Transportation Infrastructure and Heat Vulnerability

by

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ABSTRACT

In the American Southwest, an area which already experiences a significant number of cooling degree days, anthropogenic climate change is expected to result in higher average temperatures and the increasing frequency, duration, and severity of heat waves. Climatological forecasts predict heat waves will increase by 150-840% in Los Angeles County, California and 340-1800% in Maricopa County, Arizona. Heat exposure is known to increase both morbidity and mortality and rising temperatures represent a threat to public health. As a result there has been a significant amount of research into understanding existing socio-economic vulnerabilities to extreme heat which has identified population subgroups at greater risk of adverse health outcomes. Additionally, research has shown that man-made infrastructure can mitigate or exacerbate these health risks. However, while recent socio-economic heat vulnerability research has developed geospatially explicit results, research which links it directly with infrastructure characteristics is limited. Understanding how socio-economic vulnerabilities interact with infrastructure systems is a critical component to developing climate adaptation policies and programs which efficiently and effectively mitigate health risks associated with rising temperatures.

The availability of cooled space, whether public or private, has been shown to greatly reduce health risks associated with extreme heat. However, a lack of fine-scale knowledge of which households have access to this infrastructure results in an incomplete understanding of the health risks associated with heat. This knowledge gap could result in the misallocation of resources intended to mitigate negative health impacts associated with heat exposure. Additionally, when discussing accessibility to public cooled space there are underlying questions of mobility and mode choice. In addition to captive riders, a growing emphasis on

walking, biking and public transit will likely expose additional choice riders to extreme temperatures and compound existing vulnerabilities to heat.

DEDICATION

I dedicate this dissertation to my wife Abbie and our daughter Frances. Without Abbie's love, support, and sacrifice this effort would not have been possible. And to Frances, who is a daily reminder that I should work every day to make the world a better place.

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CHAPTER 1

INTRODUCTION

1.1 Infrastructure and Heat Vulnerability

Civil infrastructures are vital elements of urban systems that support economic development and quality of life. While the services provided by infrastructure are ultimately what is valued to and by the public, discussions of infrastructure, particularly in the context of climate change resilience, tends towards its physical manifestation (e.g. roadways, bridges, pipelines, and transmission lines) (Little 2003). Of course, concerns for service continuity motivate these discussions. With the growing threat of climate change, government institutions, academics, and infrastructure professionals are assessing climate change risks and identifying specific vulnerabilities to critical civil infrastructure. Engineering principles and practices are evolving to address these risks and vulnerabilities. These are significant achievements, but our focus on physical infrastructure has let us neglect the interface between people and the services that these infrastructure systems provide. The global population is rapidly urbanizing and with it the frequency of human-infrastructure interactions. As we address civil infrastructure questions related to climate change, we should better understand how we interface with these systems, what that means today, and what it will mean in a climate change impacted future.

Extreme heat is a leading cause of weather-related death in the United States but there is a lack of public recognition of this hazard (NCHS 2014). Unlike other extreme weather events, heatwaves are natural disasters that do not leave a physical path of destruction. Hurricanes, tornados, and coastal storms can destroy infrastructure leaving lasting reminders of the dangers they pose while sporadic episodes of extreme heat are quickly forgotten as temperatures dissipate (Luber and McGeehin 2008). In the absence of adaptation and mitigation efforts and human acclimatization, increasing heat-related morbidity and mortality due to anthropogenic climate change is expected (Oleson et al. 2015). Increasing average temperatures and the increasing frequency, duration, and severity of heatwaves are growing threats to public health and there are growing efforts to understand and characterize these health risks. Yet, there is little research focused on understanding how civil infrastructure can mitigate or compound these heat-health risks.

Research has shown, and it is widely accepted, that the human health impacts to extreme heat, in magnitude and direction, varies both inter- and intra-regionally (Hondula et al. 2015). Acknowledging these cross-scale differences, there has been a recent focus on studying the non-climatic factors that contribute to heat vulnerabilities in order to develop targeted interventions to protect the public during periods of extreme heat (Hondula et al. 2015; Hunt and Watkiss 2011). The existing literature has largely focused on identifying demographic, social and economic determinants of heat vulnerability. These characteristics include (but are not limited to): age, race, poverty status, education level, and measures of social isolation. By identifying these characteristics researchers have been able to develop geospatial assessments of heat vulnerability to help policymakers determine where adaptive resources should be deployed (Chow et al. 2012; Harlan et al. 2013; Johnson et al. 2012; Reid et al. 2009; Rinner et al. 2010; Weber et al. 2015). What is largely absent from the existing heat-health literature, outside of urban heat island research, is an understanding of infrastructure characteristics which may lessen or increase health risks associated with extreme heat. Research is needed to fill this knowledge gap in order to develop more effective and efficient adaptation policies to address a growing threat to public health. In this dissertation, I examine characteristics of the coupled land use and transportation systems and how these characteristics may mitigate or compound heat-health risks for system users.

Many cities and transportation planning agencies are actively promoting public transit and active modes of transportation for the simultaneous benefits of greenhouse gas emission reductions, congestion reduction, improvements in regional air quality, and public health improvement (Harlan and Ruddell 2011; Hosking et al. 2011; Sallis et al. 2004; Younger et al. 2008). While the benefits of public transit use, cycling, and walking are well-established, these modes typically require environmental exposure and may increase the risks of negative health outcomes during periods of extreme heat. In addition to direct heat-related health impacts (heat stroke, heat exhaustion, heat syncope, and heat cramps), exposure to high temperatures is also known to exacerbate existing medical conditions leading to additional urgent care and emergency room visits, hospitalizations, and potentially early mortality (Gronlund et al. 2016; Kovats and Hajat 2008; Schwartz 2005). During periods of extreme heat, public health agencies and the national weather service issue warnings and direct people to limit outdoor activities (AZDHS 2016; NWS 2016). This directive has the potential to limit access to goods and services for those reliant on public transit, cycling and walking for mobility. At the same time, mobility needs may require individuals to endure heat exposure, the length of which is directly related to how we have designed our transportation-land use infrastructure systems. At a time when the world population is rapidly urbanizing, city planners are pursuing new land use and development patterns to achieve modal shifts, and transportation agencies are heavily investing in transit, bicycle and pedestrian infrastructure. Research is needed to understand the heat-health risks for system users and how these risks may change due to climate change. With a better understanding of these exposure pathways, we can identify opportunities to limit exposure while still meeting the mobility and accessibility needs of people in order to mitigate adverse heat-health outcomes.

1.2 Case Studies Sites: Los Angeles County, CA and Maricopa County, AZ

The dissertation focuses on two regions in the American Southwest: Los Angeles County, California and Maricopa County, Arizona (**Figure 1**). These areas encompass two of the largest metropolitan regions in the southwestern United States, both in terms of population and land area. While both areas are predicted to experience increases in average summer temperatures as well as the increasing frequency, duration, and severity of heatwaves, interregional climate and topography differences make addressing climate change and heat unique to each location. Los Angeles County is spread across five climate zones that range from a moderate coastal climate to a high desert climate located in the northeast corner of the county (California Energy Commission 2014). While the coastal portion of the county typically experiences a moderate summer climate (average daily high of 22 C$^{\circ}$), inland temperatures are significantly higher. On average summer highs are 7 C$^{\circ}$ warmer in the San Fernando and San Gabriel Valley than on the coast and 12 C$^{\circ}$ warmer in the high desert areas. In contrast, extreme heat during the summer is a regular occurrence in Maricopa County with daily maximums consistently above 40 C$^{\circ}$ throughout the summer months (National Climate Data Center 2015). Though the nature of temperature extremes is quite different in these two locations, summer temperatures have been associated with elevated health risks and adverse health outcomes in both (Anderson and Bell 2009; Petitti et al. 2015; Sheridan et al. 2012).

Figure 1: Los Angeles County, CA and Maricopa County, AZ

There are several other reasons that make these two regions suitable areas of study:

- Both regions have established extreme heat response plans to address the growing threat to public health.
- Heterogeneous land use characteristics across the regions may limit access to necessary goods and services for population subsets during periods of extreme heat.
- In response to climate change and growing concerns with congestion, cities within both regions have emphasized alternative modes (walking, biking, and public transit).
- There are known spatial disparities in vulnerability to climate change and extreme heat (Cooley et al. 2012; Harlan et al. 2012; Reid et al. 2009).

1.3 Research Objectives

The dissertation addresses the following objectives:

1. Identify public cooling resources and quantifying household measures of accessibility to these resources.
2. Show that the current distribution of public cooling centers could be improved and identify locations that should be targeted during network expansion.
3. Assess and quantify environmental exposure resulting from transit use.
4. Modify existing transit schedules to reduce ridership heat-health risks.

1.3.1 Chapter 2: Assessing Household Accessibility to Public Cooling Resources.

In Chapter 2, I assess the location public cooling resources and develop an accessibility index to these resources for individual households. The availability of cooled space, whether public or private, has been shown to greatly reduce morbidity and mortality risks during periods of extreme heat (O'Neill et al. 2005). However, we lack fine scale-knowledge of where this infrastructure exists in cities and, more importantly, who does and does not have access to this infrastructure. This knowledge gap could result in a misallocation of resources intended to mitigate negative health impacts associated with heat exposure. Using Los Angeles and Maricopa as case studies I identify existing public infrastructure including cooling centers (a component of extreme heat response plans in many cities), which by virtue of being air-conditioned, may help reduce heat-health risks and quantify an accessibility metric to these resources for individual households. The metric is based on pedestrian access and considers mobility limitations due to concerns for heat exposure.

1.3.2 Chapter 3: Cooling Center Location Optimization

In Chapter 3, I develop a method for strategically locating official cooling centers. The provision of public cooling centers is a recommended strategy for emergency heat management programs and networks of these centers have been developed in many regions including Los Angeles and Maricopa (Uejio et al. 2011). These centers help the public escape the heat and prevent long-term heat exposure. However, while these centers have been effective at reducing heat health risks there has not been significant thought regarding the strategic placement of these facilities. The siting of these facilities ought to consider heat vulnerability of the population that would have access to these facilities as well as existing resources that could also provide heat relief. By applying location optimization theory, I show that re-siting existing facilities could improve regional access to a life-saving resource and identify a set of facilities that should be targeted if Los Angeles and/or Maricopa look to expand their existing networks.

1.3.3 Chapter 4: Assessing Transit Exposure

In Chapter 4, I assess exposure resulting from transit access and waiting time across the Los Angeles Metro and Velley Metro systems. The design of public transit systems, both stop placement and transit schedules, directly contribute to exposure for riders. For those dependent on transit for their mobility needs as well as choice riders, the nature of public transit requires exposure that, during heatwaves, may be a health hazard. While convenient and frequent service are goals of transit agencies, demand and funding constraints lead to variations in transit stop density and vehicle headways. These variations contribute to different exposure experiences for transit riders across the system.

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CHAPTER 2

HOUSEHOLD ACCESSIBILITY TO HEAT REFUGES: RESIDENTIAL AIR CONDITIONING, PUBLIC COOLED SPACE, AND WALKABILITY

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1.5 Introduction

The link between temperature extremes and human morbidity and mortality is well established. Currently, heat is a leading cause of weather-related mortality many developed countries In the United States, heat exposure resulted in 3,332 deaths between 2006-2010 (Berko et al. 2014). It is estimated that the 2003 European heatwave contributed to 70,000 excess mortality events across sixteen countries (Robine et al. 2008) and in May 2015, extreme temperatures were blamed for 2,500 deaths in India (Das 2015). In addition, heat exposure is known to cause distinct clinical illnesses (e.g. heat cramps, heat exhaustion, heat stroke) which often require medical attention. Heat exposure is also known to exacerbate preexisting conditions (e.g. respiratory and cardiovascular disease) contributing to additional emergency room visits, hospitalizations and premature death (Berko et al. 2014; Luber and McGeehin 2008). Although heat has long been a public health issue, programs and policies in the United States which explicitly address and manage health risks associated with heat exposure are relatively new (Maller and Strengers 2011). Furthermore, general circulation models predict increasing annual average temperatures and the increasing frequency, severity and duration of heatwaves (defined as a period of unusually hot and/or humid weather) potentially increasing the likelihood of morbidity and mortality resulting from heat exposure (Karl and Melillo 2009; Solomon et al. 2011). Urbanization is also a significant driver of changes in climate at the regional scale. In cities, temperature increases associated with urban growth may rival those associated with global warming and further exacerbate health risks to urban populations (Georgescu et al. 2014; Hondula et al. 2014; Stone Jr et al. 2014). To address the health risks associated with environmental heat, improvements to strategies used to combat heat-related morbidity and mortality will likely be needed to offset the consequences of expected future increases in heat exposure.

Epidemiological studies have shown the presence and use of air conditioning (AC) can significantly reduce the health risks associated with higher temperatures (Anderson and Bell 2009; Ferreira Braga et al. 2001; Kilbourne et al. 1982; O'Neill et al. 2005; Ostro et al. 2010). However, there is limited knowledge of the extent of residential access to AC within a city and whether this infrastructure is equitably distributed (Bell et al. 2009; O'Neill et al. 2005). The epidemiological studies have largely focused on the protective effects of residential AC ownership and use but there has not yet been a study which assesses the potential for publically available cooled space (instead of, or as a complement to, home air conditioning) to mitigate heat-health risks. Despite a lack of research regarding protective effects of public cooled space, the known association between residential AC and lower incidences of heat-related illness and death has prompted many regions to establish public cooling center networks. These networks are comprised of designated public spaces which serve as air conditioned heat refuges for those who may not have in-home access to AC or those who may not be able to afford to use it (Uejio et al. 2011).

While there is limited systematic and scientific knowledge regarding the composition, operation, and effectiveness of cooling center networks, a recent public health evaluation of the Phoenix Heat Relief Network (set in Maricopa County, Arizona) provides insights for one geographic setting (Berisha et al. 2016; MCDPH 2015; MCDPH 2015; MCDPH 2015). In Maricopa County, the cooling center network is comprised of a mixture of community centers, senior citizen centers, libraries, places of worship, humanitarian organizations, and government buildings. Some of the cooling centers are facilities operated by local governments, but many other facilities participate voluntarily. The network structure is thus more emergent than intentional, and the nature of the network may result in uneven spatial and temporal coverage of facility location and open hours (Uebelherr et al. 2015). Most facilities in the Phoenix Heat Relief Network operate as a cooling center continuously throughout the region's persistently hot summer months instead of activating during specific heat emergencies or warning periods as designated by the National Weather Service or public health agencies. In 2014, it was estimated that at least 1,500 people used cooling center facilities on a daily basis, although the specific motivation of these visits as driven by heat exposure or desire for other services offered at facilities was more difficult to ascertain. The network clearly helped many people in the region cope with summer heat, however: many of those who visited facilities spent more than an hour in the publicly accessible cooled space, and many thousands of bottles of water were distributed over the course of the summer (Berisha et al. 2016; MCDPH 2015; MCDPH 2015; MCDPH 2015). It was unclear from the public health evaluation if the formal cooling center network is an effective or useful resource for all individuals seeking cooling relief in Maricopa County, however, but a 2015 survey of 337 households in the County found that more than 75% of households in areas with a high incidence of heat-related illness were unaware of their availability (MCDPH 2015).

Previous surveys of individual-level strategies to cope with hot weather reveal that official cooling center networks are not the only resource that people use to stay cool (Hayden et al. 2011; Kalkstein and Sheridan 2007; MCDPH 2015). One strategy is to use non-residential air conditioned space that is publically available, sometimes at a cost, such as that which can be found in shopping malls, restaurants, grocery stores, and movie theaters. However, there is currently little to no information regarding the distribution of these facilities and who may have access to them creating a somewhat limited view of the options for and behaviors of people in a city when seeking heat refuge. To more effectively and efficiently deploy resources to mitigate the health risks associated with heat a better understanding of public and private cooling resources within a city and which households have access to them is needed.

Much of the research on the health-related impacts of heat has focused on socio-economic vulnerabilities (Harlan et al. 2006; Reid et al. 2012; Reid et al. 2009; Stafoggia et al. 2006; Uejio et al. 2011). However, studies that have included information about air conditioning availability and health outcomes nearly unanimously conclude that air conditioning is a significant protective factor (Kovats and Hajat 2008; Naughton et al. 2002; O'Neill et al. 2005; Ostro et al. 2010). Multiple authors have suggested that increasing prevalence of home air conditioning is a major contributor to decadal-scale declines in heat-related mortality observed in many developed countries (Davis et al. 2003; Gasparrini et al. 2015), although one study suggested that increases in air conditioning prevalence was not a significant contributor (Bobb et al. 2014). Given the apparent importance of air conditioning, we were motivated to explore how the availability of private and public access to AC is distributed across cities. To effectively address public health needs associated with heat, cities should consider differences in privately-held resources and public accommodations. Residential AC is the primary example of a privately-held cooling resource. Publicly accessible cooled spaces include county cooling centers, commercial space, and other buildings which may serve as a heat refuge. Establishing where in a city lower penetration of residential AC exists is important as it means that there is a potential vulnerability that could be mitigated with the deployment of a county cooling center. Beyond private cooling resources, knowledge of existing public cooling resources can help to effectively locate future cooling resources to areas with few opportunities. Neighborhood-scale knowledge of the distribution of AC, both private and public, can help cities effectively plan for resource investment to mitigate heat vulnerability.

1.5.1 Cooling Resource Access Case Studies

Using Los Angeles County, California and Maricopa County, Arizona (whose seat is Phoenix), we study how in-home AC and public cooled space are distributed across heat vulnerable cities. These areas encompass two of the most populous metropolitan regions in the southwestern United States and high summer temperatures and heatwaves in both counties have been associated with elevated risks of adverse heat-health outcomes (Petitti et al. 2015; Sheridan et al. 2012). We assess the availability of residential AC and accessibility to publicly cooled space at a census tract scale in both regions to i) develop a framework for comprehensively inventorying privately and publicly accessible cooled space across cities, and ii) create new insight into the equitability of access to public cooled space including county cooling centers, libraries, and commercial establishments.

1.6 Residential Access to Air Conditioning

We start by assessing the prevalence of private AC, namely central AC in residential buildings to identify which areas of each county have lower penetration of the resource thereby a greater need for access to public AC. While the presence and use of residential AC has been shown to reduce the risk associated with heat-related mortality and morbidity during heatwaves, research studying the protective effects of residential AC at the regional level has commonly been limited by a lack of fine-scale (e.g., parcel-level) knowledge of which households have access to—and are able to use—this infrastructure. To address this gap, new methods are needed to develop a systematic understanding of where this infrastructure has been deployed and what that means for social heat vulnerability. There are several types of in-home AC units including central AC, room or window unit AC, and evaporative cooling systems. The relative performance of room/window units and evaporative systems during heatwaves compared to central AC has not been established and it is unclear if these types of units are effective in reducing the health risks associated with heat exposure.

We start by estimating the prevalence of central air conditioning (CAC) at the household scale to highlight areas where this infrastructure is lacking and thus, where residents may need to rely on other cooling resources when temperatures exceed healthy thresholds. The presence of CAC may not universally lower risks associated with heat and there are scenarios in which even those households which have CAC may also need to utilize cooling center infrastructure. For example, some households may face constraints in CAC use due to the associated electricity costs, other households may be unable to afford repairs to broken CAC units, and others may prefer not to use CAC based on personal comfort preferences and/or environmental concerns (Hayden et al. 2011; MCDPH 2015).

