity data combined, we compare aggregated exposure patterns across activity types, demographic groups, and cities. We evaluate environmental exposure across major activity types (work, travel, household, etc.). These activity groupings by type are simplified from the ATUS coding and allow for simple differentiation across relevant outdoor activities.

2.3 Results

Over the 11.5-year sample period, 73,121 respondents engaged in 1.42 million total activities across the 50 examined MSAs. We estimate 3,486 respondents engaged in 6,666 activities outdoors above the 27 °C T_A threshold in this sample, totaling 6,302 hours, or 0.36% of all observed activity time in the sample period. Results are primarily presented in MET-degree-minutes (MDMs) above 27 °C T_A and activity intensity-time (MET-minutes) above 27 °C T_A to examine the combination of heat exposure and activity intensity across urban populations. The mean person-day outdoor exposure for all individuals engaging in at least one activity above 27 °C T_A is 415 deg-min above 27 °C T_A, and the mean person-day exposure intensity is 1,581 MDMs above 27 °C T_A. Summaries of population, total activities, outdoor activities, and temperatures by MSA can be found in Appendix A.1 **Table 5**.

2.3.1 Outdoor Heat Exposure and Activity Intensity by Demographics

Heat exposure intensity per person per day varies across demographic groups with at least one subgroup in each demographic indicator being significant at the $p = 0.05$ level. When controlling for other factors, we estimate females had 36.5% less intense exposure than males (CI: -46.0%, -25.4%; $p < 0.001$). Those identifying as Black race had 34.2% less intense exposure (CI: -46.2%, -19.5%; $p < 0.001$) compared the control (White), while Asian and other races were not significant. Two of five age groups were found to be significant: the elderly (ages 65 and over) accumulate 29.5% more exposure intensity (CI: 2.49%, 63.6%; $p = 0.0304$) relative to the control group (ages 35-44), while young adults (ages 25 to 34) accumulate 19.2% less exposure intensity (CI: -27.3%, -10.3%; $p < 0.001$) relative to the control group. **Table 1** summarizes the results of model.

Figure 3 shows activity intensity-time for three of the significant demographic comparisons across NWS heat index thresholds, displaying trends of differing exposure between relevant demographic groups.

Table 1. **Model Results for Predicted Daily Exposure Intensity for Respondents Who Engaged in Outdoor Activities above 27 °C T_A.** Rows highlighted in light gray are significant at the $p = 0.05$ level. Predicted percent increase in daily MDMs is estimated by transforming regression coefficients using $\left(e^{\beta} - 1\right) * 100\%$.

Variable	**Predicted % increase in daily MDMs**	***p*-value**
Age (control: 35 - 44, n = 721)		
15 - 24 (n = 401)	2.85% (-22.7%, 36.8%)	0.847
25 - 34 (n = 541)	-19.2% (-27.3%, -10.3%)	< 0.001
45 - 54 (n = 622)	16.2% (-4.05%, 40.7%)	0.124
55 - 64 (n = 513)	-4.63% (-24.4%, 20.4%)	0.690
65+ (n = 688)	29.5% (2.49%, 63.6%)	0.0304
Gender (control: Male, n = 1,746)		
Female (n = 1,740)	-36.5% (-46%, -25.4%)	< 0.001
Household Income (control: \$50,000 – \$74,999, n = 617)		
< \$15,000 (n = 470)	15.7% (0.314%, 33.4%)	0.0453
\$15,000 - \$29,999 (n = 551)	-3.07% (-14.9%, 10.4%)	0.639
\$30,000 - \$49,999 (n = 695)	1.94% (-19.9%, 29.8%)	0.876
\$75,000 - \$99,999 (n = 432)	-1.39% (-18%, 18.6%)	0.882
≥ \$100,000 (n = 721)	4.96% (-37%, 74.8%)	0.852
Race (control: White, n = 2,813)		
Asian (n = 112)	-51.1% (-77.5%, 6.68%)	0.0724
Black (n = 489)	-34.2% (-46.2%, -19.5%)	< 0.001
Other / Mixed Race (n = 72)	35.7% (-10.4%, 106%)	0.150
Multiple R^2: 0.627; Adjusted R^2: 0.349		

The activity “lawn, garden, and houseplant care” is the most significant activity that contributes to total population exposure above 27 °C T_A, and it is the main factor of higher elderly exposure: 46% of total exposure intensity above 27 °C T_A among the elderly are during “lawn, garden, and houseplant care” compared to only 30% of exposure intensity for the non-elderly population. This discrepancy of time spent engaging in plant-related care is also a component of lower exposure in the Black population; only 25% of outdoor activities above 27 °C T_A are plant-related care compared to 30% for non-Blacks. It should be acknowledged that the ‘houseplant care’ portion of this activity would occur indoors, while ‘lawn and garden care’ would occur outdoors. Despite houseplant care occurring indoors, we argue it accounts for a minimal portion of the total exposure. The median activity duration of “lawn, garden, and houseplant care” occurring above 27 °C T_A is 60 minutes. If we assume *every* “lawn, garden, and houseplant care” activity dedicated an average of 5 minutes of the total activity time to (indoor) ‘houseplant care’ with all remaining time dedicated to (outdoor) ‘lawn & garden care,’ 95% of the total outdoor exposure would still be attributed to ‘lawn & garden care.’ If instead *every* instance of the activity dedicated an average of 20 minutes to ‘houseplant care,’ 79% of total outdoor exposure would still be attributed to ‘lawn & garden care.’ Therefore, we believe ‘houseplant care’ does not significantly affect the trends in outdoor exposure as it is appears unlikely that individuals caring for houseplants would take up a significant amount of time indoors relative to the outdoor portions of ‘lawn and garden care.’

Less time spent working is casually related to an increase in exposure as individuals may choose to speed more time engaging in outdoor leisure and discretionary activities. We define discretionary activities as activities where postponing or altering the time of occurrence is largely driven by personal preference. For example, one factor that contributes to lower exposure in young adults is an elevated time spent working compared to other age groups. For individuals engaging in at least one outdoor activity above 27 °C T_A, young adults (ages 25 to 34) spent 23% more time engaged in work-related activities than all other individuals. The reverse is true in the elderly who spend more time engaging in leisure activities due to a large majority of individuals age 65 and over being retired or working less than full time. As a result, elderly exposure is slightly elevated compared to young populations. Additionally, heat exposure on weekends is higher relative to weekdays due to less individuals engaging in work-related activities on weekends (see Appendix A.2 **Figure 20**).

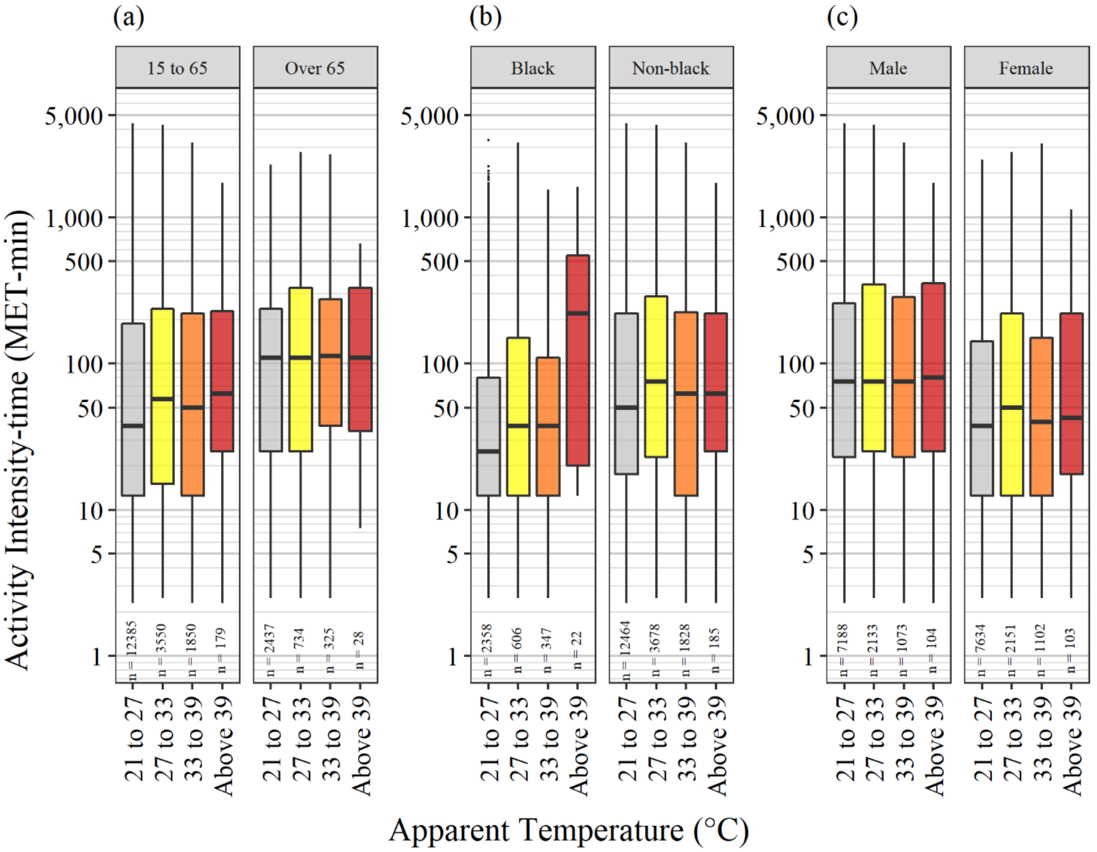

Figure 3. Weighted Outdoor Activity Intensity-times for Significant Demographic Groups. All results are displayed for three different heat thresholds and a baseline (21 to 27 °C) for the 50 studied MSAs. Note that the y-axis scales logarithmically. Boxplots are for the interquartile range (IQR) and lines/dots extend to the minima and maxima. T_A ranges 21-27 °C represent a baseline, 27-33 °C represent heat index warning ‘caution,’ 33-39 °C represent heat index warning ‘extreme caution,’ 39 °C and above represent heat index warnings ‘danger.’ The number of outdoor activities for each grouping is given by ‘n’ at the bottom of the figure.

2.3.2 Outdoor Heat Exposure and Activity Intensity by Activity Type

Discretionary activities (e.g. gardening, sports) dominate high urban outdoor heat exposure as opposed to non-discretionary activities (e.g. care for others, civic obligations). **Figure 4** shows outdoor heat exposure time by activity type across the 50 studied major US urban areas. Exposure above 27 °C T_A most commonly occurs during the discretionary activities “lawn, garden, and houseplant care” (18% of total outdoor activities), and “walking for exercise or leisure” (5.4% of total outdoor activities). Outdoor travel, which may be less discretionary depending on purpose (e.g. travel for work is less flexible while travel for leisure is more flexible), is the most frequent activity type to acquire heat exposure above 27 °C T_A (37% of all activities). However, because travel durations are often short (the 90th percentile outdoor travel time is 20 minutes), total exposure from travel is lower than other activities.

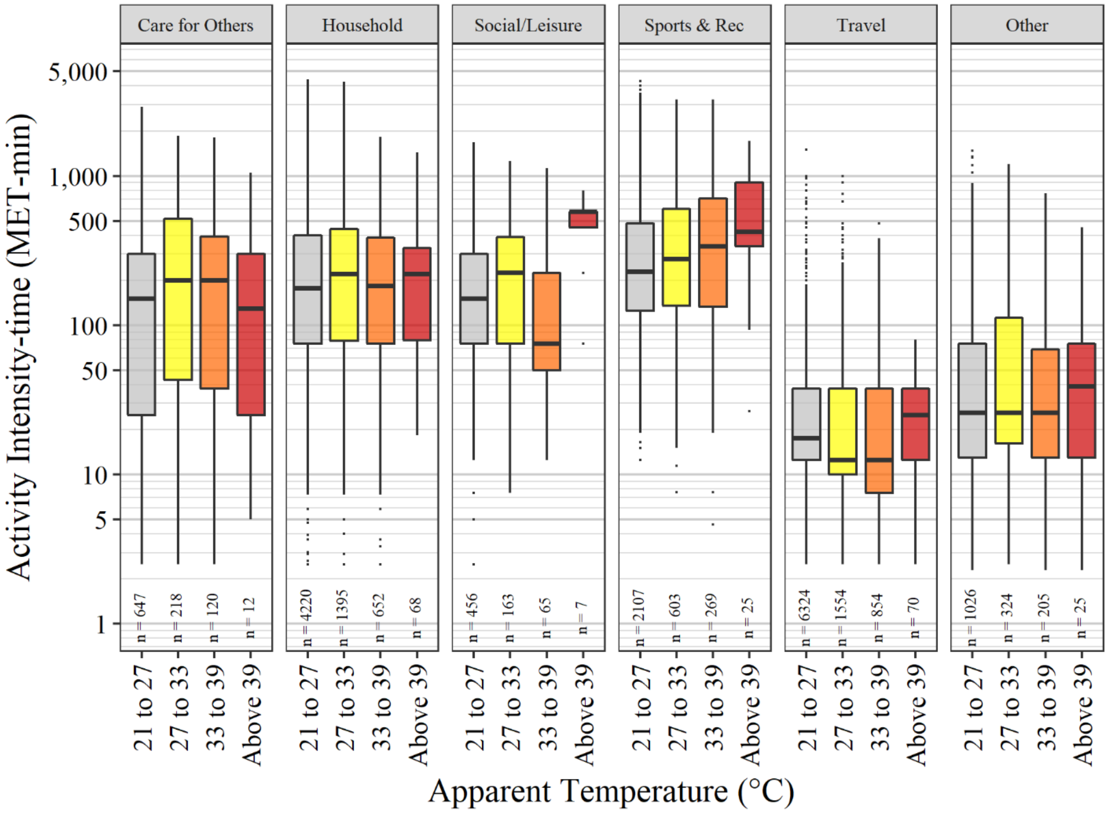

Figure 4. Weighted Outdoor Activity Intensity-times by Activity Type and Heat Thresholds. Note that the y-axis scales logarithmically. Boxplots are for the IQR and lines/dots extend to the minima and maxima. T_A ranges 21-27 °C represent a baseline, 27-33 °C represent heat index warning ‘caution,’ 33-39 °C represent heat index warning ‘extreme caution,’ 39 °C and above represent heat index warnings ‘danger.’ The number of outdoor activities for each grouping is given by ‘n’ at the bottom of the figure. ‘Work’ activities are excluded due to very low sample size. Activities in the ‘Other’ category include personal care, education, consumer purchases, giving and receiving services, civic obligations, eating and drinking, religious activities, volunteering, and telephone calls.

As heat approaches extremes, there are a smaller number and a smaller proportion of individuals engaging in outdoor activities. This decrease results from both decreased frequency and decreased duration of outdoor activities, most notably for activities of typically longer durations or higher intensities (e.g. activities occurring in the top quantile in **Figure 4**). Because outdoor activities are not frequently observed at extreme temperatures, and extreme temperatures are rarely reached even in the hottest climates, ‘extreme’ outdoor heat exposure observed via the ATUS is rare. Despite this rarity, there are still many observations of potentially high-risk activities during high temperatures; we observed 719 outdoor activities above 27 °C T_A that occurred above the 90th percentile exposure intensity (2,563 MDMs > 27 °C T_A). If we apply the individual-level survey weights to estimate the total population surpassing this threshold on a hot summer day, this would be equivalent to approximately 12 million people across the 50 studied MSAs (6.7% of the 2016 MSA populations).

2.3.3 Outdoor Heat Exposure by Urban Region and Climate

Heat exposure is partially driven by region and climate; comparing exposure across the MSAs indicates that urban populations experience different cumulative daily exposure during days with T_A above 27 °C. Personal daily MDMs above 27 °C T_A for 39 of the studied MSAs are displayed in **Figure 5** (MSAs with less than 30 samples are not displayed; for more detailed results, including all MSAs studied, see Appendix A.1 **Table 10**). Individuals in southern US MSAs more commonly experienced higher daily exposure intensities with New Orleans, LA and Birmingham, AL having the highest median and mean MDM per day, and the most extreme case of exposure intensity occurred in Phoenix, AZ.

Despite climate being a significant predictor in exposure, it is clear that other factors across MSAs contribute to varied regional exposure. In model evaluation, we included measures of regional sprawl (MSA sprawl index via Hamidi and Ewing, 2014) to evaluate if urban form is a predictor of exposure intensity. When controlling for geographic region as a random effect in mixed effects models, MSA sprawl was found to be a statistically significant but very low magnitude predictor. Therefore, we conclude that sprawl was not a significant influence on exposure intensity across the measured urban population, but future work should explore additional urban form metrics to improve understanding of inter-urban influences on extreme exposure.

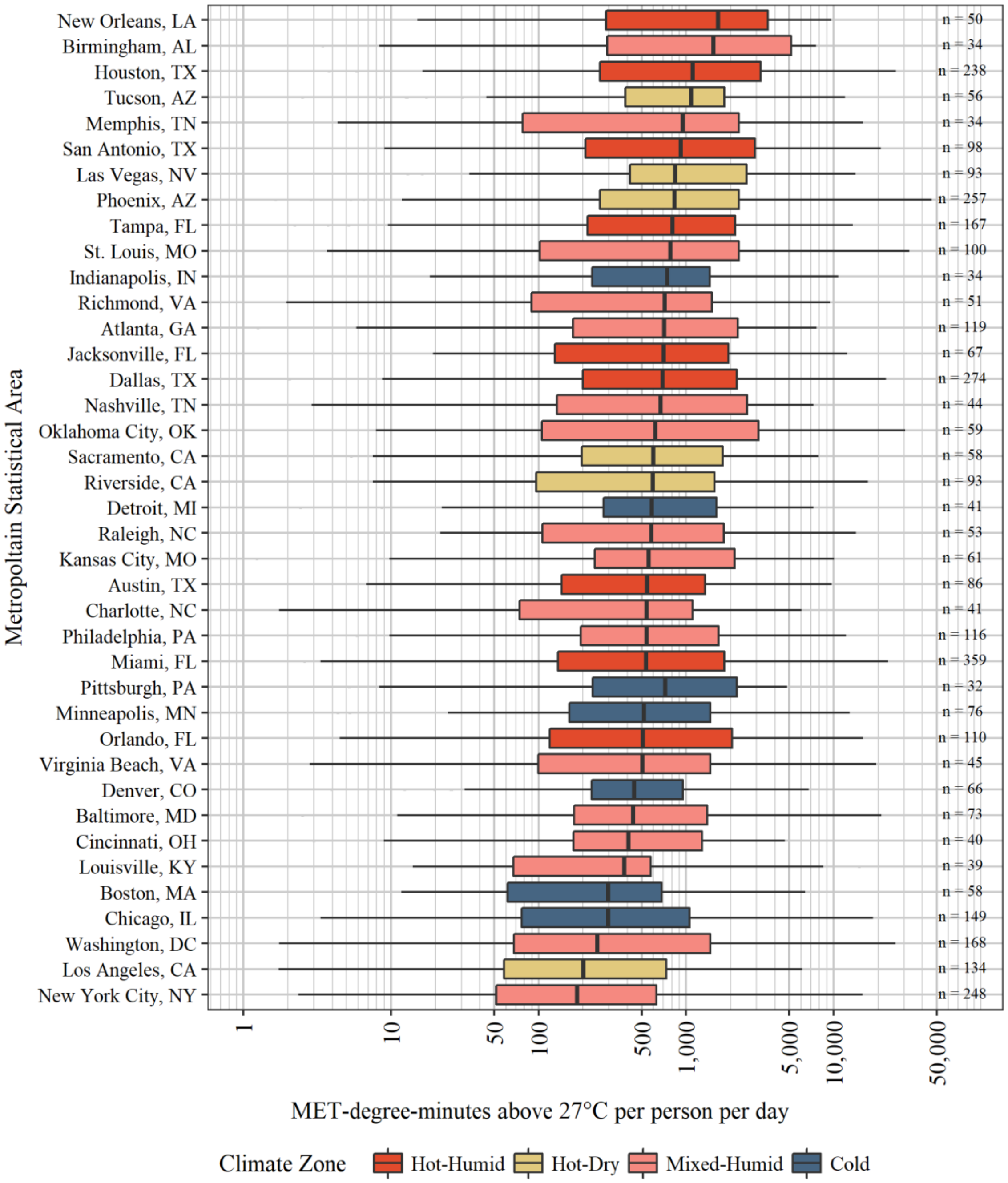

Figure 5. Personal Daily Outdoor MET-degree-minutes (above 27 °C T_A) for 39 of the Most Populated Metropolitan Statistical Areas. Note the x-axis scales logarithmically. Only MSAs with exposure significant at $p = 0.05$ are retained. Boxplots are for the IQR and lines/dots extend to the minima and maxima. All individuals in an MSA that reported at least one outdoor activity above the 27 °C T_A threshold are included. On the right of the figure, the number of person-days or each MSA is given by 'n.'

2.4 Discussion

Few studies have investigated the effect of hot days on outdoor activity at the level of the individual. Understanding individually experienced heat exposure during activities is difficult for many reasons: difficulty in obtaining a large sample size (especially for the most extreme temperatures); low spatial or temporal resolution in temperature data (especially in urban microclimates); and low spatial or temporal resolution activity data. Some previous research has evaluated the effect of temperature on personal activity and behavior using survey data. Obradovich and Fowler (2017) estimated change in likeliness to be physically active in a month and found that individuals in the US typically become less active as temperature reaches extremes. Zivin and Neidell (2014) estimated change in average time spent outdoors due to temperature, finding that less time is spent outdoors for days with more extreme temperatures. However, these studies focus on monthly and daily summary temperatures rather than individually experienced temperatures during activities and do not estimate personal heat exposure. This study improves our understanding of individually experienced heat exposure for a large, heterogeneous population sample and identifies disparities in accumulated heat exposure.

Various demographic subgroups such as those in poverty or the elderly are often cited as more vulnerable to heat stress due to reduced access to cooling, and in some cases, race has also been linked to increased negative heat-related health outcomes (Eisenman et al., 2016). These results provide further evidence of heat-vulnerability in low-income and elderly individuals as we find they accumulate higher exposure intensity when controlling for other factors. On the other hand, black individuals have lower exposure intensity than other races despite often having higher rates of heat-related morbidity and mortality compared to the general population. Males were found to accumulate more heat exposure relative to females, and males are observed to engage in activities during hot weather more often than females (54% of males engaged in outdoor activities when temperatures are above 27 °C T_A versus 46% of females). This agrees with past research that indicates males are exposed to heat more than females and may be at more risk (Kovats & Hajat, 2008). Although the most extreme exposure cases may be atypical and uncharacteristic of a demographic cohort, outdoor heat exposure and activity intensity quantified in this study (excluding work-related activities) are not solely sufficient to explain heat-related health outcomes.

Climate acclimatization and abnormally hot periods relative to typical regional weather may increase heat exposure especially if individuals engaging in moderate to high intensity activities do not reduce their activity time or physical activity intensity. After heat waves, individually perceived thermal comfort may increase due to short-term acclimatization (Lam et al., 2018). In this study, we used an absolute, fixed temperature threshold across all cities to quantify how exposure varies across cities or population groups. Future work might extend this approach to consider city-specific temperature thresholds derived as a function of local climatology, to account for possible regional acclimatization in activity patterns and/or health risks (e.g., Anderson and Bell 2009; Grundstein et al. 2015). Although heat exposure may be perceived as more severe in hotter and more humid regions, outdoor heat exposure for some individuals may be comparable across regions with varied climates. This also further highlights the potential threat of increased severity and intensity of heat waves on unacclimated individuals (e.g.

tourists, visitors), and individuals living in areas with less access to cooling infrastructure. However, the issue of smaller samples of extreme exposure in temperate and colder climates persists, limiting our understanding of extreme heat exposure in these regions despite continued warming in cities (McCarthy et al., 2010; Mora et al., 2017).

The inclusion of activity intensity (metabolic equivalent of task) allows for additional perspective in assessing heat exposure. In this analysis, the contrasts in heat exposure intensity (MDMs) among subgroups are primarily driven by the contrasts in heat exposure. Contrasts in physical activity intensity are only significant between men and women (males: 5.50 mean MET above 27 °C T_A; females: 5.14; $p < 0.001$). Although variation in MDMs is mainly driven by apparent temperature and exposure duration, we consider it important to evaluate heat exposure as a function of environmental heat, activity duration, and activity intensity to identify all causal factor that may influence the intensity of personal heat exposure. This is especially important in understanding extreme and atypical cases of exposure. Future work should explore the relationship between heat exposure, activity intensity, and health outcomes to better understand the role of physical activity intensity in heat-related health outcomes.

2.4.1 Limitations

The approach in this analysis and the nature of the survey data inherently limits our ability to fully understand urban outdoor activity exposure. In particular, important elements not captured in the ATUS are outdoor work, omission of homeless individuals, and potential sampling biases. Additionally, outdoor thermal conditions are heterogeneous within a MSA, but only one meteorological station was used per MSA.

Heat exposure among working people is a very important global concern (Kjellstrom et al., 2009), but the ATUS is poorly structured to evaluate individual level heat exposure in occupational settings. To assess heat exposure during work more accurately, more robust survey data are required that closely monitor activity intensity and duration. The ATUS coding limits the ability to determine if work related activities occurred outdoors; only 0.47% of work related activities were confidently coded as outdoors, regardless of temperature. As a result, samples of outdoor work may significantly under represent outdoor workplace behavior because ATUS reporting options obfuscate indoor versus outdoor presence during work. If work occurred outdoors and away from the respondent’s household, a more appropriate response to location could arguably be “outdoors away from home” instead of “at the respondents workplace.” Zivin and Neidell (2014) identify certain industries as more vulnerable to high temperatures, and Eisenman et al. (2016) correlated higher mortality risk for industries with higher rates of outdoor work, but there is little knowledge on the frequency of high heat outdoor work itself.

The ATUS inherently excludes homeless individuals, as it is a household study. Heat-related morbidity and mortality among the homeless can be disproportionately higher due to extended time outdoors in the heat (Yip et al., 2008) along with other exacerbating factors related to health status and access to healthcare. Quantifying urban heat exposure in the homeless population is vital, but it must be done using different approaches.

Biases in survey response rates may prevent researchers from fully understanding total population heat exposure via survey data. Between 2004 and 2015, the ATUS survey response rate was 54% (US BLS & US CB, 2017). Regarding sampling bias, Abraham et al. (2006) found certain subsets of individuals are more likely to reject participation in the ATUS (e.g. higher education and income individuals have higher response rates). However, their analysis focused only on the second survey year of data (2004) in the middle of which the survey methodology was changed. The use of ATUS person-level weights in this analysis should minimize these sampling biases as they correct for non-response, but we acknowledge that some unrecognizable biases may arise and under-represent exposure for certain sub-populations or activities. We caution the development of local policies and intervention programs without more detailed consideration of the sampling limitations. One other minor sampling limitation in this analysis is the banding of activity times. This occurs because activities are reported as ‘round’ or ‘convenient’ as respondents do not record exact durations but only estimate them after the activities have occurred (e.g. respondents most commonly report time spent traveling as 15, 30, or 45 minutes).

Throughout an urban region, individually experienced temperatures can vary due to complex microclimates and heterogeneity of urban form (Hart & Sailor, 2009; Kuras et al., 2015; Middel et al., 2014, 2017, 2016; Stewart & Oke, 2012). To test sensitivity of personal exposure due to varied urban climates, weather data inputs were varied for the Los Angeles MSA - a large geographic metropolitan area with diverse microclimates. Exposure patterns did not appear to change significantly, but sample sizes did decrease with use of more coastally located meteorological stations. Use of coastal temperatures (Los Angeles International Airport, 2 miles from coast) reduced the observed number of outdoor activities above 27 °C T_A to 0.8% of all outdoor observations (n = 5,022).

Conversely, when using observations further inland (Ontario International Airport, 35 miles from coast), 12% of outdoor activities would be classified above 27 °C T_A. This however, is an extreme example; most regions (especially non-coastal regions) have far less variation in temperatures, and inter-MSA temperature variations may have negligible impacts on time use (Graff Zivin & Neidell, 2014).

