Heat Exposure and Transit Use: Travel Behavior and Infrastructure

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A Collaborative Research Project between Arizona State University's Urban Infrastructure Anatomy & Sustainable Development and Construction Materials & Methods Classes

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PROJECT OVERVIEW

Increasing frequency and severity of heat waves and extreme heat events in Maricopa County, Arizona, puts residents at risk to heat-related morbidity and mortality. With expanding urban development and intensifying urban heat island effect, public transport users are inherently vulnerable to outdoor heat exposure as they travel and wait for transit. Research was conducted to investigate how the Tempe Valley Metro transit infrastructure affects transit use behavior within a selected study region between Rio Salado Pkwy, S. Rural Rd, E. Apache Blvd, and S. Priest Dr. Focusing on the study area, a transit survey was conducted to augment Valley Metro ridership data that lacked transit user thermal comfort perception and behavioral responses to heat at transit stops. The eighty-eight responses were linked to various research aspects in this study. Transit stop amenities were characterized based on the capacity to provide relief from heat and correlated with transit ridership; the analysis conveys that stops with higher vulnerability to extreme heat (lack of greenspace and physical shade) serve a lower volume of passengers. Geospatial analysis was conducted to assess spatial linkages using average walk time to the nearest transit stop, average daily ridership, average wait time, vegetation and shade level for each stop. The results indicate that most transit stops in the study region are not significantly vulnerable, though there is concern for stops with moderate ridership and longer than average wait times. Overall, transit stops on W Rio Salado, South Priest Dr, South Hardy Dr, and some stops on University Dr are more vulnerable to extreme heat than average, in terms of lack of vegetation, direct and indirect shading, ridership, long walk and wait times.