The presence of CAC at the household level is identified through building characteristic data available in the county assessor's databases and from the American Household Survey(AHS), which details the presence of CAC as well as other building level characteristics, such as age and type (e.g. single family, multifamily) (Census 2010; Los Angeles County Assessor Office 2009; Maricopa County Assessor Office 2010). Los Angeles and Maricopa assessor databases contain different levels of detail regarding CAC. In Los Angeles, the assessor's database details the presence of CAC in single family homes and small (< 4 stories) multi-family buildings but does not include these details for other residential buildings, such as large multifamily buildings. The presence of CAC in these buildings was estimated with the AHS (Census 2010). In contrast, the Maricopa assessor database contains information on the presence of CAC for all residential building types. The presence of CAC differs between the two regions and is likely influenced by average regional temperatures and the relative age of the residential infrastructure. In Maricopa, where daily summer maximum temperatures typically exceed 40° C, we find that approximately 95% of all households have CAC. In addition to the desert climate, the high prevalence of CAC may also be due to the relative age of buildings in the region. In 1950, around the time that installation of in-home CAC began to take hold, approximately 350,000 people lived in the region (Cooper 1998). By 2010, Maricopa County was home to 4 million people largely housed in homes built after the widespread use of CAC became common (Census 2010). The 5% that do not have CAC typically rely on evaporative cooling systems, and are mostly found in the oldest residential developments in the region (Figure 2). In contrast, Los Angeles, which is spread across 5 different climate zones that range from a moderate coastal climate to a high desert climate located in the northeast corner of the region (CEC 2014), CAC is not nearly as common. While less than 50% of households have

CAC, the distribution of households with central AC is skewed towards the areas of the region which experience higher average daily summer temperatures. The results show that there is limited residential availability of CAC, with less than 30% of the households possessing CAC along the coastline and in the Los Angeles Basin, where the typically moderate weather is influenced by the proximity of the Pacific Ocean. As average daily temperatures increase relative to the distance from the ocean, the presence of household CAC also increases. In the San Fernando and San Gabriel Valley, which experience summer highs typically 7 C° warmer than the temperatures on the coast, 60% of all households have CAC. Moving northeast into the high desert where average summer temperatures are 12 C° warmer, 82% of residential households have CAC (NCDC 2015). Similar to Maricopa, areas associated with newer development within each climate region in Los Angeles tend to have a higher penetration of CAC.

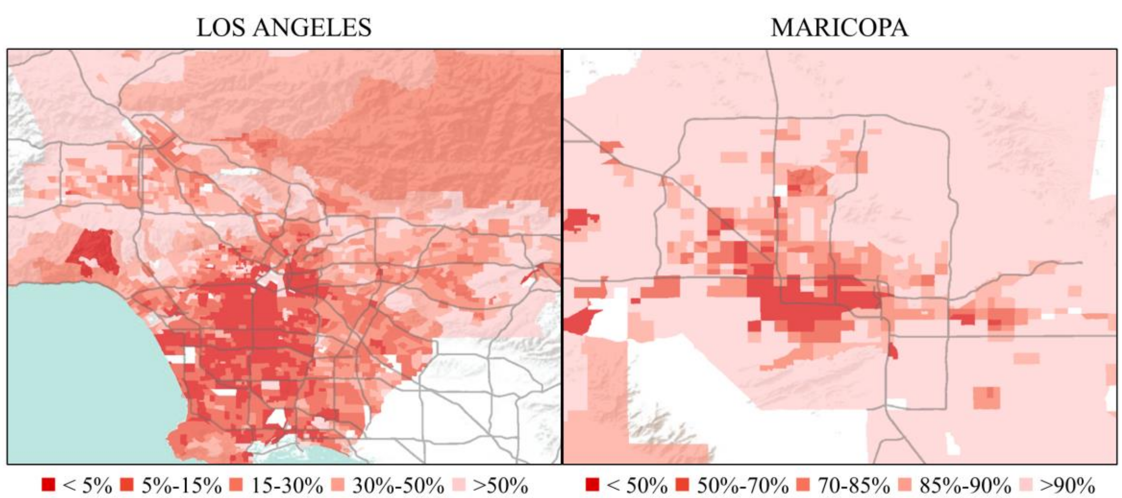

Figure 2 Proportion of Households with Central Air Conditioning (note the differing scales)

1.7 Access to Public Cooled Space

As with residential AC, little is known about the distribution and availability of cooling centers and it is unclear whether these resources are deployed to effectively mitigate health risks. Additionally, most attention is focused on the availability of county cooling centers and there remains limited insight into how publicly accessible cooled commercial space is distributed.

The location of county cooling centers is determined by the availability of government buildings, social services, and volunteer organizations. While some cooling centers are established by government agencies, other facilities participate in the network on a volunteer basis. This results in an ad hoc network that may not be optimally located to serve particularly vulnerable populations. In addition to designated cooling centers there may also be other public places which, by virtue of being air-conditioned, may help to reduce the health-related risks of heat. We explore the distribution of official cooling centers and other public spaces (collectively referred to as cooling resources) that could provide heat relief. We then develop household level accessibility measurements to these locations.

Measurements of accessibility, defined as the relative generalized transportation costs of reaching activity locations from given origins, has been a research topic in transportation planning, urban planning and geography for many decades (Geurs and Van Wee 2004; Hansen 1959; Langford et al. 2012; Luo and Qi 2009). Generalized transportation costs include both monetary (e.g. Transit Fare) and non-monetary (e.g. Time) costs of a journey. Fundamentally, accessibility studies aim to understand the impact of urban form (spatial distribution of origins and activity locations) and the transportation system (network connectivity and modal options) on an individual's ability to fulfill needs and desires (Scott and Horner 2008). Accessibility methods have been utilized to understand transportation related exclusion, health care facility service areas, economic impacts of transportation infrastructure investment, the effect of public transit on employment opportunities, and the existence of food deserts (Páez et al. 2012).

Because historic land use and transportation policies have led to the separation of land uses which then contributes to disproportionate individual access to goods and services, household accessibility metrics are an essential tool to assess inequalities. Two of the most common methods of developing an accessibility measurement are the cumulative opportunities and gravity-based approaches. Cumulative opportunities typically consider the total number of opportunities within a given distance or travel-time threshold (e.g. total number of job locations within 30 miles). Gravity-based approaches consider the generalized costs associated with reaching alternative destinations such that opportunities with lower generalized costs receive a larger weighting than opportunities associated with higher generalized costs (Páez et al. 2012). Where previous accessibility studies are often based on the generalized costs between centroid locations, increasing computational power and spatially disaggregate data allow for the development of accessibility measurements at a more granular scale. Using a modified cumulative opportunity and gravity-based approach we estimate household level access to cooling resources to understand access disparities across each region.

1.7.1 Accessibility Methods

1.7.2 Cooling Resources

We consider three types of publicly accessible cooled space: county cooling centers, libraries, and public/commercial space. The first category is official cooling centers which are established by local agencies as air-conditioned public places of refuge. These facilities are generally targeted towards those without AC at home, the elderly, and the homeless, though they are open to the public. In addition to providing a cooled space, these centers sometimes provide additional services, including basic medical care. The second category is public libraries, which are not members of the official cooling center network. While these spaces are not intended for use as heat relief locations, they are public spaces available at no cost to all residents, including vulnerable and homeless individuals (ALA 2012). The third category consists of public and commercial spaces including malls, restaurants, and museums. As with libraries, these spaces are not primarily intended as spaces of heat relief, but the cooled space can be thought of as an ancillary benefit to those who seek out goods and services at these locations.

1.7.3 Data Sources

Household accessibility to cooling resources is estimated using spatially disaggregated data for residential and cooling center locations. Residential and cooling center locations were developed from several data sources. Residential locations were determined from Los Angeles and Maricopa property assessment rolls which include information on property use and building type for all taxable land parcels (Los Angeles County Assessor Office 2009; Maricopa County Assessor Office 2010). There are approximately 2.1 million residential parcels in Los Angeles and 1.1 million in Maricopa. Residential parcels, ranging from single family homes to large multi-family apartment complexes, were weighted by the total number of dwelling units on each parcel to understand cooling center accessibility at a household scale. Addresses of official cooling centers were geocoded from information provided by the Los Angeles County Emergency Survival Program and the Maricopa Association of Governments (the regional agencies responsible for network coordination) for the 2014 cooling center network (County of Los Angeles 2014; MAG 2014). In 2014, there were 142 official cooling centers in Los Angeles and 45 in Maricopa. It should be noted that the locations of cooling centers may change from year to year depending on voluntary participation which would affect our results. Public library locations in Los Angeles and Maricopa were geocoded through an address database (Publiclibraries.com 2015). Libraries already serving as official cooling centers were excluded to prevent double counting. Libraries associated with educational institutions and specialty interests were excluded from the analysis as they are unlikely to serve the general population. The locations of other public spaces which may serve as cooling resources were also determined from property assessment rolls. For interregional comparisons, a crosswalk was developed to link similar property use and building codes between the two counties. Public spaces that directly offer goods or services to the general public were selected as potential cooling resource locations. It is assumed that individuals would need to remain in a cooled space for a prolonged time period to receive effective heat relief. Therefore, we have excluded public building types where the estimated transaction time is less than 30 minutes. By this definition county parcels coded as indoor shopping malls, movie theatres, and restaurants are accepted as potential cooling resources, while banks and gas stations (services <30 minutes) and commercial offices and private social clubs (not for the general public) were excluded.

1.7.4 Accessibility Measurement

Measures of accessibility for residential access to cooled space were based on the distance between any pair of cooling resource locations and individual residential parcels. While motorized modes of transportation are often utilized in accessibility studies, we developed an accessibility metric based strictly on pedestrian access. In this way, we defined a metric that describes accessibility for a particularly vulnerable subset of the population (those without motorized transport). In a recent survey of Maricopa County cooling centers, more than one third of all patrons walked to the facility (Berisha et al. 2016; MCDPH 2015). Additionally, while previous accessibility metrics are often based on generalized costs between centroid to centroid or centroid to specific locations, we developed our accessibility metrics for individual households.. Using this approach, individual household accessibility metrics can be aggregated to any geographic scale to allow for commensurate comparisons with socio-economic information.

Cooling center accessibility is defined by three parameters: walking time, walking speed, and the existing street network. The National Household Travel Survey (NHTS) is used to assess typical walking durations to set the maximum walk time for those attempting to seek heat relief. The 75th percentile for walking duration for non-leisure trips, 15 minutes, was selected as the maximum time for this analysis (USDOT 2009). The 15 minute time horizon was then coupled with average walking speeds for sedentary elderly (1.4 kilometers per hour) , average elderly (3.5 kilometers per hour), and active adults (5.6 kilometers per hour) to estimate maximum walking distances (d_0) (Bohannon and Andrews 2011). These distances (0.33, 0.89, and 1.4 kilometers respectively) were assessed within the regional road networks to establish catchment areas for each cooling resource. Assuming individuals would select the shortest path, ArcGIS's Network Analyst tool was used to generate the catchment areas for every cooling resource location (ESRI 2015). The tool relies upon a path-based algorithm which computes linear distance along a network from a specified origin. All roadway types except those designated as freeways or highways were included. As these catchment areas are defined by the street network, it is assumed that all pedestrian travel occurs along adjacent sidewalks. We acknowledge that the design of certain streets (particularly those without sidewalks or that are not pedestrian friendly) may be inimical to walking, but we were not able to identify information on the "pedestrian friendliness" of streets to incorporate into our assessment. Potential shortcuts through open space parcels are excluded from the analysis. A residential parcel (*i*) is considered to have access to a cooling resource (*j*) if it falls within the catchment area of cooling resource (j) (**Figure 3**).

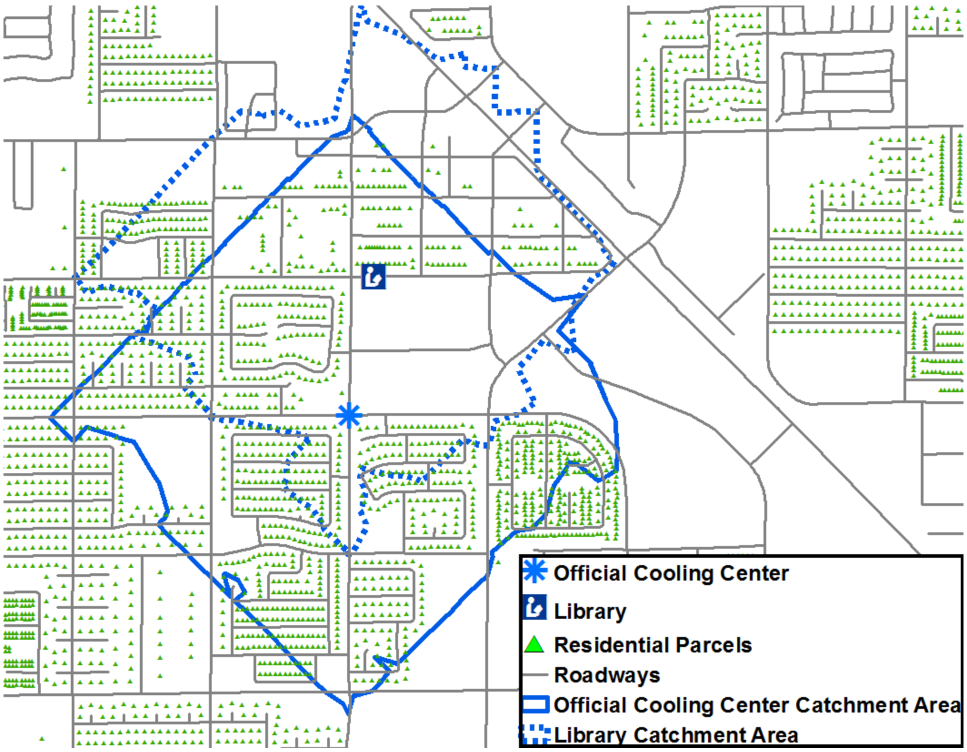

Figure 3 Residential Access to Cooling Resources by Catchment Area Method. Households are considered to have access to a cooling resource (j) if they fall within its catchment area which is defined by the geometry of the street network and maximum walking distance.

A modified cumulative opportunities and gravity-based approach is used to estimate an accessibility index for each residential parcel in Los Angeles and Maricopa. First, each type of cooling resource (*j*) is assigned a weight (w_j) which describes the utility derived at each type of facility, based on the quality of relief available at the facility and estimates of the time an individual can stay there and the associated monetary cost (Table 1). Locations where an individual may stay for extended periods of time for little to no monetary cost receive higher weightings than facilities with shorter lengths and higher associated costs. For example, official cooling centers which are dedicated to providing heat relief and where an individual is free to stay as long as the center is open received a higher weight than a restaurant where heat relief is an ancillary benefit to goods and services which have a monetary cost and a potential time limit. Facility types were determined using assessor database property use codes. Second, the total amount (*K*) of each type of cooling centeraccessible by an individual residential parcel (*i*) is determined by overlaying the catchment areas and residential parcel locations. Traditionally, accessibility measurements often consider the utility of each additional location to be equivalent. For an individual household, each cooling center (*j*) may provide the same heat relief utility; however, the temporal aspect of access should be considered when developing an accessibility metric. Because an individual may only occupy a single space at any time, the utility of each additional cooling center diminishes. We included a constant (x_j) to describe the diminishing marginal utility of each additional cooled space that is accessible from each residential parcel. This is analogous to the travel friction coefficient (*B*) utilized in gravity based methods (Hansen 1959). The accessibility measure at a residential parcel (*i*) can be expressed as:

$$A_i = \sum_{j \in S_j} \sum_{k=1}^{K_{ij}} W_j * d_{ij}^{-\mathrm{B}} * k^{-x_j}$$

where S_j is the set of all cooling centers *j* within a specified threshold distance from resideintial parcel *i* and d*ij* is the walking distance between *i* and *j*.Since there are no studies that describe the declining marginal utility of access, we considered four values (0, 1, 1.25, 2) for the diminishing utility coefficient to evaluate the sensitivity of the accessibility measure to this parameter. Because accessibility is determined at distances less than 1.4 km, we utilize zero for the travel friction coefficient based on the underlying assumption that there would be no deterrence over such short distances though we included it in the index formulation for future research.

Table 1: Cooling Resource Types and Associated Accessibility Weights

Facility Type (j)	**Length of Stay (hours)**	**Estimated Cost ($)**	**Weight (W_j)**
Official Cooling Centers	4+	None	2
Libraries	4+	None	1
Indoor Shopping Mall	4+	None-Low	0.5
Outdoor Shopping Center with Multiple Retail Locations	1-4	Low	0.4
Department Store/Big Box Retail	1-4	Low	0.4
Supermarket/Grocery Store	1-2	Low	0.35
Museums	4+	Medium	0.3
Hotel/Motel	Indefinite	High	0.3
Movie Theater, Bowling Alley, Indoor Miniature Golf, Ice & Roller Skating Rink	1-4	Medium	0.25
Restaurant/Bar	1-2	Low-High	0.2
General/Unspecified Commercial Retail	1	Low-High	0.2
Amusement Facilities	4+	High	0.1

To develop a neighborhood-level accessibility index, household-level accessibility measurements were aggregated at the census tract (Census 2014). The mean of household accessibility scores are utilized to characterize neighborhood level accessibility.

1.7.5 Results

Cooling resources are unevenly distributed throughout each region resulting in differing accessibility measurements from one census tract to another. The spectrum of residential access to publically available cooled space ranges from neighborhoods which have access to many locations, to neighborhoods where residents would not have access to even a single public cooling resource. We find that the land use characteristics, roadway network, walking speeds, total cooling resource opportunities, and declining marginal utility coefficient can all have large impacts on index values.

There are substantial interregional and intraregional differences for residential access to cooling resources. These are detailed in Table 2 which shows the proportion of residential parcels served by the various types of cooling resources in Los Angeles and Maricopa Counties for the three catchment area sizes. Residential access to official cooling centers is low in both counties because there are a limited number of these facilities. At average walking speeds, official cooling centers serve an average of 460 residential parcels in Los Angeles and 430 in Maricopa. In total, these cooling center networks are accessible only to a small fraction of households in each county, approximately 3% and 2% respectively. While there are slight interregional differences in access to official cooling centers, which might be expected given that Los Angeles has three times as many locations as Maricopa; there are notable differences among the other two categories. Interregional accessibility differences are a function of the total number of locations but are also dependent on the density of the built environment. Areas with higher building densities lead to shorter distances travelled between origin and destination. Additionally, high intersection densities increase the connectivity to the network leading to larger catchment areas (Leslie et al. 2007; Scott and Horner 2008).

Table 2 Proportion of households served by at least one cooling resource by resource type and walking speed.

	Official Cooling Center			Library			Commercial		
Walking Speed	*Slow*	*Average*	*Fast*	*Slow*	*Average*	*Fast*	*Slow*	*Average*	*Fast*
Los Angeles	0.3%	3%	10%	1%	11%	29%	36%	80%	91%
Maricopa	0.3%	2%	5%	0.2%	2%	7%	7%	39%	69%

We quantified the effect of intersection and parcel density on access to cooling resources. Figure 4 illustrates the parcel and intersection density distributions for census tracts in Los Angeles and Maricopa. The mean parcel density in Los Angeles is 870/km^2 while the mean intersection density is 89/km^2. In contrast, the Maricopa means are 580 parcels/km^2 and 63 intersections/km^2. In addition to having a built environment more suited for walkable access, the zoning paradigm in Los Angeles is more heterogeneous than Maricopa, which decreases the relative distances between residential and non-residential parcels. Based on these characteristics alone, it can be expected that residents in Los Angeles would have greater access to cooling resources of any kind than their counterparts in Maricopa.