Although this study does not consider indoor heat exposure, indoor environments can also play a significant role in accumulated heat exposure at the individual level (Quinn et al., 2014; White-Newsome et al., 2012). Coastal and temperate urban regions can have vastly different air conditioning (AC) penetration than regions with more uniform heat. In 2015, only 53% of urban households in the Marine climate zone had any AC while 94% of households in Hot-Humid climates had any AC (US EIA, 2015). Fraser et al. (2016) assessed differences in AC penetration between Los Angeles and Phoenix and found that approximately 95% of metropolitan Phoenix households had central AC while "less than 50%" of households in Los Angeles had central AC. Additionally, lower income households are less likely to have adequate cooling alternatives (US EIA, 2015), making it more difficult to cool off.

2.5 Conclusion

With the threat of increased severity and frequency of extreme heat events and subsequent adverse impacts on the health and well-being of urban residents, improvements in the strategies that cities use to mitigate and adapt to heat are needed. We contribute to the improvement of heat response policies and initiatives with new evidence concerning the drivers of urban outdoor heat exposure in the contiguous US and variability across cities and demographic groups. Using the ATUS, we found that many outdoor activities occur in US cities under conditions deemed hazardous to human health based on the heat index. Discretionary activities were a substantial contributor to exposure under high heat conditions. Inter-city comparison of aggregated personal exposure metrics revealed that cities with the most extreme temperatures do not necessarily have the highest outdoor heat exposure. Although heat exposure can vary significantly person-to-person, disproportionately high heat exposure is not necessarily exhibited in groups known to be at higher risk of adverse heat-health outcomes. Overall, the results highlight how diversity of activity types, demographic groups, and geographic regions can significantly vary outdoor urban heat exposure. Continued work in estimating heat exposure at the individual level is needed; there are still gaps in understanding how (and at what level) heat exposure for an individual could translate to increased risk for negative heat related health outcomes. More refined, spatially explicit analysis of exposure patterns and microclimate variability within cities can help provide a clearer perspective of the circumstances, people, and places where targeted mitigation and adaptation strategies will be most effective.

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CHAPTER 3

VALLEY OF THE SUN-DRENCHED PARKING SPACE: THE GROWTH, EXTENT, AND IMPLICATIONS OF PARKING INFRASTRUCTURE IN PHOENIX

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3.1 Introduction

The evidence is clear that abundant and underpriced parking creates economic, environmental, and social problems (Chester et al., 2015; Manville & Shoup, 2005; Shoup, 1999; Weinberger, 2012; Willson, 1995). Yet less is known about the growth and extent of parking infrastructure. This is true at global, national, and local scales, and is especially problematic for US cities where minimum parking requirements are perhaps the most dominating force of determining why cities are so automobile oriented (Willson, 2013). Past parking estimates for the US claim between 105 million to 2 billion total spaces (or between one space per 40 meters of roadway to one space per two meters of roadway; Chester et al. 2010). While some recent studies quantify point-in-time parking supply (Amélie Y. Davis et al., 2010; Rutman et al., 2013; Scharnhorst, 2018), there are few studies that quantify the intra-city growth and extent of parking infrastructure (one example is the Chester et al. 2015 study of Los Angeles). Without cities actively tracking and quantifying parking growth and supply, policy and land use planning towards density and non-automobile travel is blind.

Widespread automobile adoption revolutionized 20th century travel. Off-street parking facilities were initially intended to manage congestion by moving vehicles off-road when not in use (Ferguson, 2004). By the middle of the century, most cities had implemented minimum parking requirements to meet increasing demand. Parking requirements produced abundant and underpriced infrastructure, creating perverse incentives for automobile travel by shifting the costs of parking into other services (e.g., rental costs or the costs of groceries) thereby distorting modal choice (McDonnell et al., 2011; Shoup, 1999; Weinberger, 2012; Weinberger et al., 2010; Willson, 1995). Minimum parking requirements led to urban designs that favor the automobile by reducing density and increasing the frequency and distance of automobile trips (Weinberger et al., 2010; Willson, 1995). Accumulating evidence suggests that minimum parking requirements reinforce a cycle of auto-dependency and make transitions to public transit, biking, and walking more challenging.

Cities are constantly developing a myriad of strategies to combat issues such as population growth, traffic congestion, pollution, and climate change. If cities are to promote sustainable development, lower housing costs, decreased air pollution, and improved public health through biking, walking, and transit, then estimates of urban parking supply are critical for establishing local and regional policy aimed at freeing land for more valuable uses and reducing incentives to drive. Requiring parking increases the incentive to drive by effectively subsidizing it (Willson & Shoup, 1990). Reducing parking availability through relaxing parking requirements is possible (Engel-Yan et al., 2007), and would likely decrease automobile use (Weinberger, 2012).

Automobile dependence and oversupplied parking has many consequences that manifest to constrain urban development and sustainable growth. A parking space is often ‘free’ to use, at least in the sense that there is not direct payment. However, parking is not free when considering indirect costs, and there may be significant burdens associated with meeting minimum requirements (Manville & Shoup, 2005; McDonnell et al., 2011; McPherson, 2001). Typically, developers invest up-front for the required parking infrastructure, and the costs are passed to the parking space user through increased prices of goods or services (Shoup, 1997). Parking can cost tens of thousands of dollars per space constructed, leading to investments of tens to hundreds of billions of dollars collectively by developers in cities despite the value of land almost always being greater for something other than parking (Shoup, 1997; Willson, 1995). Scharnhorst's (2018) study of parking in five US cities estimates a high cost of parking: up to $118,000 per household for parking infrastructure in Jackson, Mississippi, USA and $35.8 billion to replace all parking in the City of Seattle, Washington, USA. These examples underscore the significant investment in infrastructure required by cities to support automobile dependence just through parking, and these estimates do not include the costs of maintenance. Building and maintaining parking infrastructure also requires large amounts of resources and land, and contributes non-trivial environmental life-cycle impacts to automobile travel (Chester et al., 2010). For cities with high automobile dependence, abundant and underpriced parking only adds fuel to the fire; urban pollution and urban heat are exacerbated by dense traffic and widespread automobile-related infrastructure (Allen et al., 2011; Amélie Y. Davis et al., 2010; Hart &

Sailor, 2009; Kempton et al., 2001; Van Bohemen & Van De Laak, 2003), and this cycle of automobile dependence is further cemented with each additional parking space paved.

Where minimum parking requirements seem to have the greatest impact on land use and automobile dependence are in cities that have predominantly grown in the latter half of the twentieth century, an archetypal city being Phoenix, Arizona, USA. The metropolitan region of Phoenix is unique because it is relatively young, rapidly growing, highly sprawled, and car dependent. According to the US Census Bureau (CB), the City of Phoenix is the second fastest growing large US city behind San Antonio, Texas (US CB, 2018a), and the surrounding metropolitan region is projected to continue rapidly growing and expanding. According to the Maricopa Association of Governments, (the regional metropolitan planning organization of metro Phoenix), residential developed land in the region is projected to grow 480% (from 2,100 km^2 to 10,000 km^2) by 2040 with population and employment growth of 150% (MAG, 2017). Much of this growth is due to lateral expansion into currently undeveloped peripheral land. Phoenix is also sprawling and automobile dependent. Hamidi and Ewing (2014) analyzed the 162 largest US urbanized areas (UZAs), and the Phoenix UZA was the 36th most sprawled, and the second most sprawled of the top 20 most populous UZAs. Of US UZAs with at least 2 million in population, Phoenix has the highest non-interstate per-capita vehicle miles traveled. Most cities in the Phoenix metropolitan region also have high vehicle ownership: cities in the region with household vehicle ownership above the national average of 91% include Gilbert (98%), Surprise (97%), Chandler (96%), Scottsdale (96%), Mesa (93%), and Phoenix (92%) (US CB, 2016). Yet, at the same time, the Phoenix metro region is heavily investing in high quality transit (namely a light rail network), is promoting infill development and densification, and is well-positioned to increase active transit given its active population and temperate non-summer climate.

In growing, sprawling, and hot cities like Phoenix, increasingly severe heat and pollution are two major threats to human health directly tied to urban automobile dependence. In the urban US, concrete and asphalt pavements account for approximately 30-40% of land cover (Akbari et al., 2003; Rose et al., 2003), and may reach as high as 40-66% in non-residential areas (Akbari & Rose, 2001a, 2001b). This large amount of grey infrastructure, much of which supports automobility, is a primary contributing factor to urban heat island, where temperatures in urban regions are greater than rural regions and daily lows are increased. Additionally, automobiles themselves are a direct source of heat contributing 47% to 62% of urban anthropogenic heat during summer months (Sailor & Lu, 2004). Pollution from automobile travel is also problematic, and the Phoenix metropolitan region ranks 8th worst in the US for smog (American Lung Association, 2018). With the threat of increasingly severe urban heat due to climate change and urbanization (Luber & McGeehin, 2008; Stone et al., 2010), cities (especially those with an already hot summer climate) may have increased incentives to shift away from automobile dependence and abundant and underpriced parking.

This research fills gaps in knowledge about the extent of parking infrastructure supplied in cities. Focusing on the metropolitan region of Phoenix, we aim to answer three research questions: 1) What is the current supply of parking?; 2) How has the parking supply grown?; and 3) What issues exist or may arise due to vast parking infrastructure in metropolitan regions like Phoenix?

3.2 Methodology

An inventory of on-street and off-street parking was developed for the Phoenix, Arizona metropolitan region. We define the Phoenix metropolitan region (hereafter, ‘metro Phoenix’) as the UZA of Maricopa County, Arizona, USA (note that this is not the same as the metropolitan statistical area, and excludes parts of urbanized Pinal County, sometimes considered part of the metro area). We choose this as the study region for two main reasons: 1) 94% of the Maricopa County population (approximately 4 million people in 2017) resides in the UZA (US CB, 2016); and 2) the vast extent of built infrastructure exists in the UZA. **Figure 6** shows the study area including significant highways, high capacity transit, and downtown areas. We define on-street parking as roadway shoulder space able to accommodate and legally park a vehicle. Off-street parking is defined as dedicated parking area located off the road network (e.g. residential driveways or non-residential parking lots). We started by assessing the extent of parking infrastructure (area and number of spaces by space type and location) and then conducted a time series analysis that links the initial age of land development to nearby parking spaces to develop an estimate of infrastructure growth. This methodology follows the approach established by Chester et al. (2015).

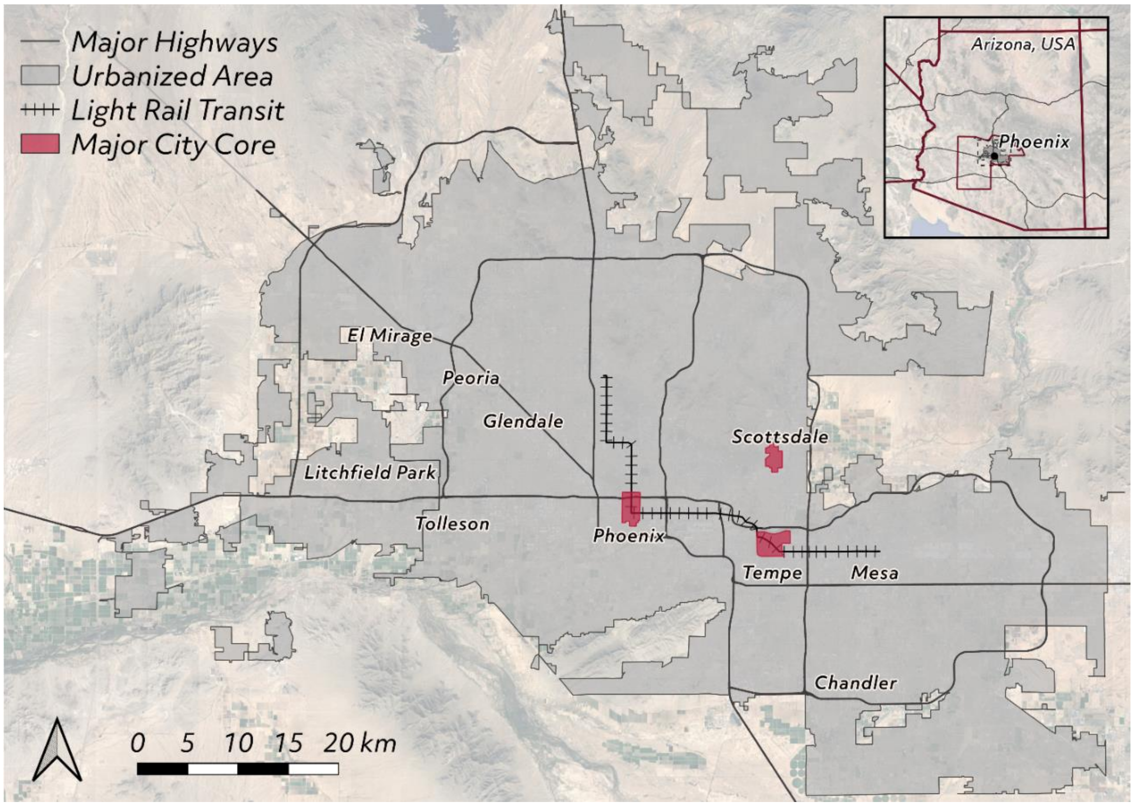


Figure 6. Metro Phoenix Including Major Highways, Major Downtowns, and the Light Rail Transit. The study region is shown along with major highways, the main light rail transit line, and three primary downtown districts (red) of the Cities of Phoenix, Scottsdale, and Tempe.

3.2.1 Estimating On-Street Parking

To estimate on-street parking, OpenStreetMap (OSM) geospatial road network data were cross-referenced with city-level on-street parking restrictions (OpenStreetMap contributors, 2019). As municipal codes in metro Phoenix prohibit on-street shoulder parking on arterials and highways, we only assign the functional road classes of 'residential' and 'unclassified' (i.e. local and collector roads) as permitted for on-street shoulder parking. We eliminated roadway space where obstructions prohibit or codes restrict parking including near intersections, in front of bus stops, crosswalks, and driveways, within tunnels, and on bridges. Remaining available space was then used to estimate available curbside parking, assuming a 6.7 meter (22 feet) length and 2.6 meter (8.5 feet) width per on-street space. Due to a lack of spatially explicit data regarding fire hydrant locations, we assumed the maximum allowed spacing between fire hydrants. This resulted in the loss of one parking space per 152 meters (500 feet) of curb space. All other obstruction locations were modeled using OSM data.

Due to a lack of data, metered or marked on-street spaces were not distinctly estimated but were assumed to be captured because metered spaces either replace where an unmetered space would exist, or on-street metered spaces substitute for required off-street parking. Regardless, on-street metered spaces are likely an insignificant fraction of the total space estimates; the City of Phoenix operates approximately 2,000 metered spaces (City of Phoenix, 2018b).

3.2.2 Estimating Off-Street Parking

To estimate off-street parking, parcel-level cadastral data (the finest resolution of land delineation data in the U.S.) from the Maricopa County Assessor’s Database was cross-referenced with municipal minimum parking requirements by property type as listed in each city’s zoning regulations (Maricopa County Assessor’s Office, 2017). A parcel is often equivalent to a building lot, but may sometimes contain multiple structures. Off-street minimum parking requirements were codified by jurisdiction with over 2,000 property use codes across 33 cities and towns in the metro region. The number of parking spaces for each of the 1.6 million parcels in urbanized Maricopa County were modeled by cross-referencing codified minimum requirements in the jurisdiction of the parcel.

For the majority of non-residential property types, the required number of spaces is based on the total floor space of the building(s) at the parcel. Most jurisdictions have very similar requirements; for example, offices in nearly all cities in the metro region require one space per 28 m^2 (300 ft^2) of floor space (City of Phoenix, 2018a; City of Scottsdale, 2018; City of Tempe, 2011). In these cases, total required off-street parking is simply a product of total parcel floor space and the parking space per floor space factor from the parking code.

Residential and commercial lodging properties often require spaces based on the expected number of residents or the number of dwelling units rather than total floor space. In every municipality in the region, two spaces are required per single-family detached dwelling unit (i.e. single family home). For multi-family units, required spaces range from 1.0 to 2.5 spaces per dwelling unit. Due to a lack of consistent reporting of the total units per residential or commercial lodging facility, total spaces were estimated by one of two methods: when total units are reported, the total spaces equal total units times spaces required per unit; and when total units are not reported, typical dwelling unit floor space sizes are assumed (e.g. studio and 1-bed apartments, hospital rooms, hotel rooms, etc.) to estimate the number of units present in a multi-unit complexes. For apartment complexes, city-average apartment sizes were referenced for each municipality via RENTCafé (Yardi Systems Inc., 2018). For other multi-dwelling units, average unit sizes are assigned based on local, regional, or national averages. For details on specific assignments for residential and commercial lodging properties, see the Appendix B.2 **Table 11**.

To estimate total surface area dedicated to parking (coverage area), we assumed 31 m^2 (330 ft^2) of paved surface per off-street space to account for access ways, accessible parking, and excess residential driveway and garage space. This is equivalent to a parking lot density of 325 spaces per hectare, consistent with typical parking lot space densities

(Holland, 2014; Manville & Shoup, 2005; VAA, 2018). For residential driveways, visible driveway areas were measured using satellite imagery and were found to be consistent with 61.5 m^2 (662 ft^2) for an average sized driveway (to accommodate at least two parked cars). Total surface area for on-street parking is allocated only by the size of the on-street space itself (17.4 m^2 or 187 ft^2). We also estimated roadway coverage area for the region using OSM data with standard lane and shoulder widths by functional class.

3.2.3 Estimating Historical Growth of Parking

To assess the historical growth of parking, off-street and on-street spaces were assigned a construction year linked to the construction year of surrounding buildings. Specifically, each parcel of land has a construction year that corresponds to the first year the property was developed. This approach assumes that all off-street spaces currently present were constructed in the year the land was initially developed. On-street spaces were assigned the construction year of the average neighborhood parcel construction year minus one standard deviation following Chester et al. (2015). This assumes that nearby local and residential streets were constructed approximately when neighborhood property development started accelerating. We assume this to be generally true in that roads and other infrastructure for housing subdivisions and commercial districts are built in order to develop adjacent properties. There are times when this does not hold, where infrastructure was built and development did not follow, but based on consistent growth in the region, this is assumed to be rare.

3.2.4 Validation

We focused on validating off-street non-residential and off-street high-density residential parking spaces for two reasons: 1) these types of spaces had significantly higher variation at the parcel level, largely due to varied inter-city requirements for non-residential and mixed-use property types; and 2) manually validating in-situ parking is time intensive and therefore effort is concentrated on these high variance property types. Low variance in on-street parking and off-street low-density residential parking is predictable because on-street parking spaces are allocated using geospatially consistent inventories of roadways minus known obstructions, and low-density residential parcels consistently have a single off-street driveway per single family dwelling unit.

To validate our estimate of parking supply, we first counted parking spaces using satellite imagery, and when available, verified with local inventory estimates via publicly available records. Then, researchers manually counted parking spaces using satellite imagery for eight representative census blockgroups with a diverse selection of property types and sizes. Some additional parcels with unique purposes and high parking estimates such as concert venues, convention centers, large higher education facilities, and hospitals were also chosen for individual validation. These results were compared against the required parking estimates. For surface lots, counting spaces was straightforward as individual stalls were clearly visible in the images. For above-ground parking structures, the total number of spaces were estimated by multiplying visible space on the top floor by the number of stories of the structure.

3.2.5 Supplementary Data Sources

We investigate the amount of urban parking compared to other urban statistics on automobile registrations, employment, and population. Passenger vehicle registration data are referenced from the Arizona Department of Transportation (ADOT, 2019a) and Kenworthy et al. (1999). Non-farm employment data are referenced from the US Bureau of Labor Statistics (US BLS, 2018b) and the Arizona Office of Economic Opportunity (AZ OEO, 2018a). Historical, current, and future population estimates are referenced from the US Census Bureau (US CB, 2018b) and the Arizona Office of Economic Opportunity (AZ OEO, 2018b, 2018c).

3.3 Results

3.3.1 Current Parking Inventory

In 2017, there were a total of over 12 million spaces and 4.0 million inhabitants in metro Phoenix, or approximately 3.0 parking spaces per person. For every registered non-commercial passenger vehicle there are 4.3 total parking spaces of which 1.3 are off-street residential spaces, 1.3 are off-street non-residential spaces, and 1.7 are on-street spaces. For every (non-farm) employed individual, there are 6.6 parking spaces, 2.16 of which are non-residential (on or off-street). Parking and roadway pavements have a coverage area of 36% of the metro's land area (10% parking and 26% roadway). This agrees with previous estimates of urban pavement land cover being between 30-40% (Akbari et al., 2003). Coverage area is defined as the total surface area of pavements including access ways, accessible parking spots, parking spaces located in parking garages, residential driveways, etc. Note that these estimates of coverage area are *not* land cover of roadway and parking pavements; parking spaces and roadways may occasionally be vertically stacked (e.g. parking garages). Also note we did not include coverage area of pedestrian or transit travel ways (e.g. sidewalks). Summary statistics of the parking inventory are displayed in **Figure 7** (for results in table format, see Appendix B.2 **Table 12**).

In 2017, Metro Phoenix had:
4.04 million inhabitants,
2.86 million cars, &
1.84 million jobs.

Total parking spaces:

3.67
million off-street residential spaces
+
3.60
million off-street non-residential spaces
+
4.93
million on-street spaces

12.2 million total parking spaces

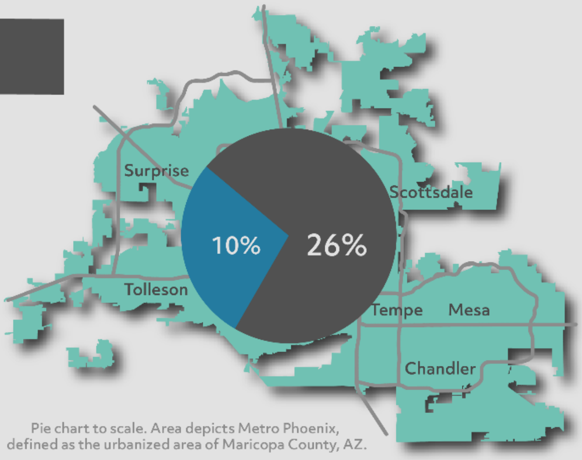
Spaces per ____:

6.6 spaces per job

4.27 spaces per car

Total coverage area:

approximately
36%
of urban area a is covered by parking & roads



Pie chart to scale. Area depicts Metro Phoenix, defined as the urbanized area of Maricopa County, AZ.

Figure 7. Summary Parking Statistics for Metro Phoenix in 2017. All values are for the UZA of Maricopa County only. “Cars” are defined as all registered non-commercial passenger vehicles in the region; “jobs” are defined as all non-farm employment in the region. Note that coverage area is an estimate that includes excess space needed to maneuver and space within parking garages.

Parking density is highest in urban and commercial cores and lowest in the suburbs and natural preserve and park land. The entire metro Phoenix has a parking density of approximately 39 spaces per hectare. Spatial distribution of parking density is shown in **Figure 8**. At the blockgroup level, median parking density is 48 total spaces per hectare, 25 off-street spaces per hectare, and 19 on-street spaces per hectare. The median parking coverage area per blockgroup is 12%. The downtown areas of Phoenix, Scottsdale, and Tempe, which are the three largest employment and activity centers, (see **Figure 6** for boundaries) have some of the highest density of parking in the region. Of the three, Downtown Scottsdale has the highest density of parking (127 spaces per hectare) compared to Downtown Tempe (113) and Downtown City of Phoenix (112).

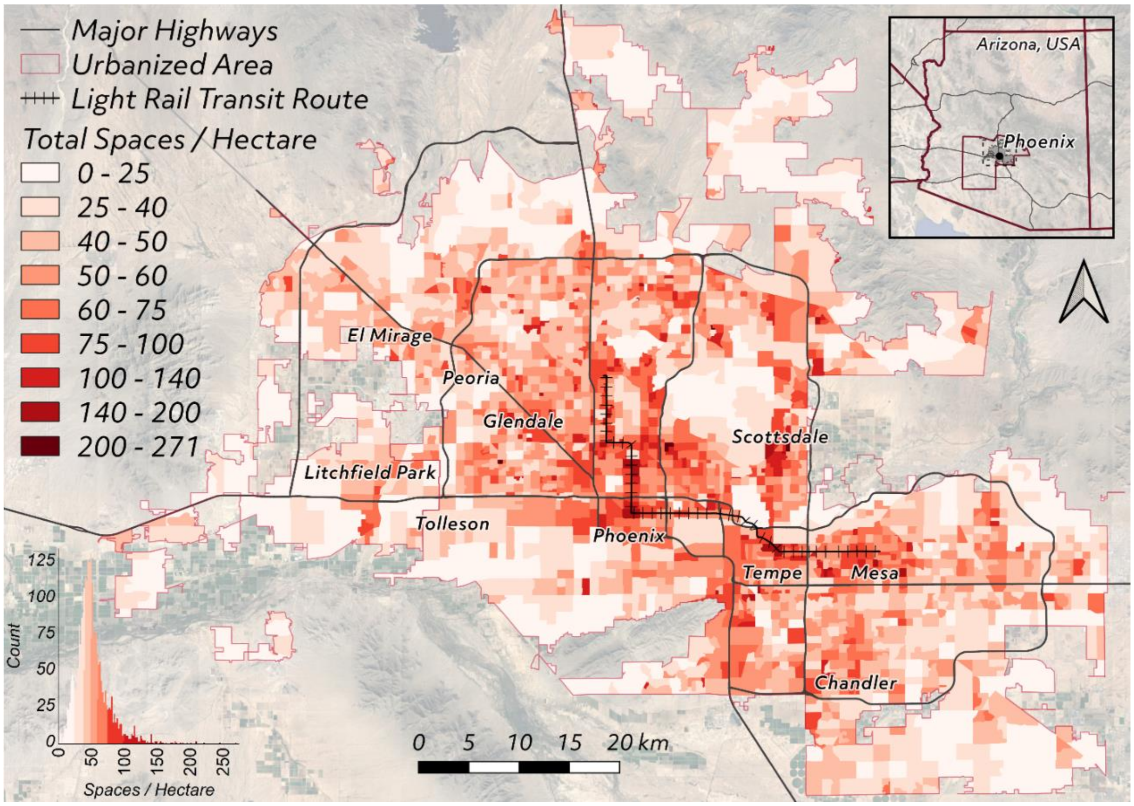


Figure 8. Total Parking Density in Metro Phoenix by Census Blockgroup. The distribution of parking space density by blockgroup is located in the bottom left. Estimates are for the UZA of Maricopa County only. Corresponding parking coverage area (%) can be approximated by multiplying total spaces per hectare by 0.3 (e.g. the first bin is 0% to 7.5% coverage area).

Parking density in metro Phoenix is spatially heterogeneous and may vary significantly by parking space type. In addition to classifying parking spaces as on or off-street, spaces are also classified as residential or non-residential based on dominant surrounding property type and road classification. Spatial distribution of parking spaces by these four major types is shown in **Figure 9**. On-street and residential parking appears relatively spatially homogenous due to the high amount of residentially zoned land in urban Phoenix; over two-thirds (67%) of urban parcels are designated as single family residential (SFR) dwellings. Residential and off-street parking are the dominant types of parking; residential parking (on and off-street) accounts for 69% of total spaces, and off-street parking (residential and non-residential) accounts for 60% of total spaces. Conversely, off-street and non-residential parking is highly concentrated around major travel ways and centered on downtown Phoenix.