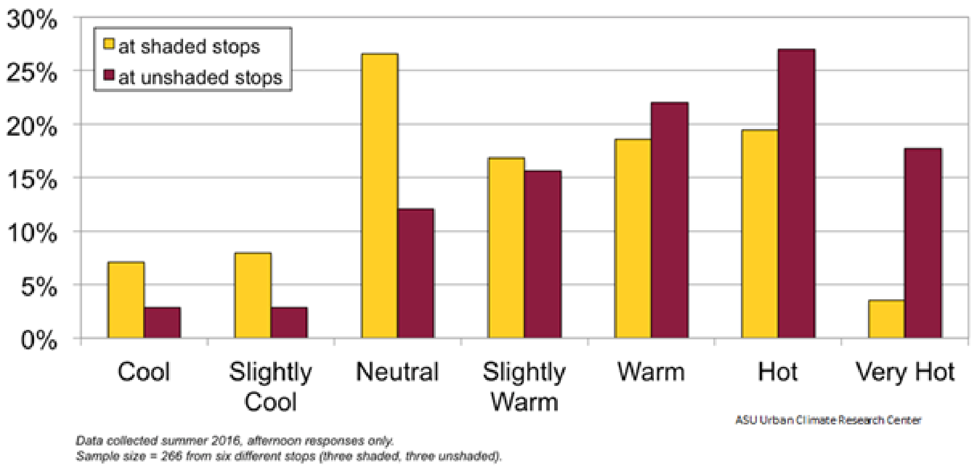
1 CHAPTER I: TRAVEL BEHAVIOR

1.1 INTRODUCTION

Extreme heat events due to climatic changes and excessive urbanization have been increasing since the beginning of 21st century. In the United States alone, extreme heat events (EHE) have caused over 3000 deaths occurring from 1991 to 2003, with arid Arizona leading the nation (CDC, 2006). In Maricopa, there is growing concern that increased frequency and severity of extreme heat events may put its inhabitants at risk, especially those needing to be outdoors to travel. Increased extreme heat events coupled with continued urbanization and the urban heat island effect worsens heat in metropolitan regions such as Maricopa (Kim, 2007; Tan et al., 2010). A number of studies found that increased heat waves, increased frequency of extremely hot days, and increased average temperatures will cause an increase in heat related morbidity and mortality (Eisenman et al., 2016; Harlan et al., 2013; Saha et al., 2013; Sarofim et al., 2016; Uejio et al., 2011). From 2003 to 2013 in Arizona, 1,391 deaths were directly caused by heat, while 1,761 were heat related (AZDHS, 2015). Arizonans age 24 or older have the highest rate of extreme heat related deaths (Uejio et al., 2011). Heat exposure can cause other clinical illnesses and can exacerbate pre-existing health conditions such as respiratory and cardiovascular diseases which increase public health expenses in a society (Berko et al., 2014; Luber and McGeehin, 2008). In addition, Karner et al. (2015) argue that outdoor activities and physical exertion increase the risk of health hazards in an EHE. Therefore, urban public transport users are inherently vulnerable to adverse heat related health impacts due to the necessity to walk and wait outdoors.

The Tempe Transportation Master Plan (City of Tempe, 2016) prioritizes multi-modal transportation and aims to decrease car dependency. Their goals include improving bus service, expanding the transit network by introducing additional routes (Orbit Saturn circulator in South Tempe), developing new modes of transit (Tempe Streetcar Project), and maximizing biking and walking. However, extreme heat conditions in Maricopa County may become an impediment to ridership and even pose health hazards on pedestrians and public transit riders. Moreover, this problem is exacerbated by the fact that the majority of public transit users are also socio-economically vulnerable (Fraser and Chester, 2016; Karner et al., 2015; Valley Metro, 2017). For this reason, it is important to understand the dependencies between heat, ridership, and the effect of urban form and amenities at transit stops and streets.

Fan et al. (2016) found that wait times at stops without benches and shelter are perceived to be at least 1.3 times longer than their actual wait time, and this does not consider extreme heat. According to Middel et al. (2016), outdoor thermal comfort is "a complex function of atmospheric conditions and physical, physiological, psychological, and behavioral factors", with mostly subjective thermal sensations and responses. Surveys conducted at City of Phoenix bus stops during the summer of 2016 by the Arizona State University (ASU) Urban Climate Research Center showed that 90% of surveyed respondents preferred to be in the shade. At unshaded bus stops, transit riders reported feeling extremely hot (3.5 times more often) (Figure 1) and 'very uncomfortable' (twice as much) than at shaded bus stops.



Data collected summer 2016, afternoon responses only.
Sample size = 266 from six different stops (three shaded, three unshaded).

Figure 1 - ASU Urban Climate Research Center survey of City of Phoenix Bus riders indicating perceived Thermal Condition at shaded and unshaded transit stops during the summer of 2016.

The ASU Climate Research Center results showed that physical transit stop amenities play an important role in rider's comfort and perception of heat. Valley Metro's 2016 ridership survey did not include any information on how heat affects rider's experiences (Valley Metro, 2016). Thus, it is necessary to explore the technological, behavioral, or physiological adaptations to heat exposure in Arizona, where EHEs are chronic rather than episodic (Chuang et al., 2015).

1.1.1 PROBLEM STATEMENT AND RESEARCH QUESTIONS:

Considering the issues with increased morbidity and mortality associated with high and extreme heat exposure, it is clear that there is an increased potential for extreme heat to adversely affect transit users in the Tempe region in the next few decades. This report will look to answer how the Tempe transit infrastructure affects transit use behavior within the selected study region. Furthermore, the research investigated whether there are certain Tempe transit stops or corridors that may be more vulnerable to heat exposure, as well as any existing correlations between heat vulnerable locations and ridership.

1.1.2 STUDY REGION

A specific and bounded area of study was selected for this assessment. Figure 2 below illustrates the 127 Tempe transit stop locations within the study boundary of Rio Salado Parkway (north border), South Priest Drive (west), West 13th Street/East Apache Boulevard (south), and South Rural Road (east). The region includes the ASU Tempe campus, Downtown Tempe, stadiums, residential housing units and businesses. Thus, the area is partially highly trafficked (human and vehicular) due to the ASU campus and inclusion of Downtown Tempe, a popular attraction.