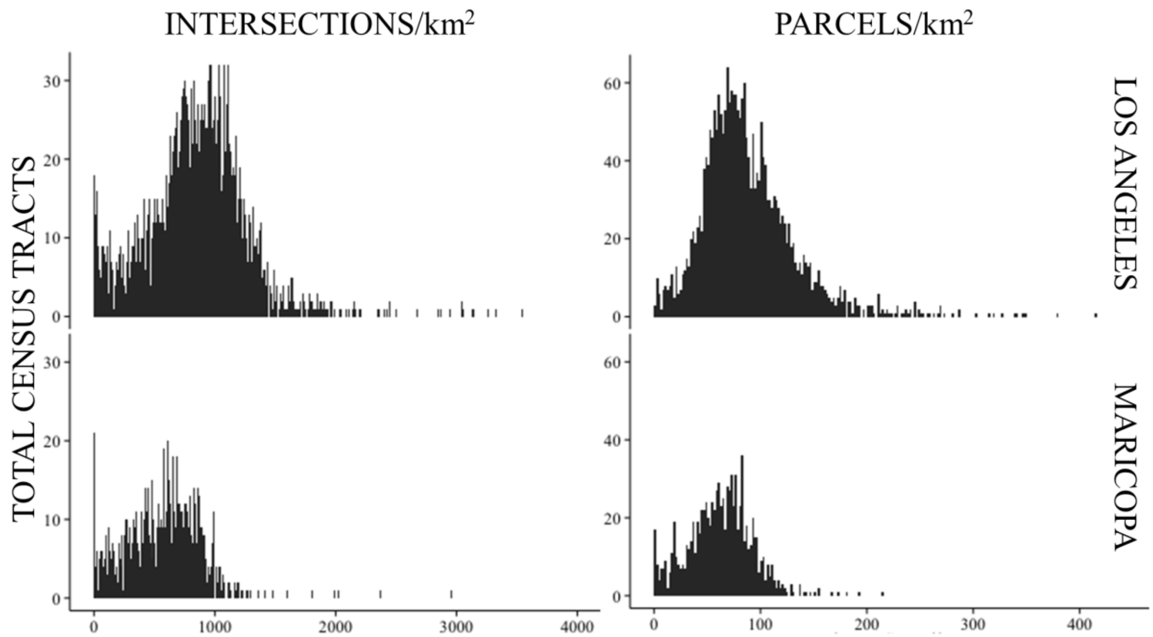

Figure 4 Intersection and Parcel Density by Census Tracts

Developing an accessibility index with household level resolution makes it easier to understand inter- and intra-regional accessibility differences. Aggregated at the census tract scale, the results illustrate how access to cooled space differs across the two regions; it also indicates which areas may be particularly vulnerable due to a lack of available cooling resource infrastructure. Moreover, individual walking speed and the declining marginal utility coefficient have a significant impact on the accessibility index (Table 3). Across all permutations, census tracts in Los Angeles consistently have higher accessibility scores than those in Maricopa. The most significant factor impacting the inter-regional accessibility score discrepancy is the relative proximity of commercial space and residential parcels. The interregional differences are the most pronounced when the marginal utility coefficient is zero, i.e., each cooled space has equal weight in terms of its utility (Table 3). As the marginal utility coefficient increases, that is, that each additional accessible cooled space is worth less and less to those seeking a heat refuge, the relative difference between the two counties decreases. Higher coefficients may offer a more balanced view of cooling resource accessibility by limiting the range of accessibility scores. When all accessible cooled spaces are weighted equally, the range of accessibility scores is significantly impacted by mixed use neighborhoods where residents have access to numerous locations. Further research is needed to determine an appropriate coefficient, which likely varies for each cooling resource type. Also noted in Table 3 is the correlation between accessibility scores with parcel and intersection density. The coefficient of determination (R^2) ranges between 0.32 and 0.48 between the 12 permutations which means that parcel density and intersection density are important determinants of access to publically available cooled space. While the variance is not fully explained by parcel and intersection densities, these measures may be good starting points to evaluate neighborhood access to other goods and services.

Table 3: Mean Census Tract Accessibility Index Score. In addition to total resource opportunities, index scores are influenced by the declining utility coefficient, walking speed, parcel density and intersection density.

Declining Utility Coefficient	Walking Speed	Los Angeles	Maricopa	Correlation with Parcel and Intersection Density
0	Slow	1.58	0.14	0.38
	Average	16.60	1.60	0.45
	Fast	39.89	5.29	0.46
1	Slow	0.53	0.09	0.41
	Average	1.80	0.55	0.48
	Fast	2.69	1.21	0.46
1.25	Slow	0.46	0.08	0.41
	Average	1.36	0.48	0.45
	Fast	1.99	1.02	0.41
2	Slow	0.34	0.07	0.40
	Average	0.87	0.38	0.37
	Fast	1.31	0.76	0.32

Accessibility scores vary across each region and tend to be highest in urban areas and lowest in fringe suburbs. **Figure 5** illustrates the mean accessibility score for Los Angeles and Maricopa counties at the census tract scale. These scores reflect all three walking speeds and a marginal utility coefficient of 2. At slow walking speeds, access scores tend to be highest in older areas of each region. At the neighborhood scale we find that cooling resources are more accessible in Los Angeles than in Maricopa County. In the Los Angeles Basin and San Fernando Valley area of Los Angeles, most neighborhoods have access to at least at least one cooled space within 0.87 km. At 1.4 km the only areas of Los Angeles with limited access are the neighborhoods located in Palos Verdes, the Santa Monica Mountains, and the San Gabriel Mountains. Palos Verdes is a large, affluent, residential neighborhood located just north of Long Beach, CA with relatively low intersection and parcel density as well as a limited number of cooling resources. Intuitively, one might expect the neighborhoods associated with the Santa Monica and San Gabriel foothills and mountains to have limited access due to the topography and limited development.

In contrast, Maricopa County, a region that has experienced rapid growth since the early 1990s, has significantly lower accessibility scores across all three walking speeds. In addition to lower building and intersection densities, one of the primary contributors to this difference is the large separation of residential developments from other land uses leading to greater distances between residential locations and cooling resources. Much of the population growth in Maricopa since 1990 has been accommodated by fringe suburban growth which is characterized by large residential developments served by few commercial centers (Census 2010; Heim 2001). One of the most significant contrasts between the two regions is the relative proportion of census tracts which receive an average access score of zero (Table 4).

Table 4: Proportion of Census Tracts with an Average Accessibility Score of Zero

	Walking Speed		
	Slow	**Average**	**Fast**
Los Angeles	4%	1%	0.4%
Maricopa	25%	9%	5%

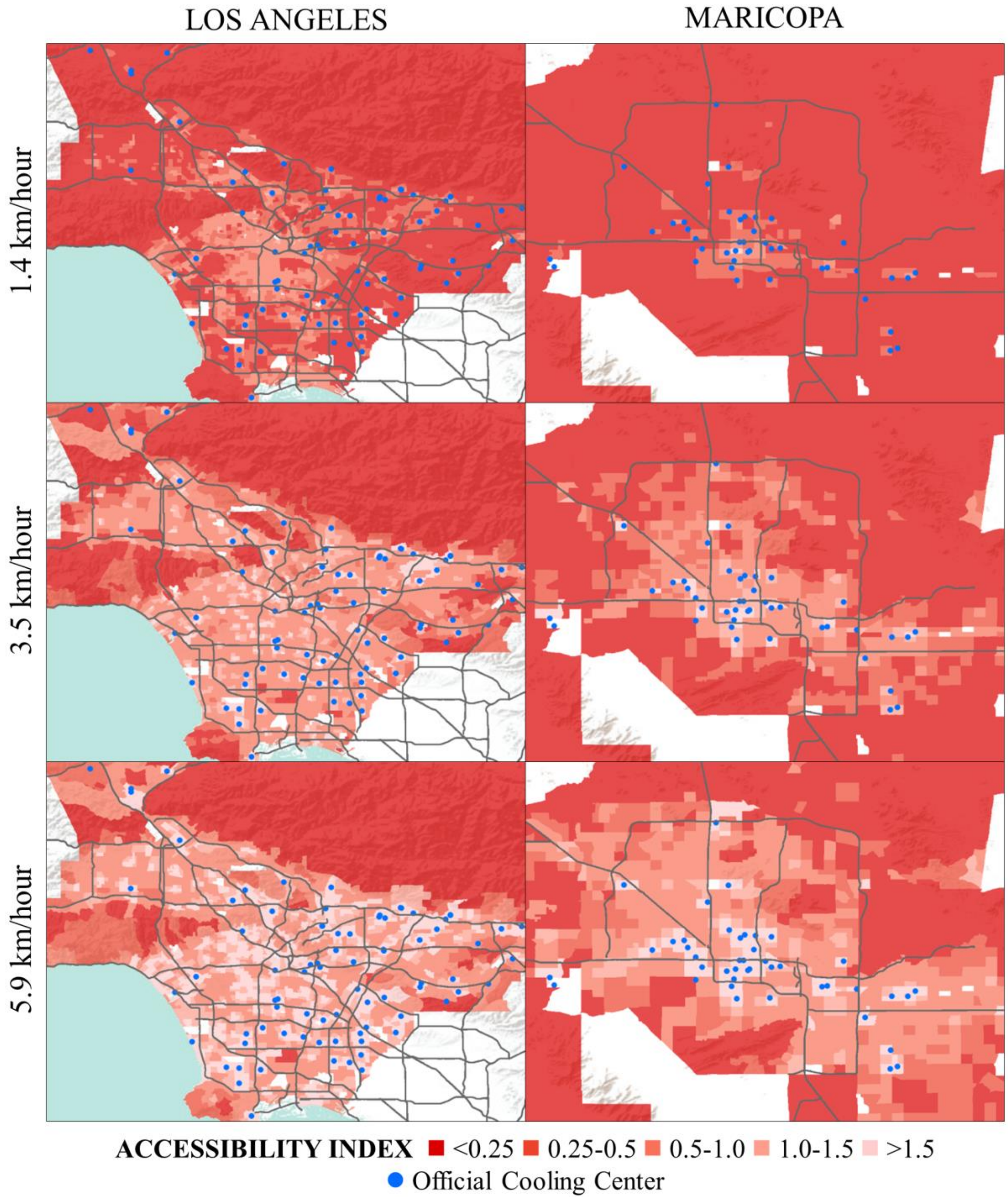

Figure 5 Neighborhood Accessibility to Cooling Resources. The figure illustrates the effect of walking speed on mean household accessibility index score for each census tract. Land-use and street network characteristics significantly impact individual access to cooling resources.

1.8 Discussion

From our analysis come three major findings. First, officially designated cooling centers are unlikely to serve large portions of the population in both counties. Second, commercial cooled public spaces are widely dispersed and could provide access for large portions of the population in each region. Lastly, land use characteristics and the design of the street network impact individual household accessibility to cooled spaces.

The goal of cooling center networks is to provide relief on particularly hot days and during prolonged heatwaves. However, given the limited number of locations of official cooling centers, there is an underlying assumption that residents have adequate transportation to these locations. This assumption is problematic for several reasons. As we show, these locations can only serve a small fraction of households in each region if the transportation mode utilized was walking. For most households to reach these resources some form of motorized transport would be needed (either personal or public). We could generally expect households with access to automobiles to have the financial means to utilize other relief resources making them unlikely to seek out designated cooling centers. Public transportation provides another potential means for accessing these locations; however, access may not be universally available or practical for several reasons. Public transit use would necessitate heat exposure resulting from ingress/egress (which also requires modest physical activity further exacerbating potential heat stress) and waiting time at transit stop locations increases heat-related health risks which cooling centers attempt to mitigate (Fraser and Chester 2016; Karner et al. 2015) .This is potentially more problematic in areas where transit service is infrequent and/or unreliable. For some groups, such as the elderly, which have some of the highest risk levels associated with heat exposure, designated cooling centers may be inaccessible due to a lack of mobility options (Luber and McGeehin 2008;

Taylor and Tripodes 2001). Designated cooling centers may help reduce risks but the results suggest that they likely serve only a small fraction of households. To increase the effectiveness and coverage of official cooling centers, locations should be optimally chosen to serve those at greatest risk and in accordance with transportation provisions. Future efforts to aid in the optimization of cooling center networks and other public resources aimed at reducing heat exposure could engage additional data sources, including incidence of heat-related morbidity and mortality and its spatial variability within the city (Harlan et al. 2013; Hondula et al. 2015), vulnerability indicators (Reid et al. 2009), or additional survey- and interview-based data about air conditioning use and constraints (Hayden et al. 2011). Based on their quantity and distribution, cooled public commercial space has the greatest potential to provide relief during heatwaves to regional populations. However, since these spaces are not intended for use as heat relief locations they likely do not provide ancillary health services to address negative heat-health outcomes. It should be acknowledged that these spaces likely have different operating hours and capacity constraints which cannot be determined through available data. Future research could develop a time- and capacity-dependent accessibility index for these public buildings. While these spaces do not provide the same quality of service that might be found at formally designated cooling centers, they can provide heat relief. Publically accessible cooling resources and the ability of nearby households to utilize these spaces should be considered when deploying additional resources to mitigate the health risks associated with heat exposure.Additionally heat management programs could stress the importance of cooled space and suggest the use of these types of facilities for those without in-home AC and for those whose mobility may be constrained. This analysis reflects a type of theoretical accessibility score, but there could also be important social and cultural dynamics at work in terms of the types of people who are willing to/welcome at/able to visit certain types of locations that could provide additional constraints on accessibility.

In both Los Angeles and Maricopa counties, accessibility to cooling resources decreases when moving from the urban areas to the outlying suburbs. Both counties have developed around the automobile, which resulted in transportation land-use decisions emphasizing automobile mobility over other modes. The disaggregation of land uses (residential and commercial) further increases travel costs for accessing necessary goods and services. The transportation and land-use systems in both regions, which cater to the automobile, place greater generalized transportation costs on the outer regions. The declining accessibility from the core to the outer areas results from decreasing parcel density, decreasing intersection density, and the increasing homogeneity of land use (e.g. separation of residential and commercial land uses). Households in the suburbs have limited access to cooled space via walking and would be the most reliant on motorized forms of transportation in order to access these resources. This effect is more pronounced in Phoenix where residential developments tend to be larger and commercial locations are clustered in commercial parks

The relative increase in risk for negative heat-health outcomes that may be associated with a lack of access to cooled space may be disproportionate depending on socio-economic variables. Though extreme heat can adversely affect the health of anyone, there are population subsets which may be particularly vulnerable. Previous research has shown these subsets, which include the elderly, low-income, and socially or linguistically isolated, exhibit higher morbidity and mortality incidence rates during hot weather. To minimize overall health risks associated with heat, policies and programs should target areas of cities that lack both the infrastructure to mitigate the effect of heat and those where residents may be more vulnerable to heat based on intrinsic socio-economic characteristics.

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CHAPTER 3

OPTIMAL LOCATION ANALYSIS FOR PUBLIC COOLING CENTERS

1.10 Introduction

With increasing evidence of climate change, cities are developing response and management plans to mitigate its potential impacts (Rockefeller Foundation 2016). In addition to the impacts to infrastructure, there is also a significant concern for how climate change and the increasing frequency, intensity and duration of extreme weather events will affect people (Epstein 2005; Haines et al. 2006; Huang et al. 2011; McMichael and Lindgren 2011). Hurricanes, tornadoes, and coastal storms are widely recognized for their destructive potential but there is also a growing concern for the impact that rising average temperatures and future heatwaves will have on public health (Luber and McGeehin 2008). Health impacts resulting from heat exposure can range from mild discomfort and fatigue to death. In addition to known heat-related clinical syndromes, environmental heat stress is also known to exacerbate existing medical conditions leading to increases in hospitalizations and mortality (Schwartz 2005; Stafoggia et al. 2006). Still in their infancy, heat management plans and programs are being implemented in many cities across the United States to reduce public health risks. Evaluation of these programs finds positive impacts but there are still concerns as to whether they are adequately reaching those who are at the greatest risk of negative health outcomes (Bassil and Cole 2010).

One solution for reducing health risks associated with high temperatures is to ensure that individuals have access to cooled space (Kovats and Hajat 2008). Air-conditioning has been shown to be an important protective factor and the prevalence of in-home units has increased but there are many places (e.g. older neighborhoods and temperate climate cities) where it is still uncommon in residential buildings (Braga et al. 2001; Curriero et al. 2002; Kaiser et al. 2001; O'Neill et al. 2005). In response to known disparities in access to in-home air-conditioning, cities across the United States have developed networks of public cooling centers to provide heat refuges. These facilities help the public to escape the heat and prevent long-term heat exposure. Cooling centers are often sited at public libraries, senior citizen centers, and community based organizations. However, while these centers can help reduce health risks there has not been significant thought regarding the strategic placement of these facilities. Everyone is vulnerable to heat but there are particular population subsets that are more likely to experience negative health outcomes when exposed to extreme temperatures (Harlan et al. 2013; O'Neill et al. 2005; Reid et al. 2009; Weisskopf et al. 2002). The strategic placement of these facilities should consider underlying characteristics (age, ethnicity, economic status, etc.) of nearby communities that contribute to higher heat-health risk. A recent study by Bradford et al. (2015) used heat vulnerability indices to strategically site new cooling centers in Pittsburgh, PA but there are additional factors that authors could have also considered.

Public cooling centers are meant to serve as the alternative for those who may not have access to or are unable to use in-home air-conditioning. However, there are other types of facilities that could serve, and may currently be serving, as de facto cooling centers. These facilities include public libraries, indoor shopping malls, museums and commercial establishments that, because they are air-conditioned, could also provide heat relief. In addition to population vulnerabilities, the strategic placement of these cooling center facilities ought to consider other resources that are already available to the public.

1.10.1 Case Study – Maricopa County

Since the summer of 2006 the Maricopa County Department of Public Health (MCDPH) has promoted a network of cooling centers to the community. Maricopa County, whose seat is Phoenix, Arizona, is a region of 4 million people as of 2015 forecasted to grow to 6.9 million people by 2050 (ADOA-EPS 2015). The county is located in the Sonoran Desert and experiences daily summer highs in excess of 40˚ C (National Climate Data Center 2015). The county's cooling center network is largely comprised of volunteer locations. Additionally, the locations of these centers tend to change annually with facilities opting in and out of the program (MCDPH 2015). Due to the ad-hoc nature of the network, the facilities are scattered across the county (Figure 6) and it is unclear if the current sites are capable of serving the most vulnerable peoples. While the Phoenix-Mesa and Avondale-Goodyear urban areas (the two urban areas in Maricopa County) cover more than 1,200 mi^2 more than half (24 of 46) of the 2015 cooling center locations are located within 5 miles of downtown Phoenix (MAG 2012).

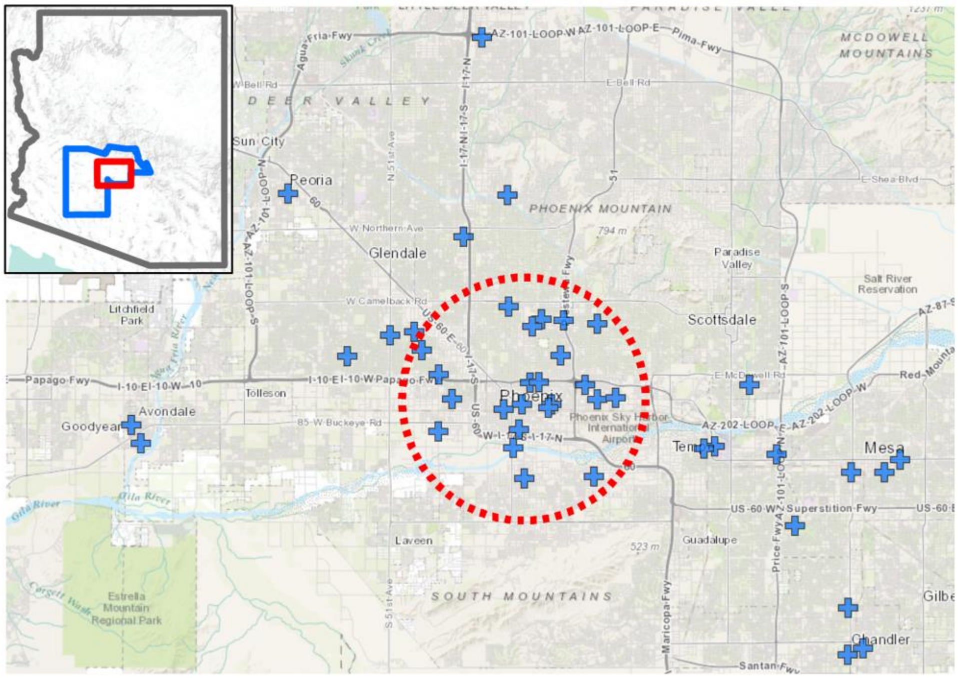

Figure 6: Maricopa Department of Public Health 2015 Cooling Centers. The map shows the cooling centers found in the urbanized areas (red) of Maricopa County (blue). The doted red line is a 5 mile buffer around downtown Phoenix, AZ.

Due to high summer temperatures, Maricopa County has been a focus of a significant amount of research related to public health, extreme heat, and social heat vulnerability (Golden et al. 2008; Harlan et al. 2006; Harlan et al. 2013; Kalkstein and Sheridan 2007; Petitti et al. 2013; Reid et al. 2009; Ruddell et al. 2009; Yip et al. 2008). These and other studies note that specific population and community characteristics are known to increase the risks of negative heat health outcomes and find that vulnerability to heat varies from neighborhood to neighborhood. It has been recommended that public health interventions to mitigate the risks associated with heat exposure, including the provision of cooling centers, target areas where the underlying characteristics make the population particularly vulnerable to extreme heat. Extreme heat is defined as "periods of summertime weather that are substantially hotter and/or more humid than average for a given location at that time of year" (U.S. EPA 2006).

Using location analysis, this paper identifies a method to improve the siting of cooling center facilities in order to provide a life-saving resource to those who need it the most, and identify new facilities that should be targeted for the expansion of Maricopa's cooling center network. Specifically, the paper addresses the following: i) how is the existing network positioned relative to vulnerable populations and existing cooling resources, ii) to what degree would location analysis improve the ability of these facilities to reach those who might need their services, iii) what areas, and more specifically which facilities, should MCDPH target to expand their network of cooling centers?