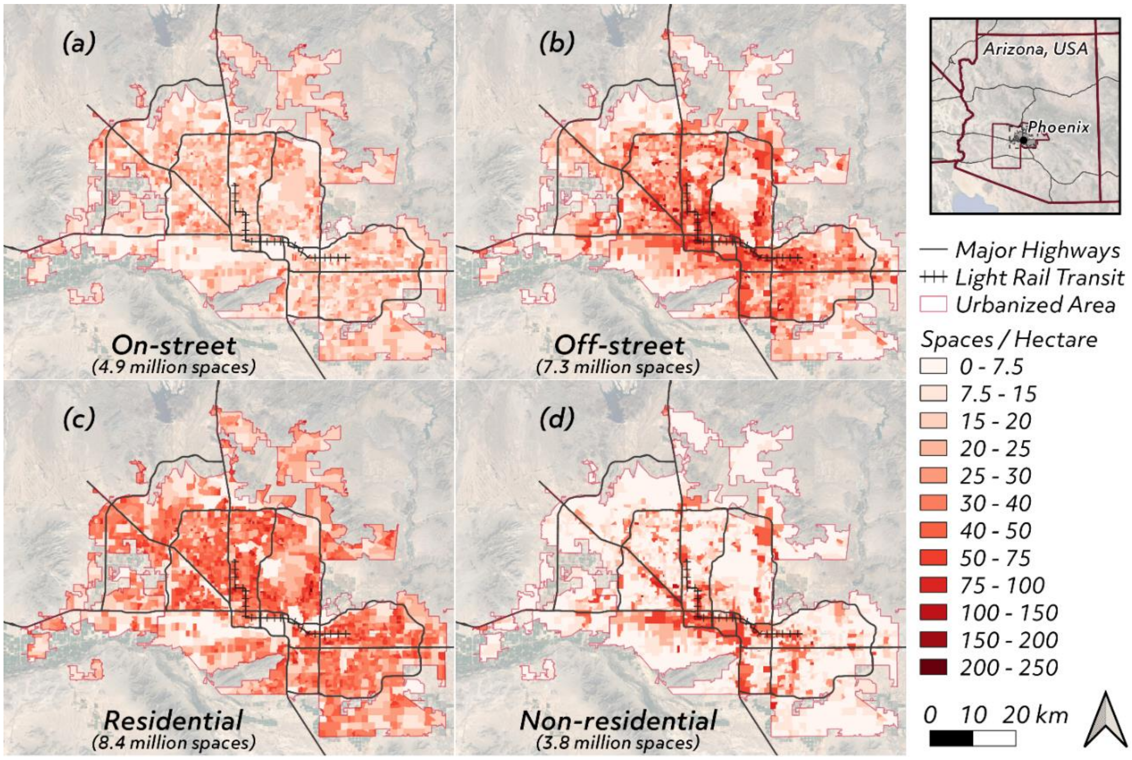


Figure 9. Parking Density in Metro Phoenix by Type at the Census Blockgroup Level. Four types of parking classification are shown with total spaces in parenthesis below type name. Note that types are only mutually exclusive between on and off-street and between residential and non-residential (e.g. on-street spaces can be residential or non-residential). Estimates are for the UZA of Maricopa County only.

3.3.2 Historical Parking Growth

Since the middle of the 20th century, parking supply has grown rapidly in metro Phoenix, but since the 2008 recession, growth has significantly slowed. This is consistent with infrastructure maturation theory (Chester & Allenby, 2018) and infrastructure results for other cities (Chester et al., 2015; Chester & Cano, 2016). Before 1960, there was less than one off-street parking space per resident, and the majority of available parking was on-street. Since 1960, metro Phoenix has seen an increase of 11 million parking spaces, 3.4 million residents, 2.6 million personal and non-commercial vehicles, and 1.6 million non-farm jobs (**Figure 10**). The volume of parking space growth has been driven by residential and off-street additions, but the densest growth occurred in downtown and commercial areas with significant parking growth around metro Phoenix's light rail corridor (**Figure 11**). Since the 2008 recession, parking space additions have slowed significantly. From 1960 until 2000, there was an average parking space growth rate of 5.2% per year. From 2000 to 2008, the parking growth rate declined all but one year from 3.8% to 1.3%. Since 2008, growth of parking spaces has dramatically slowed with an average growth of 0.44% spaces per year.

There is a wide range of possibilities when considering future growth of parking in metro Phoenix. Recent trends allude to a significant slowing in parking growth. However, if the development and parking growth in metro Phoenix returns to 2000-2008 rates (2.8% average growth per year), as many as 3.9 million spaces could be added in the next 10 years, and current parking capacity could nearly double by 2040 to 23 million spaces. Conversely, if post-2008 trends hold, roughly 1.1 million spaces would be added by 2040. For comparison, urbanized Maricopa County is projected to add 1.2 to 2.1 million residents by 2040 (AZ OEO, 2018c).

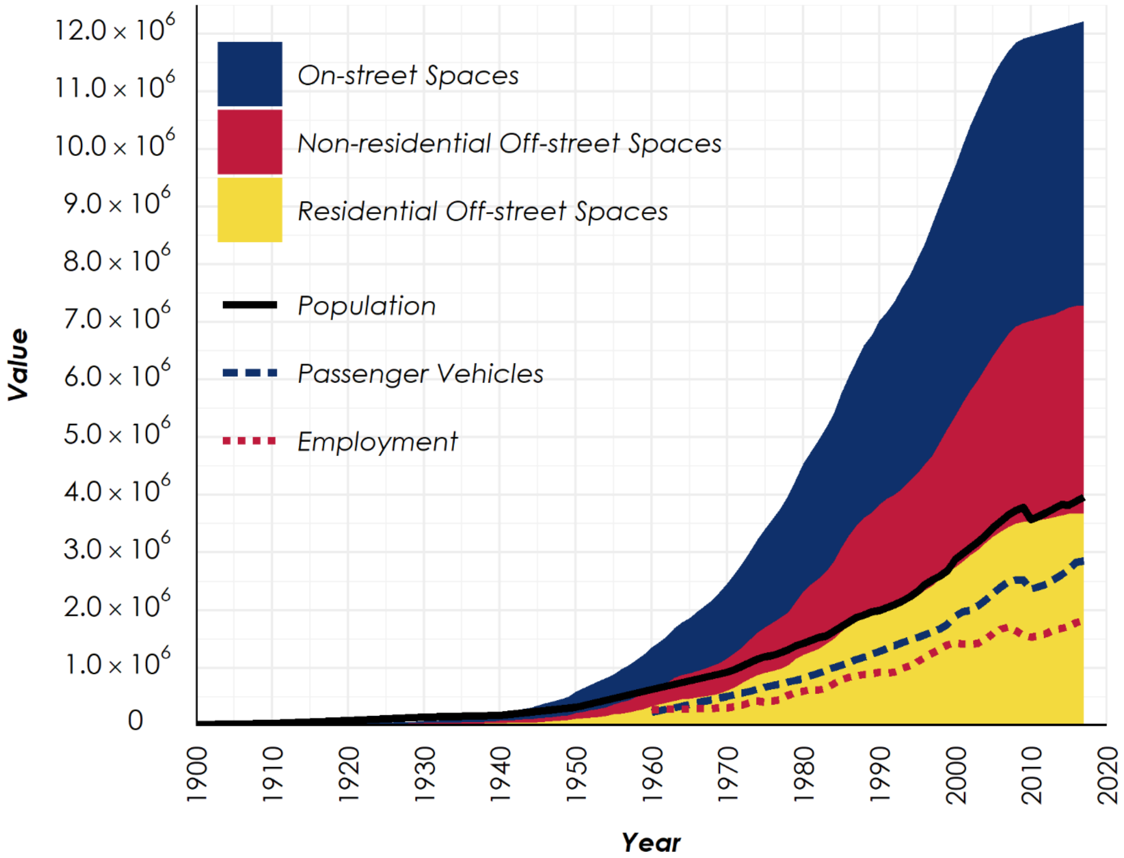


Figure 10. Growth of Parking, Population, Vehicles, and Employment in Metro Phoenix, 1900 - 2017. Parking growth is shown in stacked area. All values are estimates for the UZA of Maricopa County only. “Passenger Vehicles” include registered vehicles only and exclude commercial vehicles, non-motorized vehicles, recreational vehicles, and heavy duty vehicles. “Employment” excludes farm-related employment.

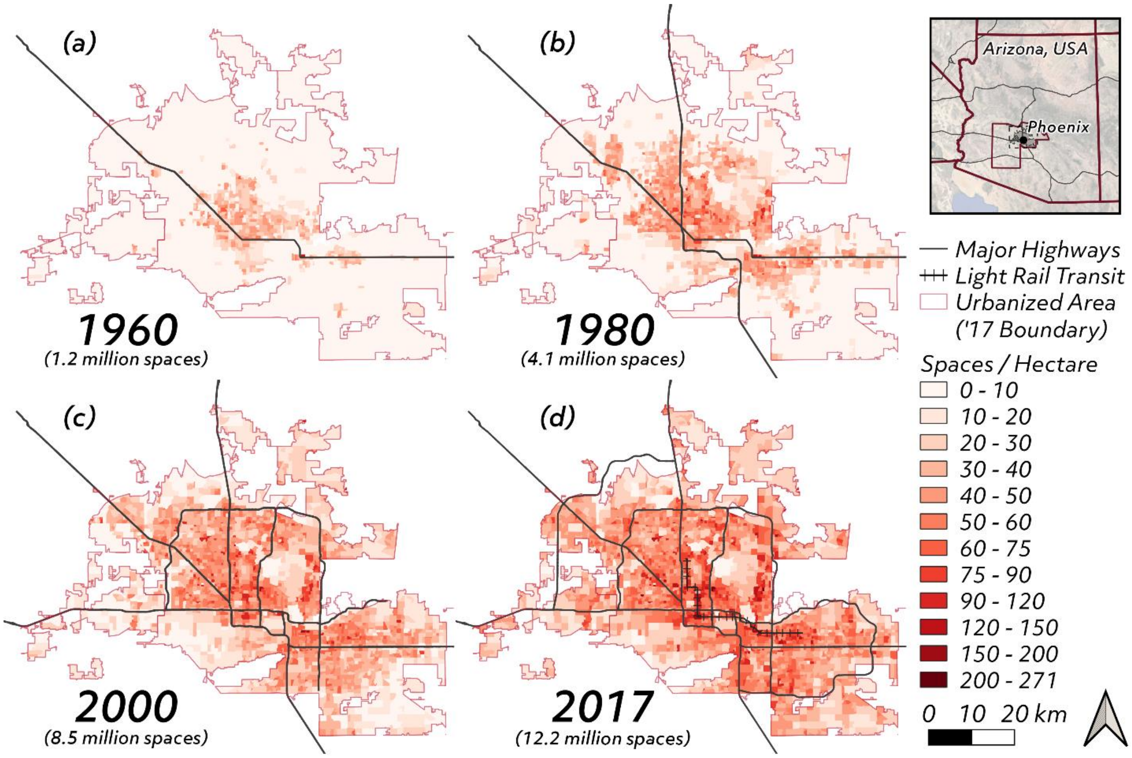


Figure 11. Parking Growth in Metro Phoenix, 1960 - 2017. Historical parking growth is shown for the 2017 urbanized area boundary in Maricopa County at four points in time. Note that the growth of major highways and the addition of the light rail transit line is captured.

3.3.3 Comparing Phoenix and Los Angeles Parking

To further evaluate parking in metro Phoenix, we compare results of this analysis with a past analysis of parking in Los Angeles, California (Chester et al., 2015). These regions have many similarities including that the bulk of their growth occurred in the latter half of the 20th century, although Los Angeles developed well before Phoenix. A statistical comparison is shown in **Figure 12** (for results in table format, see the Appendix B.2 **Table 13**).

Notable differences and similarities arise when comparing the parking in the metros of the Phoenix and Los Angeles. First, it should be noted that the boundaries of comparison between these studies are slightly different: we assess the urbanized area of Maricopa

County and Chester et al. assess parking throughout the whole County of Los Angeles. While these boundaries are different, both capture significant portions of each metro region including the densest areas of population and employment. Los Angeles County had a greater amount of parking in 2010 compared to urbanized Maricopa County now (**Figure 12**). This is expected as Los Angeles is arguably the most extreme case of urban parking prevalence with more space dedicated to parking than any other city in the world (Shoup, 1997). Overall, urbanized Los Angeles was denser in 2010 compared to urbanized Maricopa County in 2017; 2,702 people per square kilometer in urbanized Los Angeles compared to 1,276 in urbanized Phoenix. Hamidi and Ewing (2014) also found that Los Angeles is denser than Phoenix for the county and metropolitan statistical area (MSA) across multiple metrics including land use mix, activity centering, and street connectivity.

Despite the greater overall parking supply and density in Los Angeles, we estimate that metro Phoenix has 36% more on-street parking, largely driven by increased residential on-street parking space. Although Los Angeles appears denser in nearly all apparent metrics, there is not a significant difference in the density of total roadway miles in the urbanized areas of Los Angeles and Maricopa County (urbanized Los Angeles County roadway density: 12.47 km roadway / km^2 urbanized area; urbanized Maricopa County roadway density: 12.45 km roadway / km^2 urbanized area). Although the roadway density is not significantly different between the two regions, Los Angeles parcels are smaller on average, and the road network is more connected. The mean parcel density in Los Angeles County in 2010 was 870 parcels/km^2 compared to 512 parcels/km^2 in urbanized Maricopa County in 2017. The mean intersection density in Los Angeles County was 89 intersections per square kilometer compared to 63 for Maricopa County in 2010 (Fraser et al., 2016), and the street connectivity score was 154 for Los Angeles MSA compared to 111 for the Phoenix MSA (a higher score equates to higher street connectivity; Hamidi and Ewing 2014). As a result, there is less curb space for on-street parking in Los Angeles per 'parkable roadway length' due to increased obstructions from intersections and driveways due to higher intersection and parcel density. Additionally, there may be higher density of other obstructions like fire hydrants and bus stops given the higher density of parcels and travel demand. Despite the higher availability of on-street parking in Phoenix, it is likely that on-street parking in Los Angeles has higher utilization due to less spaces per vehicle and a greater travel density.

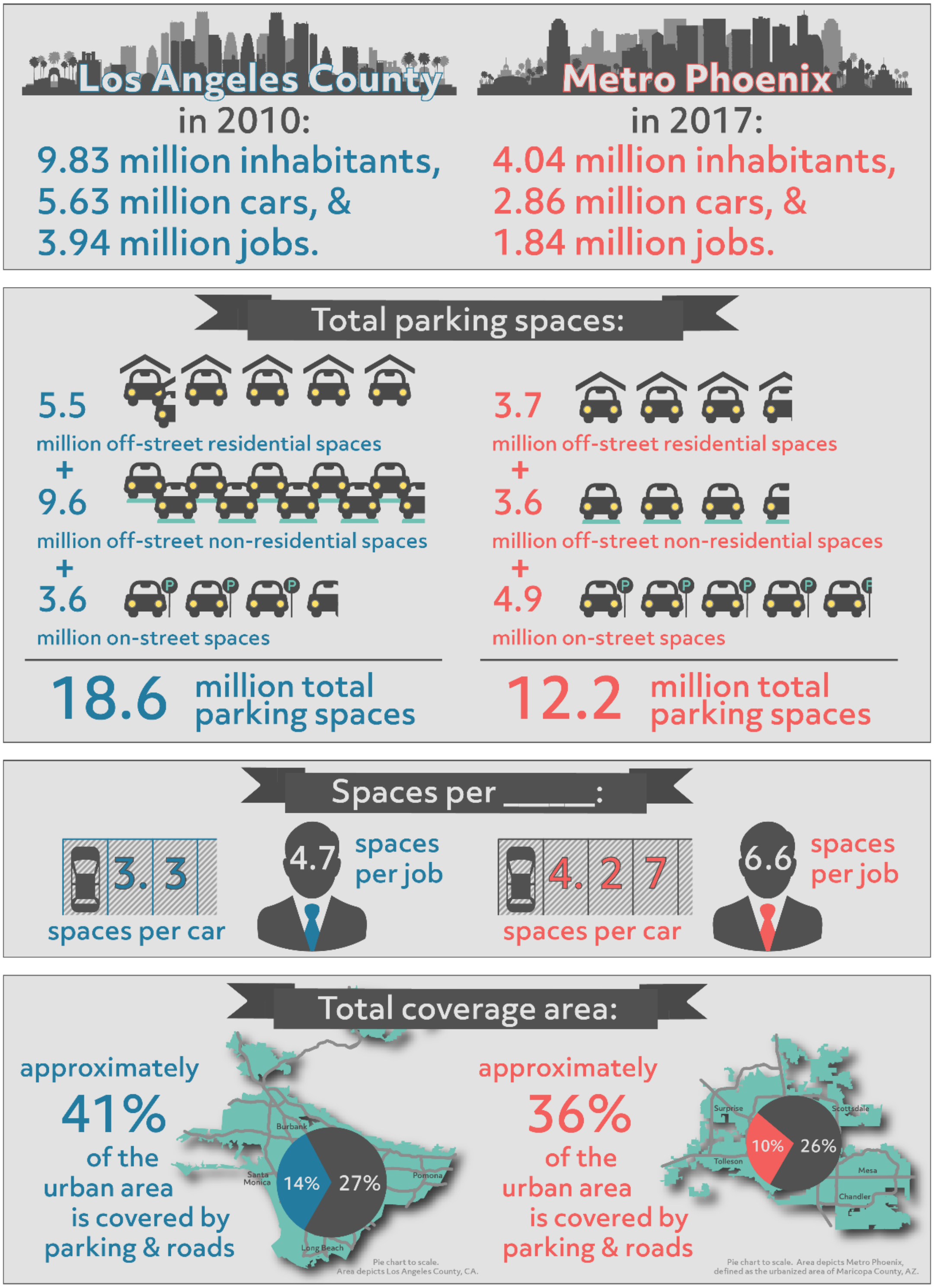


Figure 12. Summary Parking Statistics for Urbanized Maricopa County (Metro Phoenix) in 2017 compared to Los Angeles County in 2010. "Cars" are defined as all registered non-commercial passenger vehicles in the region; "jobs" are defined as all non-farm employment in the region. Note that coverage area is an estimate that includes excess space needed to maneuver and space within parking garages. UZAs of Los Angeles County (bottom left) and Maricopa County (bottom right) pictured are at the same scale.

3.3.4 Validation Results

Over 22,000 parking spaces were manually counted using satellite imagery across 585 non-residential and high density residential parcels. Co-located parcels were often grouped by neighborhood to ameliorate issues such as shared parking in commercial developments. Percent error in estimated spaces versus counted spaces varied from +110% to -73%, but the highest errors occurred at individual parcels or small groupings of parcels. For all parcels validated, the total error was 6.2% more spaces predicted than counted, and the median error across the grouped parcels was 1.1% more spaces predicted per parcel.

Due to limited historical satellite imagery available at high resolution and almost no other attempts to inventory parking in Phoenix, it is difficult to validate our historical parking growth approach. However, a few data points from a past synthesis of transportation statistics in major cities are useful: Kenworthy et al. (1999) estimated parking densities in downtown areas of major cities in 1960, 1970, 1980, and 1990, and there was 36, 57, 69, and 81 spaces per hectare respectively in the downtown City of Phoenix. We estimate 47, 56, 67, and 79 spaces per hectare for the same four years. These estimates are remarkably close, indicating that this historical approach is likely reasonable.

The high variance in actual versus predicated spaces at fine resolution may result from many cases such as: shared parking lots in commercial zones; exceptions in special cases; discrepancies in reported versus existing property characteristics; and, developers building beyond minimum requirements. Despite the high variance at a fine resolution, our methods are aimed at accurately estimating parking at a neighborhood level, and given the more reasonable variance at a neighborhood scale, this indicates our approach is reasonable. For more details on the validation results, and for discussion of parking inventory limitations and sensitivity, see Appendix B.1.

3.4 Discussion

It is clear there is an abundant supply of parking in metro Phoenix. Shoup (1997) estimated that automobiles are parked 95% of the time, and following Shoup's methodology, which used the National Household Travel Survey, we estimate that the average private automobile in metro Phoenix is parked approximately 98% of the time (USDOT & FHWA, 2017). As a result, 23% of available parking spaces contain a parked private vehicle on average, but without further understanding of the parking demand, it is difficult to conclude if parking is oversupplied. Conversely, it is reasonable to conclude that a residential parking imbalance exists in metro Phoenix given that private vehicle registrations are a reasonable estimate for residential parking space demand. For every private vehicle in Phoenix there is approximately 1.3 off-street residential spaces and 1.7 on-street residential spaces. Comparing to Los Angeles in 2010, there was approximately one off-street residential space per private vehicle and 27% less total on-street spaces. Another specific instance where there is a significant supply-demand imbalance for parking is along the light rail transit corridor between Downtown Tempe and Downtown Phoenix. Along this corridor, there are between four to six off-street residential parking spaces per household vehicle (US CB, 2016). Whether this imbalance is caused by economic reasons, the proximity of a high quality transit, or other reasons, it implies that minimum parking requirements have led to a local oversupply, potentially hindering redevelopment in the area. Regardless of demand, this supply side estimate supports the notion that additional spaces may not be required for urban infill development.

Given the abundant and underpriced parking in metro Phoenix, and the many consequences tied to automobile dependence, planners and policymakers should consider reform of minimum requirements as well as opportunities for improved parking management and parking space repurposing. At a minimum, the precision with which parking regulations force developers to build new parking should reflect the amount of parking that is already built and promote opportunities to share existing spaces. One example in metro Phoenix could be to address the residential parking imbalance by reforming or even removing residential minimum parking requirements. Identifying current and future areas where excess parking could be repurposed will become increasingly valuable, especially as reforming standards will not immediately address issues with already built infrastructure. Excess parking area could be increasingly repurposed for temporary alternative uses such as hosting special events, greenspaces, or increased bike storage. Parking management strategies could also be useful to ensure parking spaces are more efficiently used (Barter, 2010; Cao et al., 2017), optioning further parking repurposing and reform of minimum requirements.

The most common parcel types in metro Phoenix to contribute to the off-street parking supply are SFR properties. An estimated 2.1 million off-street spaces in the region exist due to SFR minimum requirements. Additionally, some jurisdictions in the region require two spaces of sheltered garage parking for SFR properties (e.g. City of Avondale, City of Gilbert). As there are also large amounts of on-street parking in residential neighborhoods, minimum requirements for off-street residential parking could be removed or reduced. For example, minimum requirements could instead be replaced with maximum requirements to encourage use of on-street parking (Manville & Shoup, 2005).

We estimate parking growth has significantly slowed since the 2008 recession. The primary explanation for this is the significant decrease in reported property developments or redevelopments in the Maricopa County Assessors Database. From 2000 to 2008, an average of 4,310 parcels were developed or redeveloped per year compared to only an average of 1,290 parcels per year since 2009. Population and employment growth also suffered following the 2008 recession, but have since recovered, outpacing parking growth significantly since the recession. Since 2011, 0.66 spaces have been added per new resident, and 1.1 spaces have been added per new job. For comparison, from 2000 to 2008, an average of 2.5 spaces were added per new resident and 6.9 spaces per new job. The overall decrease in property development is the primary reason for decreased parking additions, but there may be two supplementary explanations for slowed growth of parking: 1) a larger amount of property redevelopment in place of new development causes a small increase in space additions relative to existing parking from prior developments; 2) population and employment growth lag behind parking development as land development can precede a property being fully utilized by months or years. Regardless of the specific causes, the slowing raises interesting questions about future parking trends, whether space additions will continue to slow or return to historical trends.

There are many negative externalities of urban sprawl and haphazard parking development independent of sustained automobile dependence, such as further exacerbating urban heat, dis-incentivizing walkability, hindering nearby vegetation growth, and decreasing neighborhood aesthetic appeal. In hot climates, urban heat island and pedestrian thermal comfort are common problems expected to become worse. Local heat islands occur due to high amounts of diurnal solar energy stored in impervious materials (such as parking lot and roadway pavements) slowing radiating back into local air (Asaeda et al., 1996; Golden & Kaloush, 2006). Being predominantly surrounded by pavements also increases the total amount of reflected solar energy hitting the human body. Wider street canyon widths ratios will decrease shade and increase the total solar radiation reaching the urban floor, decreasing pedestrian thermal comfort (Norton et al., 2015). Parking lot location is also important when promoting walkability and urban greenery. It is common in metro Phoenix to have commercial parking lots wedged between travel ways (roads, bike paths, sidewalks) and buildings. This marginally increases the travel distance and time of pedestrians because they must cross a parking lot to reach a building, potentially also extending their time in local heat islands in summer months. Vegetation near parking lots in hot desert climates may grow poorly compared to vegetation not near asphalt surfaces (Celestian & Martin, 2004). Locating parking lots in-front of instead of behind their associated facility may harm the aesthetic appeal of a neighborhood. Cities in hot climates should be cognizant of these negative externalities from parking lot design and automobile dependence and consider parking lot location, pavement type, and surrounding vegetation in parking standards.

This analysis provides further evidence of several negative outcomes with minimum parking requirements and the consequential state of parking infrastructure development. Furthermore, inconsistencies in current parking standard specifications impede planners and academics from easily understanding the current supply of parking in cities. To most effectively quantify the growth and extent of parking infrastructure in cities, significant improvements in reporting of built and required parking is necessary.

3.5 Conclusion

Driven by high automobile dependence and the rapid expansion of property development in the latter half of the 20th century, a significant amount of parking infrastructure exists in metro Phoenix. Considering the many unnecessary negative externalities related to parking such as high land and resource use, increased pollution, and continued promotion of automobile dependence, there is a need to rethink parking development. In addition to all of the negative externalities of parking that any city may face, the impact on urban heat island and pedestrian thermal comfort in hot climates such as in Phoenix are likely significant and potentially hazardous. This research provides further evidence that the current lack of parking inventories paired with inconsistent and misguided parking requirements significantly obstructs efficient use of space and may constrain sustainable urban growth. As a result, there is clear value in identifying opportunities for parking reform, quantifying existing parking supply, repurposing excess parking supply, and further exploring the consequences of abundant parking and urban automobile dependence.

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CHAPTER 4

URBAN HEAT IMPLICATIONS FROM PARKING, ROADS, AND CARS: A CASE STUDY OF METRO PHOENIX

5.1 Introduction

As global urbanization and climate change persists, cities are becoming gradually warmer. One consequence of urbanization is Urban Heat Island (UHI), a phenomenon where urban areas are warmer than rural areas. Increasing urban heat from UHI and climate change threatens urban vitality and prosperity by potentially reducing productivity and economic development (Graff Zivin & Neidell, 2014; Kjellstrom et al., 2009), increasing demand for energy (Burillo et al., 2019; Miller et al., 2008; Reyna & Chester, 2017), increased urban infrastructure vulnerability (Bondank et al., 2018; Markolf et al., 2017; Schaeffer et al., 2012), dissuading outdoor activity and travel (Karner et al., 2015; Obradovich & Fowler, 2017; Stamatakis et al., 2013), and causing increased heat-related injury or death (CDC, 2012; Eisenman et al., 2016; Gasparrini et al., 2015; Kovats & Hajat, 2008). Given the breadth of externalities, there is great desire to fully understand and mitigate urban heat.

UHI is caused by anthropogenic infrastructure and activity, and previous research has established anthropogenic heat from vehicles and pavements as significant. Impervious and engineered materials of an urban surface (such as asphalt and concrete) have greater ability to absorb and store heat compared to the Earth’s natural terrain due to different intensive properties. Increased coverage of built infrastructure and decreased vegetation in urban areas also reduces the potential for evaporative cooling. Asaeda et al. (1996) found asphalt pavements to contribute significant heat fluxes relative to bare ground; afternoon heat absorption from asphalt pavements within 30 m of the ground accounted for four times the daily averaged total anthropogenic heat across the Tokyo metropolitan area. Wasted heat from human activity also contributes to urban warming; buildings and vehicles dissipate large amounts of energy as waste heat. While it is well established that internal combustion engines waste significant amounts of energy as heat (Rajoo et al., 2014; Reddy et al., 2015), the influence of urban vehicle travel on the urban energy balance has been less rigorously studied compared to other heat sources in part due poor quality travel and vehicle thermal performance data (Smith et al., 2009). Hart & Sailor (2009) found up to 2 °C warmer air masses above urban roads during the weekday compared to the weekend in Portland, Oregon, indicating that increased weekday vehicle travel may be the primary cause. Sailor & Lu (2004) found that heating from vehicles dominated the summer anthropogenic heating in six US cities, accounting for 47% to 62% of the total.