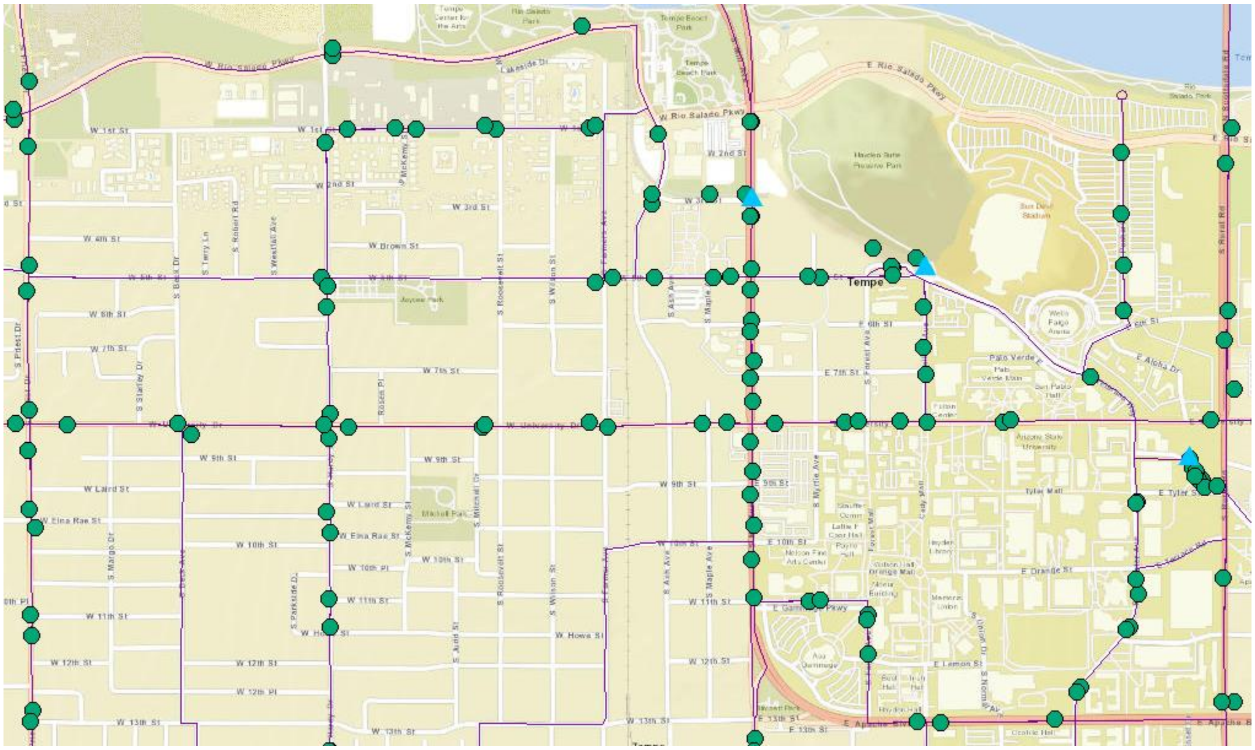


Figure 2 - Transit stop locations in Tempe study region
Bound by Rio Salado Pkwy (north), S. Priest Dr. (west), W. 13th St./E. Apache. Blvd. (south), S. Rural Rd. (east). Light rail stops are blue triangles and bus stops are green circles (Valley Metro, 2017).

Based on Valley Metro's Transit System Map (2017), the study transit routes (124 bus stops inclusive of 3 light rail stops) in Figure 2 would be:

- Bus Routes: 30, 48, 56, 62, 65, 66, and 72.
- Orbit Neighborhood Circulators with same stops as selected bus routes: Jupiter, Mars, Mercury, and Venus.
- Light rail stops: University/Rural, Veterans Way/Tempe Transit Center, and Mill/3rd.