1.11 Location Analysis

Location Analysis refers to a class of problems that locate facilities to optimize some objective. Various models have been utilized to strategically locate both private and public facilities including warehouses, airline hubs, restaurants, schools, fire stations and emergency medical services(Current et al. 2001). In the private sector the location of a facility influences a firm's ability to compete in the marketplace and in the public sector, facility location influences the efficiency with which public services are provided (Current et al. 2001). Humans have been making location decisions since before the first cities were built but the location analysis field formally began in 1909 with the Weber problem, which sought to locate a single facility (a warehouse) in order to minimize the total transportation cost between the warehouse and demands. There were a number of early studies that were inspired by the Weber problem but the field really began to develop following a 1964 Hakimi publication, *Optimum locations of switching centers and the absolute centers and medians of a graph* (Owen and Daskin 1998). Since Hakimi's seminal work there have been a large number of models developed (see: (Owen and Daskin (1998), ReVelle and Eiselt (2005) & Revelle et al. (2008) for detailed overviews of various location model formulations and previous studies). The selection of a particular model for application depends on the models parameters (objectives, constraints, and variables) and the specific location problem being analyzed.

Broadly, static and deterministic location analysis problems can be classified in three groups based on their objectives: Median Problems, Covering Problems, and Center Problems (Owen and Daskin 1998). Median models seek to locate facilities to minimize the demand weighted average distance between demand nodes and facilities. Covering models locate facilities in order to cover all or as much weighted demand as possible within a specified service distance. A service distance threshold or maximum service distance implies that the proximity of a demand to a facility is critically important. Center problems are another class where the objective is based on the relationship between positioning of facilities and the most remote demand. The most common center problem seeks to minimize the distance between the most remote demand node and its nearest facility. These classifications reflect three of the most common structural forms and there are countless variants which have been developed to address specific location problems.

The selection of a particular model depends on the model's functional form and the location problem being addressed. In order to select an appropriate model for locating cooling centers the context of their use needs to be considered. Cooling centers are meant to be utilized during periods of extreme heat because exposure to extreme heat is a known health hazard. There are a number of exposure pathways, but one that is critical to understand when siting cooling centers is mobility-based exposure. For those who utilize active modes of transportation, walking or cycling, accessing a cooling center requires exposure to a hazard that cooling centers are trying to protect them from. If mobility-based exposure is ignored, it would be reasonable to select a median or center based model for siting cooling center facilities. However, because cooling centers are a public service designed to protect people from heat their placement needs to consider exposure thresholds for those who may be limited to active transportation modes. It is well documented in the literature that the elderly and those living in poverty are among the most vulnerable populations to heat and are among the groups that are more reliant upon non-automobile transportation modes (U.S. DOT FHWA 2011). The Occupational Safety and Health Administration recommends limiting work to 15 minutes during periods of extreme temperatures to avoid negative health outcomes (USDOL 2014). For the same reasons walking or cycling trips longer than 15 minutes should also be avoided during heatwaves. Because of this threshold, a covering model should be utilized for siting cooling centers. Covering models have also been used to site other time-dependent public services such as fire stations and emergency medicals services (Eaton et al. 1985; Schilling et al. 1980).

There are two distinct subclasses of the covering problem: location set covering problem (LSCP) and maximal covering location problem (MCLP). LSCP, first developed by Toregas et al. (1971), requires that every demand be covered by at least one facility and minimizes the total number of facilities selected. A demand node is considered covered if the distance between it and the nearest facility is less than the maximum service distance. The complete coverage requirement is restrictive and can produce a number of facilities that is unrealistic given budget constraints. Additionally, depending on the spatial relationship between facility locations and demand nodes a feasible solution may not exist. Recognizing these shortcomings Church and ReVelle (1974) developed MCLP. The problem relaxes the complete coverage constraint and seeks to site a set number of facilities such that the weighted sum of demand nodes that are covered is maximized. MCLP is particularly suited for siting cooling centers for two reasons: i) due to resource constraints it would not be feasible to offer a set of cooling centers which would result in complete coverage of Maricopa County, ii) MCLP specifies a maximum service distance to define coverage.

1.11.1 Geographic Information Systems and Location Analysis

The combination of geographic information systems (GIS) and traditional location analysis has been at the forefront of advances in spatial analysis capabilities in recent years (Murray 2010). GIS is a collection of hardware, software and procedures that support decision-making using spatially referenced information. While the two fields developed independently, location analysis problems have become increasingly complex and the need for better and more accurate spatial data has been supported by GIS (Chruch and Murray 2009). One of the initial challenges of integrating these two fields was the incompatibility of their applications and data having to be frequently transferred between the two. However, recent GIS software has developed location analysis tools and integrated them into the GIS platform. ArcGIS's *Network Analyst* extension and the *Location-allocation* toolset provide users with the functionality to solve location analysis problems with spatially referenced data. For large-scale applications, the toolset expedites the location analysis process by automatically generating much of data that would be needed to solve the problems using optimization software including a shortest-path cost matrix between all candidate sites and demand nodes. ArcGIS's location analysis solver relies on Hillsman editing (Hillsman 1984) and a vertex substitution heuristic (Teitz and Bart 1968), and metaheuristic to return near-optimal results (ESRI 2016). Because of its functionality and ease of use ArcGIS has been used to solve a number of location analysis problems (Bradford et al. 2015; Escavy and Herrero 2013; García-Palomares et al. 2012; Haines et al. 2006; Ripley et al. 2014; Vijay et al. 2008).

1.12 Methods

The 2015 cooling center network in Maricopa County featured 46 facilities. The analysis identifies a set of candidate facilities and proceeds to selects locations to improve the coverage provided by these and future facilities. A new method is developed in order to develop a solution that is both robust and computationally feasible. The analysis is completed exclusively with ArcGIS 10.3 using general GIS functions and those included in the *Network Analyst* extension.

1.12.1 Data

A critical issue for using any location analysis model is obtaining and deriving the data needed in order to use the framework. Model and components and their sources are identified below:

Demand Locations – Demand locations are considered to be all residential parcels in Maricopa County (1.1 million). These data were developed from the Maricopa County Assessor database (MCAO 2010). The database details the location of each parcel, type of residential building, and total number of dwelling units. Additionally, an index describing parcel access to nearby public cooling resources is included as an additional demand node attribute (Fraser et al. 2016).

Candidate Sites – Official cooling centers in Maricopa County have previously been sited at a number of different types of facilities including libraries, senior centers, community centers, and humanitarian and religious organizations (MAG 2014). All existing libraries, senior centers, community centers, and humanitarian and religious organizations within the county were considered candidate facilities (≈ 2,300 locations, Figure 6). The addresses of these facilities, with the exception of religious facilities, were geocoded from directory searches and the assessor database. Religious facilities were identified with the county assessor database using property use codes. Some have suggested that public schools could serve as cooling centers (Bradford et al. 2015) but schools have increasingly moved toward closed campus policies for student safety and have been excluded as candidates in this analysis (Perumean-Chaney and Sutton 2013).

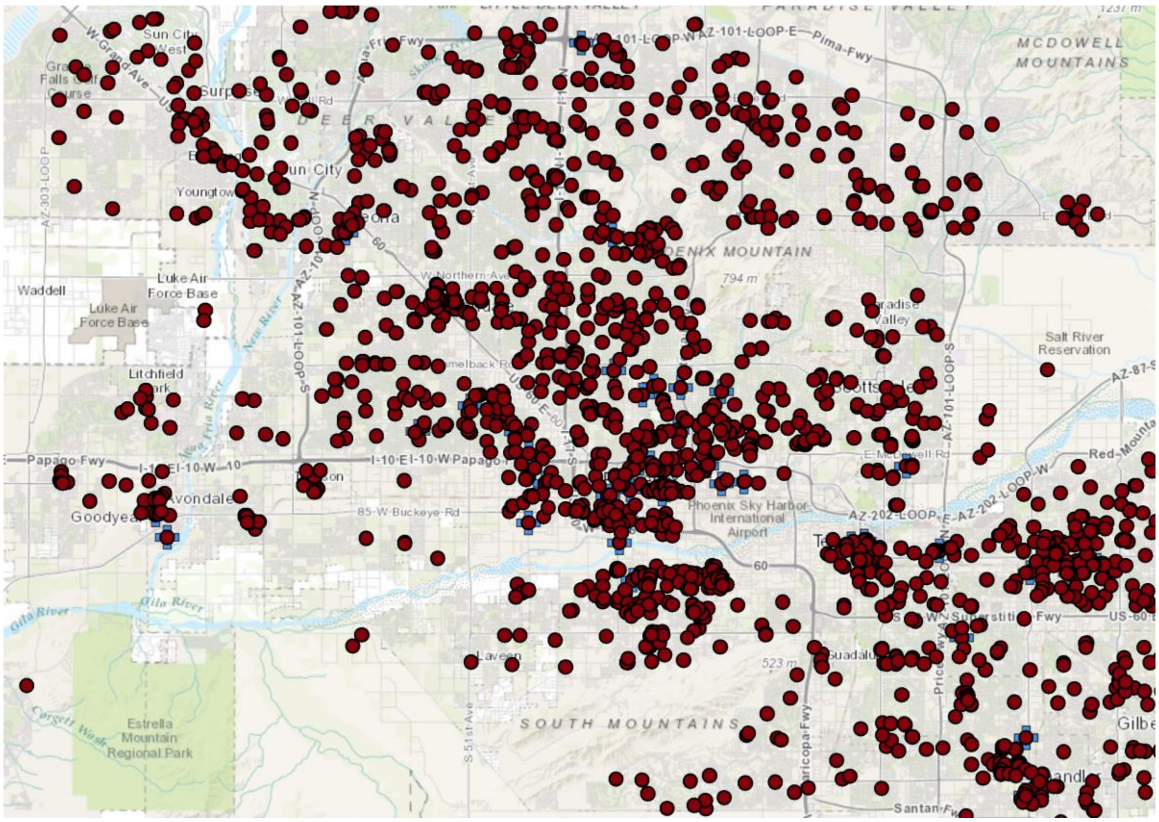

Figure 7: Cooling Center Candidate Sites

Network Dataset – In order to utilize ArcMaps's location-allocation models a network dataset is needed. A line shapefile for the Maricopa County Street network was used to generate the network data set (ESRI 2007). The assessment assumes pedestrian paths would follow the existing street network and all existing roadways, with the exception of freeways and highways, are considered to be pedestrian accessible.

Heat Vulnerability Estimates – In order to identify areas of Maricopa County where residents may be particularly vulnerable to heat, morbidity and mortality data were used to identify social and economic characteristics associated with negative health outcomes. Following the work of Eisenman et al. (IN REVIEW) vulnerability scores are developed for each census tract based on the principal component which was found to be the overall best predictor of both all-internal causes and heat-related deaths during periods of extreme heat. The variables used to estimate the relative heat-health risk for census tracts include percent Hispanic/Latino, percent foreign born, percent uninsured, percent income below the poverty level, percent construction works, and percent female householder (no husband present) (Figure 8).

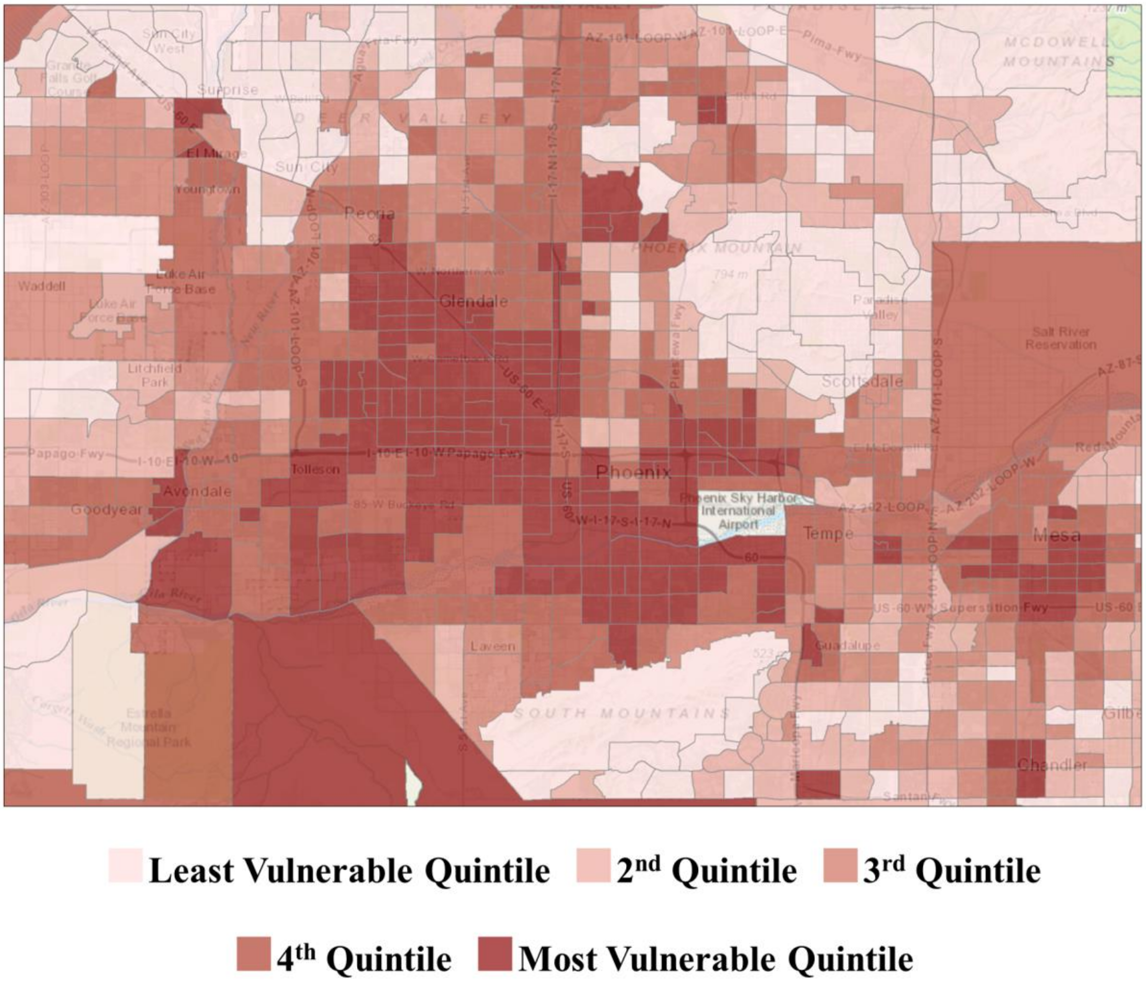

Figure 8 - Socio-economic Heat Vulnerability

1.12.2 Random Thiessen Aggregation

Location models are difficult to solve and their computational complexity is a key reason why widespread interest in the field did not begin until after the development of computers. Realistically scaled problems can have hundreds of thousands of constraints and variables and standard optimization methods can consume an unreasonable amount of computer resources and time (Current et al. 2001). Due to computational constraints, heuristics are often used to identify a near-optimal solution. However, even with heuristics, realistically scaled problems can be intractable using average computer hardware. In this case study, computer resources were insufficient to generate an origin-destination matrix between the specified demand nodes and candidate sites largely due to the total number of demand nodes. In order to eliminate demand points but still establish a solution at a residential parcel resolution a new method developed using GIS tools. The stepwise procedure is described below and partially illustrated in Figure 9.

Step 1: Population information from the U.S. Census was used to generate random points within each census tract for every 100 residents (rounded down). This procedure produces approximately 34,000 points throughout the county. This step is identical to the procedure employed by Bradford et al. (2015) in a similar study for siting cooling centers in Pittsburgh, PA.

Step 2: Thiessen polygons are then generated from the set of random points within each census tract. This subdivides the 915 census tracts in Maricopa County into 34,000 irregular polygons.

Step 3: Individual residential parcels are then aggregated to the Thiessen polygons. Each polygon was assigned characteristics of the residential parcels that fall within its boundaries including the total number of households and the mean accessibility index score.

Step 4: Centroids are then generated for each polygon and assigned a weight. These centroids are used as representative demand locations and weighted based on the total number of households within each, the average cooling resource accessibility index, and a measure of social-economic vulnerability based on the following:

$$W_i = HH_i * SV_i * CRA_i^{-1}$$

$Where:$

$HH_i = Total\ number\ of\ households\ in\ i$

$SV_i = The\ social\ vulnerability\ of\ households\ in\ i\ to\ heat$

$CRA_i = Average\ cooling\ resource\ accessibility\ measurement\ for\ households\ in\ i$

Step 5: Remove all new demand locations where the weighted demand is equal to zero to produce the final set of demand nodes. Steps 1-5 reduce the total number of demand nodes from 1.1 million to 27,000 (a 97.5% reduction).

Step 6: The Location Allocation tool in ArcMap's Network Analyst package is used to determine a maximal coverage solution. The coverage distance was defined by a 15 minute exposure time limit and average walking speed for adults at 0.75 miles (Bohannon and Andrews 2011).

Step 7: Iterate. Steps 1-4 can contribute to solution uncertainty for several reasons. First, there are known issues with aggregating data to larger geographic scales and the procedures artificially groups households together (Dark and Bram 2007). The demand weights are directly related to how the parcel level data was randomly aggregated in steps 1-3. Secondly, centroid locations may not be a good representation of an average demand position. Lastly, because ArcMap's *location-allocation* tool relies on a heuristic we can only say that any solution derived from it is simply a good solution rather than one that is optimal. Due to these three issues, it is unlikely that any two iterations would identify the same set of facilities. By comparing the solutions of repeated iterations, it is possible to identify candidate site sets that were chosen in most iterations, sometimes, rarely, or not at all. At the scale of this case study, a complete iteration takes 3.5 hours to complete. The generation of the of the Thiessen polygons is the most significant in terms of computational processing at over 2.5 hours.

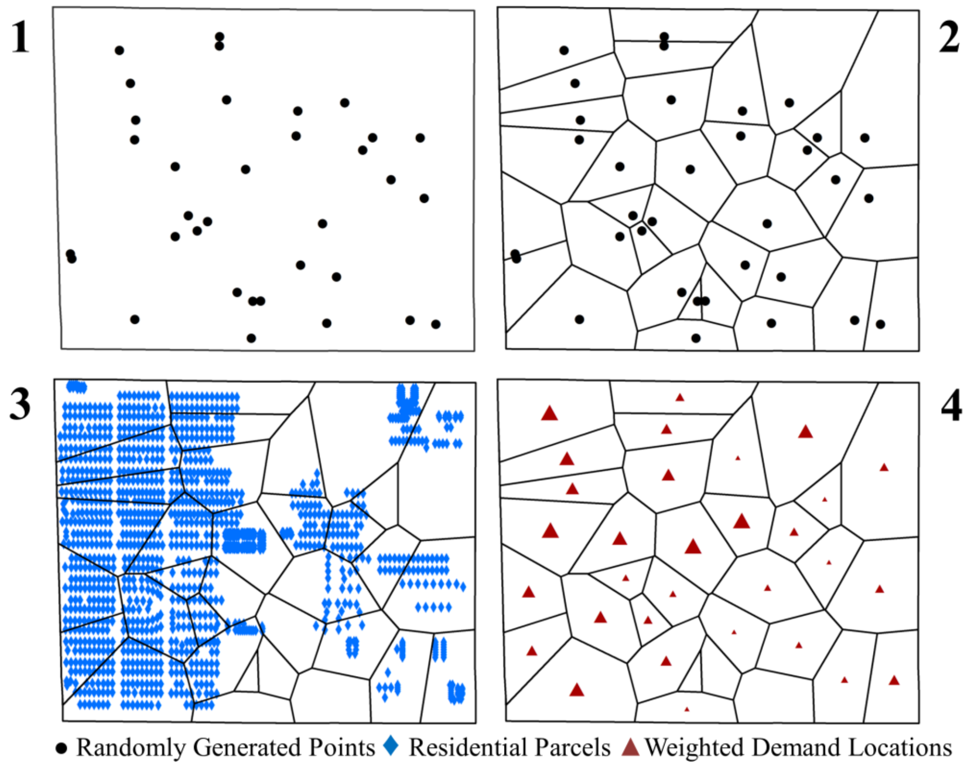

Figure 9: Random Thiessen Method Step 1 – Generate Random Points, Step 2 – Generate Thiessen Polygons, Step 3 – Aggregate Residential Parcels to Thiessen Polygons, Step 4 – Generate Thiessen Centroids and Assign Weights.