Heat transfer models have been used frequently for many purposes, and have proven a viable tool to estimate the surface heat transfer in materials including urban pavements. Even before wide availability of computer programing, heat transfer models were constructed and validated to asses pavement thermal performance (Dempsey & Thompson, 1970). With increased interest in UHI in the late 20th century (Arnfield, 2003; T. R. Oke, 1982), more research emerged that focused on explicitly modeling paved surfaces to understand their influence on UHI; Asaeda et al. (1996) were the first to model and assess the effects of paved surfaces on the near surface urban climate. One-dimensional heat transfer models using finite difference solving schemes are among the most popular due to straight-forward implementation and ability to achieve reasonable predictions of pavement surface temperatures (Gui et al., 2007; Hall et al., 2012; Hermansson, 2004; Wang & Roesler, 2012). Despite the increased popularity in heat transfer modeling in pavements, most pavement heat transfer modelling applications are not driven by understanding infrastructures influences on UHI. Instead, the urban surface's influence on UHI is more commonly assessed by relating UHI intensities to spatial variability in land use and albedo (Carnielo & Zinzi, 2013; Dai et al., 2018; Golden & Kaloush, 2006; Hart & Sailor, 2009; Minjun Kim et al., 2017; Sun et al., 2018; Wicki et al., 2018).

Numerous studies have quantified urban anthropogenic heat fluxes from pavements and vehicles independently within their scope (Allen et al., 2011; Arnfield & Grimmond, 1998; Golden & Kaloush, 2006; Ichinose et al., 1999; Smith et al., 2009), however, only one study has quantified both simultaneously. Fujimoto et al. (2015) investigated the influence of vehicle travel on the heat balance surrounding an urban intersection in Fukui, Japan. The authors found that vehicle related heat fluxes accounted for a 3% to 12% of the total winter heat balance depending on traffic density and time of day. As a result of increased vehicle travel, they predicted increased pavement surface temperatures of 1.5 °C to 4 °C compared to measured pavement surface temperature increases of 3.5 °C.

Urban automobile travel is pervasive and often dominants mode share and land use in cities (Kenworthy & Laube, 1999). Pavement infrastructure can make up 30 to 66% of the urban land cover (Akbari et al., 1999, 2003), and parking infrastructure alone may account for as much as 10 to 14% of incorporated urban land (Chester et al., 2015; Hoehne et al., 2019). To help understand how city planning and the transportation sector can influence urban heat, this research aims to quantify contributions to urban heat from vehicle travel and pavement infrastructure. We focus this study on the Phoenix metropolitan region for three primary reasons: 1) Phoenix has a very auto-centric urban design with high automobile dependence and supporting infrastructure; 2) Phoenix may suffer significant consequences of urban heat due to urban heat island, climate change, and rapid urban growth; 3) the arid climate in Phoenix makes it a desirable for modeling of sensible heat transfer. This study aims to answer two research questions: 1) What aspects of urban pavements are most or least influential to sensible heat flux magnitudes?; and 2) How does pavement infrastructure and vehicle travel contribute to the urban heat balance?

5.2 Methodology

Two approaches are used to quantify spatial and temporal urban sensible heat flux magnitudes from pavements and vehicles in metropolitan Phoenix, Arizona. First, a one-dimensional (1D) model based on fundamental heat transfer is developed to approximate diurnal sensible heat fluxes from various types of pavements. The model is validated by comparing simulated material surface temperatures to remotely sensed land surface temperatures at various sites in metro Phoenix that are dominantly bare ground or covered by pavement. Additional pavement designs are then simulated to represent the various expected urban roadway or parking pavements designs found in the region. Next, regional vehicle travel data for a typical day is combined with internal combustion engine (ICE) vehicle efficiency estimates from literature to estimate rates of wasted heat from vehicle travel. Lastly, diurnal heat fluxes from vehicle travel across the urban road network are combined with simulated diurnal sensible heat flux profiles of typical pavements and assessed at a 250m^2 resolution across the Phoenix metropolitan area.

4.2.1 One-dimensional Heat Transfer Model Overview

Following extensive previous research on modeling fundamental heat transfer, a 1D model is developed that predicts temperatures and sensible heat flux of a delineated material according to its thermophysical properties and surrounding environmental conditions. A 1D approach is deemed sufficient as opposed to higher dimensional modeling because lateral conduction is only significant at the edges of a material. The model balances surface energy transfer from convection, incoming solar radiation, and outgoing infrared radiation as well subsurface energy transfer via conduction (**Figure 13**). Simulated materials are idealized as a series of stacked nodes starting at the surface at continuing downward to a defined depth. Heat transfer is first balanced between the nodes at an initial condition, then solved by stepping forward in time using an explicit finite difference scheme. While many 1D models have been implemented and validated in literature, this methodology most closely replicates the implementation and assumptions of Gui et al. (2007) because it was implemented and validated for conditions in Phoenix, Arizona.

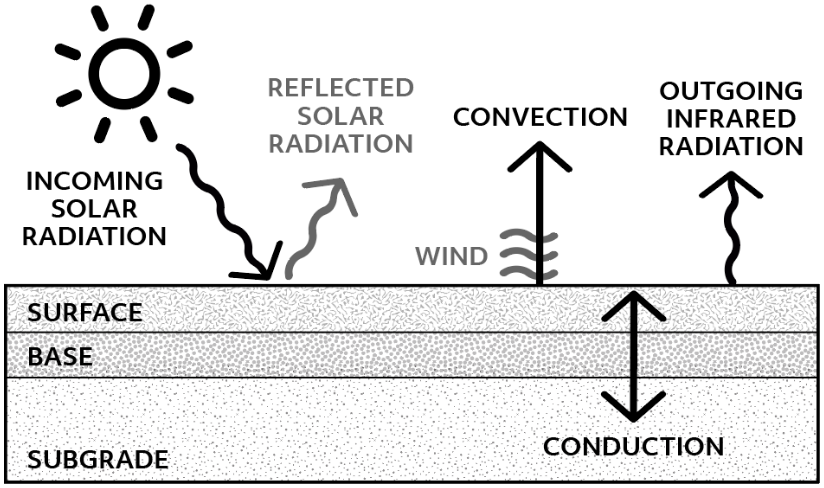

Figure 13. One-dimensional Heat Transfer Diagram for a Typical Pavement.

To simulate heat transfer of a pavement or bare ground, a number of input variables are utilized. Uniform or composite materials may be simulated, and for each unique layer of material, various material properties are required: albedo (surface layer only), emissivity (surface layer only), layer thickness, thermal conductivity, and volumetric heat capacity. Other parameters that must be defined include: sky view factor (SVF), characteristic length of the surface, initial starting temperature profile, nodal spacing, and time step length. The model is forced using hourly or sub-hourly measured solar radiation, air temperature, humidity, and wind velocity data.

Temperature and sensible heat transfer is estimated by transient energy balance of surface convection, incoming surface solar radiation, outgoing surface infrared radiation, and subsurface conduction. The generalized equation for net heat transfer (in W m^{-2}) at the surface is defined as

$$q_{net} = q_{rad} + q_{conv} - q_{sol} \tag{4.1}$$

where q_{rad} is outgoing infrared radiation, q_{conv} is convection, and q_{sol} is incoming solar radiation. Outgoing infrared radiation is assumed to obey the Stefan-Boltzman law where the surface is assumed to emit longwave radiation as a black body. Therefore, outgoing infrared radiation at the surface is defined as

$$q_{rad} = \Psi_{sky}\varepsilon\sigma(T_s^4 - T_{sky}^4) \tag{4.2}$$

where Ψ_{sky} is the SVF, ε is emssivity of the surface, σ is the Stefan-Boltzmann constant, T_s is the surface temperature, and T_{sky} is the sky. Convective heat transfer at the surface is defined as

$$q_{conv} = h_\infty(T_s - T_\infty) \tag{4.3}$$

where h_∞ is the convective heat coefficient of air, and T_∞ is the dry-bulb temperature of air. Incoming solar radiation is defined as

$$q_{sol} = q_{sol,raw}\Psi_{sky}\alpha \tag{4.4}$$

where $q_{sol,raw}$ is the raw incoming solar radiation and α is the albedo of the surface. Note that The generalized equation for subsurface sensible heat transfer (conduction) is defined as

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\frac{\partial^2 T}{\partial x^2} \tag{4.5}$$

where T is temperature, t is time, k is thermal diffusivity, ρ is density, c is specific heat capacity, and x is depth. Where multiple layers of differing materials are present (as is common in pavements), boundary conditions are also implemented. Due to a lack of information, it is assumed that thermal contact resistance between layers is zero. While this assumption will affect subsurface pavement temperatures, a similar pervious model did not find significant impacts on near-surface temperatures with zero thermal contact resistance between layers (Gui et al., 2007). As a result, the upper and lower interfaces at the boundary can be assumed to be equal, and are idealized as a single node. Therefore, the boundary condition must obey

$$k_{b-1}\frac{T_{b-1} - T_b}{\Delta x_{b,b-1}} = k_{b+1}\frac{T_b - T_{b+1}}{\Delta x_{b,b+1}} \tag{4.6}$$

where subscript b refers to the node at the boundary and $b-1$ and $b+1$ refer to the conditions at nodes immediately above and below the boundary node. This outlined heat transfer model is implemented using R statistical software, and its full documentation for application in this analysis is maintained in a GitHub repository (Hoehne, 2019).

To ensure feasible results from the explicit finite difference scheme, all calculations are required to satisfy the Courant-Friedrichs-Lewy (CFL) condition for stability (Gui et al., 2007; Heath, 2002). In order to satisfy the CFL stability condition, sufficiently small time and nodal spacing are required. To achieve stable solutions such that simulation times were reasonable, a nodal spacing of 10 mm and time step spacing of 30 seconds was chosen. Therefore, linear interpolation between weather observations is required to achieve matching temporal frequency.

To ensure initial conditions begin at an equilibrium, the initial conditions are iteratively simulated until convergence occurs between the initial (t_0) and first time step (t_1). The tolerance for convergence is defined such that each nodal temperature at t_1 is within 0.1 Kelvin of its t_0 temperature for the first 100 iterations of the initial conditions, after which the tolerance for convergence is relaxed to 1.0 Kelvin.

4.2.2 Selected Pavement Designs and Model Validation for Phoenix Sites

Validation is performed by comparing various modeled pavement and bare ground surface pavement temperatures to remotely sensed land surface temperatures from

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) onboard the Terra satellite (NASA, 2019). ASTER On Demand Surface Kinetic Temperature measurements are generated from five thermal infrared bands and are atmospherically corrected (USGS, 2018). Validation sites are selected across the Phoenix metro region such that the materials of interest uniformly cover a 90 m^2 ASTER raster pixel. Major roadways in Phoenix do not reach 90 meters in width, and as a result, the sites selected are asphalt or concrete parking lots and airport tarmacs. **Figure 14** displays a sample of the selected sites highlighted on an ASTER surface temperature image. For a detailed list of the selected sites for validation, see Appendix C.1.

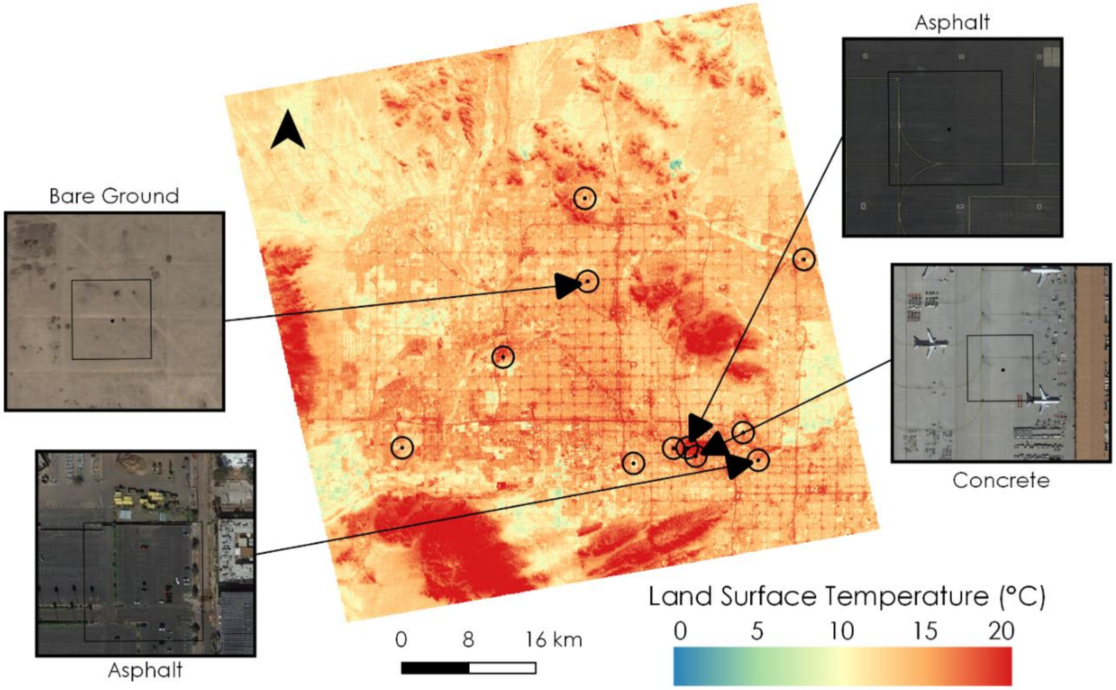

Figure 14. ASTER Nighttime Land Surface Temperature across Phoenix Metro on March 22nd, 2014 with Selected Validation Sites Highlighted. Satellite imagery of four validation sites are shown where the inner box is the 90 m^2 pixel location of the ASTER cell.

A variety of pavement designs are categorized in three classes and developed by referencing relevant literature and pavement engineering design recommendations or requirements. A summary of the range of material parameters for various pavements and bare ground is displayed in **Table 2**. Pavement designs are classified in one of three pavement classes: (1) asphalt pavement (primarily hot-mixed asphalt) which utilizes a bitumen binder with aggregate; (2) concrete pavement (primarily Portland cement concrete) which utilizes a cement binder with aggregate; and (3) composite asphalt-concrete pavements that combine distinct bitumen-bound and cement-bound layers in a single pavement design such as whitetopping overlaid on an asphalt pavement or rubberized asphalt overlaid on Portland cement concrete (PCC). Whitetopping is a common method where a thin PCC layer is overlaid on top of an existing asphalt pavement. Whitetopping has become increasingly popular for existing pavement rehabilitation and to increase the surface layer albedo for potential cooling benefits. Lastly, a fourth material class emulating desert soil is created to serve as a reference for undeveloped natural land that would be found in an arid region such as Phoenix.

Table 2. Ranges of Material Parameters Utilized for Pavement Design and Bare Ground from Literature. 'Ground' refers to bare, native, and uncompacted material consistent with materials found in the Phoenix region (i.e. desert soil or sand) that would represent undeveloped land. 'Subbase' refers to the aggregate supporting layer between the pavement wearing course and compacted ground. 'Subgrade' refers to compacted ground underneath the pavement.

Parameter	Units	Asphalt	Concrete	Subbase	Ground or Subgrade
Albedo, $\tilde{\alpha}$	*dimension-less*	0.05 – 0.15 [a] 0.08 – 0.09 [b] 0.17 [c] 0.12 – 0.20 [d]	0.18 – 0.29 [b] 0.20 – 0.40 [a] 0.31 – 0.43 [c] 0.42 – 0.46 [d]	NA	0.30 [e] 0.40 – 0.50 [f]
Emissivity, ε	*dimension-less*	0.85 [c, g] 0.90 [h] 0.90 – 0.95[i]	0.90 [j] 0.92 – 0.96 [k]	NA	0.90 – 0.97 [e]
Thermal conductivity, k	$\frac{W}{m \cdot K}$	1.2 [c] 1.4 – 1.8 [l] 1.5 [h] 1.6 [m] 1.9 – 2.2 [n]	1.2 [o] 1.2 – 1.4 [k] 1.5 [j] 2.2 [m]	1.5 [h] 3.0 [m]	1.0 [c] 1.2 [m] 1.8 [h]
Density, ρ	$\frac{kg}{m^3}$	2200 [c] 2300 [n] 2300 – 2500 [l] 2400 – 2600 [h]	1810 – 2100 [k] 2300 [o] 2400 [j]	2400 [h]	1500 [c] 2200 [h]

		1800 – 2500 [o]			
Specific heat capacity, c	$\frac{J}{kg \cdot K}$	810 – 960 [k] 850 – 860 [h] 900 [o] 920 [k] 1200 – 1900 [l]	840 – 1050 [k] 1000 [j]	800 [h]	1100 [h] 1900 [c]
Layer thickness	mm	40 – 200 [o, p, q]	100 – 300 [p, r]	100 – 300 [o, p, q]	NA

[a] (Qin, 2015)
[b] (Li, Harvey, & Kendall, 2013)
[c] (Gui et al., 2007)
[d] (Golden & Kaloush, 2006)
[e] (Monteith & Unsworth, 2013)
[f] (Dobos, 2011)
[g] (Hermansson, 2004)
[h] (Minhoto et al., 2006)
[i] (Tan & Fwa, 1992)
[j] (Bentz & Turpin, 2007)
[k] (Hu et al., 2017)
[l] (Luca & Mrawira, 2005)
[m] (Wang & Roesler, 2012)
[n] (Im et al., 2015)
[o] (Hall et al., 2012)
[p] (ADOT, 2017b)
[q] (FAA, 2016)
[r] (USACE, 2018)

Various pavement designs and bare ground compositions are simulated to emulate the expected materials observed at each site. Simulation time periods are chosen by identifying ASTER observation dates that have less than 10% cloud cover and all data passing quality control checks. ASTER observation dates occurring during the day and night as well as occurring across all four seasons are selected to ensure a variety of dry weather conditions. Historical weather data for the same periods as the ASTER observation dates is retrieved for all stations across the entire metro Phoenix region from the MesoWest weather data network (University of Utah, 2019). All weather stations with consistent weather observations for each simulation date are chosen. Consistent weather observations are defined as: (1) having an average of at least one weather observation per hour for all relevant variables during the desired dates (solar radiation, air temperature, humidity, and wind speed); (2) having no gaps in observations for greater than two hours for all relevant variables; (3) no rainfall during analysis period; and (4) 95% of intra-station observations fall within two standard deviations of the intra-hour mean across all relevant variables and all stations in the region. Each validation site is assumed to have a SVF of 0.947, the mean of the Phoenix metro area (Middel et al., 2018). Pavement and bare ground compositions are then simulated for a period of three days such that the final day corresponds to a desired ASTER measurement using the hourly mean for all selected weather stations and specified material design parameters emulating the validation site materials.

4.2.3 Estimating Pavement and Vehicle Heat at a City-wide Scale

Profiles of pavement and vehicle heat-transfer are applied to regional pavement and traffic flow data to approximate spatial and diurnal heat flux magnitudes across the Phoenix metropolitan region. A pavement infrastructure inventory for metro Phoenix is developed by combining OpenStreetMap (OSM) roadway data (OpenStreetMap contributors, 2019) and Phoenix parking inventory data from Hoehne et al. (2019). Average annual daily traffic estimates are obtained from Maricopa County origin-destination travel demand data simulated in MATSim travel modeling software. Simulation outputs for pavement designs by roadway and parking functional classes are combined with waste heat flux estimates from vehicle travel and linked to the roadway and parking inventory data. Spatial and temporal mean daily and hourly anthropogenic sensible heat fluxes for a typical clear spring or fall day are estimated at a 250m by 250m spatial resolution for all of metro Phoenix.

Utilizing Phoenix parking inventory data at the individual property (parcel) level from Chapter 3 (Hoehne et al., 2019) and OSM roadway network data, fractional pavement area is estimated across the region. Fractional areas of pavements are estimated by different functional classes corresponding to expected variations in functional design. Roadway pavements are split into four major classes: highway, major arterial, minor arterial, and local roads. Parking pavements are split into two major classes: residential parking, and non-residential parking. Each parking space (residential or non-residential) is assumed to occupy approximately 31 m^2 of space consistent with previous research (Hoehne et al., 2019; Holland, 2014; Manville & Shoup, 2005). On-street parking is ignored as the roadway inventory accounts for parking space on roadway shoulders and metered on-street parking in Phoenix is insignificant. Links from the OSM road network are spatially buffered by the mean expected roadway widths and rasterized at a 250m resolution by functional class. To ameliorate the issue of parking inventory data not explicitly spatially locating spaces, parking area is spatially assigned at each property by buffering around the property centroid to create an area of parking centered on the property.

Each functional class of pavement is assigned pavement designs such that it corresponds to the expected in-situ pavement and complies with required engineering design specifications by the local municipality. The majority of urban pavements in Phoenix fully or partially utilize asphalt with over 80% of Arizona highways utilizing rubberized asphalt pavement (EPA, 2016). Commonly, local city streets and highways are paved or resurfaced with rubberized asphalt to improve durability, reduce traffic noise, and improve ride smoothness (ADOT, 2017a, 2019b). Asphalt pavements are often preferred for pavement design due to their viscoelastic properties that can provide improved long-term performance under thermal and load-bearing stress in contrast to rigid concrete pavement designs (Hall et al., 2012). Pavements made only of concrete are primarily found in single family residential parking (e.g. driveways). As a result, asphalt is assumed to be the dominant pavement type. **Table 3** overviews the assumed pavement designs assigned by pavement functional class following guidelines from the Arizona Department of Transportation (ADOT, 2017b) and typical pavement designs from literature in **Table 2**.

Table 3. Assumptions for Pavement Design and Vehicle Travel Applied to the Phoenix Metropolitan Area. Vehicle energy released per kilometer is estimated from urban city and highway driving efficiencies from Davis & Boundy (2019) using a mean of 31.7 MJ per liter of gasoline or gasoline equivalent fuel.

Generalized functional class description	Assumed mean pavement thickness	Assumed two-way road width or parking space size	Assumed coverage of asphalt vs. concrete pavement	Assumed energy released from vehicles
Highway or freeway	280 mm	43 m	95% Asphalt 5% Concrete	356 Wh/km (40 MPGe)
Major or minor arterial road	210 mm	28 m	90% Asphalt 10% Concrete	561 Wh/km (25 MPGe)
Major or minor collector road	170 mm	18 m	90% Asphalt 10% Concrete	718 Wh/km (20 MPGe)
Minor Collector or local road	140 mm	11 m	90% Asphalt 10% Concrete	718 Wh/km (20 MPGe)
Commercial parking	140 mm	31 m^2	85% Asphalt 15% Concrete	NA
Residential Parking	140 mm	31 m^2	10% Asphalt 90% Concrete	NA

The selected pavement designs to estimate roadway and parking heat fluxes are simulated using the same specifications as the validation phase with two alterations: (1)

measured solar radiation is replaced with estimated solar radiation using the ‘insol’ R package (Corripio, 2019) with inputs of local latitude, observed relative humidity, observed air temperature, Julian day, time of day, and an ozone thickness of 2.75 mm; and (2) all pavement designs for all dates are simulated under 1.0 SVF and 0.1 SVF to capture shaded and unshaded pavement scenarios. Estimated insolation is used represent a clear day and avoid impacts of sporadic cloud cover. For full details on all parameters simulated, see Appendix C.1.

As pavements in the region are not completely visible to the sky, the heat transfer of partially shaded pavements is incorporated by utilizing SVF data along the Phoenix roadway network from Middel et al. (2018) to calibrate heat transfer from pavements under direct solar radiation exposure versus pavements under shade. Moise & Aynsley, (1999) found that incoming daylight shaded-to-unshaded radiation had a median ratio of 0.09 for horizontal shading and 0.11 for vertical shading. Therefore, we assume pavement in the shade receives 0.10 of estimated unshaded incoming radiation. This is implemented in modelling such that any areas where partial shade is present (SVF < 1.0), the portion of shaded pavement is treated as though it has 0.10 SVF and the unshaded portion has 1.0 SVF. For example, a neighborhood with 0.80 SVF would have 80% of pavement modeled as unshaded (SVF = 1.0), and 20% of the pavement that is shaded is modeled with a SVF of 0.10. All pavements (parking and roadway) are applied the SVF measured along the roadway in the 250m^2 cell with exceptions for extremely high cases of parking. Properties that require large amounts of parking are increasingly likely to be underground or inside a parking structure. Therefore, for properties requiring greater than 100 spaces, we assume a conservative approach where parking area visible to the sky follows a non-linear decay under such that properties at 100 spaces have an unadjusted parking SVF of 1.0 which decays to a mean SVF of 0.325 at 100,000 spaces. While these assumptions for high densities of parking are difficult to validate given the lack of research and data on parking and SVFs, these are edge cases; only 497 properties of the 1.55 million in the urbanized area have greater than 1,000 parking spaces. However, if left unadjusted, numerous adjacent 250 m^2 are otherwise found to be entirely covered by parking pavement. For details on the specific parking SVF decay functions assumed, see Appendix C.2 **Figure 21**.

Metropolitan-wide vehicle travel data are combined with vehicle efficiencies to estimate vehicle waste heat from energy consumption by OSM roadway link. The partial amount of consumed energy wasted as heat is uniformly attributed to the traversed roadway link. Vehicle travel data are obtained from a MATSim regional travel demand model that utilizes travel and population data provided by the Maricopa County Association of Governments. This obtained data represents all personal light duty vehicle trips across the regional OSM road network for a typical spring or fall day. This travel data excludes heavy duty vehicle travel such as freight and public transit, and due to a lack of similar high fidelity data, heavy vehicle traffic on links is not considered. As vehicle driving efficiencies depend on the vehicles characteristics and driving patterns, different efficiencies are assigned by roadway functional class. A typical passenger vehicle may lose 60 – 64% of energy to heat during city driving and 56 – 60% of energy to heat during highway driving (DOE, 2019). Other academic literature cites ranges of 30% to 80% of fuel energy wasted as heat during vehicle operation (Hsiao et al., 2010; Shiho Kim et al., 2011; Orr et al., 2016; Rajoo et al., 2014; Yang & Stabler, 2009). Given the most commonly cited factor is ‘nearly two thirds,’ this analysis assumes a static mean of 65% of fuel energy lost as heat to the surrounding environment for all vehicles during vehicle travel. It should be noted that nearly all fuel energy used for vehicle travel will eventually be lost as heat (e.g. kinetic energy is converted to thermal energy via friction braking), but this analysis focuses only on the heat lost during travel (e.g. heat from exhaust). Total energy consumed by vehicles for each link is calculated by multiplying vehicle kilometers traveled (VKT) by the assumed traversed vehicle efficiency. Recent studies indicate light duty vehicles efficiencies for can range widely (Stacy C. Davis & Boundy, 2019). In 2017, the estimated real-world fuel economy for US light duty vehicles was 10.6 km/L (24.9 mi/gal) (EPA, 2017). Vehicles are assumed to have highest efficiency on highways and lowest efficiency on local roads. For details on the applied vehicle efficiencies, see **Table 3**. Vehicles dominantly emit waste heat as thermal radiation from the engine and convection from the exhaust; impacts from tire friction and convective cooling have been found be insignificant, accounting for 1% or less of total balance near the road surface (Fujimoto et al., 2015). As a result, we assume all heat from vehicles is emitted via exhaust and the engine as sensible heat.

5.3 Results

4.3.1 Evaluating Factors Influencing the Thermal Performance of Pavements

Across all seasons in Phoenix, asphalt and concrete pavements have greater diurnal outgoing heat fluxes relative to the natural bare ground. The increase of outgoing heat flux from pavements relative to the bare ground is defined as the anthropogenic heat from pavements. Asphalt surfaced pavements have mean daily anthropogenic heat fluxes of 70 W m^{-2} relative to the bare ground, and concrete surfaced pavements have mean daily heat fluxes of 33 for W m^{-2} relative to the bare ground. **Figure 15** displays the summer and winter mean diurnal outgoing heat fluxes for simulated asphalt pavements, concrete pavements, and bare ground (desert soil). The largest anthropogenic heat flux magnitudes from pavements occur in summer around 3pm when asphalt surfaced pavements contribute 143 W m^{-2} more than the natural ground, and concrete surfaced pavements contribute 80 W m^{-2} more than the natural ground. During summer nights, anthropogenic heat from pavements is still significant with magnitudes of 44 W m^{-2} from asphalt surfaced pavements and 18 W m^{-2} from concrete surfaced pavements. During the winter, anthropogenic heat flux magnitudes decline with daytime magnitudes of 110 W m^{-2} for asphalt surfaced pavements and 66 W m^{-2} for concrete surfaced pavements. Nighttime winter anthropogenic heat flux magnitudes are 27 W m^{-2} asphalt surfaced pavements and 10 W m^{-2} concrete surfaced pavements.