1.2 METHODOLOGY

1.2.1 VALLEY METRO RIDERSHIP

To investigate seasonal ridership and transit stop vulnerability, various data was collected and processed. Valley Metro average daily boardings were obtained for each stop in the study region across seven seasonal periods from 2015 to 2016 (Valley Metro, 2017). Figure 3 displays the Tempe Bus boardings by stop for 2015 to 2016.

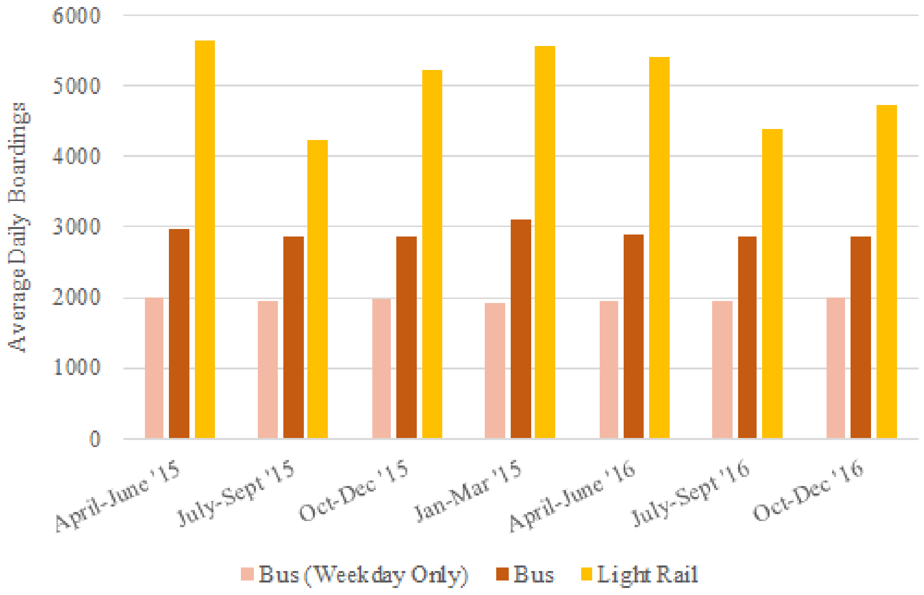


Figure 3 - Average daily boardings by season for Tempe transit stops. Note that this figure only includes Tempe transit stops within the study region. Tempe stops outside the study region were not included in this analysis.

As of 2015, Tempe has an estimated population of 175,826 (US Census Bureau, 2017) and Arizona State University's Tempe campus had a fall 2016 enrollment of 51,869 (ASU, 2017). While not all ASU Tempe students and employees live in the analysis region, a large fraction of them will use the transit within the study region during the fall and spring seasons. This is especially true for the light rail, as the light rail route includes many transit-oriented developments that have targeted student living. However, bus ridership fluctuates far less from season-to-season. Although this data is aggregated at a low temporal resolution, we hypothesize that temperature has little to no influence on seasonal ridership. It is unclear to what extent transit rider behavior is influenced by temperature at a day-to-day basis. For example, it is unclear if an extreme heat wave would cause any noticeable perturbations in ridership. In order to collect a higher resolution set of data, we conducted a survey and asked Valley Metro riders about their travel behavior. The transit survey will be explained in the following section.

1.2.2 TRANSIT SURVEY

Our focus group, with assistance from the rest of the class, put a transit survey together to investigate the travel behavior and heat exposure of Valley Metro riders. The survey (available in Appendix A) consists of 10 questions asking about:

1. Demographics of the participants
2. Travel behavior of the participants
3. Heat perception and heat exposure experience of the participants

The students of the UIA class conducted the survey, by going to roughly 30 different bus stops in the study area. We surveyed 88 people during a short-term heat wave in April 2017 during daylight hours. The average temperature during the course of survey was 85°F, which is far from maximum annual temperature in the study area during summer, however, it was relatively hot for that time of the year. The result of the survey will be discussed in more detail in section 3.