1.13 Results

The model was used to evaluate the existing cooling center network by comparing their current locations and those identified using location analysis. The 2015 Cooling Center Network in Maricopa included 46 locations. The model was iterated 50 times to determine which 46 locations would have been better suited to serve as cooling center locations. Across all 50 iterations, 117 of the 2,300 candidates were selected as facility locations at least once. Of these, 48 were selected in fewer than 10% of the iterations and 20 were selected only once. Of the 46 facilities that were selected most often, 26 were selected in 90% of the iterations, 12 facilities were selected every time, and only one is an existing cooling center. Figure 10 illustrates the selection percentage for all 117 facilities and the average demand weight covered. Beyond the top 26, there is a rapid decay in how frequently the facilities are chosen. Despite this decay, each facility among the top 46 was selected in at least 50% of the iterations. While it is not possible to describe these 46 locations as the optimal solution, the selection percentage implies that these facilities are likely positioned to serve vulnerable communities without access to cooling alternatives. There is a weak but positive correlation between the frequency with which facilities are chosen and the average weighted demand they cover meaning that the method generally identifies those that could serve the greatest deamnd. However, additional consideration should be given to those facilities outside the top 46 where the average weighted demand served significantly exceeds those among the top 46.

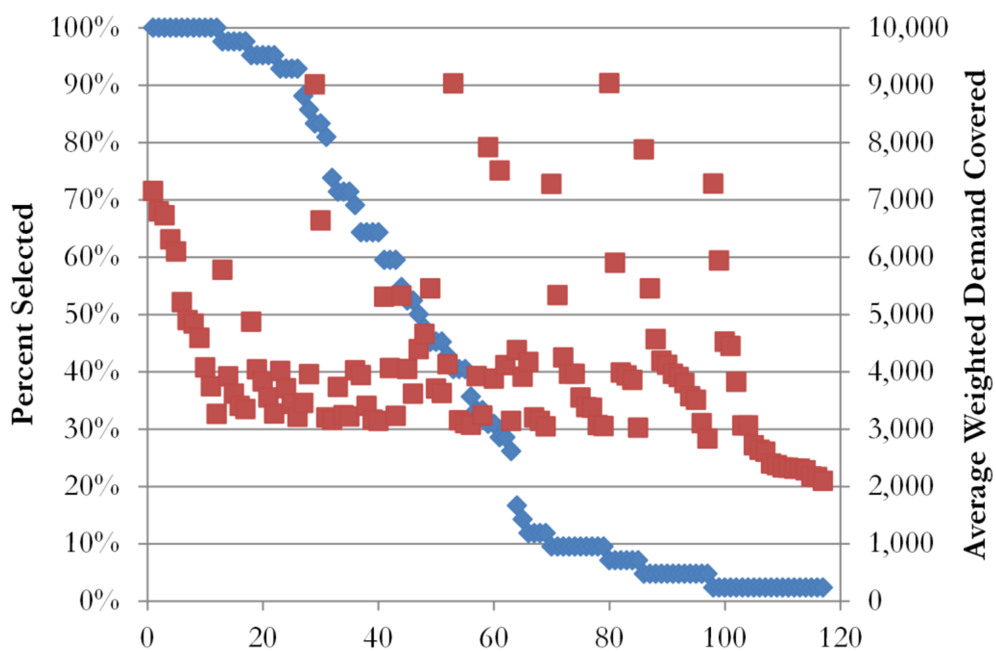

Figure 10 Facility Selection Percentage and Average Weighted Demand Covered

The 2015 Maricopa County cooling centers were well positioned to serve vulnerable people with 25 of the 46 facilities found in census tracts in the upper quintile for heat vulnerability. However, many of these facilities were also located in areas where residents would have significant access to cooled space alternatives. More than 75% of the 2015 facilities were located in tracts with the highest access to public cooling resources. The network was largely concentrated in the urban core with limited facilities serving the urban fringe where residents have no or little access to publically available cooled space. Figure 11 shows the 2015 centers and the top 46 facilities identified using location analysis. In contrast, none of the identified locations are found in tracts in the highest quintile for cooled space access and 17 are located in highly vulnerable areas. The greatest density of selected facilities occurs in an area bounded by the I-10 Interstate, Arizona State Route 101, and US 60. The Maryvale community is predominantly Hispanic and has a poverty rate of 36%; two characteristics associated with heat vulnerability (Eisenman et al. IN REVIEW). Additionally, this is primarily a residential area with very few public cooling alternatives. The model also identifies a number of locations in North and South Phoenix in areas that were not served by the 2015 network. In total, the identified facilities cover nearly 2.5 times as many residential parcels as the 2015 cooling center network (89,000 compared to 35,000). Although it has more to do with social and infrastructure characteristics than the covering model framework used, the identified set of facilities is more dispersed than the 2015 network. While the focus of this analysis was to provide coverage to those who may access cooling centers via walking, the increased dispersion likely reduces the average distance for those who would drive to these facilities making this set of facilities more accessible to the general population in Maricopa County than those in the 2015 network.

While these 46 identified facilities would provide better coverage than those in the 2015 network, closing the existing facilities, or removing them from the list of designated cooling centers, is not be recommended. These facilities are likely familiar to existing users and closing them would remove a resource they now rely on. Alternatively, the methods can be used to identify a set of facilities to target for network expansion that complement existing facilities. Using the same procedure but fixing the existing cooling center locations an additional 50 iterations were performed to identify 10 facilities to target to expand the network. In all 50 iterations, the same 10 facilities were selected (Figure 12). Although there are a number of cooling centers already in the Maryvale Community, 4 of the 10 sites to target for network expansion are found in an unserved portion on the west side of the community. All 10 of the identified facilities are found in areas with high population density, high socio-economic heat vulnerability, and limited access to alternative cooling resources.

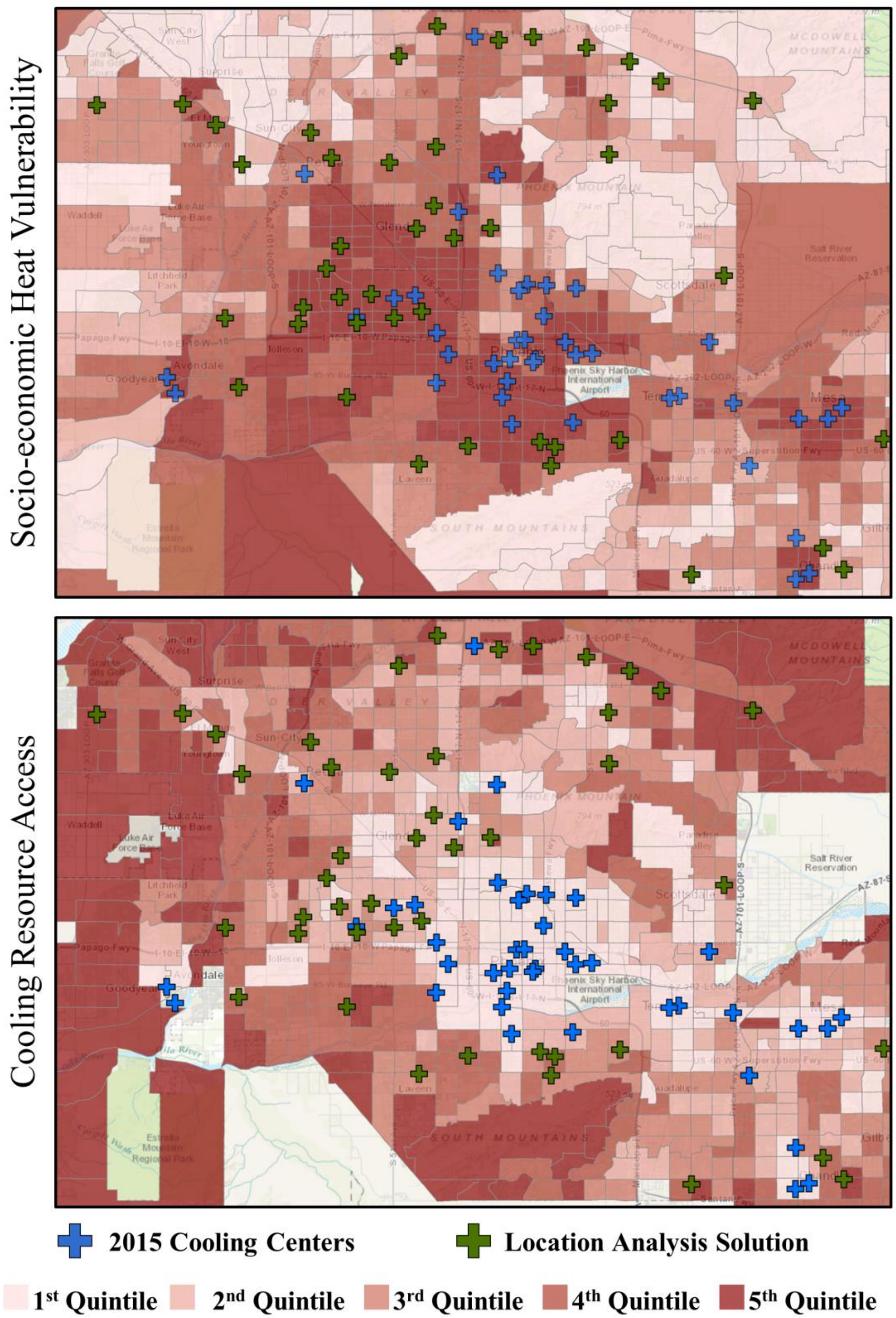

Figure 11: Improved Location of Cooling Center Facilities

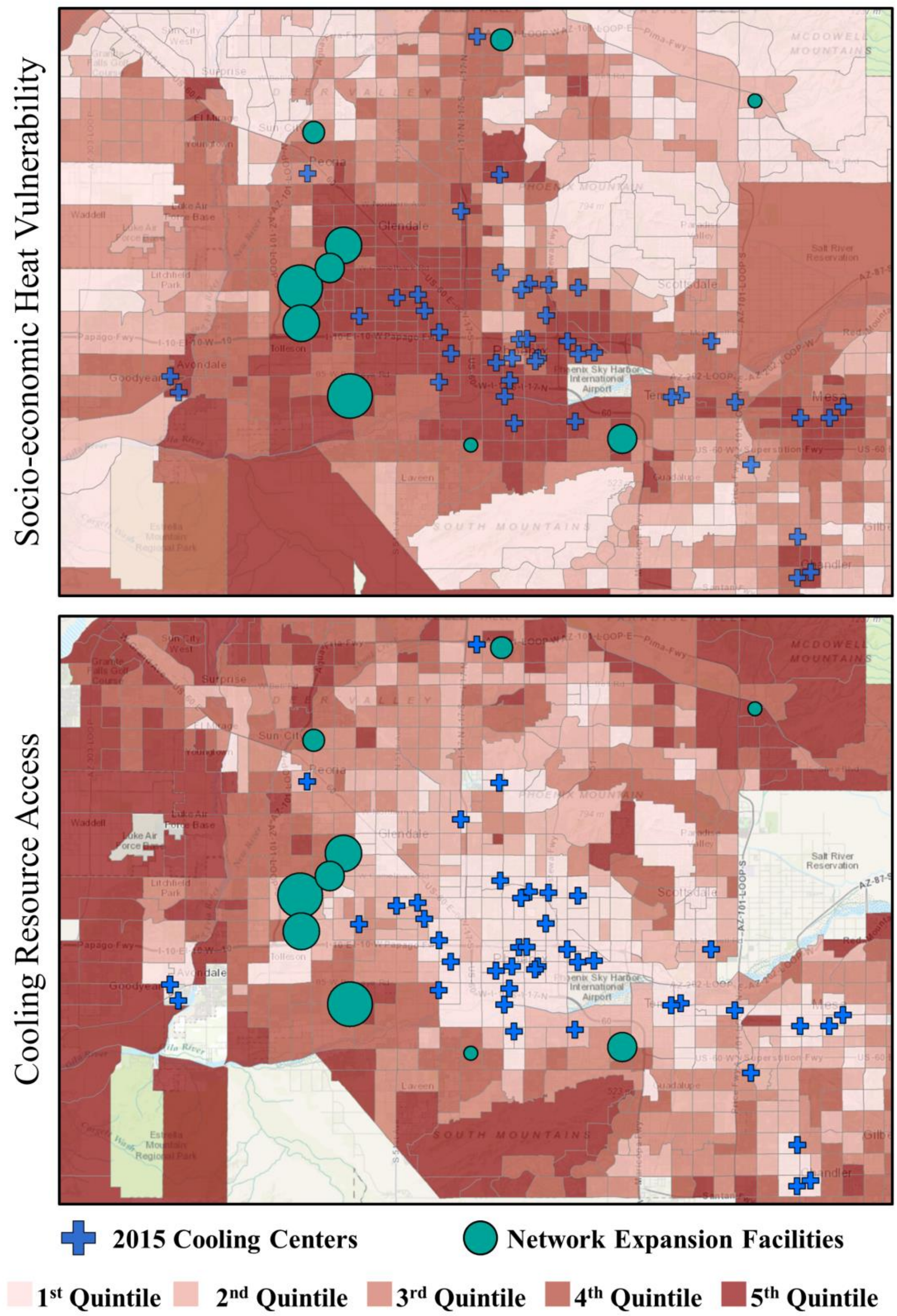

Figure 12: Target Facilities for Network Expansion The size of the green dots are relative to the weighted demand covered by each facility. Network expansion should target the largest circles first.

1.14 Discussion

Location analysis has been used to site many different types of public facilities and the results suggest that these methods should also be employed for developing networks of cooling center facilities. This type of analysis has been made easier with the advent of GIS, MCDPH and any other region looking to establish or expand cooling center networks should make use of these tools. However, the solutions we derive from these methods are dependent on the quality of the input data. GIS makes it possible to make decisions using extremely precise spatial data but the attributes and weights ascribed to the spatial data are what drive the selection of specific facilities. In this case study, weights were derived from census data, relative heat-health risk estimates, and measurements of access to cooling resource alternatives and each is associated with its own uncertainty. While the census data may suggest a highly vulnerable population inhabits particular neighborhood, immigration and emigration can change the demographics of a neighborhood quickly. This may be especially true in urban core neighborhoods in Phoenix and many other U.S. cities that have attracted young and relatively affluent millennials who are less vulnerable to heat while displacing lower income minorities who are more vulnerable to heat. (Walker 2016). Similarly, our understanding of the social, economic, and infrastructure factors that contribute to individual heat vulnerability continue to improve. While existing heat vulnerability assessments have been shown to perform well in predicting negative health outcomes(Reid et al. 2012), determining cooling center locations should use the most up-to-date and state-of-the-art heat vulnerability metrics. Lastly, our understanding of individual behavior during heat waves and the manner in which people engage public cooling resources is limited. The results are based on the assumption that people will seek out and use these spaces but Sampson et al. (2013) found that the tendency to engage in cooling behaviors can vary across populations. Additional research is needed to understand adaptive cooling behaviors. Despite this uncertainty, the principles of location analysis, would help public health agencies determine facilities that would be better positioned to serve vulnerable populations and those with limited access to cooling alternatives. As new and improved spatial attribute data become available, cooling center networks should be revaluated to insure that they are positioned to serve those who need the services the most.

A large fraction of the facilities identified in this analysis as ideal for sites for cooling centers are associated with religious institutions. Religious facilities are good candidates for cooling center locations because they are ubiquitous in most U.S. cities and many of them are located in close proximity to or in residential neighborhoods. Additionally, many of these facilities would be available for use on most days aside from periods of worship. While many religions are compelled to engage in community service, not all may be willing to participate as a public cooling center. Specifically, certain religious facilities may be wary to open their doors to the public. If any of the facilities identified in the analysis are found to be unwilling to participate, the analysis should be repeated excluding their location as a candidate site. While cooling centers have previously been sited at religious facilities, there may be individual reluctance to utilize these facilities. Non-believers and those belonging to other faiths may feel uncomfortable going to certain facilities. If religious facilities are used as cooling centers, it is important to make sure their services are marketed as inclusionary of all individuals regardless of faith.

There are several other issues that public health officials should consider in the siting of cooling center facilities. Despite the large number of candidate sites, there are still areas of Maricopa County that could not be covered by any facility (Figure 7). Alternative interventions may need to be considered for neighborhoods without candidate sites where residents are particularly vulnerable to heat and have limited access to other cooling resources. These alternatives could include the construction of new facilities, mobile cooling centers, or providing transportation to existing facilities. This analysis uses residential parcels to describe the location of demand for cooling centers. Homeless and transient individuals have been identified as highly vulnerable subgroups (Ramin and Svoboda 2009; Uejio et al. 2011)and their demand and need for cooling centers would not be captured using residential parcels or census data. Their whereabouts and movements should also be considered when siting facilities. Additionally, location analysis methods could also consider the daily movements of a population to site cooling center facilities. However, without a fully developed travel demand model detailing the characteristics of the population it would be difficult to define a time-of-day dependent vulnerability measure. Finally, this analysis assumes that vulnerable populations are particularly reliant upon walking. Research into how cooling centers are accessed could provide additional insight for siting these facilities. It is also possible to use location analysis principles to site facilities based on alternative transportation modes.

Computer power is increasing and location analysis problems of this scale and resolution may be within reach in the future. In the short-term, however, the methods described in this analysis can assist policy and decision makers in identifying better solutions for siting facilities by simplifying the location decisions. For location analysis problems siting a relatively small number of facilities these methods can produce robust results. In this case study, the methods produced the same set of facilities across all iterations when the total number of facilities to site was equal to ten. However, this type of result is also dependent upon the study area. In particular, these methods may not be applicable in rural areas where limited density may lead to significant aggregation errors and centroid positions that are not representative of actual demand locations. For larger problems, these methods are capable of identifying critical facilities (those selected in every or almost every iteration) and eliminating large quantities of facilities for consideration (those that are never selected). Decision makers can then focus their attention on facilities that are chosen in some but not all iterations. While siting facilities based on the number of times they are selected will lead to a good solution it is possible that a better solution exists if coverage areas of any of the selected facilities overlap. In this instance, the modeler could select the top facilities as fixed facilities and repeat the process until a set of non-overlapping facilities is identified.

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CHAPTER 4

TRANSIT SYSTEM DESIGN AND VULNERABILITY OF RIDERS TO HEAT

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1.16 Introduction

In response to climate change concerns, the Federal Transit Administration (FTA) has identified public transit systems, and their increased utilization, as a critical component in reducing energy use and greenhouse gas emissions associated with the transportation sector (Hodges 2010). Additionally, public transportation offers ancillary benefits including congestion reduction, reduced mobility costs, improved public health (by stimulating additional walking/cycling trips), and increased mobility equity (Litman 2011). As a result, policies and programs, such as the *Safe, Accountable, Flexible, Efficient Transportation Equity Act* and *Moving Ahead for Progress in the 21st Century Act*, have encouraged the growth of public transportation infrastructure and transit ridership. In the United States between 2000 and 2012 public transit services (operated vehicle kilometers) increased by 32%, ridership (unlinked passenger trips) increased by 13%, and funding allocated to public transportation increased by 81% (APTA 2014). While these metrics indicate that policies and programs designed to promote and improve public transit in the U.S. have had some measure of success, there is a tension between policies and programs which promote transit use as a climate change mitigation strategy and the potential impact of an uncertain climate future on transit infrastructure and its riders. Recent research has begun to study the potential impacts associated with climate change on transit infrastructure but there is still very little known regarding how climate change may impact transit riders or how transit operators should respond to reduce environmental risks to their riders (Coumou and Rahmstorf 2012; Ma et al. 2013; Meyer 2008; Molarius et al. 2014; Rosenzweig et al. 2011).

Temperature, precipitation and wind have been shown to affect transit ridership (Arana et al. 2014; Guo et al. 2007; Kalkstein et al. 2009; Kuby et al. 2004; Singhal et al. 2014; Tao et al. 2016). These studies are largely concerned with predicting and understanding the loss of transit riders due to adverse weather and developing strategies to mitigate these losses. These studies do not, however, consider the impact adverse weather may have on the remaining transit users who may not have modal alternatives for necessary trips. Specifically, exposure during to weather extremes may increase certain health risks for transit riders. General circulation models predict the increasing duration, severity, and frequency of extreme weather events potentially compounding existing health risks. While the risks associated with some extreme weather events, such as hurricanes, may be obvious to riders and operators alike, previous research has found that individuals are generally less aware of the dangers of extreme heat exposure and even among those who acknowledge that heat exposure is a potential health threat, the level of perceived risk is often low (Abrahamson et al. 2009; Bittner and Stößel 2012; Kalkstein and Sheridan 2007). Despite individual perceptions, extreme heat is known to be a serious threat to public health and exposure to extreme heat, while often preventable, is a leading cause of weather-related mortality worldwide (Berko et al. 2014; Robine et al. 2008; USEPA 2006). Moreover, exposure to extreme heat can result in heat-related illnesses such as heat cramps, heat stroke and heat exhaustion and exacerbate preexisting chronic conditions such as respiratory and cardiovascular diseases contributing to emergency room visits, hospitalizations, and premature death (Berko et al. 2014; Luber and McGeehin 2008). Transit agencies and future transit policies should consider the potential risks of negative health-related outcomes due to extreme temperature exposure when designing and planning transit systems.