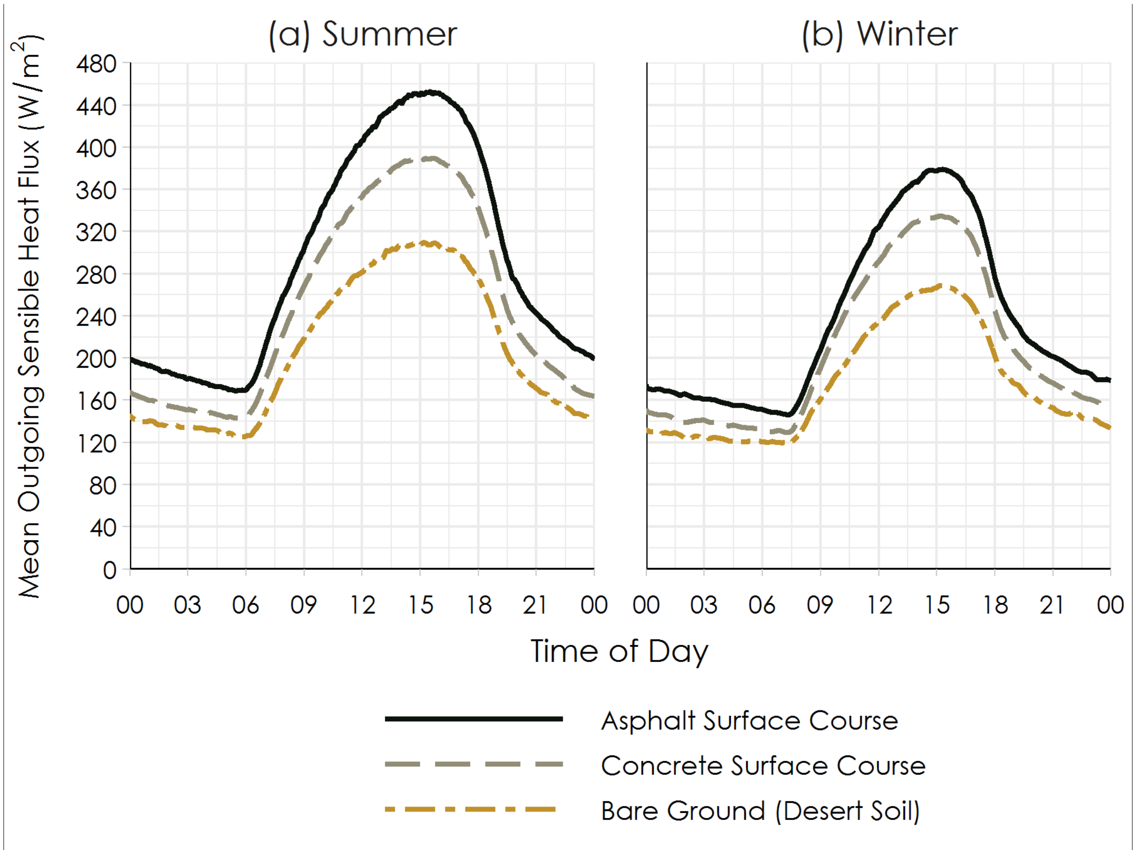

Figure 15. Mean Diurnal Outgoing Heat Flux for Simulated Asphalt Pavements, Concrete Pavements, and Bare Ground (Desert Soil) during Summer and Winter Periods. Outgoing heat flux is defined as outgoing convecion plus outgoing infrared radiation. All pavements are assumed as completely unshaded. For these simulations, asphalt surfaces had a mean albedo of 0.15, concrete surfaces had a mean albedo of 0.30, and the bare ground had a mean albedo of 0.40.

A pavement's daytime maximum outgoing heat flux is most influenced by its albedo, while its nighttime minimum outgoing heat flux is most influenced by its emissivity. An increase in albedo of 0.01 resulted in a decrease of maximum afternoon outgoing heat fluxes by 5.5 W m^{-2} (95% confidence interval: 4.7 to 6.2 W m^{-2}; $R^2 = 0.96$; $p < 0.001$). A decrease in emissivity of 0.01 resulted in a decrease of minimum nighttime outgoing heat fluxes by 1.4 W m^{-2} (95% confidence interval: 0.73 to 2.0 W m^{-2}; $R^2 = 0.69$; $p < 0.001$). Albedo more strongly impacts maximum (daytime) heat fluxes because albedo impacts the fraction of incoming solar radiation which occurs only during sunlight hours.

In addition to albedo and emissivity, altering a pavement's thermal inertia properties has noticeable impacts on the diurnal heat flux magnitudes. Thermal inertia describes the slowness of material to approach thermal equilibrium (e.g. high thermal inertia materials are slower to reach thermal equilibrium) and is equivalent to the square-root of the product of the thermal conductivity (k), density (ρ), and specific heat capacity (c) with SI units of J m^{-2} K^{-1} $s^{-1/2}$. An increase in a pavements surface layer thermal inertia by 100 J m^{-2} K^{-1} $s^{-1/2}$ resulted in a decrease of maximum afternoon outgoing heat fluxes 8.6 W m^{-2} (95% confidence interval: 1.1 to 16 W m^{-2}; $R^2 = 0.57$; $p = 0.031$) and an increase in minimum nighttime outgoing heat fluxes by 1.7 W m^{-2} (95% confidence interval: 1.1 to 2.3 W m^{-2}; $R^2 = 0.88$; $p < 0.001$). Thermal conductivity was the most influential thermal inertia factor influencing minimum and maximum heat fluxes, while specific heat capacity was the least impactful. With the exception of subsurface thermal conductivity, subsurface layer thermal inertia properties were insignificant in influencing the diurnal outgoing heat fluxes.

To further explore the impact thermal inertia properties have on heat flux magnitudes, the highest and lowest literature values of thermal conductivity, density, and specific heat capacity (**Table 2**) are compared with all other parameters constant to test a materials dirurnal heat flux sensitivity to it's thermal inertia properteis. **Figure *16*** displays diurnal outgoing heat fluxes from four different types of pavments with varaitions only to the thermal inertia properites. Overall, high thermal inertia pavements reduced the mean daily outgoing heat flux across all seasons by 23 W m^{-2} compared to low thermal inertia pavements (asphalt only: 28 W m^{-2}; asphalt overlays on PCC: 26 W m^{-2}; concrete only: 21 W m^{-2}; and whitetopped asphalt 19 W m^{-2}). Low thermal inertia pavements increased maximum daytime outgoing heat fluxes by 86 to 134 W m^{-2} relative to high thermal inertia pavements. During nighttime, low thermal inertia pavements decrease the minimum outgoing heat fluxes by 15 to 23 W m^{-2} relative to high thermal inertia pavements. High thermal inertia pavements were found to have delayed maximum heat flux magnitudes by up to 45 minutes for asphalt surfaced pavements and up to 60 minutes for concrete surfaced pavements. Only the thermal inertia properties of a pavement's surface layer were found to significantly affect a pavements thermal response. It should be noted that these results reflect a shorter timescale of these pavements' thermal behavior. While in the short term over periods without rapidly changing environmental conditions, high thermal inertia pavements reduce total outgoing heat fluxes by storing more energy due to higher thermal capacities. This extra stored energy could gradually be released over extended periods of cooling.

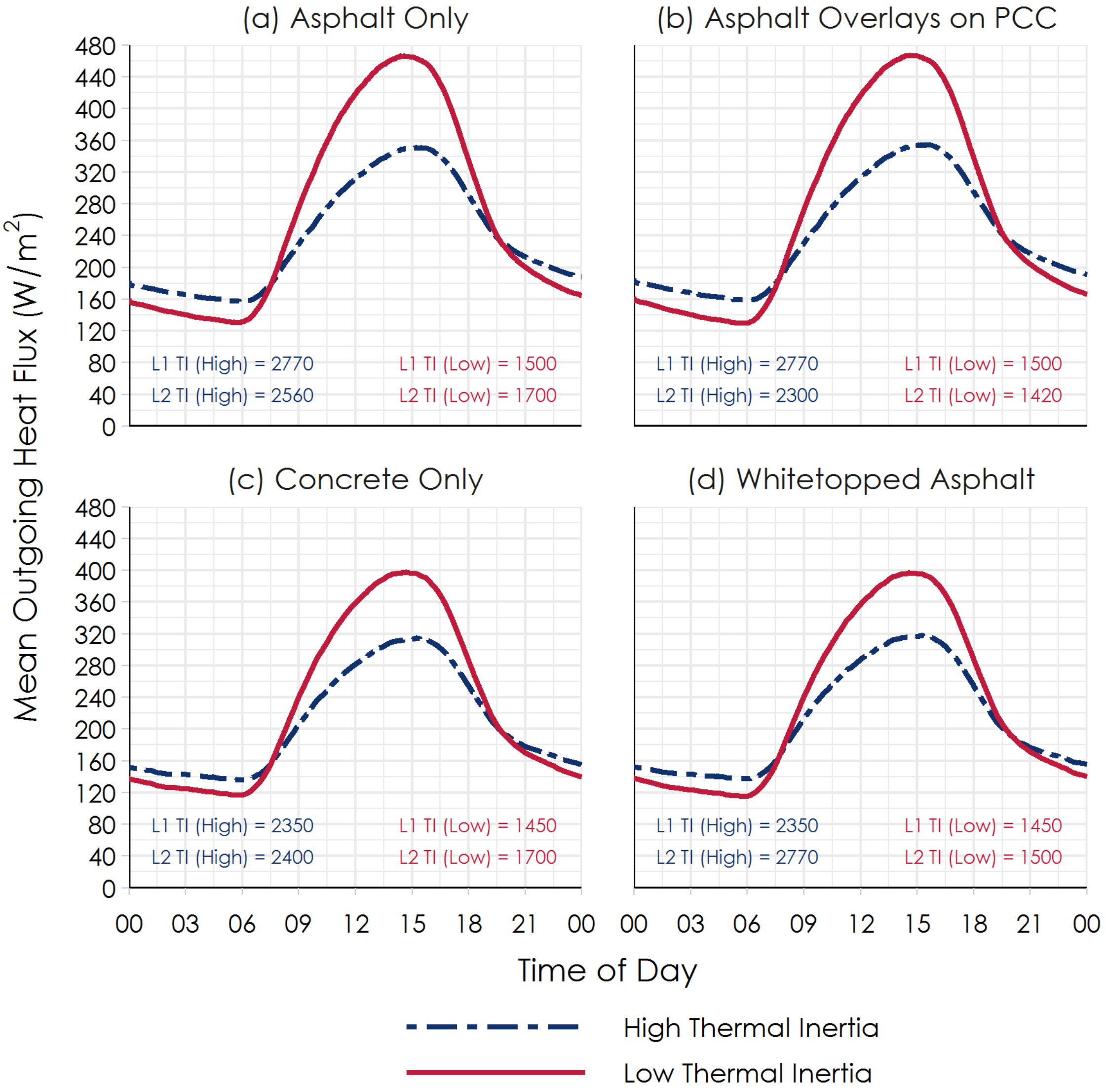

Figure 16. Comparison of High and Low Thermal Inertia Properties across Four Simulated Pavement Types. The first layer (L1) and second layer (L2) thermal inertias (TI) are displayed for each simulated case in J m^{-2} K^{-1} s$^{-1/2}$. All non thermal inertia parameters were held constant. Composite pavement design in (b) and (d) are identical to pavements (a) and (b) with only the additional asphalt and concrete overlay. All pavements are assumed as completely unshaded.

4.3.2 Spatiotemporal Heat Fluxes from Pavements and Vehicles in Phoenix

Spatiotemporal heat fluxes from pavements and vehicles are assessed for a typical (aseaonal) day at a resolution of 250 m^2 for areas with at least 1% coverage of pavement per 250 m^2. We find a mean daily anthropogenic sensible heat flux from pavement infrastructure and vehicle travel of 13 W m^{-2} across metro Phoenix for; roadway pavement contribute 8.5 W m^{-2}, parking pavement contribute contributes 3.6 W m^{-2}, and vehicles contribute 0.49 W m^{-2}. For areas with 10% or greater coverage of pavement infrastructure, the total mean daily heat flux rises to 19 W m^{-2}. In more dense regions with high pavement coverage and vehicle travel, heat fluxes from vehicles and pavements may reach as high as 73 W m^{-2}.

Pavement infrastructure typically dominates contributions to the urban heat balance relative to waste heat from vehicle travel both spatially and temporally in metro Phoenix. **Figure 17** displays the spatial variation in mean daily anthropogenic sensible heat fluxes from roadways and pavements in metro Phoenix. **Figure 18** displays the temporal variation in mean daily sensible heat fluxes from roadways and vehicles in metro Phoenix. Total heat from pavements and vehicles is comprised of 67% from roadway pavements, 29% from parking pavements, and 3.9% from light duty vehicles. However, during peak daytime travel periods, total heat from vehicles makes up 30% in the morning rush hour (8am) and 18% in the evening rush hour (5pm). These results agree with Fujimoto et al. (2015) which found vehicle heat fluxes accounted for 3 – 12% of total heat flux across a road surface with constant traffic.

Heat flux magnitudes from vehicles can reach as high as 132 W m^{-2} over the highest trafficked highways during rush hour, making up 74% of the pavement-vehicle heat balance. However, the mean daily heat flux magnitudes from vehicles across all highway and arterial roads is much lower at 22 W m^{-2} and 17 W m^{-2} respectively. Across low trafficked collector and local roads, vehicles contribute a daily average of 2.7 W m^{-2} and 0.64 W m^{-2} respectively while the pavement contributed a mean of 66 W m^{-2} (relative to unpaved natural ground). This indicates that areas surrounding major arterials and highways with high vehicle traffic are the only areas that would see measureable impacts to local climate as a result of vehicle use.

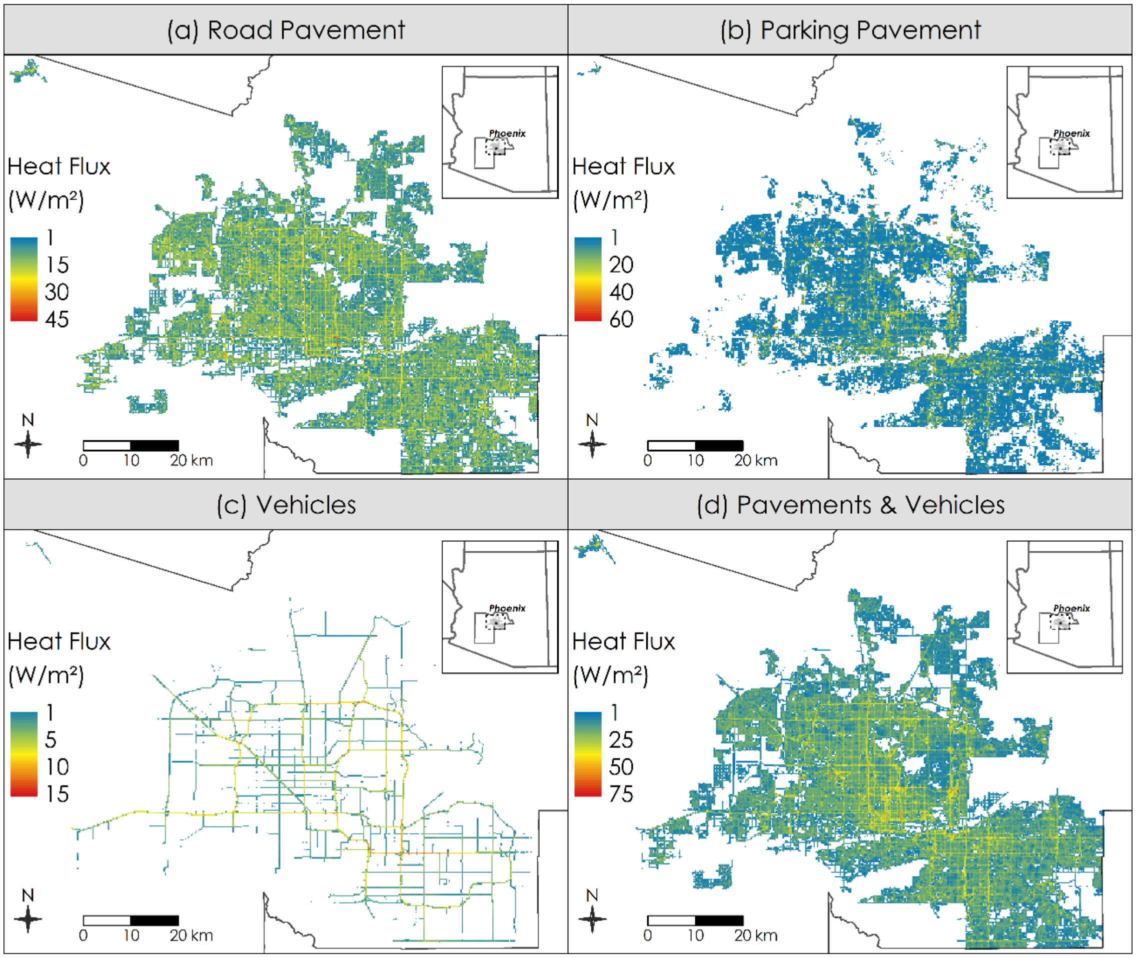

Figure 17. Mean daily anthropogenic sensible heat flux from roadway pavements, parking pavements, and vehicles in metropolitan Phoenix, AZ (urbanized Maricopa County) at a 250 m^2 resolution. Only light duty vehicle travel is included. Cells with less than 1.0 W m^{-2} are ignored.

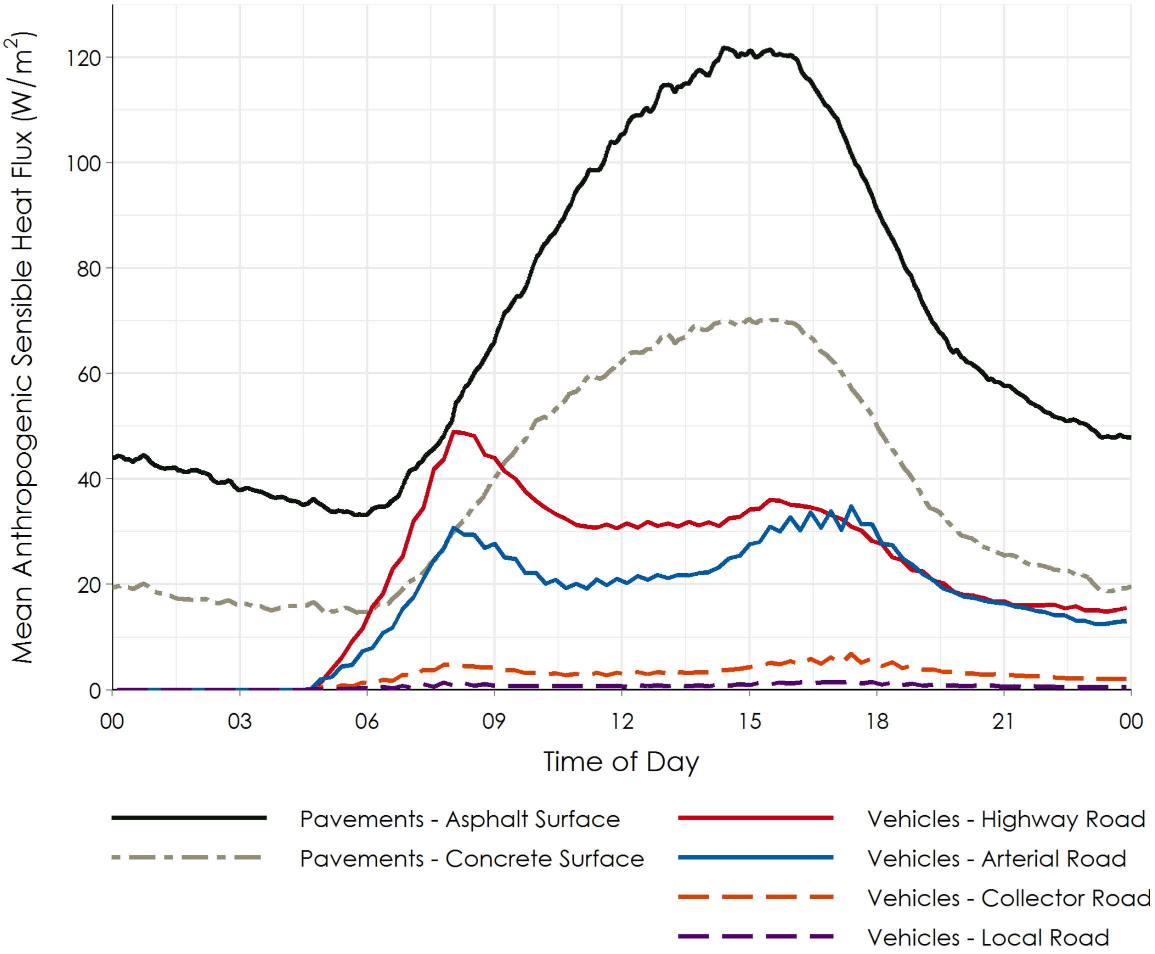

Figure 18. Mean Diurnal Anthropogenic Heat Flux over Roadway Area from Pavements and Vehicles. Heat fluxes are averaged across the roadway area only. Pavement heat fluxes are for an unshaded pavement. Vehicle travel before 4:30am is not present in the travel data and therefore vehicle heat fluxes before this time are not estimated and shown as zero.

4.3.3 Pavement Heat Transfer Model Validation

Across all validation simulations, modeled surface temperatures of various pavement designs were compared to the measured ASTER satellite land surface temperatures at the validation sites. Root Mean Square Error (RMSE) across all sites and pavements was 5.8 °C and Mean Average Percent Error (MAPE) was 14%. **Figure 19** shows the modeled versus observed surface temperatures by season and time of day. Seasonality had little effect on errors with spring and summer having slightly higher RMSEs of 6.7 °C and 6.1 °C than winter and fall RMSEs of 5.3 °C and 5.2 °C. Daytime predicted surface temperatures had a RMSE of 5.7 °C versus 5.6 °C for night time predictions. The most accurate pavement designs were a 400 mm thick PCC pavement with high albedo (3.2 °C RMSE), and a 100 mm asphalt pavement with 50 mm thin whitetopping (3.8 °C RMSE). Asphalt pavements typically had higher predicted surface temperatures than the ASTER observed surface temperatures (**Figure 19a**). There are a number of reasons that may cause this discrepancy, but the most likely factor is differing in-situ albedos because albedo is the strongest single parameter to predict pavement surface temperature. While sites selected are nearly covered by a uniform material, small amounts of non-asphalt materials may alter the average ASTER pixel albedo and thermal properties, causing less absorbed and retained heat over time. For example, one site of an asphalt parking lot had a small amount of concrete, vegetation, and white stripping paint.

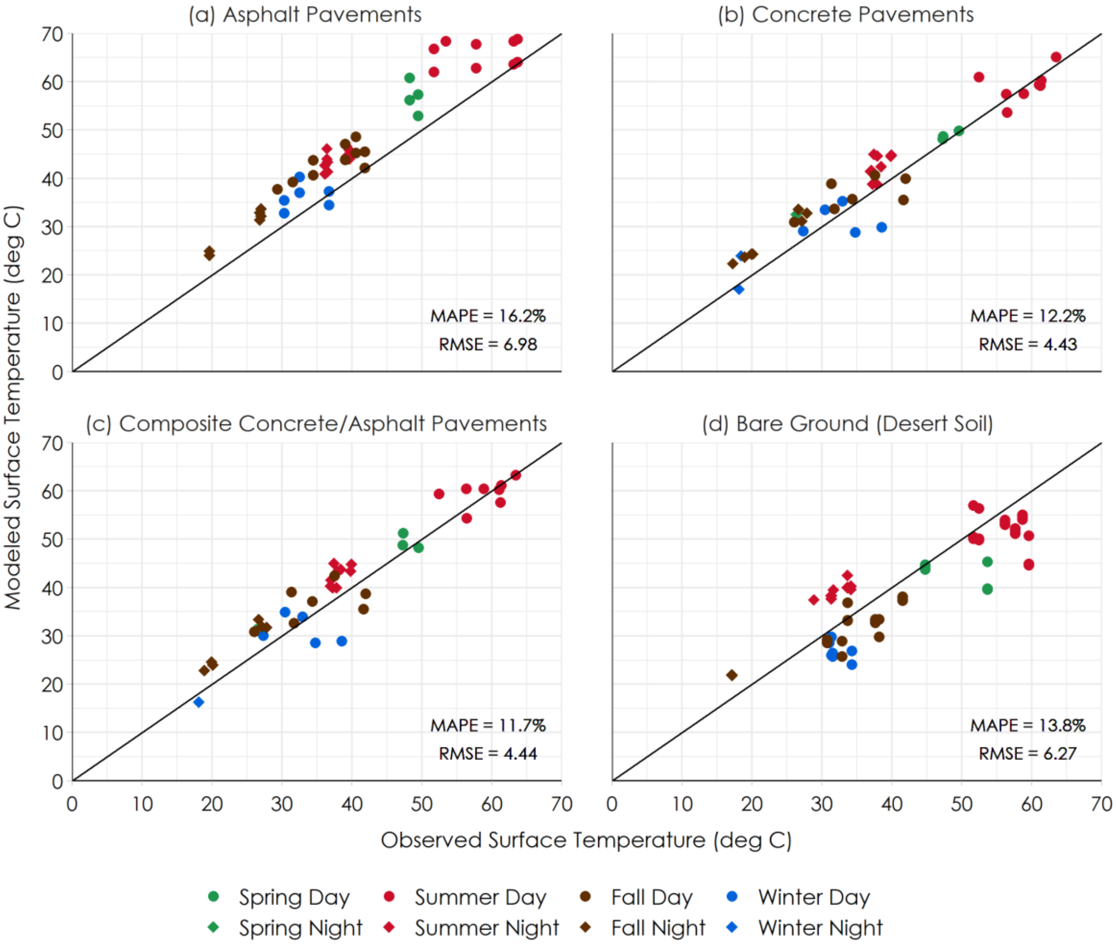

Figure 19. Modeled Versus Observed Surface Temperatures for Four Material Classes by Season and Time of Day. Note that not all sites had ASTER observations for every simulation date.

4.3.4 Sensitivity, Uncertainty, and Limitations

Many factors of urban vehicle travel and pavement infrastructure design may influence the sensitivity and uncertainty of sensible heat flux magnitudes such as roadway design widths, vehicle driving efficiencies, asphalt versus concrete pavement coverage, and the intensive properties of a pavement. High and low estimates for many of these factors were modeled to evaluate the sensitivity of results.

Assuming smaller roadway widths, increased vehicle efficiencies, high use of concrete pavements relative to asphalt, and smaller anthropogenic heat magnitudes from pavements, the mean daily anthropogenic sensible heat flux of from pavement infrastructure and vehicle travel decreases from 13 W m^{-2} to 6.1 W m^{-2} across metro Phoenix for areas with at least 1% coverage of pavement per 250 m^2. Conversely, mean daily anthropogenic sensible heat flux of from pavement infrastructure and vehicle travel could increase to 19 W m^{-2} across the urban area with the opposite of aforementioned assumptions. In both of the extreme cases, contributions from vehicles are marginal across the whole urbanized area, accounting for 0.38 to 0.60 W m^{-2}. Roadway pavement anthropogenic heat contributions have a total sensitivity of 3.2 to 13.7, and parking pavements a sensitivity of 2.5 to 4.8 W m^{-2}. For details on sensitivity values test, see Appendix C.1.

Some aspects of heat transfer between vehicles and pavements are not considered. Vehicles traveling across a pavement will provide transient shading, blocking marginal amounts of incoming solar radiation during the daytime. Some wasted heat from vehicles may also affect the surface temperature of the pavement through friction and downward heat flux from bottom of the vehicle. Vehicles traveling over a roadway will also induce convection at the roadway surface by creating air flow from their motion.

5.4 Discussion

Previous estimates of anthropogenic heating from buildings, vehicles, and metabolism are similar in magnitude to this analysis of only pavement and vehicle heating in metro Phoenix. Anthropogenic heat fluxes in cities (excluding pavements) commonly range from 2 to 60 W m^{-2} during the summer to 4 to 210 W m^{-2} in the winter, with buildings contributing the highest proportions, followed by contributions from vehicles and marginal contributions from metabolic activity (Allen et al., 2011; Sailor &

Lu, 2004; Taha, 1997). Allen et al. (2011) found mean urban anthropogenic heat fluxes from buildings, vehicles, and metabolic processes to be 20 W m^{-2} across London and 60 W m^{-2} across Tokyo. Smith et al. (2009) quantified heat fluxes in greater Manchester, UK from buildings, traffic, and metabolism at the same spatial resolution of this study (250 m^2) and found mean heat emission of 6.12 W m^{-2}, reaching as high as 23 W m^{-2} in city center areas. In greater Manchester (1,960 people per km^2), buildings accounted for approximately 3.67 W m^{-2} and vehicles accounted for 1.96 W m^{-2} while in greater Phoenix (1,210 people per km^2), pavement contributions alone accounted for 12.1 W m^{-2} but a smaller amount from vehicles of 0.49 W m^{-2}. Given that higher anthropogenic heating typically occurs in the winter due to increased building energy use, relative contributions from pavement infrastructure may be much more significant in the summer. Sailor & Lu (2004) estimated peak summer anthropogenic heat fluxes of 30 – 60 W m^{-2} in Chicago, San Francisco, and Philadelphia, but the less dense Atlanta and Salt Lake City had peaks less than 15 W m^{-2}. This study finds heat fluxes from pavements in Phoenix relative to the native ground reach as high as 70 W m^{-2} at 250m^2 resolution and 143 W m^{-2} directly over the pavement during summer afternoons. This indicates pavement infrastructure may make up a significant portion of urban heat fluxes, especially during summers and in more sprawled urban areas. However, more research is needed that compares pavements to other anthropogenic sources for the same region, scale, and time period.

Many studies quantify urban anthropogenic heat from buildings, vehicles, and metabolic processes, but none consider the added heat from pavement infrastructure as anthropogenic. As a result, no research has quantified heat flux from pavements simultaneously with other anthropogenic heat sources. This may be because pavements do not waste heat through mechanical or metabolic processes, but heat from pavement infrastructure is undoubtedly a consequence of urban anthropogenic activity. While these outcomes for metro Phoenix may not be generalizable due its climate, natural geology, and auto-centric urban design, pavement infrastructure contributes significant urban heating. Additionally, previous research has firmly established the significant role of imperious surfaces in urban heat island creation. Therefore, future research that aims to holistically quantify urban heat flux magnitudes should include estimates of added heating from pavement infrastructure and other unnatural surface materials in combination with typical anthropogenic sources.

Planning for urban density over urban sprawl may reduce urban heat contributions from the transportation sector, but it is unclear if it would provide a net benefit to mitigating urban heat. Auto-centric urban design inhibits urban density, and can lead to high coverage of pavement infrastructure supporting automobile dependence. In metro Phoenix, total pavement coverage is dominated by low trafficked local and collector roads, often in residential neighborhoods, contributing to 56% of the total mean daily heat balance from all pavements and vehicles despite accounting for only 22% of the total daily VKT. An analysis of Atlanta found lower density residential developments contribute more radiant heat energy than higher density developments to surface heat island (Stone & Rodgers, 2001). This sprawled urban design may be problematic for cities concerned with issues of urban heat and climate change; more sprawled urban metros have a higher prevalence and increased rate of extreme heat events after controlling for climate and populations growth (Stone et al., 2010). Increasing urban density could reduce automobile VKT and pavement infrastructure needs due to closer destinations, mixed use planning, and more effective public transit, thus reducing the transportation sectors influence on anthropogenic urban heat. Additionally, densification contributes to increased prevalence of urban canyons which improve human thermal comfort (Andreou & Axarli, 2012; Johansson, 2006; Middel et al., 2014). However, an issue still exists: cities with higher population densities consistently have higher estimates of total urban anthropogenic heat (Allen et al., 2011; Sailor & Lu, 2004). Yet these analyses exclude pavement infrastructure heat fluxes, so the implications of increased urban density on urban heat is unclear. As urban areas grow and tackle issues associated with urban heat and climate change, moving towards auto independence has pathways to reducing urban heat, but more research and strategic planning are necessary to ensure desirable outcomes.

For a typical day across metro Phoenix, pavements contribute nearly 25 times as much heat to the urban heat balance compared to vehicles, but in some cases such as during rush hour in a densely traveled corridor, vehicles can contribute nearly three times as much as pavements to the local heat balance. When vehicle travel density is at its peak during rush hour, heat flux magnitudes can reach 132 W m^{-2} directly over the roadway, while pavement can reach 143 W m^{-2}. This indicates that during warmer months in hot climates, areas surrounding high trafficked roads may be increasingly undesirable for outdoor travel or activities due to high amounts of anthropogenic heat from pavements and dense vehicle travel. As a result, urban planning strategies to improve a community's net thermal comfort during hot periods (especially late afternoon in the summer) should be cognizant of these issues and should consider targeting active transportation developments away from corridors with high pavement coverage and vehicle traffic.

Many strategies to mitigate urban heat through pavement design focus heavily on altering pavement albedo (Li et al., 2013; Santamouris et al., 2012), but this study indicates there may be potential to mitigate the severity of urban heat by increasing the thermal inertia of pavement infrastructure. While increasing pavement albedo can significantly reduce the total heat stored and emitted, it also comes at the sacrifice of increasing the incident reflected solar radiation. As a result, high albedo pavements may compromise thermal comfort of nearby pedestrians (Erell et al., 2014; Li et al., 2016), and may increase mean radiant temperatures experienced by 7.8 °C (Taleghani et al., 2016). To avoid this drawback but still improve the thermal environment through pavement design, increasing pavement thermal inertia may be a viable alternative. The feasibility of increasing pavement thermal inertia has been rarely discussed, but Yun et al. (2014) found using surrogate aggregates practical for reducing concrete thermal conductivities in building applications and noted that aggregate size does not appear to affect thermal behaviors. Increasing a pavement’s thermal inertia will slow its ability to warm and reach thermal equilibrium, resulting in an average decrease in daytime heat fluxes but an average increase in nighttime heat fluxes. During periods of extended heating of cooling, high thermal inertia pavements will more slowly warm up or cool off. As a result, the primary benefit of thermal inertia pavements is likely in reducing extreme magnitudes of outgoing heat by offsetting the release of energy to nighttime or generally cooler periods. For example, this behavior could be beneficial in reducing the local heat severity during heat waves by increasing the pavement energy storage capacity and delaying heat emissions until less severe periods. Overall, the potential for high thermal inertia properties in pavements should be more deeply explored to flatten diurnal urban heat fluxes and potentially mitigate impacts of increasingly severe weather under climate change.

5.5 Limitations

Some limitations of this analysis exist as a consequence of available data, selected methodologies, and the selected analysis region. Only sensible heat fluxes are estimated for clear and dry conditions in metro Phoenix. Heat transfer between vehicles and the pavement they traverse was ignored. The interplay between heat radiating off roads or vehicles may be absorbed by each other, altering the warming effects from pavements and vehicle in the surface boundary layer. Additionally, the impact of vehicles shading the roadways was not considered. The presence of vehicles partially shading the road may cause slightly lower amounts of energy to reach the pavement layer, but because some of this energy will still be absorbed by the vehicles, we suspect this affect to be marginal. Some variables vary by time of day, such as albedo or the SVF; this could alter diurnal heat flux magnitudes, especially during around sunrise and sunset. Limitations in available travel data and limited established vehicle waste modeling made it difficult to assess how changing traffic patterns would spatially and temporally affect vehicle heat fluxes. More accurate vehicle drive cycle modeling paired with micro traffic simulations could be valuable to improve the accuracy of estimating vehicle’s contributions to heat flux magnitudes at a more local scale.

5.6 Conclusion

An analysis was conducted to quantify contributions to urban heat from vehicle travel and pavement infrastructure in metropolitan Phoenix, Arizona to help understand how city planning and the transportation sector can influence urban heat. Pavement infrastructure typically dominates contributions to the urban heat balance relative to waste heat from vehicle travel both spatially and temporally in metro Phoenix. Relative to the natural ground, pavement infrastructure contributes the most to the Phoenix urban heat balance during summer afternoons. Vehicles may contribute significant amounts of heat but only in high travel corridors during rush hours. Urban densification could mitigate urban heat contributions from the transportation sector by promoting less auto dependent infrastructure, mixed use, and higher density transit. To promote pedestrian thermal comfort, active transportation plans could separate active transit corridors from high trafficked roadways and incorporate targets to reduce nearby pavement coverage and traffic density. Altering pavement design to achieve high thermal inertia properties in pavements should be more deeply explored as a method to mitigate impacts of increasingly severe daytime heat in urban areas. Future research should consider quantifying added heat from pavement infrastructure in addition to anthropogenic heating for a more holistic understanding of urban heat flux magnitudes.

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CHAPTER 5

CONCLUSION

The impacts of urban heat are well documented, and its consequences can affect human health and infrastructure systems. Extreme urban heat can negatively impact public health by increasing morbidity and mortality (Berko et al., 2014; Robert E. Davis et al., 2003; Gasparrini et al., 2015; Patz et al., 2005) and by decreasing outdoor activity and exercise (Graff Zivin & Neidell, 2014; Obradovich & Fowler, 2017; Stamatakis et al., 2013). Additionally, some subgroups of urban populations may be more vulnerable due to lack of resources, age, or pre-existing health conditions (Kovats & Hajat, 2008; Uejio et al., 2011). Heat can also negatively impact urban infrastructure systems; rising temperatures will increase demand for water and energy while increasing the risk for system failures (Bondank et al., 2018; Burillo et al., 2019; Guhathakurta & Gober, 2007; Reyna & Chester, 2017). Continued urbanization and climate change threatens to exacerbate these issues and put increased stress on urban communities.

Transportation infrastructure and the need to travel play a major role in human heat exposure and the pervasiveness of urban heat island. Yet there are gaps in our understanding of how urban communities accumulate heat exposure, and how significantly the urban transportation system influences or exacerbates the many issues of urban heat. This dissertation focused on advancing the understanding of how modern urban transportation influences urban heat and human heat exposure. This final chapter focuses on summarizing the major takeaways, opportunities for mitigation, and needs for future research.

In examining heat exposure accumulation from urban US outdoor activity (Chapter 2), it was revealed that outdoor travel was the most frequent outdoor activity under high temperatures. However, travel did not contribute the most to an urban population’s total outdoor heat exposure; outdoor household activities contributed the most (e.g. yardwork). Heat exposure from travel accounted for 9% of total exposure but 52% of activities above 27 °C. Non-travel outdoor activities such as leisure and housework were less frequently observed but had much higher exposure per activity due to longer activity durations. This indicates that heat exposure through travel is most relevant due to its frequency, but less significant in contributing to total population heat exposure. The results of Chapter 2’s analysis also suggest that cumulative exposure within demographic subgroups is a poor sole predictor of heat-health outcomes; those who identified as black race often had lower total heat exposure despite higher prevalence of heat-related health issues. Other individual-level characteristics are necessary to accurately predict negative heat-health outcomes such as access to cooling resources and pre-existing health conditions. Due to ambiguity in the ATUS survey, two types of outdoor activity exposure are underexplored; exposure during transit and work activities are not assessed as indoor versus outdoor presence within these activities could not be reliably determined. Future work should continue to explore exposure during transit and work activities. With urban heat exposure most frequently occurring during travel, mitigating heat exposure during travel should be a goal of any region concerned with urban heat for two reasons: 1) vulnerable populations more frequently use active and public transit; and 2) improving thermal comfort for active and public transit will further encourage more livable and heat resilient communities. Cities concerned with heat-related morbidity and mortality should focus more on minimizing severe exposure to vulnerable populations and less on minimizing total cumulative heat exposure in the community.

While previous research has established that impervious surfaces are one of the leading contributors to urban heat island by artificially increasing the urban fabric's thermal storage, little research has quantified total and direct additions of heat to urban areas from pavements. Often, research focuses on quantifying heat fluxes of anthropogenic sources (buildings, vehicles and metabolic processes) or through remote sensing or land cover techniques. As a result, it is unclear how excess heat stored and emitted in pavements compares to other classically defined anthropogenic sources. While this research did not seek to explicitly quantify anthropogenic heat from buildings and metabolic processes, it did quantify pavement and vehicle heat in metropolitan Phoenix at the city scale. Chapter 4 applied a frequently used methodology (one-dimensional heat transfer modeling) but extended the modeling to apply to the entire Phoenix pavement inventory. Findings in Chapter 4 reveal that, on average, added heat from pavements (increased heat relative to the natural ground) is significantly greater than heat from vehicles across Phoenix for a typical day, contributing nearly 25 times as much heat. However, vehicles could still contribute significantly; in areas with high density vehicle traffic during rush hours, vehicles contributed up to three times as much heat as pavements in the same area. Overall, these findings indicated that pavements are the dominant heat contributor from the transportation sector in Phoenix. Past research has found that vehicle travel could make up as much as 62% of summer anthropogenic heating in some cities (Sailor & Lu, 2004), which indicates pavement heating could dwarf other anthropogenic heating during summer for some regions. Future research should consider similar methodologies and include added heat from pavements as part of the anthropogenic heat equation. This will allow for a more comprehensive understanding of the urban heat balance resulting from human activity.

This dissertation research has explored some aspects of how urban sprawl may be related to urban heat and human heat exposure. Chapter 2 established the most significant single activity contributing to US urban outdoor heat exposure was “lawn, garden, and houseplant care,” followed by “walking for exercise or leisure.” This indicates that a significant amount of heat exposure may occur at or near one’s place of residence. Additionally, urban sprawl could induce elevated population exposure indirectly if lawns and gardens are more frequent or available in sprawled regions. Through the American Time Use Survey, this was difficult to establish due to less robust intra-city sample sizes and activity heterogeneity. Future research should consider more deeply exploring the role of heat exposure during outdoor household activities. It was also established that an urban regions sprawl factor (Hamidi & Ewing, 2014) was statistically significant but very weak at predicting elevated heat exposure. Previous research has highlighted that more sprawled regions experience increased frequencies of extreme heat events (Stone et al., 2010), and this could be related to the high extent of impervious surfaces. On the other hand, more dense parts of cities are typically where urban heat island is most intense, but this is likely attributed to the higher amounts of anthropogenic heat (Allen et al., 2011). While anthropogenic heat magnitudes clearly increase as urban regions densify, added heat from pavements would likely only increase with densification if the unshaded pavement density increases significantly. In other words, as regions densify, building density and building heights increase, causing a decrease in the sky view factors (SVFs) of pavements. While the densest parts of some US cities have the highest coverage of impervious surfaces (Akbari et al., 1999; Rose et al., 2003), the urban canyon effect disrupts the SVF and heat storage of the urban surface (T. R. Oke, 1982). An increase in absorbed infrared radiation from other urban materials may increase, however this would likely be overshadowed by the decrease in direct incoming solar radiation, causing less total energy absorption by pavements. Chapter 4's analysis of Phoenix did find higher pavement and vehicle heat fluxes in the denser urban downtown due higher concentrations of roadway and parking pavement, but this can be partially attributed to the relatively high SVFs in the urban core of Phoenix compared to less sprawled cities. Metro Phoenix had the highest mean SVF of 15 global cites quantified by Middel et al. (2018) at 0.947; very dense cities had much lower mean sky view factors: Manhattan, 0.545; Seoul, 0.680; Tokyo, 0.693; San Francisco, 0.811. Future research could continue the approach outlined in Chapter 4 with local weather, SVF data, pavement designs, and bare ground conditions to model urban heat additions from pavements and further explore how urban design influences anthropogenic pavement heat in variety of scenarios.

5.1 Urban Transportations Role in Mitigating Urban Heat

Future development of urban areas (especially those with concerns of extreme heat) should focus on ensuring access and mobility for its inhabitants without sacrificing thermal comfort. In the face of rapid urbanization and increasingly severe periods of heat, transportation system design should embrace efforts to mitigate urban heat. This research helps identify and support numerous opportunities to mitigate urban heat and human heat exposure.

Presence of pavements in urban areas are an inherent cause of urban heat, thus reducing urban area dedicated to pavement infrastructure may be the most straightforward and effective way to reduce impacts of urban heat through transportation design. Auto-centric urban design influences urban heat due to the often high amounts of dedicated paved surfaces for vehicle travel and storage. Less auto dependent infrastructure could also be indirectly achieved by increasing residential density, increasing mixed use zoning, and planning higher density transit to replace automobility. Parking reform may be another pathway to reducing urban pavement coverage. Minimum parking requirements encourage auto dependence through convenience and potential surpluses of parking. Promoting roadway diets could be another method to reduce urban pavement prevalence and improve pedestrian travel experiences. Roadway diets involve roadway configuration and often include narrowing lanes, reducing the number of lanes, or removing some pavement. Promoting roadway diets can also reduce driver speeds, improve driver reaction times, and ultimately reduce accident frequency and severity (Ewing & Dumbaugh, 2009). However, travel accessibility and mobility may be negatively affected if total parking supply or roadway capacities are rapidly reduced. Cities should focus on intelligently transitioning towards automobile independence to effectively reduce automobile-related infrastructure.

In regions concerned with pedestrian thermal comfort during travel, active transportation developments should be isolated from corridors with high vehicle traffic and pavement coverage. Areas surrounding high trafficked roads may negatively affect pedestrian thermal comfort, especially during the late afternoon rush hour, when large amounts of heat can be radiated from pavements and vehicles. Increasing shade prevalence on commonly used pedestrian paths near roads could be an alternative to separating active travel corridors from high vehicle travel corridors. Shading sidewalks adjacent to roadways will provide synergistic benefits of reducing incoming solar radiation to both the pedestrians and the pavement. This would lead to less solar energy stored and radiated by the pavements over time.

While automobiles themselves are often a marginal portion of the urban heat balance, they may negatively affect local urban environments in high travel density areas, so mitigation of urban heat should not ignore their contributions. Promoting vehicle technologies or travel behavior that reduces vehicle waste heat could be incentivized to alleviate peak heat fluxes in dense travel corridors. Electric vehicles are significantly more efficient and waste far less heat than conventional internal combustion engines. Increasing travel occupancies (carpooling) would consolidate passengers into less vehicles, reducing vehicle kilometers traveled. Mitigating stop-and-go traffic, optimizing traffic lights, and general alleviation of traffic congestion could also provide marginal reductions in wasted heat from vehicles through improved on-road driving efficiencies. While these strategies may cause minimal reductions heat in many cases, they can still be used as an additional reasons to promote sustainable urban transportation practices.

When considering pedestrian thermal comfort, altering thermal properties of pavements besides albedo may be more desirable to reduce human heat exposure from pavement infrastructure. Albedo is the most commonly cited factor for a pavements capacity to mitigate contributions to urban heat island, and while it can be effective at reducing near surface air temperatures, many studies overlook the impact of the increased reflected radiation on human thermal comfort. Chapter 4 investigated altering other material parameters used in pavements and found that the thermal inertia properties of a pavement (the slowness to approach thermal equilibrium) could offer significant reductions to daytime outgoing heat fluxes. This is achieved primarily by storing more energy during the daytime and emitting it during the night time. It is difficult to know the exact thermal properties of in-situ pavements due to a lack of engineering records and pavement mix designs often being proprietary. The variance of potential pavement thermal inertias tested in Chapter 4 however are derived from various literature studying pavement design and thermal response, indicating the values test are representative of realistic pavement designs. Further research is needed to identify the feasibility of implementing pavement designs that benefit from altered thermal inertia properties.

Human heat exposure is driven by human interaction with the built environment, much of which is driven or influenced by transportation planning and engineering. This naturally indicates transportation planners and engineers are in a position to influence the urban thermal environment for as long as the transportation system significantly influences urban form. Communication and knowledge dissemination of heat-related issues with the transportation planning and engineering community is of high importance. Urban transportation planners and engineers need to be cognizant of the pathways to increased urban heat and human heat exposure through future planning and design of urban transportation.

One major issue largely unaddressed by this and other research is the potential problematic transitioning from a highly auto-dependent city towards a less auto-dependent city. Rigid infrastructure and firm institutional support of automobile use makes complete urban redesign independent of personal automobiles impossible. Yet parking and roadway pavement infrastructure supporting automobile dependence may be the most significant urban characteristic that leads to increased urban heat. Public and mass transit are significantly more efficient and effective at moving people in high density urban areas, but are likely to fail if they precede sufficient urban density. Encouraging more walkable and bikable neighborhoods also promotes more active and healthy community lifestyles, less dedicated hard infrastructure, and encourage mixed use neighborhoods. However, in auto-centric urban regions with threats of extreme heat (like metropolitan Phoenix), densifying and shifting more heavily towards active and public transit may have the unintended side effect of increasing a communities' heat exposure. By the middle of the 21st century, global infrastructure assets will have doubled and over two-thirds of the world's population will reside in urban areas (NCE, 2018; UN, 2018). Impacts from climate change and urbanization persist, and will only worsen. Without clear pathways to mitigating impacts of urban heat, it may be difficult to promote transitions to more sustainable travel modes that inherently necessitate heat exposure.

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APPENDIX A

CHAPTER 2 SUPPLEMENATARY INFORMATION

A.1 Data Tables

A.1.1 Metropolitan Statistical Areas Summaries

Table 4. Summary of MSAs Included in Study with Corresponding Abbreviations and Meteorological Stations.

Abbr.	MSA	Meteorological Station
ABQ	Albuquerque, NM	Albuquerque International Airport
ATL	Atlanta-Sandy Springs-Roswell, GA	Hartsfield-Jackson International Airport
AST	Austin-Round Rock, TX	Austin International Airport
BAL	Baltimore-Columbia-Towson, MD	Baltimore Downtown
BIR	Birmingham-Hoover, AL	Birmingham International Airport
BOS	Boston-Cambridge-Newton, MA-NH	Logon International Airport
CHA	Charlotte-Concord-Gastonia, NC-SC	Charlotte/Douglas International Airport
CHI	Chicago-Naperville-Elgin, IL-IN-WI	O'Hare International Airport
CIN	Cincinnati, OH-KY-IN	Cincinnati International Airport
CLV	Cleveland-Elyria, OH	Cleveland Hopkins International Airport
CLB	Columbus, OH	Port of Columbus International Airport
DAL	Dallas-Fort Worth-Arlington, TX	Dallas/Fort Worth International Airport
DEV	Denver-Aurora-Lakewood, CO	Denver International Airport
DET	Detroit-Warren-Dearborn, MI	Detroit City Airport
ELP	El Paso, TX	El Paso International Airport
HOU	Houston-The Woodlands-Sugar Land, TX	George Bush International Airport
IND	Indianapolis-Carmel-Anderson, IN	Indy International Airport
JAK	Jacksonville, FL	Jacksonville International Airport
KC	Kansas City, MO-KS	Kansas City International Airport
LV	Las Vegas-Henderson-Paradise, NV	McCarran International Airport
LA	Los Angeles-Long Beach-Anaheim, CA	University of Southern California Downtown Campus
LOU	Louisville/Jefferson County, KY-IN	Louisville International Airport
MPH	Memphis, TN-MS-AR	MPH International Airport
MIA	Miami-Fort Lauderdale-West Palm Beach, FL	Miami International Airport

Abbr.	MSA	Meteorological Station
MIL	Milwaukee-Waukesha-West Allis, WI	Gen. Mitchell International Airport
MIN	Minneapolis-St. Paul-Bloomington, MN-WI	Minneapolis-St. Paul International Airport
NSH	Nashville-Davidson-Murfreesboro-Franklin, TN	Nashville International Airport
NO	New Orleans-Metairie, LA	Louis Armstrong New Orleans International Airport
NYC	New York-Newark-Jersey City, NY-NJ-PA	John F. Kennedy International Airport
OKL	Oklahoma City, OK	Will Rodgers World Airport
ORL	Orlando-Kissimmee-Sanford, FL	Executive Airport
PHI	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	Philly International Airport
PHX	Phoenix-Mesa-Scottsdale, AZ	Sky Harbor International Airport
PIT	Pittsburgh, PA	Pittsburgh International Airport
POR	Portland-Vancouver-Hillsboro, OR-WA	Portland International Airport
PRO	Providence-Warwick, RI-MA	Theodore F Green Airport
RAL	Raleigh, NC	Raleigh International Airport
RCH	Richmond, VA	Richmond International Airport
RIV	Riverside-San Bernardino-Ontario, CA	Ontario International Airport
SAC	Sacramento-Roseville-Arden-Arcade, CA	Sacramento International Airport
SA	San Antonio-New Braunfels, TX	San Antonio International Airport
SD	San Diego-Carlsbad, CA	San Diego International Airport
SF	San Francisco-Oakland-Hayward, CA	San Francisco International Airport
SJ	San Jose-Sunnyvale-Santa Clara, CA	N Y. Mineta SJ International Airport
SEA	Seattle-Tacoma-Bellevue, WA	Boeing Airport
STL	St. Louis, MO-IL	Lambert International Airport
TB	Tampa-St. Petersburg-Clearwater, FL	Tampa International Airport
TUC	Tucson, AZ	Tucson International Airport
VB	Virginia Beach-Norfolk-Newport News, VA-NC	Norfolk International Airport
WAS	Washington-Arlington-Alexandria, DC-VA-MD-WV	Ronald Regan Airport

Table 5. Summary of Population, Total Activities, Outdoor Activities, and Temperatures by MSA. 90th percentile and maximum Air temperatures (T) and apparent temperatures (AT) for the sample period of ATUS activities (2004-15). Temperatures are shown in degrees Fahrenheit.

Abbr.	2016 Population	Total Activities	Outdoor Activities	T_{90}	T_{MAX}	AT_{90}	AT_{MAX}
NYC	20,153,634	143,783	11,007	77	102	81	112
LA	13,310,447	93,424	5,021	76	112	77	108
CHI	9,512,999	81,729	3,754	76	103	79	109
DAL	7,233,323	51,030	1,603	89	109	94	111
HOU	6,772,470	40,334	1,453	87	108	95	111
WAS	6,131,977	58,677	2,867	81	105	86	115
PHI	6,070,500	52,039	2,369	79	104	84	114
MIA	6,066,387	42,870	1,758	86	97	95	107
ATL	5,789,700	40,309	1,408	82	105	87	108
BOS	4,794,447	41,716	2,031	74	102	77	107
SF	4,679,166	36,170	2,248	67	98	66	96
PHX	4,661,537	30,214	1,212	99	118	98	114
RIV	4,527,837	26,659	1,106	84	113	82	114
DET	4,297,617	37,910	1,538	75	101	78	110
SEA	3,798,902	35,226	1,873	68	124	66	120
MIN	3,551,036	39,242	1,727	76	102	78	111
SD	3,317,749	23,186	1,171	73	101	75	102
TB	3,032,171	23,043	932	86	97	94	108
DEV	2,853,077	25,936	1,166	77	103	74	101
STL	2,807,002	30,657	1,076	82	108	87	113
BAL	2,798,886	26,455	1,081	83	107	87	117
CHA	2,474,314	16,442	637	81	103	86	109
ORL	2,441,257	15,814	603	85	99	93	108
SA	2,429,609	17,740	691	88	109	94	110
POR	2,424,955	24,356	1,275	70	105	69	105
PIT	2,342,299	22,989	1,086	75	97	78	105
SAC	2,296,418	16,928	807	82	110	80	112
CIN	2,165,139	19,220	676	78	103	82	108
LV	2,155,664	16,088	620	96	116	93	123
KC	2,104,509	21,856	759	80	107	85	111
AST	2,056,405	14,026	546	88	110	94	116
CLV	2,055,612	19,502	756	75	98	78	109
CLB	2,041,520	16,706	602	78	101	81	107
IND	2,004,230	17,786	644	78	105	82	111
SJ	1,978,816	17,239	855	73	103	72	103

Abbr.	**2016 Population**	**Total Activities**	**Outdoor Activities**	**T_{90}**	**T_{MAX}**	**AT_{90}**	**AT_{MAX}**
NSH	1,865,298	13,978	457	82	107	87	110
VB	1,726,907	17,561	635	81	104	88	112
PRO	1,614,750	12,086	468	75	101	79	108
MIL	1,572,482	17,587	635	73	101	77	107
JAK	1,478,212	10,813	392	84	101	92	111
OKL	1,373,211	15,199	434	85	111	89	112
MPH	1,342,842	9,543	297	85	105	91	113
RAL	1,302,946	12,408	496	82	105	87	111
LOU	1,283,430	11,999	423	81	105	86	110
RCH	1,281,708	12,858	488	81	105	87	111
NO	1,268,883	9,759	346	85	100	94	109
BIR	1,147,417	11,419	284	83	105	89	109
TUC	1,016,206	8,437	364	93	112	92	123
ABQ	909,906	9,825	372	82	104	79	104
ELP	841,971	7,209	294	89	109	87	110

Table 6. MSAs with More than One Climate Zone Classification. Data for 12 MSAs showing the 2016 population estimates and percent population for each county by MSA under the Department of Energy's Building America Climate Zone classification (Baecheler et al., 2010). For each of these regions, the dominant climate zone was chosen as the zone with the highest population coverage.