The design of a public transportation system contributes to outdoor exposure in two ways. First, transit stop location relative to a rider's origin or destination influences the mode used and time spent to access transit. In the United States, public transit systems are typically designed for pedestrians and as a result the dominant mode used to access transit in urban areas is walking, accounting for 85% of all U.S. transit trips with an average duration of 7.1 minutes (USDOT 2009). Once at the transit stop, any rider would then experience waiting for the next transit vehicle, the duration of which is directly influenced by service frequency and reliability. On average, U.S. transit riders experience a wait time of 9.9 minutes (USDOT 2009). While the average transit rider would experience 17 minutes of outdoor exposure there are likely areas served by a transit system where urban form characteristics and demand-based transit scheduling contribute to extended access and wait times.

To this end, this study develops a methodology to assess how current transit design contributes to environmental exposure for transit riders and where transit design may contribute to prolonged periods of outdoor exposure. Using Los Angeles Metro (Los Angeles, California) and Valley Metro (Phoenix, AZ) as case studies, we estimate environmental exposure resulting from transit use by examining transit ingress/egress walking times and waiting times. The method spatially identifies areas of the transit systems where current design may result in prolonged heat exposure. Though this research focuses on extreme heat exposure for pedestrian-transit users, the methods could also be utilized to assess exposure to extreme cold and exposure from alternative access modes including cycling.

The Los Angeles Metro and Valley Metro systems serve two of the largest metropolitan areas in the American Southwest and rank as the 3rd and 37th largest transit agencies in the country respectively based on total unlinked passenger trips (APTA 2014). Each agency is the largest transit provider in their respective region and the transit service areas for each agency, depicted in Figure 13, extend across numerous municipalities with services that include local, commuter, and rapid bus service as well as rail options. These services are almost exclusively surface level (the exception being two subway lines operating in Los Angeles) and a majority of the stops (>99%) are exposed to the environment. While Valley Metro operates as the primary provider of public transit in the Phoenix Metropolitan Area, Los Angeles Metro's service area includes regions where there are also additional local transit services (e.g. Santa Monica's Big Blue Bus). Though these other transit agencies may offer complimentary service, and sometimes redundant mobility options, the case study focuses specifically on transit users of these transit agencies.

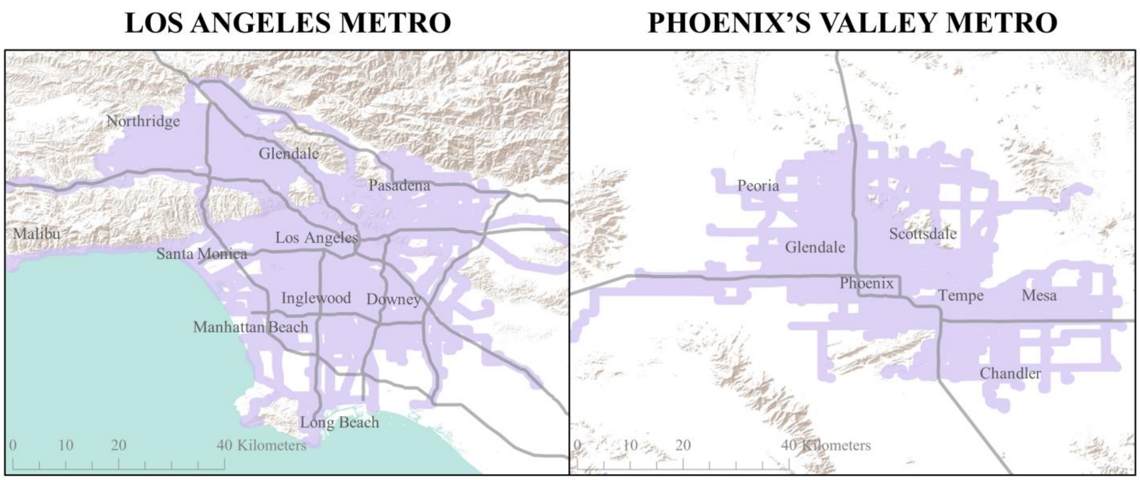

Figure 13: Los Angeles and Valley Metro Service Areas. The colored portion of the map shows the areas of the Los Angeles and Phoenix Metropolitan regions within 800m of a transit stop which are served by Los Angeles Metro and Valley Metro respectively.

These two agencies and regions are particularly suited for this case study as both are actively expanding service, have experienced significant ridership increases over the last decade, and found in areas where climate models predict increasing average summer temperatures as well as the increasing frequency, severity, and duration of extreme heat events (APTA 2014; Bartos and Chester 2014; Bartos and Chester 2015). The results provide a perspective on how transit system design within urban environments contributes to environmental exposure and can be used to develop transit strategies to respond to aspects of climate change which may impact transit riders.

1.17 Methods

The potential for transit rider heat exposure resulting from transit stop positioning and vehicle scheduling for the Los Angeles Metro and Valley Metro Systems is analyzed. Exposure to extreme heat and its potential to increase health risks is evaluated in three steps. First, access exposure is estimated for each residential location within the service areas by estimating walking times to/from the nearest transit stops. Second, exposure resulting from waiting at individual transit stops is established from published transit schedules. Lastly, access and waiting exposure estimates are aggregated at a neighborhood scale to identify areas where current transit system designs contribute to longer than average exposure. The service areas for both transit agencies are defined as the areas within a reasonable walking distance of any transit stop.

1.17.1 Estimating Access Exposure

Walking times are estimated using geospatially explicit data for household locations and individual transit stop locations. The locations of residential parcels were determined from county property assessment rolls, which includes property use and building type information (including total dwelling units), for all taxable land parcels, and the accompanying GIS shape files (Los Angeles County Assessor Office 2009; Maricopa County Assessor Office 2010). While Los Angeles Metro's service extends slightly into other counties, the case study is limited to areas that lie within Los Angeles County. To develop household level estimates, each residential parcel – which range from single family homes to multi-story sprawling apartment complexes – was weighted by the total dwelling units associated with the property. Transit stop locations were determined from publically available general transit feed specification data (GTFS) for Los Angeles Metro and Valley Metro (Los Angeles Metro 2015; Valley Metro 2015). While reasonable walking distances are likely to differ among transit riders we assume a maximum of 800 meters which is consistent with the *Transit Capacity and Quality of Service Manual* standard and existing research (Arrington and Cervero 2008; Cervero et al. 2002; TCRP 2013). Approximately 60% of residential parcels in both Los Angeles and Maricopa Counties are found to be within a reasonable walking distance of transit stops.

Walking times to transit for individual households are based on two parameters: the distance, which is based on the relative positions of residential parcels and transit stops, and walking speed. A walking speed of 4.7 km/hour was chosen as the average walking speed for a transit rider and is consistent with speeds for average adults established by gait studies (Bohannon and Andrews 2011). Walking distances for each residential parcel to the nearest three transit stops are determined using a shortest path algorithm based on linear distance. It is assumed that pedestrians who access transit do so using available sidewalks and so potential pathways are defined by the roadway networks in Los Angeles and Phoenix and include all roadway types except freeways and highways (ESRI 2015). Associated walking times to the three nearest transit stops are then averaged and assigned to each household. The underlying assumptions are that an individual's mobility needs would be met by lines closest to their household and that the closest stop may not meet all of their mobility needs.

1.17.2 Estimating Waiting Times

Passenger waiting time is affected by service frequency and reliability as well as knowledge of transit schedules by transit riders. For urban transportation systems, it is common to assume an average passenger wait time equivalent to half the headway between subsequent arrivals. However, as Larsen and Sunde (2008) note, this approach, which assumes a random normal distribution of passenger arrivals, may not be applicable for areas where transit service is less frequent due to extrinsic knowledge of service schedules. It is suspected that passengers, especially those who frequently use the same transit service, arrive at transit stops based on expected vehicle arrivals. The validity of the "half the headway" approach was assessed by comparing headway based estimates with reported wait times from Los Angeles Metro's on-

on board passenger survey on individual service routes (Los Angeles Metro 2014; Los Angeles Metro 2015).

Comparisons between the half-the-headway estimates and survey response waiting times show that using the half-the-headway approach is likely to underestimate waiting times along high frequency routes and significantly overestimate waiting times along low frequency routes. Figure 14 compares half-the-headway estimates with average passenger response waiting times for individual routes, rank ordered from shortest to longest based on half-the-headway approach. Along high frequency routes, the discrepancy between the two may result from the tendency of survey respondents to round time estimates to the nearest five minutes as well as overestimate waiting time. However, for low frequency routes the results suggest that transit passengers are responsive to transit schedules resulting in a skewed distribution of passenger arrivals based on vehicle schedules rather than a normal distribution assumed by the half-the-headway approach. Though there is some variation, average passenger waiting time appears to approach a limit between 10 and 15 minutes. To estimate wait times along all routes a simple model is developed to relate published transit schedules and actual passenger wait times reported in the on-board surveys. Figure 14 shows the linear relationship between half-the-headway estimates for passenger wait times and the difference between half-the-headway estimates and average rider responses for individual transit routes. The following liner model is used to estimate passenger wait time for individual vehicles based on scheduled headways (minutes) (H):

$$Average\ Passenger\ Wait\ Time = 0.10615H + 7.8959$$

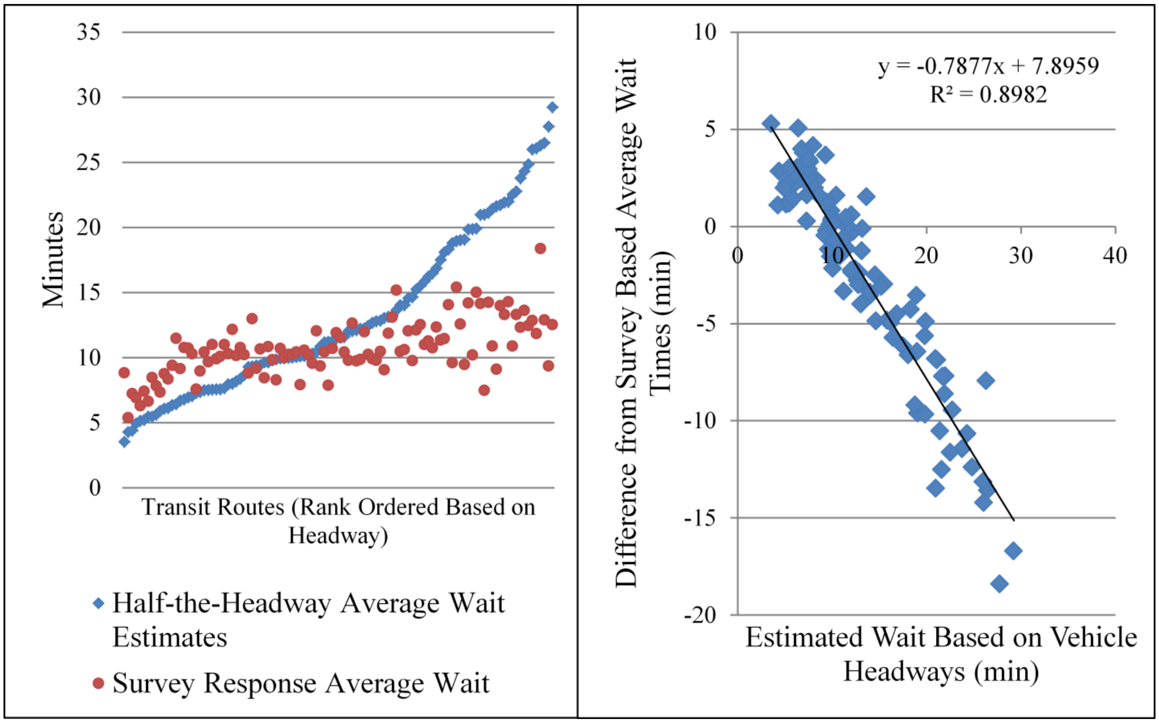

Figure 14: Average Transit Rider Waiting Time – Survey Responses vs. Estimates Based on Headway. The half-the-headway approach for estimate average passenger waiting time tends to underestimate passenger wait times along routes where headways are less than 20 minutes and overestimate wait times along routes with headways greater than 20 minutes (Left Figure). The linear relationship between half-the-headway estimated wait times and ridership survey response wait times are used to estimate waiting times across the Los Angeles and Valley Metro Service Areas (Right Figure).

The relationship between half-the-headway estimates and actual passenger waiting times for Los Angeles Metro transit lines are used to establish waiting time estimates at both Los Angeles Metro and Valley Metro transit stops from published transit schedules(Los Angeles Metro 2014; Watkins et al. 2011). In addition to capturing arrival behavior that is influenced by schedule knowledge, this method may also effectively capture longer waiting periods associated with breakdowns in schedule reliability for Los Angeles Metro. However, the factors that influence transit reliability (e.g. traffic congestion, vehicle breakdowns) may differ between the two agencies leading to some uncertainty associated with Valley Metro waiting time estimates. Another potential shortcoming of this method is its inability to accurately capture waiting time associated with route transfers. To develop waiting time estimates for transit stops that include transfer waiting time, additional information is needed. This includes a travel demand model detailing origin-destination demand of transit passengers and survey questions and responses that specifically address wait time associated with route transfers. This aspect is left for future research. Despite the uncertainty associated with additional transfer waiting time, the methods establish waiting time estimates for single ride transit trips, which make up 60% of all transit trips, and a baseline for transfer trips by capturing waiting associated with the first leg (Iseki et al. 2012).

1.17.3 Neighborhood Scale

To identify areas where extended walk and wait times may increase the risks associated with extreme heat exposure, household estimates for walking and stop waiting times are aggregated at the neighborhood scale as defined by U.S. census tract boundaries (Census 2014).

1.18 Results

The results focus on evaluating environmental exposure heterogeneity in neighborhoods served by the Los Angeles and Valley Metro systems. We explore how several key variables including transit system layout, transit scheduling, and urban form characteristics contribute to longer access and waiting exposures for transit riders.

1.18.1 Access Time

Households within the Los Angeles Metro service area are found to have an average ingress/egress walking time of 4.7 (σ = 1.0) minutes while households in the Valley Metro service area experience an average walk time of 6.2 minutes (σ = 1.5). For individual households, access time is influenced by the existing street network and the relative position of the three nearest transit locations. However, when individual household walk times are aggregated to the neighborhood scale the impact of transportation land-use decisions become more apparent. Figure 15 shows average access walking times for neighborhoods served by Los Angeles Metro and Valley Metro which range from 0.5 to 7.6 minutes and 1.9 to 9.9 respectively. Residential density is often cited as a precondition for transit effectiveness and neighborhoods with lower residential densities are found to have fewer transit stops per square kilometer (Handy 2005). The discrepancy in average walk times between the two regions results largely from differences in residential density. Within the Los Angeles Metro service area, the average population density is 7,200/mi^2 and the average population density in neighborhoods served by Valley Metro is 2,900/mi^2. Decreased residential density coupled with fewer transit stop alternatives results in greater access times for these low density neighborhoods. Conversely, as residential density increases we find that average access times tend to decrease.

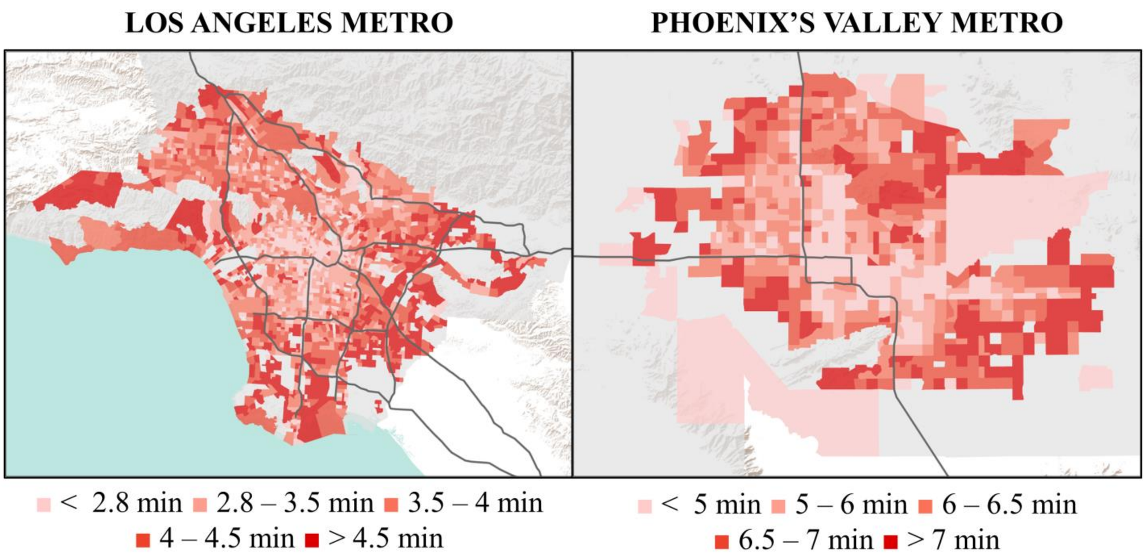

Figure 15: Average Walk Time Quintiles (minutes) to Transit. Neighborhood walk times, which are impacted by residential density, transit stop placement, transit stop density,

and the geometry of the street network, are lowest in the urban core and highest in neighborhoods along the fringe of the service area.

Intra-regional disparities result from the interaction of urban form characteristics and the design of the transit systems. In addition to overall residential density, density around transit stops and routes are found to impact average access times. Within the dense urban core where access times are found to be the lowest, mid to large sized multifamily residential buildings (> 4 dwelling units) tend to be proximate to higher capacity roads featuring transit stops and routes while smaller multifamily buildings and single family home are typically found further from these types of facilities. The relative proximity of large multifamily buildings to transit facilities reduces average access time for urban neighborhoods. In less dense neighborhoods, especially at the suburban fringe, there is often limited residential development and density adjacent to transit stops and routes. Even in less dense neighborhoods bisected by transit routes, residential household density tends to be more homogenous and made up of smaller multifamily units and single family homes. Proportionately there are fewer households adjacent to transit facilities in these areas and the result is longer average access times. Additionally, neighborhoods found in the dense urban core tend to feature highly gridded street networks that improve pedestrian access reducing walking distances to nearby transit facilities. Movement away from the urban core finds gridded street networks that feature longer block lengths as well as irregular branching networks terminating in cul-de-sacs resulting in longer walking distances and times. The density of the built environment and the design of the street network have been cited as a critical determinants of pedestrian mode choice (Cervero and Kockelman 1997; Moudon et al. 2006; Rodríguez and Joo 2004) but for transit users these elements, in conjunction with the placement of transit stops, also impact how long they are exposed to the environment potentially leaving them at risk for negative heat-related health outcomes.

1.18.2 Waiting Time

Applying the linear model to GTFS schedules, average wait times are found to be fairly consistent for both Los Angeles Metro and Valley Metro. Overall, the average wait time at transit stops is found to be 11.2 minutes ($\sigma = 0.59$) for Los Angeles Metro riders and 11.1 minutes ($\sigma = 1.0$) for Valley Metro riders. Neighborhood stop averages range between 8.9 to 14.3 minutes in the Los Angeles Metro service area and 9.0 – 14.1 minutes in the Valley Metro service area (Figure 16) which are consistent with waiting times reported by 2009 NHTS respondents (USDOT 2009).