Metropolitan Statistical Area	Climate Zone	Population	% Population
Albuquerque, NM	Cold	157,327	17.3%
Albuquerque, NM	Mixed-Dry	752,579	82.7%
Cincinnati, OH-KY-IN	Cold	611,812	28.3%
Cincinnati, OH-KY-IN	Mixed-Humid	1,553,327	71.7%
Dallas-Fort Worth-Arlington, TX	Hot-Humid	7,168,868	99.1%
Dallas-Fort Worth-Arlington, TX	Mixed-Humid	64,455	0.89%
Denver-Aurora-Lakewood, CO	Cold	2,826,475	99.1%
Denver-Aurora-Lakewood, CO	Very Cold	26,602	0.93%
Indianapolis-Carmel-Anderson, IN	Cold	1,989,318	99.3%
Indianapolis-Carmel-Anderson, IN	Mixed-Humid	14,912	0.74%
Kansas City, MO-KS	Cold	29,672	1.41%
Kansas City, MO-KS	Mixed-Humid	2,074,837	98.6%
Minneapolis-St. Paul-Bloomington, MN-WI	Cold	3,525,170	99.3%
Minneapolis-St. Paul-Bloomington, MN-WI	Very Cold	25,866	0.73%
New York-Newark-Jersey City, NY-NJ-PA	Cold	3,701,393	18.4%
New York-Newark-Jersey City, NY-NJ-PA	Mixed-Humid	16,452,241	81.6%
Portland-Vancouver-Hillsboro, OR-WA	Cold	11,510	0.47%
Portland-Vancouver-Hillsboro, OR-WA	Marine	2,413,445	99.5%
Sacramento--Roseville--Arden-Arcade, CA	Hot-Dry	2,110,793	91.9%
Sacramento--Roseville--Arden-Arcade, CA	Mixed-Dry	185,625	8.08%
San Francisco-Oakland-Hayward, CA	Hot-Dry	1,135,127	24.3%
San Francisco-Oakland-Hayward, CA	Marine	3,544,039	75.7%
St. Louis, MO-IL	Cold	26,919	0.96%
St. Louis, MO-IL	Mixed-Humid	2,780,083	99.0%

A.1.2 ATUS Activity Classification Summaries

Table 7. Indoor-outdoor Classification and Metabolic Equivalent of Task by ATUS Activity. Metabolic Equivalent of Task (MET) values marked with an asterisk are assumed based on similar activities due to changes in the ATUS coding for the 2003-15 scheme from Tudor-Locke et al. (2009). Abbreviations: n.e.c. = not elsewhere classified; hh = household services; nonhh = non household; svrs = services; maint = maintenance, inc = including; govt = government. Note $1.0\ MET = 3.5\ \text{ml O2} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$.

ATUS Activity Code	ATUS Activity Description	Indoor/Outdoor Classification	MET
010101	Sleeping	Indoor	0.92
010102	Sleeplessness	Indoor	1.0
010199	Sleeping, n.e.c.	Indoor	0.94
010201	Washing, dressing and grooming oneself	Indoor	2.1
010299	Grooming, n.e.c.	Indoor	2.1
010301	Health-related self care	Indoor	1.29
010399	Self care, n.e.c.	Indoor	1.29
010401	Personal/Private activities	Indoor	1.04
010499	Personal activities, n.e.c.	Indoor	1.04
010501	Personal emergencies	Indoor	1.52
010599	Personal care emergencies, n.e.c.	Indoor	1.52
019999	Personal care, n.e.c.	Indoor	1.29
020101	Interior cleaning	Indoor	3.01
020102	Laundry	Indoor	2.07
020103	Sewing, repairing, & maintaining textiles	Indoor	1.5
020104	Storing interior hh items, inc. food	Indoor	3.39
020199	Housework, n.e.c.	Indoor	2.51
020201	Food and drink preparation	Indoor	2.16
020202	Food presentation	Indoor	2.38
020203	Kitchen and food clean-up	Indoor	2.54
020299	Food & drink prep, presentation, & clean-up, n.e.c.	Indoor	2.32
020301	Interior arrangement, decoration, & repairs	Indoor	3.33
020302	Building and repairing furniture	Indoor	4.25
020303	Heating and cooling	Indoor	4.42
020399	Interior maintenance, repair, & decoration, n.e.c.	Indoor	3.85
020401	Exterior cleaning	Outdoor	3.93
020402	Exterior repair, improvements, & decoration	Outdoor	4.75
020499	Exterior maintenance, repair & decoration, n.e.c.	Outdoor	4.49
020501	Lawn, garden, and houseplant care	Outdoor	3.66
020502	Ponds, pools, and hot tubs	Outdoor	2.64

ATUS Activity Code	ATUS Activity Description	Indoor/Outdoor Classification	MET
020599	Lawn and garden, n.e.c.	Outdoor	3.45
020601	Care for animals and pets (not veterinary care)	Indoor	2.72
020699	Pet and animal care, n.e.c.	Indoor	2.72
020701	Vehicle repair and maintenance (by self)	Outdoor	2.93
020799	Vehicles, n.e.c.	Outdoor	2.93
020801	Appliance, tool, and toy set-up, repair, & maintenance (by self)	Indoor	2.98
020899	Appliances and tools, n.e.c.	Indoor	2.98
020901	Financial management	Indoor	1.8
020902	Household & personal organization and planning	Indoor	2.11
020903	HH & personal mail & messages (except e-mail)	Indoor	1.9
020904	HH & personal e-mail and messages	Indoor	1.8
020905	Home security	Indoor	2.88
020999	Household management, n.e.c.	Indoor	2.13
029999	Household activities, n.e.c.	Indoor	2.93
030101	Physical care for hh children	Indoor	2.67
030102	Reading to/with hh children	Indoor	1.3
030103	Playing with hh children, not sports	Indoor	3.26
030104	Arts and crafts with hh children	Indoor	1.5
030105	Playing sports with hh children	Outdoor	5.0
030186	Talking with/listening to hh children	Indoor	1.5
030108	Organization & planning for hh children	Indoor	1.81
030109	Looking after hh children (as a primary activity)	Indoor	1.71
030110	Attending hh children's events	Unknown	1.5
030111	Waiting for/with hh children	Unknown	1.3
030112	Picking up/dropping off hh children	Unknown	2.0
030199	Caring for & helping hh children, n.e.c.	Indoor	2.21
030201	Homework (hh children)	Indoor	1.66
030202	Meetings and school conferences (hh children)	Indoor	1.53
030203	Home schooling of hh children	Indoor	1.5
030204	Waiting associated with hh children's education	Indoor	1.3
030299	Activities related to hh child's education, n.e.c.	Indoor	1.57
030301	Providing medical care to hh children	Indoor	2.5
030302	Obtaining medical care for hh children	Indoor	1.5
030303	Waiting associated with hh children's health	Indoor	1.3
030399	Activities related to hh child's health, n.e.c.	Indoor	2.03
030401	Physical care for hh adults	Indoor	2.89

ATUS Activity Code	ATUS Activity Description	Indoor/Outdoor Classification	MET
030402	Looking after hh adult (as a primary activity)	Indoor	2.0
030403	Providing medical care to hh adult	Indoor	2.5
030404	Obtaining medical and care services for hh adult	Indoor	1.5
030405	Waiting associated with caring for household adults	Indoor	1.3
030499	Caring for household adults, n.e.c.	Indoor	2.16
030501	Helping hh adults	Indoor	2.05
030502	Organization & planning for hh adults	Indoor	1.68
030503	Picking up/dropping off hh adult	Unknown	2.0
030504	Waiting associated with helping hh adults	Indoor	1.5
030599	Helping household adults, n.e.c.	Indoor	1.81
039999	Caring for & helping hh members, n.e.c.	Indoor	2.08
040101	Physical care for nonhh children	Indoor	2.72
040102	Reading to/with nonhh children	Indoor	1.3
040103	Playing with nonhh children, not sports	Indoor	3.3
040104	Arts and crafts with nonhh children	Indoor	1.5
040105	Playing sports with nonhh children	Outdoor	5.0
040186	Talking with/listening to nonhh children	Indoor	1.5
040108	Organization & planning for nonhh children	Indoor	1.84
040109	Looking after nonhh children (as primary activity)	Indoor	1.67
040110	Attending nonhh children's events	Unknown	1.5
040111	Waiting for/with nonhh children	Unknown	1.3
040112	Dropping off/picking up nonhh children	Unknown	1.0
040199	Caring for and helping nonhh children, n.e.c.	Indoor	2.16
040201	Homework (nonhh children)	Indoor	1.66
040202	Meetings and school conferences (nonhh children)	Indoor	1.53
040203	Home schooling of nonhh children	Indoor	1.5
040204	Waiting associated with nonhh children's education	Indoor	1.3
040299	Activities related to nonhh child's educ., n.e.c.	Indoor	1.57
040301	Providing medical care to nonhh children	Indoor	2.5
040302	Obtaining medical care for nonhh children	Indoor	1.5
040303	Waiting associated with nonhh children's health	Indoor	1.3
040399	Activities related to nonhh child's health, n.e.c.	Indoor	2.03
040401	Physical care for nonhh adults	Indoor	2.89
040402	Looking after nonhh adult (as a primary activity)	Indoor	2.0
040403	Providing medical care to nonhh adult	Indoor	2.5
040404	Obtaining medical and care services for nonhh adult	Indoor	1.5
040405	Waiting associated with caring for nonhh adults	Indoor	1.3

ATUS Activity Code	ATUS Activity Description	Indoor/Outdoor Classification	MET
040499	Caring for nonhh adults, n.e.c.	Indoor	2.16
040501	Housework, cooking, & shopping assistance for nonhh adults	Indoor	2.38
040502	House & lawn maint & repair assistance for nonhh adults	Outdoor	4.3
040503	Animal & pet care assistance for nonhh adults	Indoor	3.0
040504	Vehicle & appliance maint/repair assistance for nonhh adults	Unknown	3.33
040505	Financial management assistance for nonhh adults	Indoor	1.8
040506	Hh management & paperwork assistance for nonhh adults	Indoor	1.74
040507	Picking up/dropping off nonhh adult	Unknown	2.0
040508	Waiting associated with helping nonhh adults	Indoor	1.5
040599	Helping nonhh adults, n.e.c.	Indoor	2.64
049999	Caring for & helping nonhh members, n.e.c.	Indoor	2.18
060101	Taking class for degree, certification, or licensure	Indoor	1.82
060102	Taking class for personal interest	Indoor	2.4
060103	Waiting associated with taking classes	Indoor	1.8
060104	Security procedures rel. to taking classes	Indoor	2.33
060199	Taking class, n.e.c.	Indoor	2.23
060201	Extracurricular club activities	Unknown	1.63
060202	Extracurricular music & performance activities	Indoor	2.5
060203	Extracurricular student government activities	Indoor	1.9
060289	Education-related extracurricular activities, n.e.c.	Indoor	1.84
060301	Research/homework for class for degree, certification, or licensure	Indoor	1.8
060302	Research/homework for class for pers. interest	Indoor	1.8
060303	Waiting associated with research/homework	Indoor	1.0
060399	Research/homework n.e.c.	Indoor	1.75
060401	Administrative activities: class for degree, certification, or licensure	Indoor	1.9
060402	Administrative activities: class for personal interest	Indoor	2.0
060403	Waiting associated w/admin. activities (education)	Indoor	2.0
060499	Administrative for education, n.e.c.	Indoor	1.96
069999	Education, n.e.c.	Indoor	2.02
070101	Grocery shopping	Indoor	2.1
070102	Purchasing gas	Outdoor	2.1
070103	Purchasing food (not groceries)	Indoor	2.33
070104	Shopping, except groceries, food and gas	Indoor	2.21
070105	Waiting associated with shopping	Indoor	1.2
070199	Shopping, n.e.c.	Indoor	2.16

ATUS Activity Code	ATUS Activity Description	Indoor/Outdoor Classification	MET
070201	Comparison shopping	Indoor	1.9
070299	Researching purchases, n.e.c.	Indoor	1.9
070301	Security procedures rel. to consumer purchases	Indoor	2.33
070399	Security procedures rel. to consumer purchases, n.e.c.	Indoor	2.33
079999	Consumer purchases, n.e.c.	Indoor	2.15
080101	Using paid childcare services	Indoor	1.91
080102	Waiting associated w/purchasing childcare svcs	Indoor	1.3
080199	Using paid childcare services, n.e.c.	Indoor	1.86
080201	Banking	Indoor	1.84
080202	Using other financial services	Indoor	1.53
080203	Waiting associated w/banking/financial services	Indoor	1.2
080299	Using financial services and banking, n.e.c.	Indoor	1.67
080301	Using legal services	Indoor	1.65
080302	Waiting associated with legal services	Indoor	1.3
080399	Using legal services, n.e.c.	Indoor	1.6
080401	Using health and care services outside the home	Indoor	1.5
080402	Using in-home health and care services	Indoor	1.5
080403	Waiting associated with medical services	Indoor	1.8
080499	Using medical services, n.e.c.	Indoor	1.53
080501	Using personal care services	Indoor	1.18
080502	Waiting associated w/personal care services	Indoor	1.3
080599	Using personal care services, n.e.c.	Indoor	1.19
080601	Activities rel. to purchasing/selling real estate	Indoor	2.02
080602	Waiting associated w/purchasing/selling real estate	Indoor	1.3
080699	Using real estate services, n.e.c.	Indoor	1.98
080701	Using veterinary services	Indoor	1.84
080702	Waiting associated with veterinary services	Indoor	1.3
080799	Using veterinary services, n.e.c.	Indoor	1.75
080801	Security procedures rel. to professional/personal svcs.	Indoor	2.33
080899	Security procedures rel. to professional/personal svcs n.e.c.	Indoor	2.33
089999	Professional and personal services, n.e.c.	Indoor	1.68
090101	Using interior cleaning services	Indoor	1.56
090102	Using meal preparation services	Indoor	1.62
090103	Using clothing repair and cleaning services	Indoor	2.0
090104	Waiting associated with using household services	Indoor	1.53
090199	Using household services, n.e.c.	Indoor	1.7
090201	Using home maint/repair/décor/construction svcs	Indoor	1.54

ATUS Activity Code	ATUS Activity Description	Indoor/Outdoor Classification	MET
090202	Waiting associated w/ home main/repair/décor/constr	Indoor	1.65
090299	Using home maint/repair/décor/constr services, n.e.c.	Indoor	1.55
090301	Using pet services	Indoor	1.66
090302	Waiting associated with pet services	Indoor	1.77
090399	Using pet services, n.e.c.	Indoor	1.68
090401	Using lawn and garden services	Unknown	1.5
090402	Waiting associated with using lawn & garden services	Unknown	1.3
090499	Using lawn and garden services, n.e.c.	Unknown	1.47
090501	Using vehicle maintenance or repair services	Unknown	1.75
090502	Waiting associated with vehicle main. or repair svcs	Indoor	1.53
090599	Using vehicle maint. & repair svcs, n.e.c.	Unknown	1.68
099999	Using household services, n.e.c.	Unknown	1.61
100101	Using police and fire services	Unknown	1.72
100102	Using social services	Indoor	1.71
100103	Obtaining licenses & paying fines, fees, taxes	Indoor	1.87
100199	Using government services, n.e.c.	Indoor	1.78
100201	Civic obligations & participation	Indoor	1.65
100299	Civic obligations & participation, n.e.c.	Indoor	1.65
100381	Waiting associated with using government services	Indoor	2.0
100383	Waiting associated w/civic obligations & participation	Indoor	2.0
100399	Waiting assoc. w/govt svcs or civic obligations, n.e.c.	Indoor	2.0
100401	Security procedures rel. to govt svcs/civic obligations	Indoor	2.33
100499	Security procedures rel. to govt svcs/civic obligations, n.e.c.	Indoor	2.33
109999	Government services, n.e.c.	Indoor	1.78
110101	Eating and drinking	Indoor	1.5
110199	Eating and drinking, n.e.c.	Indoor	1.5
110281	Waiting associated w/eating & drinking	Indoor	2.0
110289	Waiting associated with eating & drinking, n.e.c.	Indoor	1.67
119999	Eating and drinking, n.e.c.	Indoor	1.83
120101	Socializing and communicating with others	Unknown	1.5
120199	Socializing and communicating, n.e.c.	Unknown	1.5
120201	Attending or hosting parties/receptions/ceremonies	Indoor	1.86
120202	Attending meetings for personal interest (not volunteering)	Indoor	1.5
120299	Attending/hosting social events, n.e.c.	Indoor	1.64
120301	Relaxing, thinking	Indoor	1.21
120302	Tobacco and drug use	Indoor	1.13
120303	Television and movies (not religious)	Indoor	1.33

ATUS Activity Code	ATUS Activity Description	Indoor/Outdoor Classification	MET
120304	Television (religious)	Indoor	1.0
120305	Listening to the radio	Indoor	1.15
120306	Listening to/playing music (not radio)	Indoor	1.38
120307	Playing games	Indoor	1.5
120308	Computer use for leisure (exc. Games)	Indoor	1.9
120309	Arts and crafts as a hobby	Indoor	2.18
120310	Collecting as a hobby	Indoor	1.7
120311	Hobbies, except arts & crafts and collecting	Indoor	2.15
120312	Reading for personal interest	Indoor	1.6
120313	Writing for personal interest	Indoor	1.8
120399	Relaxing and leisure, n.e.c.	Indoor	1.54
120401	Attending performing arts	Indoor	1.5
120402	Attending museums	Indoor	2.1
120403	Attending movies/film	Indoor	2.1
120404	Attending gambling establishments	Indoor	2.3
120405	Security procedures rel. to arts & entertainment	Indoor	2.33
120499	Arts and entertainment, n.e.c.	Indoor	1.63
120501	Waiting assoc. w/socializing & communicating	Indoor	1.3
120502	Waiting assoc. w/attending/hosting social events	Indoor	1.3
120503	Waiting associated with relaxing/leisure	Indoor	1.3
120504	Waiting associated with arts & entertainment	Indoor	1.3
120599	Waiting associated with socializing, n.e.c.	Indoor	1.3
129999	Socializing, relaxing, and leisure, n.e.c.	Indoor	1.62
130101	Doing aerobics	Indoor	6.83
130102	Playing baseball	Outdoor	5.0
130103	Playing basketball	Unknown	8.0
130104	Biking	Outdoor	8.0
130105	Playing billiards	Indoor	2.5
130106	Boating	Outdoor	4.64
130107	Bowling	Indoor	3.0
130108	Climbing, spelunking, caving	Outdoor	9.5
130109	Dancing	Indoor	4.5
130110	Participating in equestrian sports	Outdoor	5.33
130111	Fencing	Indoor	6.0
130112	Fishing	Outdoor	4.5
130113	Playing football	Outdoor	8.0
130114	Golfing	Outdoor	3.75

ATUS Activity Code	ATUS Activity Description	Indoor/Outdoor Classification	MET
130115	Doing gymnastics	Indoor	4.0
130116	Hiking	Outdoor	6.0
130117	Playing hockey	Indoor	8.0
130118	Hunting	Outdoor	4.5
130119	Participating in martial arts	Indoor	10
130120	Playing racquet sports	Indoor	8.5
130121	Participating in rodeo competitions	Outdoor	6.0
130122	Rollerblading	Outdoor	6.0
130123	Playing rugby	Outdoor	10
130124	Running	Outdoor	7.5
130125	Skiing, ice skating, snowboarding	Outdoor	7.0
130126	Playing soccer	Unknown	7.0
130127	Softball	Outdoor	5.0
130128	Using cardiovascular equipment	Indoor	8.0
130129	Vehicle touring/racing	Unknown	3.3
130130	Playing volleyball	Unknown	5.5
130131	Walking	Outdoor	3.8
130132	Participating in water sports	Unknown	5.22
130133	Weightlifting/strength training	Indoor	3.0
130134	Working out, unspecified	Unknown	2.5
130135	Wrestling	Indoor	6.0
130136	Doing yoga	Indoor	3.0
130199	Playing sports n.e.c.	Unknown	5.1
130201	Watching aerobics	Unknown	1.5
130202	Watching baseball	Unknown	1.5
130203	Watching basketball	Unknown	1.5
130204	Watching biking	Unknown	1.5
130205	Watching billiards	Indoor	1.5
130206	Watching boating	Unknown	1.5
130207	Watching bowling	Indoor	1.5
130208	Watching climbing, spelunking, caving	Unknown	1.5
130209	Watching dancing	Unknown	1.5
130210	Watching equestrian sports	Unknown	1.5
130211	Watching fencing	Indoor	1.5
130212	Watching fishing	Unknown	1.5
130213	Watching football	Unknown	1.5
130214	Watching golfing	Unknown	1.5

ATUS Activity Code	ATUS Activity Description	Indoor/Outdoor Classification	MET
130215	Watching gymnastics	Indoor	1.5
130216	Watching hockey	Indoor	1.5
130217	Watching martial arts	Indoor	1.5
130218	Watching racquet sports	Unknown	1.5
130219	Watching rodeo competitions	Unknown	1.5
130220	Watching rollerblading	Unknown	1.5
130221	Watching rugby	Unknown	1.5
130222	Watching running	Unknown	1.5
130223	Watching skiing, ice skating, snowboarding	Unknown	1.5
130224	Watching soccer	Unknown	1.5
130225	Watching softball	Unknown	1.5
130226	Watching vehicle touring/racing	Unknown	1.5
130227	Watching volleyball	Unknown	1.5
130228	Watching walking	Unknown	1.5
130229	Watching water sports	Unknown	1.5
130230	Watching weightlifting/strength training	Indoor	1.5
130231	Watching people working out, unspecified	Unknown	1.5
130232	Watching wrestling	Indoor	1.5
130299	Attending sporting events, n.e.c.	Unknown	1.5
130301	Waiting related to playing sports or exercising	Unknown	1.5
130302	Waiting related to attending sporting events	Unknown	1.5
130399	Waiting associated with sports, exercise, & recreation, n.e.c.	Unknown	1.5
130401	Security related to playing sports or exercising	Indoor	2.33
130402	Security related to attending sporting events	Indoor	2.33
130499	Security related to sports, exercise, & recreation, n.e.c.	Indoor	2.33
139999	Sports, exercise, & recreation, n.e.c.	Indoor	4.78
140101	Attending religious services	Indoor	1.42
140102	Participation in religious practices	Indoor	1.89
140103	Waiting associated w/religious & spiritual activities	Indoor	1.5
140104	Security procedures rel. to religious & spiritual activities	Indoor	2.33
140105	Religious education activities	Indoor	2.2
149999	Religious and spiritual activities, n.e.c.	Indoor	1.75
150101	Computer use	Indoor	1.5
150102	Organizing and preparing	Indoor	1.5
150103	Reading	Indoor	1.5
150104	Telephone calls (except hotline counseling)	Indoor	1.5

ATUS Activity Code	ATUS Activity Description	Indoor/Outdoor Classification	MET
150105	Writing	Indoor	1.5
150106	Fundraising	Indoor	1.7
150199	Administrative & support activities, n.e.c.	Indoor	1.55
150201	Food preparation, presentation, clean-up	Indoor	2.45
150202	Collecting & delivering clothing & other goods	Indoor	2.65
150203	Providing care	Indoor	2.25
150204	Teaching, leading, counseling, mentoring	Indoor	2.14
150299	Social service & care activities, n.e.c.	Indoor	1.97
150301	Building houses, wildlife sites, & other structures	Outdoor	4.5
150302	Indoor & outdoor maintenance, repair, & clean-up	Unknown	3.56
150399	Indoor & outdoor maint, building & clean-up activities, n.e.c.	Unknown	3.82
150401	Performing	Indoor	2.92
150402	Serving at volunteer events & cultural activities	Unknown	1.83
150499	Participating in performance & cultural activities, n.e.c.	Unknown	2.51
150501	Attending meetings, conferences, & training	Indoor	1.5
150599	Attending meetings, conferences, & training, n.e.c.	Indoor	1.5
150601	Public health activities	Indoor	2
150602	Public safety activities	Indoor	2.5
150699	Public health & safety activities, n.e.c.	Indoor	2.25
159989	Volunteer activities, n.e.c.	Unknown	2.29
160101	Telephone calls to/from family members	Indoor	1.5
160102	Telephone calls to/from friends, neighbors, or acquaintances	Indoor	1.5
160103	Telephone calls to/from education services providers	Indoor	1.5
160104	Telephone calls to/from salespeople	Indoor	1.5
160105	Telephone calls to/from professional or personal care svcs providers	Indoor	1.5
160106	Telephone calls to/from household services providers	Indoor	1.5
160107	Telephone calls to/from paid child or adult care providers	Indoor	1.5
160108	Telephone calls to/from government officials	Indoor	1.5
169989	Telephone calls, n.e.c.	Indoor	1.5

Table 8. Metabolic Equivalent of Task by ATUS Occupation Code for Work Activities. MET values from Tudor-Locke et al. (2009). Note: $1.0\ MET = 3.5$ ml O2 $\cdot$ kg^{-1} $\cdot$ min^{-1}.

ATUS Occupational Code (TRDTOCC1)	MET
Management	1.73
Business and Financial	1.67
Computer and Mathematical	1.58
Architecture and Engineering	1.64
Life, Physical, and Social Science	2.0
Community and Social Services	2.08
Legal	1.5
Education, Training, and Library	2.5
Arts, Design, Entertainment, Sports, Media	2.13
Healthcare Practitioner and Technical	2.22
Healthcare Support	2.83
Protective Service	2.56
Food Preparation and Serving Related	2.58
Bldg & Grounds Cleaning, Maintenance	3.58
Personal Care and Service	2.53
Sales and Related Occupations	2.0
Office and Administrative Support	1.83
Farming, Fishing, and Forestry	3.67
Construction and Extraction	4.29
Installation, Maintenance, and Repair	3.19
Production	2.69
Transportation	2.67

Table 9. **Indoor-outdoor Classification and Metabolic Equivalent of Task by ATUS Activity Location Code.** MET values from Tudor-Locke et al. (2009). Note $1.0\ MET = 3.5$ ml O2 $\cdot$ $\text{kg}^{-1} \cdot \text{min}^{-1}$.

ATUS Activity Location (TEWHERE)	**Indoor/Outdoor Classification**	**MET**
Respondent’s home or yard	Unknown	2.0
Respondent’s workplace	Indoor	3.3
Someone else's home	Indoor	2.0
Restaurant/Bar	Indoor	2.5
Place of worship	Indoor	2.5
Grocery store	Indoor	2.3
Other store/Mall	Indoor	2.3
School	Indoor	4.0
Outdoors away from home	Outdoor	2.5
Library	Indoor	2.5
Other place (not specified)	Indoor	2.59
Car, truck, or motorcycle (driver)	Indoor	2.0
Car, truck, or motorcycle (passenger)	Indoor	1.0
Walking	Outdoor	2.5
Bus	Indoor	1.0
Subway/Train	Indoor	1.0
Bicycle	Outdoor	8.0
Boat/Ferry	Outdoor	1.0
Taxi/Limousine Service	Indoor	1.0
Airplane	Indoor	1.0
Other mode of transportation	Unknown	2.06
Unspecified place	Unknown	2.59
Unspecified mode of transportation	Unknown	2.06

A.1.3 Expanded Exposure Results by MSA

Table 10. Summary of Exposure Intensity by MSA. Rows highlighted with light gray have mean exposure intensity significant at the *p* = 0.05 level.