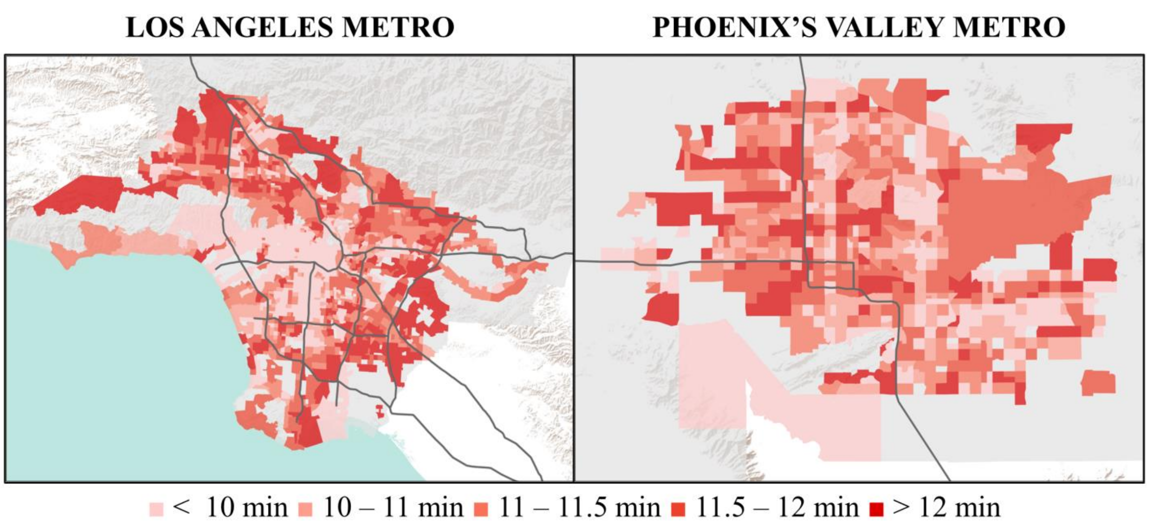

Figure 16: Average Waiting Time Quintiles (minutes) for Transit. Transit riders in neighborhoods adjacent to high capacity roadways and along direct paths connecting major activity centers experience the most frequent transit service and lowest average waiting times across the service areas. Lower frequency service and longer average waiting times occur in neighborhoods with lower capacity roadways and those which are not along direct routes connecting activity centers.

Transit route design and scheduling is a complex task that ultimately contributes passenger waiting times that are uneven across the transit system. The process usually includes accounting for mobility demand, road network geography, in-route travel times, expected delays, fiscal and resource constraints. Because a single route can cover large portions of the transit service area, waiting times are less dependent on density characteristics than access times are. Within the service areas of Los Angeles and Valley Metro, the highest frequency routes are typically found connecting major activity centers (business & commercial centers). Though these routes are not always linear, they are typically the most direct way of connecting these locations. In the transit context directness implies the path with the shortest travel time and high frequency routes tend to utilize high capacity roadways. Neighborhoods that are adjacent to arterial roadways connecting activity centers will, on average, experience the lowest waiting times across transit systems. In contrast, transit frequencies are found to be lower along non-arterial roadways and the lowest in the fringe neighborhoods of the service area leading to increases in expected waiting time. A decrease in total transit demand is often associated with a reduction in transit service frequency, however, these neighborhoods may also experience decreased frequency owing to the fact that they are not located along direct paths between major activity centers. Cost-effective resource allocation to meet the competing transit goals of area coverage and total ridership, combined with the distribution of activity locations and the geography of the street network leads to waiting times that are longer for some riders than others and may increase the risks associated with heat exposure.

1.18.3 Uncertainty

Exposure estimates are sensitive to several methodological assumptions. First, access time estimates are based on walking speeds of an average adult, though walking speeds can vary significantly by age and physical condition. Walking times may increase by up to 30 % for the slowest age group (females, age 80-89) and decrease by up to 10% for fastest group (males, age 40-49) (Bohannon and Andrews 2011). In assessing access time, it was assumed that individual mobility needs would be met by routes serving the nearest transit stops and that the existing street network defines pedestrian pathways. It is possible that some transit users may walk to stops farther away leading to an underestimate of walking time at the household level. Transit users may rely on shorter paths through parking lots or other cut throughs which are not captured using the street network and may also select routes that are longer than the shortest path. The analysis also excludes all households where the distance to the nearest transit stop is greater than 800 meters. While existing data suggest that the probability of transit riders walking more than 800 meters is low, excluding these riders leads to lower average neighborhood walking times. Access times may be fairly consistent for individual transit riders but there may be issues with schedule reliability which impact waiting time that are obscured or not captured with the current methods. Specifically, the methods are unable to address waiting times which may vary throughout the day due to demand-based transit schedules as well inter-route service reliability issues. Finally, characterizing and comparing neighborhoods by average access and waiting times may not identify transit riders who experience the greatest exposure, the riders who are at the right most extreme for access and/or waiting time. It should also be noted that the relative health risks associated with heat exposure are likely higher during physical activity (e.g., walking to transit) than sedentary activity (e.g., waiting for transit) though the relative risk will vary depending on individual characteristics and behavior.

1.19 Discussion

In most places transit agencies are tasked with designing and implementing transit systems that work within the context of existing urban infrastructure. Even though urban infrastructure systems are primarily out of the control of transit agencies, often a legacy of land use and transportation decisions stretching across decades, they impact how and where an agency will operate and overall service quality. For transit riders, some amount of environmental exposure is inevitable. Upon closer inspection of the results, we find that transit riders living in areas where residential density is low, with limited high capacity roadways and irregular street networks, and not along direct paths between major activity centers are likely to experience the greatest total exposure (access and waiting). Areas with these characteristics tend to have lower demand for public transit (Bento et al. 2005; Cervero and Kockelman 1997; Chen et al. 2008; Frank et al. 2008), however, riders in these areas that are dependent on transit services for mobility may be at the greatest risk for heat-related health effects. For Los Angeles and Valley Metro, the areas with highest total exposure are found primarily along the edge of the service areas (Figure 17) and might be areas where the agencies could focus efforts to reduce exposure and its health impacts during summer months and other periods of unusually warm weather.

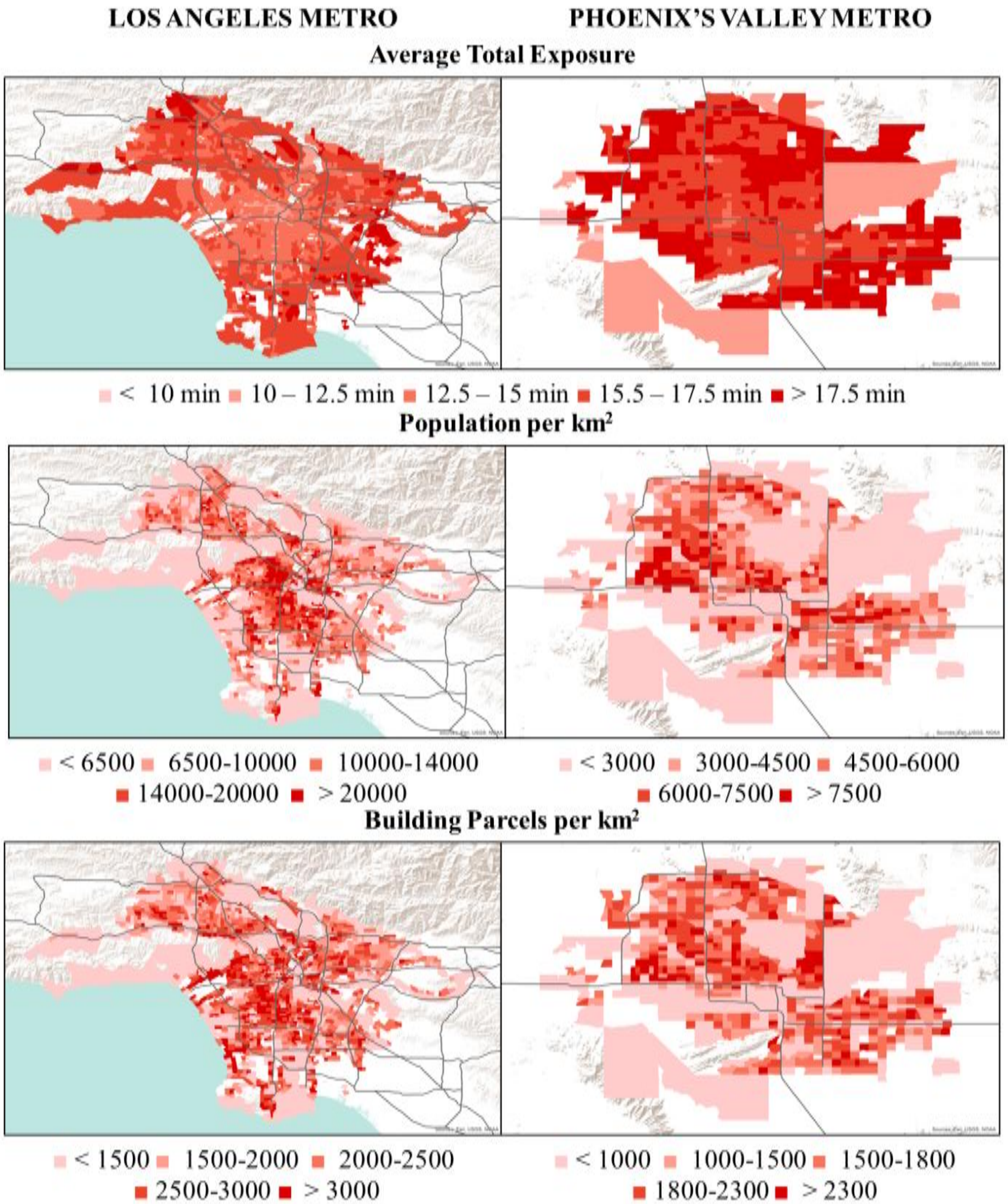

Figure 17: Average Total Exposure Resulting from Transit Use. Total exposure is access time plus wait time. Transit riders living in low density neighborhoods with irregular street networks along the fringe of the service area are likely to experience the longest average exposure associated with transit use.

Exposure to extreme heat is a universal health risk but there are some individuals who are more susceptible to harm than others. The ability to respond and cope with heat stress can vary significantly from one individual to another but research has shown that certain population subgroups including the elderly, young children, those living in poverty, and those with underlying medical conditions are predisposed to heat-related morbidity and mortality (Kenny et al. 2010; Kovats and Hajat 2008). By combining characteristics known to increase heat vulnerability and population demographics researchers have developed methods that spatially identify neighborhoods and regions where residents are more at risk of negative heat-health outcomes (Cooley et al. 2012; Harlan et al. 2012; Reid et al. 2009). In addition to socio-economic traits indices can also include environmental factors such as vegetation and surface temperatures which have been shown to be significant factors in predicting heat-related morbidity and mortality (Harlan et al. 2012). When developing policies and programs aimed at reducing health risks for riders, transit agencies should also consider spatial variations in rider demographics and environment characteristics which may increase heat vulnerabilities.

While transit systems have been designed and implemented to meet mobility needs, climate change gives cause to rethink system designs in order to protect users from extreme weather events. Because extreme heat can be forecasted with sufficient lead time, identifying areas with relatively longer access and waiting times can help transit planners and operators adjust system designs to reduce overall outdoor exposure. Transit systems are subject to a number of constraints, notably funding, but there are a number of options available which may reduce health risks. Despite the recent increase in public transit spending the costs associated with the additional stops, drivers, and vehicles required to significantly reduce access and waiting time across the system are likely prohibitive. However, the results indicate that existing transit resources could be temporarily reallocated across the system in order to reduce waiting time in areas where total exposure is the greatest and/or areas with high social vulnerabilities to heat.

There are existing transit system components which may mitigate transit user health risks during periods of hot weather. Paratransit and other dial-a-ride services already serve potentially vulnerable groups (elderly and the disabled) though there are other groups with underlying heat vulnerabilities that may not be eligible for these services. Yet, for these services to be effective in mitigating health risks during hot weather, riders must first acknowledge their own vulnerability to heat and opt for these services instead of public transit. Transit agencies should actively promote the use of these services for all riders with underlying vulnerabilities to heat in addition to expanding these service options. Existing transit shelters and other cooling amenities (e.g., water fountains) may also reduce risks associated with transit use during periods of hot weather. Agencies should give consideration to current exposure as well as underlying social vulnerabilities to heat when determining appropriate locations for additional shelters. Although temperatures in the shade are generally cooler, the extent to which these facilities may protect riders during severe heat is not understood and additional research is needed to determine whether current shelter designs are adequate in mitigating potential heat-health effects. In places where agencies are developing new routes or expanding existing routes to service new developments, transit planners should consider the two elements of exposure, access and waiting, when siting transit stops and developing transit schedules.

There are potential technological solutions which may mitigate health risks for transit riders. Real-time schedule arrival applications, which use GPS location data and historical travel times to predict transit vehicle arrivals at individual stops, are being implemented by some transit agencies in the U.S. and have been shown to reduce passenger waiting times by 30% (Watkins et al. 2011). While these applications were primarily developed to increase rider satisfaction and increase transit ridership by improving the perception of reliability, the widespread use of real-time information could significantly reduce waiting times during periods of extreme heat. These real-time services can provide next vehicle arrival information to riders through a number of mediums including website, telephone, SMS text messaging and smart-phone applications (Watkins et al. 2011) allowing riders to reduce their wait time even when transit services are running off schedule. Even so, there is some question as to whether this type of technical solution would be available to vulnerable riders, especially those living in poverty. This type of service also opens up the possibility of partnering with nearby air conditioned public spaces or businesses which could display real-time arrival information and offer a respite from heat while riders wait for the next vehicle. While the benefit to the transit rider is obvious, a digital reader board which displays real-time transit schedule information could also bring new customers to businesses adjacent to transit stop locations.

In addition to concerns for rider health, cities and transportation planners ought to consider the impact that extreme heat may have on the demand for transit and other non-motorized modes. In the United States, transit, cycling, and walking have experienced mode share increases in recent years but climate uncertainty and weather extremes may make these modes less viable in the future. At a time when cities are encouraging more transit, biking and walking by expanding service and improving infrastructure for these modes, efforts should also be made to design these systems with elements to protect individuals from climate extremes.

Los Angeles and Valley Metro are specific transit systems and the broader application of the methods to other transit systems should consider a few caveats. First, because the Los Angeles and Valley Metro vehicles feature air conditioning, the analysis assumes that heat exposure would not occur during the transit trip. For transit agencies operating vehicles without air conditioning, vehicle conditions and in-transit exposure should also be considered. Secondly, Los Angeles and Valley Metro are formalized transit systems that operate on specified routes, stops, and schedules. More advanced methods are needed to understand exposure in areas where people reliant on informal and unregulated transit networks. These networks are common in many developing regions including major cities in sub-Saharan Africa, Latin America, and Asia (Cervero and Golub 2007). Lastly, the transit stops across these two systems are largely exposed and other systems may feature indoor air-conditioned stops (e.g. Air-conditioned bus shelters in Dubai) which should be accounted for.

1.20 Conclusion

Policymakers and planners need to consider the impacts of climate change on transit riders and the associated risks. While public transit can help reduce the energy use and greenhouse gas emissions of individual mobility, it also contributes to environmental exposure which may be detrimental to rider health, especially in the face of climate change. As populations continue to urbanize and public transit becomes an increasingly important form of transportation the health risks associated with extreme weather events should be considered and planned for in system design.

1.21 Acknowledgements

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Chapter 5

CONCLUSION

This dissertation advances thinking surrounding transportation and climate change by examining the potential for infrastructure to affect individual heat-health risks. Population vulnerability to heat has been shown to vary across cities (Harlan et al. 2013; Reid et al. 2009) and this research identifies specific infrastructure characteristic which can mitigate or exacerbate these risks. Assessments of existing civil infrastructure systems are critical to developing effective policies, programs, and adaptions to reduce a growing health threat. By comparing assessments of population heat vulnerabilities and assessments of infrastructure characteristics that may contribute to or reduce heat stress, decision makers can make informed choices on where interventions should be targeted.

Los Angeles and Maricopa developed concurrently with the adoption of the personal automobile and their land use and transportation systems are, by and large, dedicated to their use. Despite infrastructure systems that incentivize automobile travel that at the same time discourages alternative modes, there are still large populations in each region that rely on walking, cycling and using transit for their mobility. Pedestrians, cyclists, and transit users are frequently exposed to the environment, which could be a health hazard during periods of extreme heat. While this work has focused on two regions that are heavily auto-dependent, the underlying methods can be applied in other cities where larger fractions of the population rely on these modes. Already a public health threat, climate change is predicted to increase average temperatures as well as the frequency, severity and duration of extreme heat events. This research is needed to understand how alternative mode usage contributes to environmental exposure alternative modes as and how users may be affected in a climate impacted future

In Los Angeles and Maricopa, public air conditioned spaces can mitigate the health risks associated with extreme heat. These spaces were found to be unevenly distributed throughout each region making access more difficult for some. In both regions, there are areas with an abundance of these spaces and others where there presence is extremely limited. This variation largely results from different land use patterns and the separation of residential and commercial uses. Large residentially zoned areas (e.g., suburbs) were found to significantly reduce the presence of public cooling resources. For those with automobiles, these disparities may not matter, but for those who rely on walking as a primary form of mobility these variations may limit their access to a resource that can reduce the risk of negative health outcomes. Concerns for prolonged exposure may prevent individuals from walking to these spaces if the time-cost is beyond comfort or safety thresholds. Conversely, individuals who are unaware of their own heat-health risks with limited access to facilities in close proximity may engage in unsafe behavior attempting to access further locations. Broadly, the underlying methods in Chapter 2 can help identify regions in cities where individuals may be deprived of, or experience undue exposure in accessing, necessary goods and services during periods of extreme heat.

Designated public cooling centers can help reduce the disparities in cooling resources but the research has shown that they have largely been located in areas with an abundance of alternatives. Organizations that coordinate cooling center networks need to consider these alternatives when siting facilities. Although existing facilities are a service to those in close proximity, in many cases they may be redundant. These facilities are needed in locations near vulnerable populations with limited access to cooling alternatives. Beyond Los Angeles and

Maricopa, many other major cities have also developed networks of cooling centers for heat emergencies. Chapter 3 identifies a method that combines heat vulnerability assessments, accessibility measures, and location analysis that agencies can use to evaluate the efficacy of the existing network and to effectively site future cooling center facilities

While the private automobile has been the primary method of personal transportation in the US Southwest for decades, the issues surrounding congestion, air quality, and climate change has led to an increase in public transit spending and usage in Los Angeles and Maricopa counties in recent years (FTA 2016). Championed as the "most efficient means for large numbers of people to move freely in cities", public transit also exposes people to the environment (Walker 2012). While access time and wait time have been shown to be determinants of transit use (Taylor et al. 2009), previous research has not considered these elements for their potential to increase heat-health risks. Because transit systems are typically designed for cities rather than cities being designed around transit systems, locked-in urban forms influence transit stop placement and transit schedules that in turn influence exposure for individuals. This dissertation demonstrates that the design of the Los Angeles Metro and Valley Metro systems leads to different exposure experiences for riders across the system and quantifies that experience. There is a correlation between heat-vulnerable populations and those that ride transit and overall these transit systems are currently designed in a way that leads to lower exposure times for vulnerable populations. However, because waiting time is found to be larger on average than access time, transit agencies have an opportunity to limit exposure by making improvements to stops and transit schedules during periods of extreme heat. As cities continue to urbanize and if public transit use continues to grow this research can help transit agencies understand transit use as an exposure pathway and where interventions may be needed during periods of extreme heat.

1.23 Future Work

Public transportation planning is a complex process that seeks to maximize the quality of service to users within agency budgets. Because these are two competing goals, tradeoffs need to be made and optimization techniques are frequently used to evaluate these tradeoffs (Guihaire and Hao 2008). However, it may be possible to establish alternative services and schedules that incorporate an objective of reducing climate risks to passengers. . The public transit process is generally divided into five steps: i) network design (route structure and stop placement), ii) route frequencies, iii) timetabling, iv) vehicle scheduling, and v) crew scheduling and rostering (Guihaire and Hao 2008). Each is a significant undertaking and is typically solved in sequence as separate optimization problems (Desaulniers and Hickman 2007). There are opportunities to incorporate rider health risks in the overall planning process and the framework described below aims to reduce system wide heat health risks by adjusting transit schedules to reduce wait times for vulnerable population. The framework is tested by developing new transit frequencies for the Los Angeles Metro (LA Metro) local bus system.

1.23.1 Los Angeles Metro Case Study

LA Metro ranks among the top five public transit systems in the United States for total transit vehicles operated, revenue kilometers, revenue hours, unlinked passenger trips, and passenger kilometers (APTA 2015). Between bus and rail service, the system supports approximately 1.4 million unlinked daily trips (weekday) originating from 16,047 transit stops and covers a service area of 3,711 square kilometers as of 2015 (LA Metro 2015). LA Metro, like other transit agencies, develops service frequencies from time-dependent estimates of demand and bus passenger capacities. LA Metro’s frequencies vary throughout the day and during peak periods bus frequencies are as high as 10 times per hour for high demand routes. These high frequency routes typically follow major arterials. During off-peak times frequencies are typically reduced and some routes are even taken out of service. Due to demand based service, transit riders using the system during off peak periods likely experience longer waiting times than those who use transit during peak periods. Coincidently, off peak hours during 1pm to 3pm can be some of the hottest hours of the day (Figure 18).