Abbr.	**Outdoor Activities above 27°C (80°F) T_A**	**Individuals with Outdoor Activities above 27°C (80°F) T_A**	**Mean Exposure Intensity (MET-deg-min > 27°C T_A)**	**Median Exposure Intensity (MET-deg-min > 27°C T_A)**	***p*-value (mean exposure intensity)**
ABQ	23	20	555 (± 41)	196	0.126
AST	119	86	1,381 (± 34)	528	< 0.001
ATL	178	119	1,389 (± 19)	709	0.876
BAL	113	73	1,439 (± 50)	422	0.888
BIR	50	34	2,514 (± 94)	1,512	0.016
BOS	87	58	791 (± 24)	282	< 0.001
CHA	61	41	1,205 (± 69)	533	0.018
CHI	246	149	986 (± 17)	286	< 0.001
CIN	52	40	955 (± 36)	404	0.076
CLB	35	22	2,402 (± 131)	1,082	< 0.001
CLV	23	18	1,194 (± 111)	322	< 0.001
DAL	434	274	1,767 (± 10)	690	< 0.001
DEN	99	66	855 (± 15)	442	0.118
DET	270	41	1,243 (± 60)	558	< 0.001
ELP	38	24	885 (± 41)	709	0.262
HOU	386	238	2,681 (± 23)	1,106	< 0.001
IND	52	34	1,223 (± 46)	741	0.004
JAK	106	67	2,196 (± 62)	688	< 0.001
KC	112	61	1,550 (± 38)	555	0.466
LA	205	134	573 (± 7)	200	< 0.001
LOU	65	39	920 (± 54)	350	0.100
LV	172	93	2,267 (± 55)	778	< 0.001
MIA	613	359	1,524 (± 9)	529	< 0.001
MIL	32	18	991 (± 116)	272	< 0.001
MIN	123	76	1,153 (± 28)	516	< 0.001
MPH	56	34	1,597 (± 73)	938	0.600
NO	81	50	2,499 (± 83)	1,575	< 0.001
NSH	64	44	1,696 (± 52)	626	0.552
NYC	470	248	730 (± 8)	182	< 0.001
OKC	84	59	2,286 (± 63)	541	0.002
ORL	159	110	1,854 (± 40)	494	< 0.001

Abbr.	**Outdoor Activities above 27°C (80°F) T_A**	**Individuals with Outdoor Activities above 27°C (80°F) T_A**	**Mean Exposure Intensity (MET-deg-min > 27°C T_A)**	**Median Exposure Intensity (MET-deg-min > 27°C T_A)**	***p*-value (mean exposure intensity)**
PHI	200	116	1,076 (± 15)	504	0.01
PHX	445	257	2,456 (± 31)	823	< 0.001
PIT	64	32	1,286 (± 65)	505	< 0.001
POR	24	17	273 (± 20)	145	< 0.001
PRO	46	27	885 (± 32)	420	0.198
RAL	95	53	1,773 (± 56)	539	0.012
RCH	72	51	1,433 (± 54)	685	0.036
RIV	138	93	1,241 (± 18)	546	0.012
SA	149	98	1,842 (± 30)	890	< 0.001
SAC	80	58	1,322 (± 40)	593	0.086
SD	22	11	173 (± 28)	46	< 0.001
SEA	27	13	402 (± 46)	223	< 0.001
SF	11	8	537 (± 109)	169	< 0.001
SJ	26	16	433 (± 38)	164	< 0.001
STL	153	100	1,747 (± 27)	748	0.210
TB	278	167	1,806 (± 20)	798	< 0.001
TUC	93	56	1,582 (± 53)	1,066	< 0.001
VB	70	45	1,388 (± 54)	507	0.720
WAS	275	168	1,692 (± 32)	249	0.662

A.2 Figures

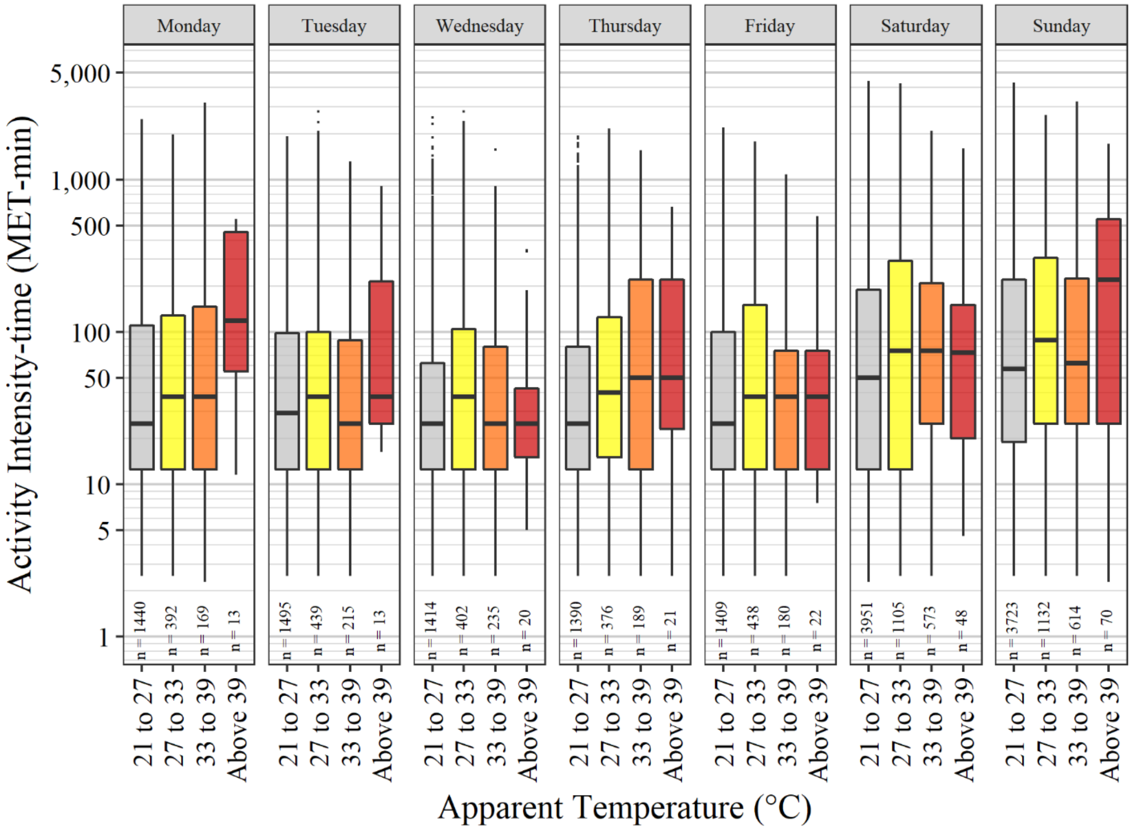

Figure 20. Weighted Outdoor Activity Intensity-times by Day of Week under Different Heat Thresholds for the 50 studied MSAs. Note that the y-axis scales logarithmically. Boxplots are for the interquartile range and lines/dots extend to the minima and maxima. T_A ranges 21-27°C represent a baseline, 27-33°C represent heat index warning 'caution,' 33-39°C represent heat index warning 'extreme caution,' 39°C and above represent heat index warnings 'danger.' The number of outdoor activities for each grouping is given by 'n' at the bottom of the figure.

A.3 Equations

A.3.1 Equations for National Weather Service Heat Index

Heat index (HI) is calculated by using the NWS refined approach of the Rothfusz regression (Rothfusz, 1990), which simplifies the Steadman approach (Steadman, 1979). The approach follows

$$HI = \begin{cases} HI_1, & HI_1 < 80 \\ HI_2, & HI_1 \geq 80,\ 13 \leq RH \leq 85 \\ HI_2, & HI_1 > 87,\ RH \leq 85 \\ HI_2 - HI_3, & 80 \leq HI_1 \leq 120,\ RH < 13 \\ HI_2 + HI_4, & 80 \leq HI_1 \leq 87,\ RH > 85 \end{cases} \tag{A1}$$

$$HI_1 = \frac{0.5\left(T + 61.0 + 1.2(T - 68.0) + (RH \times 0.094)\right) + T}{2} \tag{A2}$$

$$\begin{aligned} HI_2 = {} & -42.379 + 2.04901523(T) + 10.14333127(RH) \\ & - 0.22475541(T)(RH) - 0.00683783(T^2) - 0.05481717(RH^2) \\ & + 0.00122874(T^2)(RH) + 0.00085282(T)(RH^2) \\ & - 0.00000199(T^2)(RH^2) \end{aligned} \tag{A3}$$

$$HI_3 = \frac{13 - RH}{4}\sqrt{\frac{17 - |T - 95|}{17}} \tag{A4}$$

$$HI_4 = \frac{RH - 85}{10} \times \frac{87 - T}{5} \tag{A5}$$

where T is air temperature in degrees Fahrenheit, RH is relative humidity in percent, and HI is expressed as apparent temperature in degrees Fahrenheit.

A.4 References

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Rothfusz LP. 1990. The heat index equation. NWS Technical Attachment SR 90-23. Available: https://www.weather.gov/media/ffc/ta_htindx.PDF [accessed 25 October 2017].

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Tudor-Locke C, Washington TL, Ainsworth BE, Troiano RP. 2009. Linking the American Time Use Survey (ATUS) and the Compendium of Physical Activities: methods and rationale. J. Phys. Act. Health 6:347–53; doi:10.1123/jpah.6.3.347.

APPENDIX B

CHAPTER 3 SUPPLEMENTARY INFORMATION

B.1 Inventory Limitations and Sensitivity

We focus on estimating only the minimum required off-street parking because cities are rarely observed to have greater than the minimum required parking (Cutter & Franco, 2012; Willson, 1995). Although developers may occasionally over develop land and provide excess parking to allow flexible future development, there is little incentive to do so (mainly because it is cost prohibitive), and we find little evidence of this occurring in Phoenix. In validating the parking spaces currently present, we estimate spaces within above ground parking garages by assuming space density is consistent on all floors. This may not be the case as parking garage designs may vary in layout from floor to floor. Additionally, we were unable to validate for underground parking unless part of an underground section was visible in satellite imagery. Therefore, some validation of results may not account for spaces that are not visible in satellite imagery. For historical estimates, we assume that the current parking availability is directly linked to (and therefore constructed when) the surrounding land was developed or redeveloped.

There are many factors that the parking estimates may be sensitive to including on-street space length, parking space lost to non-residential driveways, parking space lost to fire hydrants, and classification of ‘parkable’ roadways via OSM functional roadway classification. Although roadway classifications are consistent, on-street parking may still occur on roads that are not deemed as ‘parkable’ as defined in this analysis. For example, the OSM functional roadway class ‘tertiary’ refers to lower volume service roads with little to no available shoulder space for parking. In some cases however, this roadway class may legally be utilized for shoulder parking.

B.2 Data Tables

Table 11. Assumed Minimum Parking Required for Residential and Commercial Multi-unit Lodging Properties. Due to a lack of data on some residential and commercial multi-unit lodging properties, conversions are made to spaces per unit floor space to estimate the minimum required spaces.

Multi-dwelling unit type	Assumed spaces per ft^2	Source
Apartment	Varies by city; between 1 space per 373 ft^2 and 1 space per 620 ft^2.	Yardi Systems Inc. (2018)
Condo	Assumed equivalent to apartments in same city.	N/A
Duplex, Triplex, or Quadpex	Unnecessary; total units implied by property use code (e.g. two duplexes, four triplexes, etc.).	N/A
Hotel or Motel	1 space per 360 ft^2.	Average of all available data in Maricopa County Assessor's database (ft^2 / units).
Mobile Home	1 space per 1430 ft^2.	Average of all available data in Maricopa County Assessor's database (ft^2 / units).
Sorority or Fraternity House	1 space per 700 ft^2.	Average of select national facilities (beds per floor space): Lambda Chi Alpha, Tallahassee, FL[1]; Phi Gamma Delta, Troy, NY[2]; Phi Kappa Alpha, Champaign, IL[3]; Gamma Phi Beta, Tuscaloosa, AL[4]; Kappa Kappa Gamma, Fayetteville, AK[5]
Boarding or Rooming House	Assumed equivalent to Sorority of Fraternity House.	N/A

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[1] http://www.maddogweb.com/Projects/ProjectsByCategory.aspx?prc=5&p=46

[2] https://poly.rpi.edu/2014/10/15/phi_gamma_delta_moves_into_new_housing/

[3] http://www.news-gazette.com/news/local/2010-06-14/fraternities-rehabbing-rebuilding-houses-newest-touches-ui-campus.html

[4] http://blog.al.com/tuscaloosa/2013/08/new_university_of_alabama_larg.html

[5] https://web.archive.org/web/20130807013136/http://askbrinkmann.com/success-stories/multifamily-residential/kappa-kappa-gamma-sorority

Table 12. Summary Parking Statistics for Metro Phoenix in 2017. All values are for the urbanized area (UZA) of Maricopa County only.

Total population	4.04 million
Total employment	1.84 million
Total registered non-commercial passenger vehicles	2.86 million
Total parking spaces	12.2 million
Off-street residential spaces	3.67 million
Off-street non-residential spaces	3.60 million
On-street spaces	4.93 million
Total spaces per employed person	6.64
Total non-residential spaces per employed person	2.06
Total spaces per passenger vehicle	4.27
Size of UZA	3,110 km^2
Total parking coverage area	9.97%*
Total roadway coverage area	26.2%
Roadway and parking coverage area	36.2%*

* This estimate includes excess space needed to maneuver and space within parking garages.

Table 13. Summary Statistics for Urbanized Maricopa County (Metro Phoenix) in 2017 Compared to Los Angeles County in 2010.

Los Angeles County (2010)	Statistic	Maricopa County UA (2017)
9.83 million	Total population	4.04 million
3.94 million	Total employment	1.84 million
18.6 million	Total parking spaces	12.2 million
5.5 million	Off-street residential spaces	3.67 million
9.6 million	Off-street non-residential spaces	3.60 million
3.6 million	On-street spaces	4.93 million
3.3	Total spaces per non-commercial passenger vehicle	4.27
1.9	Total spaces per person	3.03
4.7	Total spaces per employed person	6.64
3,724 km^2	Size of UZA	3,110 km^2
13.9%	UZA parking coverage area	9.97%
27.3%	UZA roadway coverage area	26.2%
41.2%	UZA roadway and parking coverage area	36.2%

Table 14. Summary of Parking Space Validation. Due to the commonality of shared parking among developments in non-residential areas, parcels were often grouped (column 3: n > 1) to remove ambiguity of parking space ownership.

	Spaces Counted	Spaces Predicted	Number of Grouped Parcels	Percent Error	Percent Error per Parcel
	357	587	1	+64.4%	64.4%
	124	176	1	+41.9%	41.9%
	142	186	1	+31.0%	31.0%
	954	1,249	1	+30.9%	30.9%
	195	408	4	+109.2%	27.3%
	300	377	1	+25.7%	25.7%
	1,010	1,256	1	+24.4%	24.4%
	660	984	3	+49.1%	16.4%
	4,751	5,518	1	+16.1%	16.1%
	134	232	6	+73.1%	12.2%
	584	824	4	+41.1%	10.3%
	37	39	1	+5.41%	5.41%
	40	65	12	+62.5%	5.21%
	73	76	1	+4.11%	4.11%
	30	44	15	+46.7%	3.11%
	217	248	5	+14.3%	2.86%
	120	131	8	+9.17%	1.15%
	106	135	26	+27.4%	1.05%
	80	89	13	+11.3%	0.87%
	278	280	1	+0.72%	0.72%
	162	164	17	+1.23%	0.07%
	2,484	2,565	391[*]	+3.26%	0.01%
	109	109	10	0.00%	0.00%
	35	34	11	-2.86%	-0.26%
	558	537	8	-3.76%	-0.47%
	5,788	5,562	6	-3.90%	-0.65%
	38	37	3	-2.63%	-0.88%
	56	51	3	-8.93%	-2.98%
	500	480	1	-4.00%	-4.00%
	750	447	10	-40.4%	-4.04%
	215	169	4	-21.4%	-5.35%
	15	14	1	-6.67%	-6.67%
	525	361	4	-31.2%	-7.81%
	262	169	3	-35.5%	-11.8%
	187	108	2	-42.2%	-21.1%
	181	49	2	-72.9%	-36.5%
	272	171	1	-37.1%	-37.1%
	82	25	1	-69.5%	-69.5%
	170	35	1	-79.4%	-79.4%
Total	**22,581**	**23,991**	**585**	-	-
Median	**195**	**186**	**4**	**+5.4%**	**+1.1%**
Average	**579**	**615**	**15**	**+6.2%**	

B.3 References

Cutter, W. B., & Franco, S. F. (2012). Do parking requirements significantly increase the area dedicated to parking? A test of the effect of parking requirements values in Los Angeles County. *Transportation Research Part A: Policy and Practice*, *46*(6), 901–925. https://doi.org/10.1016/J.TRA.2012.02.012

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APPENDIX C

CHAPTER 4 SUPPLEMENTARY INFORMATION

C.1 Data Tables

Table 15. Bare Ground Profiles Used in One-dimensional Heat Transfer Model.

Profile	**Layer**	**Thickness**	**k**	**ρ**	c	$\tilde{\alpha}$	**ε**
Units	**-**	m	$\frac{W}{m \cdot K}$	$\frac{kg}{m^3}$	$\frac{J}{kg \cdot K}$	***dimension-less***	***dimension-less***
Bare Dry Soil #1	surface	0.75	1.8	2000	1900	0.40	0.900
Bare Dry Soil #1	subgrade	0.75	1.8	2000	1900	NA	NA
Bare Dry Soil #2	surface	0.75	1.4	1750	1500	0.45	0.935
Bare Dry Soil #2	subgrade	0.75	1.4	1750	1500	NA	NA
Bare Dry Soil #3	surface	0.75	1.0	1500	1100	0.50	0.970
Bare Dry Soil #3	subgrade	0.75	1.0	1500	1100	NA	NA

Table 16. Asphalt Surfaced Pavement Profiles Used in One-dimensional Heat Transfer Model.

Profile	**Layer**	**Thickness**	**k**	**ρ**	***c***	$\tilde{\alpha}$	**ε**
Units	**-**	m	$\frac{W}{m \cdot K}$	$\frac{kg}{m^3}$	$\frac{J}{kg \cdot K}$	***dimension-less***	***dimension-less***
Asphalt 80mm	surface	0.08	1.70	2350	950	0.15	0.9
Asphalt 80mm	base	0.10	2.25	2350	875	NA	NA
Asphalt 80mm	subgrade	1.32	1.40	1850	1500	NA	NA
Asphalt 140mm	surface	0.14	1.70	2350	950	0.15	0.9
Asphalt 140mm	base	0.20	2.25	2350	875	NA	NA
Asphalt 140mm	subgrade	1.16	1.40	1850	1500	NA	NA
Asphalt 200mm	surface	0.20	1.70	2350	950	0.15	0.9
Asphalt 200mm	base	0.30	2.25	2350	875	NA	NA
Asphalt 200mm	subgrade	1.00	1.40	1850	1500	NA	NA
Asphalt Overlay on PCC 100+100mm	surface	0.10	1.70	2350	950	0.15	0.9
Asphalt Overlay on PCC 100+100mm	PCC	0.10	1.70	2250	900	NA	NA
Asphalt Overlay on PCC 100+100mm	base	0.10	2.25	2400	800	NA	NA
Asphalt Overlay on PCC 100+100mm	subgrade	1.06	1.40	1850	1500	NA	NA
Asphalt Overlay on PCC 125+150mm	surface	0.13	1.70	2350	950	0.15	0.9
Asphalt Overlay on PCC 125+150mm	PCC	0.15	1.70	2250	900	NA	NA
Asphalt Overlay on PCC 125+150mm	base	0.20	2.25	2400	800	NA	NA
Asphalt Overlay on PCC 125+150mm	subgrade	1.02	1.40	1850	1500	NA	NA
Asphalt Overlay on PCC 150+200mm	surface	0.15	1.70	2350	950	0.15	0.9
Asphalt Overlay on PCC 150+200mm	PCC	0.20	1.70	2250	900	NA	NA
Asphalt Overlay on PCC 150+200mm	base	0.30	2.25	2400	800	NA	NA
Asphalt Overlay on PCC 150+200mm	subgrade	0.85	1.40	1850	1500	NA	NA

Table 17. Concrete Surfaced Pavement Profiles Used in One-dimensional Heat Transfer Model.

Profile	Layer	Thickness	k	ρ	c	$\tilde{\alpha}$	ε
Units	**-**	$\boldsymbol{m}$	$\frac{W}{m \cdot K}$	$\frac{kg}{m^3}$	$\frac{J}{kg \cdot K}$	***dimension-less***	***dimension-less***
Portland Cement Concrete 100mm	surface	0.20	1.70	2250	945	0.2	0.90
Portland Cement Concrete 100mm	base	0.20	2.25	2400	800	NA	NA
Portland Cement Concrete 100mm	subgrade	1.10	1.40	1850	1500	NA	NA
Portland Cement Concrete 200mm	surface	0.20	1.70	2250	945	0.3	0.93
Portland Cement Concrete 200mm	base	0.20	2.25	2400	800	NA	NA
Portland Cement Concrete 200mm	subgrade	1.10	1.40	1850	1500	NA	NA
Portland Cement Concrete 300mm	surface	0.20	1.70	2250	945	0.4	0.96
Portland Cement Concrete 300mm	base	0.20	2.25	2400	800	NA	NA
Portland Cement Concrete 300mm	subgrade	1.10	1.40	1850	1500	NA	NA
Whitetopped Asphalt 80+80mm	surface	0.08	1.70	2250	945	0.3	0.93
Whitetopped Asphalt 80+80mm	asphalt	0.08	1.70	2350	950	NA	NA
Whitetopped Asphalt 80+80mm	base	0.10	2.25	2400	800	NA	NA
Whitetopped Asphalt 80+80mm	subgrade	1.24	1.40	1850	1500	NA	NA
Whitetopped Asphalt 100+140mm	surface	0.10	1.70	2250	945	0.3	0.93
Whitetopped Asphalt 100+140mm	asphalt	0.14	1.70	2350	950	NA	NA
Whitetopped Asphalt 100+140mm	base	0.20	2.25	2400	800	NA	NA
Whitetopped Asphalt 100+140mm	subgrade	1.06	1.40	1850	1500	NA	NA
Whitetopped Asphalt 150+200mm	surface	0.15	1.70	2250	945	0.3	0.93
Whitetopped Asphalt 150+200mm	asphalt	0.20	1.70	2350	950	NA	NA
Whitetopped Asphalt 150+200mm	base	0.30	2.25	2400	800	NA	NA
Whitetopped Asphalt 150+200mm	subgrade	0.85	1.40	1850	1500	NA	NA

Table 18. Ranges of Assumptions for Pavement Design and Vehicle Travel Applied to the Phoenix Metropolitan Area. Upper bounds for two-way road widths include cases with wider shoulders and center turn lanes.

Generalized functional class description	**Assumed mean pavement thickness**	**Assumed two-way road width or parking space size**	**Assumed asphalt/ concrete pavement Split**	**Assumed energy released from vehicles**
Highway or freeway	200 – 350 mm	30 – 55 m	90/10 - 100/0	448 - 269 Wh/km (30 - 50 MPGe)
Major or minor arterial road	140 – 280 mm	20 – 35 m	80/20 – 100/0	673 – 448 Wh/km (20 - 30 MPGe)
Major or minor collector road	140 – 200 mm	10 – 25 m	80/20 – 100/0	897 – 538 Wh/km (15 - 25 MPGe)
Minor Collector or local road	80 – 200 mm	6 – 15 m	80/20 – 100/0	897 – 538 Wh/km (15 - 25 MPGe)
Commercial parking	80 – 200 mm	31 m^2	70/10 - 100/0	NA
Residential Parking	80 – 200 mm	31 m^2	10/90 – 0/100	NA

C.2 Figures

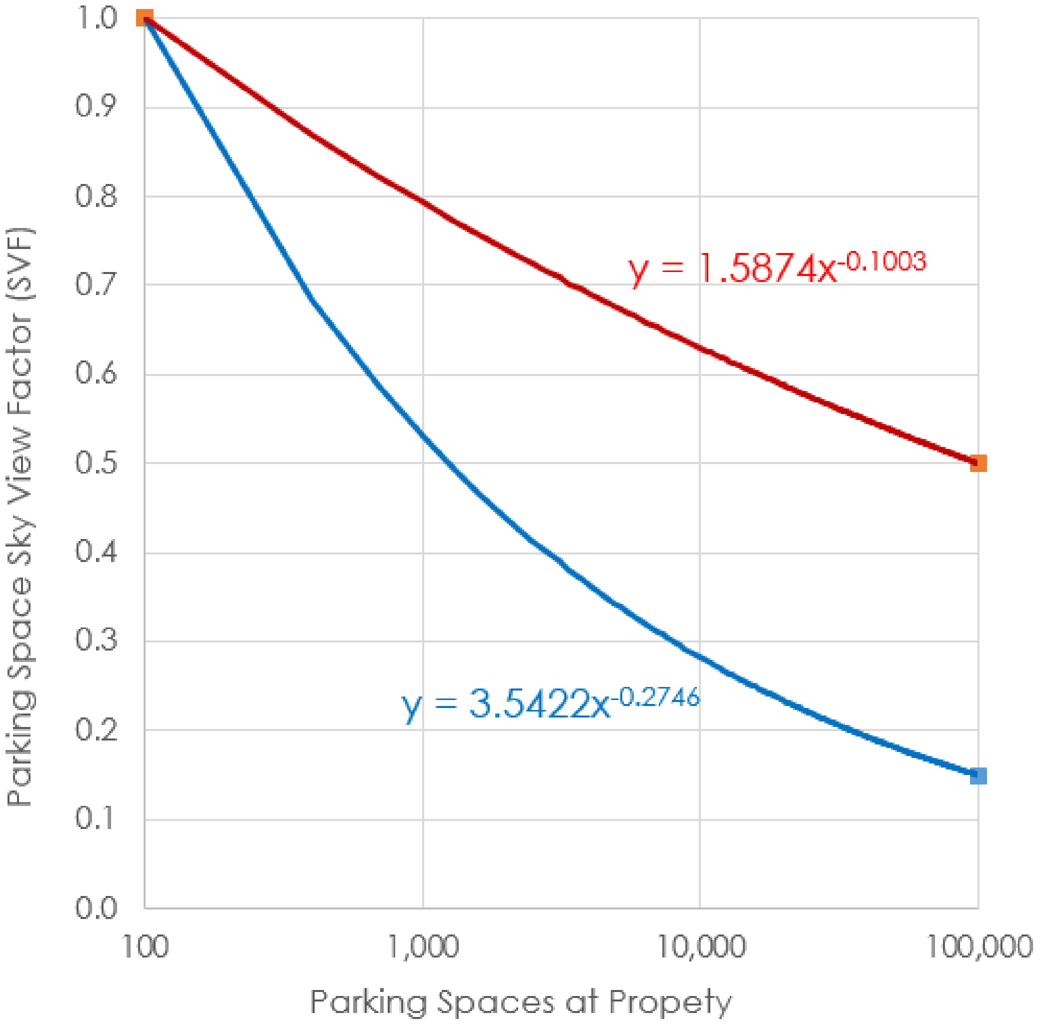

Figure 21. Assumed Minimum and Maximum Sky View Factor Decay Functions for Properties with Greater than 100 Parking Spaces.

APPENDIX D

CO-AUTHOR PERMISSION

Chapters 2 and 3 are previously published journal articles. All co-authors have granted their permission for the use of this material in this dissertation.