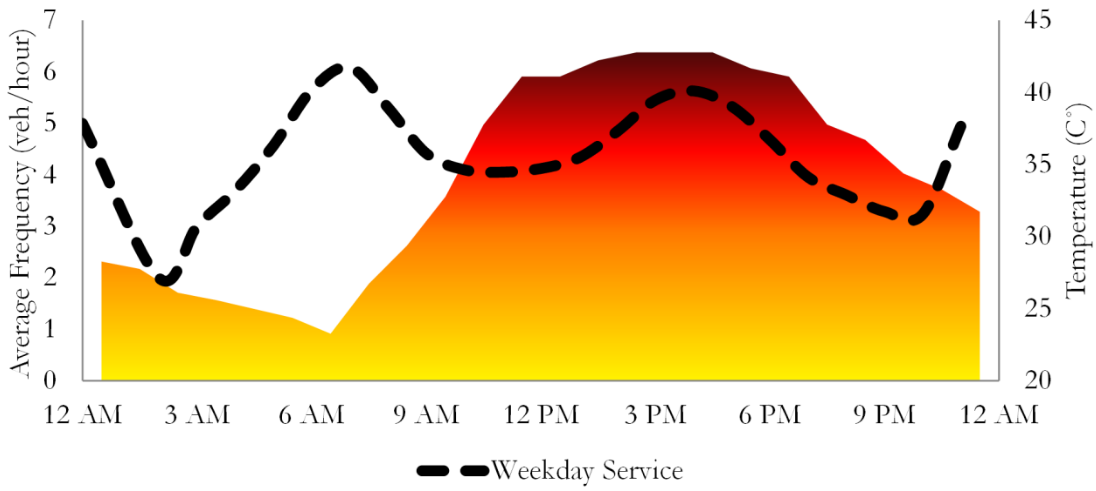

Figure 18 Average Transit Frequency and Daily Temperatures. The dotted lines depicts average frequency across all active local routes by time of day and the shaded background shows ambient air temperature during an extreme heat event (September 27, 2010)(NCDC 2016). Demand-based scheduling reduces waiting times during peak periods. Waiting times are longer between the hours of 9am and 3pm when outdoor temperatures exceeded 43 C˚

A simple solution to reducing waiting times during extreme heat events would be to increase frequencies along all routes. However, given budget constraints, this type of solution is infeasible. A framework is developed to reduce health risks for vulnerable transit riders by altering transit frequencies without increasing the costs for the transit agency.

1.24 Methods

This case study develops new frequencies for all weekday LA Metro local bus routes operating between 2pm and 3pm. This time slot was identified as an off peak time where service frequencies are low on a number of a routes and temperatures are expected to be near daily maximums. General transit specification data for LA Metro was used to determine existing transit frequencies and the total number of vehicles beginning operation during this time period (LA Metro 2015).

1.24.1 Determining Transit Rider Demand Potential

Detailed time-dependent demand is the most difficult data requirement to obtain for developing transit frequencies. Transit agencies rely on on-board surveys and statistical forecasting to generate time-dependent origin-destination matrices. Due to the expense and effort required to generate system wide demand estimates, transit agencies are often reluctant to share these data (Guihaire and Hao 2008). For this assessment, rider demand was estimated using the American Community Survey which details transit use among workers. For Los Angeles census tracts, potential transit demand is estimated based on the relative use of public transit among resident workers and the general population of the census tract (USCB 2015).

1.24.2 Rider Heat Vulnerability

As in Chapter 3, relative heat vulnerability scores are developed for each census tract. The scores are based on the principle component that was found to be the overall best predictor of both all-internal causes and heat related deaths during periods of extreme heat (Figure 19).

1.24.3 Transit Route Weights

Individual transit routes are weighted based on total ridership demand potential and ridership vulnerability. GIS tools developed by Morang (2016) are used to develop shapefiles for LA Metro transit routes and stop locations (Figure 19). Routes are assigned weights that are equal to the sum of the transit demand potential multiplied by heat vulnerability for all census tracts served by the transit route (Eisenman et al. IN REVIEW).

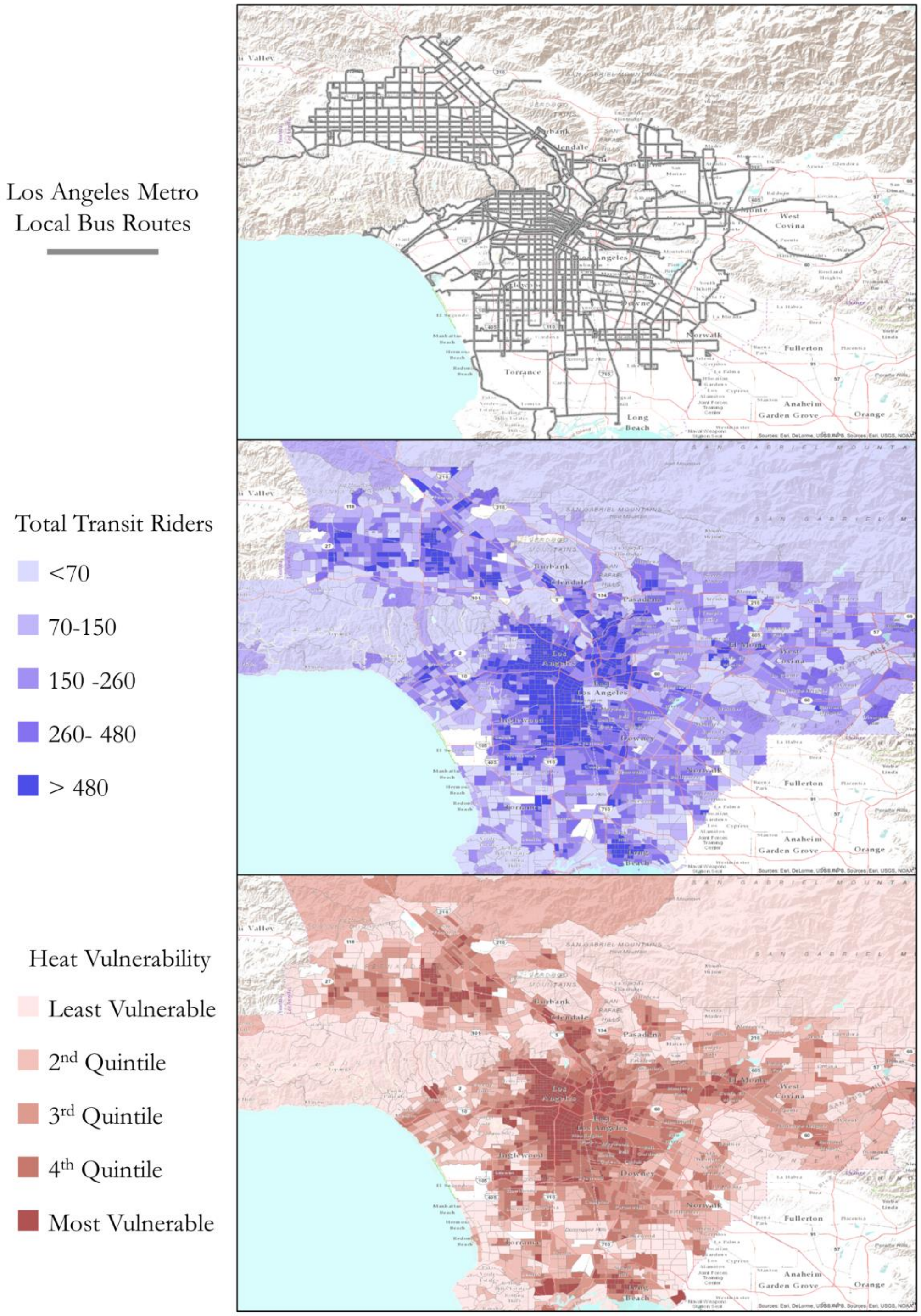

Figure 19: LA Metro Local Bus Routes, Potential Ridership Demand, and Heat Vulnerability

1.24.4 Optimization Framework

A non-linear integer programing based optimization model could be used to determine new transit frequencies and is defined below:

$$Min \sum_{i} \sum_{j \in C_i} \left(\frac{6.369}{F_i} + 7.8959 \right) D_j V_j$$

$$S.T.$$

$$1) \sum_{i} F_i < B$$

$$2) \ \frac{F_{i_0} LF_i}{F_i} \leq 1.42 \ \forall i$$

$$3) 1 \leq \ F_i \leq 10, \in Z \ \forall i$$

$Where$:

$i = Transit\ route$

$C_i = The\ set\ of\ census\ tracts\ served\ by\ transit\ route\ i$

$D_j = Transit\ demand\ in\ census\ tract\ j\ (\#\ of\ transit\ riders)$

$V_j = Heat\ vulnerability\ of\ census\ tract\ j$

$F_i = Frequency\ of\ route\ i\ (\frac{vehicles}{hour})$

$B = The\ total\ number\ of\ buses\ available$

$F_{i_0} = Current\ frequency\ of\ route\ i\ (\frac{vehicles}{hour})$

$LF_i = Average\ load\ factor\ for\ route\ i\ (\frac{total\ passengers}{seats})$

Constraint 1) limits the total number of buses that can be assigned to all routes to those that are currently scheduled for service. Constraint 2) ensures that there is sufficient capacity to meet existing demand based on current load factors. The maximum load factor for weekday service in Los Angeles is 1.42 (LA Metro 2016). Constraint 3) ensures that at least one vehicle runs along all routes that currently have service, limits the total vehicles servicing each route to 10, and only allows integer values to be assigned.

1.25 Results

The routes serving the greatest vulnerable demand are those that serve the center of LA Metro's service area. The West Los Angeles, Mid-Wilshire, Mid-City West, Mid-City, West Adams, and Crenshaw neighborhoods are some of the most heat vulnerable neighborhoods in Los Angeles. These neighborhoods are in close proximity to downtown and are served by a large number of routes which currently operate at mid to high frequencies. Additionally, some of the routes that serve central part of Los Angeles are long routes that crisscross the LA Metro system which contributes to their high overall demand weight (Figure 20).

The 736 local buses beginning operation between 2 and 3pm are reallocated across 95 active bus routes (LA Metro 2015) using the optimization model. Current frequencies range from 8 to 1 times vehicles per hour. The optimization of route frequencies to reduce waiting times for vulnerable groups was able to improve the objective function by 13%. Routes in the center of LA Metro's service area generally received an increase in frequency due to the potential for high demand from vulnerable groups of riders. Vehicles that are reallocated to the these central routes are largely drawn from routes operating in the periphery of the LA Metro System and in the San Fernando Valley where both potential rider demand and heat vulnerability are lower (Figure 20).

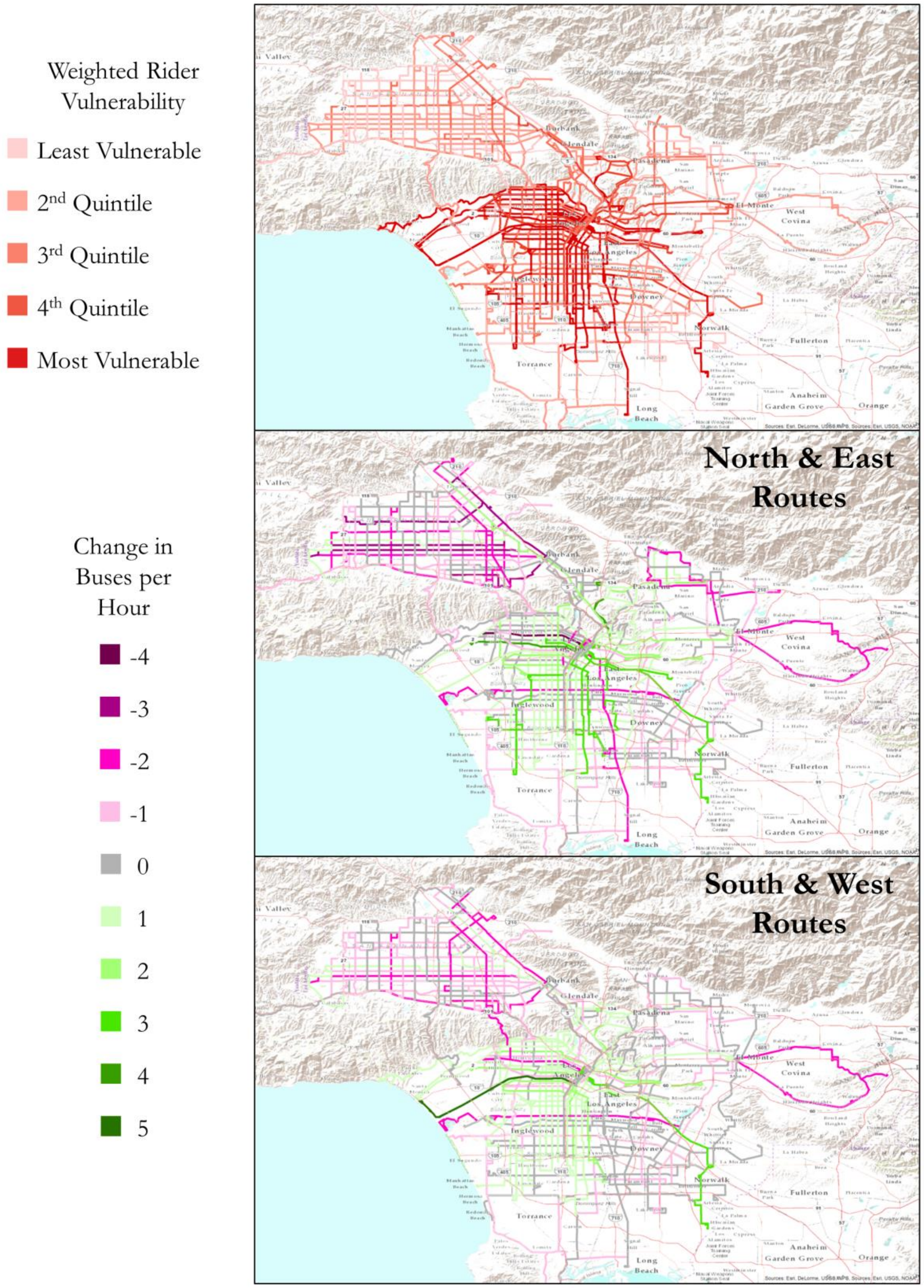

Figure 20 Weighted Transit Route Demand Vulnerability and Frequency Changes from Existing Schedules

The results show that it is possible for LA Metro to adjust transit schedules to reduce waiting time for vulnerable populations without incurring additional costs. During periods of extreme heat, services should be concentrated on the routes serving the center of the LA Metro System. The application of real demand data and rider demographics would significantly improve the ability of the model to identify routes should that be targeted for frequency increases and where these vehicles could come from. A consequence of this method is that it will increase waiting for those along routes where frequencies decrease. Additional constraints could be added to the model to limit frequency decreases and establish a ceiling for additional wait time on all routes. Because heat waves can be predicted with sufficient lead-time, it may also be possible to notify riders of alternative schedules in advance to minimize the impact of reduced frequencies on waiting time. This case study reflects a single step in the public transit planning process. The next steps for developing a functional emergency heat bus service include developing timetables, vehicle scheduling, and crew assignment.

Recently, LA Metro suggested changes to their bus system that mirror some of the changes developed in this case study. Motivated by a service review conducted by the American Public Transportation Association (APTA), LA Metro has proposed to make changes to their system based on a route performance (RPI) (LA Metro 2015). RPI is based on total passenger boarding, passenger miles, and overall operation cost. The APTA review included a recommendation to "critically review services & reallocate resources from poorer performers to higher productivity"(LA Metro 2015). Overall, the LA Metro proposal calls for no additional hours of bus service but reallocates existing services from lower demand routes to high demand routes. While the overall objective between LA Metro's proposal and the one presented here different, the results are similar. The network recommended by LA Metro's Blue Ribbon Committee strongly resembles the frequency shifts identified in this analysis (Figure 21). LA Metro has not yet implemented these changes but if they do, the new network may also help reduce heat vulnerability because of the routes they are targeting for increased frequency.

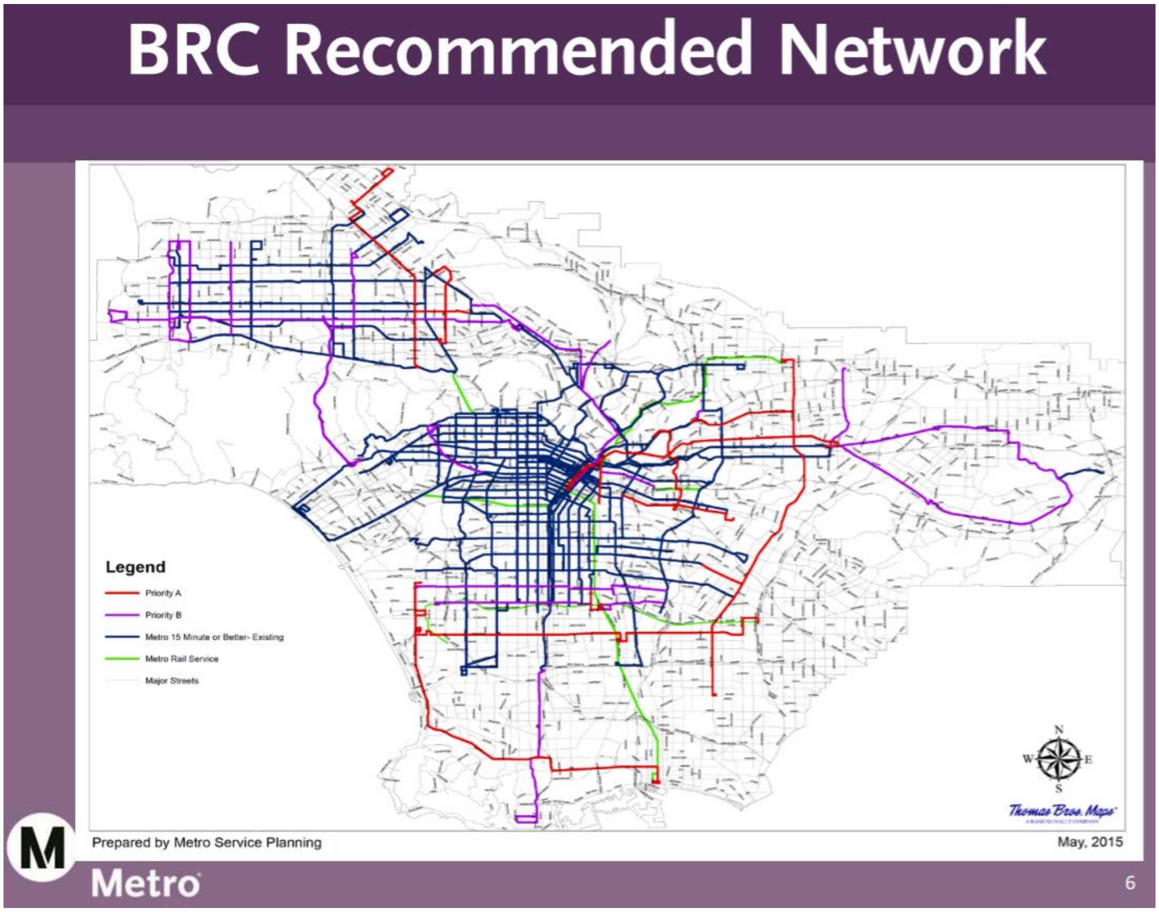

Figure 21 Blue Ribbon Committee Recommended Bus Network (LA Metro 2015)

1.26 Conclusion

The issues identified in this dissertation are applicable to areas outside the US Southwest as global climate models project that many cities will experience increasing temperatures and more frequent and severe heat (and even cold) events (Wuebbles et al. 2014). Understanding these characteristics is critical to developing policy and programs that effectively address heat as a public health issue. The application of these methods is not limited to just high temperature environments. Extreme cold is also known to contribute to excess morbidity and mortality (Díaz et al. 2005; Medina-Ramón and Schwartz 2007) and the methods could also be applied to understanding the disparities in residential heating, public heating resources, official warming centers, and mode-based exposure.

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APPENDIX A

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