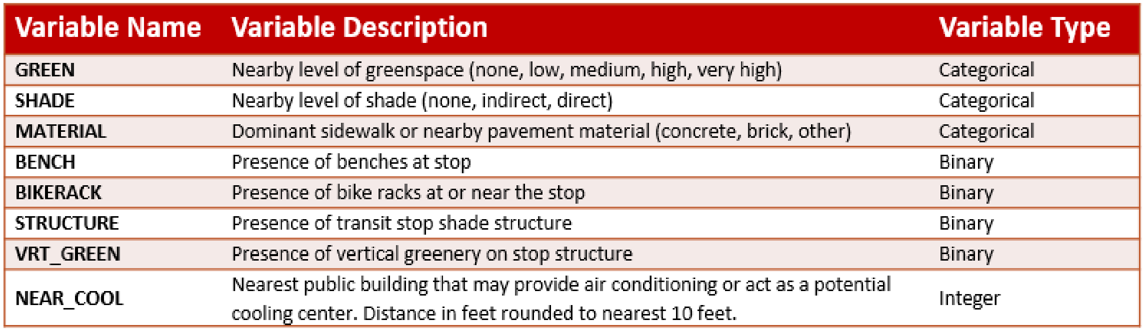
1.2.3 TRANSIT STOP CHARACTERIZATION

The intent of characterizing transit stops amenities was to identify any relationships between infrastructure present at transit stops and ridership to better understand how extreme heat and transit stop infrastructure impact riders in Tempe. Characteristics were selected based on having some capacity to impact the degree of experienced or perceived heat by an individual. A different method for evaluating each characteristic was used due to the inherent differences between characteristics.

The vegetative greenspace characteristic of transit stops was labeled as "Green" and rated on a scale from 0-3 with 0 representing no vegetation or green landscaping infrastructure within 10 feet (3m) and 3 representing extensive vegetation within 10 feet (3m). This evaluation is subjective because the stops were rated based upon the presence of greenspace using transit stop photos from Valley Metro's GeoCenter database (2017). The rating method for "Green" is the primary limitation of this assessment due to potential reproducibility issues of results. "Shade" was rated to identify the presence and type of shading, these options are: no shade, direct shading from transit structure, indirect tree shade, indirect shade from building or other gray infrastructure, and both indirect tree shade and building shade. The purpose of the "Material" characteristic is to identify paving materials. Understanding the type of paving material can provide information on heat experienced at transit stops, since different paving materials have different albedos and heat absorption capacities. The characterization rating for materials are: concrete, asphalt, and brick. "Near cool" evaluated the distance (in feet) to the nearest indoor location that could provide refuge for passengers. This was done using the measurement feet feature within Google Earth, or alternatively Google Maps.

The characteristics: "Bench", "Bikerack", "Structure" and "VRT Green" are ranked as a binary yes or no based on whether they exist at the stop. Benches were selected because they provide physical comfort and a place for a person to sit, which can alleviate heat experienced. Bike racks were included in the study to determine if the presence of bike racks increases use of a given transit stop. This is partially because the presence of a bike rack at a stop enhances biking accessibility to a transit stop by providing a location for riders to leave their bike if they either do not want to mount their bike on the bus or if mounting is not an option. "Structure" represents a physical structure built as part of the stop to provide shade for passengers. "VRT Green" refers to a vertical plant installation that provides direct shade, such as vines. Both Structure and VRT Green were considered to investigate the effectiveness of intentional installations for providing shade. Table 1 summarizes the stop characteristics and their variable type.

Table 1 - Summary of Tempe study region transit stop classification variables. Only Tempe transit stops in the study region were classified with these variables. This inventory of amenities includes 124 bus stops including 3 light rail stops for the given Tempe study region.



Variable Name	Variable Description	Variable Type
GREEN	Nearby level of greenspace (none, low, medium, high, very high)	Categorical
SHADE	Nearby level of shade (none, indirect, direct)	Categorical
MATERIAL	Dominant sidewalk or nearby pavement material (concrete, brick, other)	Categorical
BENCH	Presence of benches at stop	Binary
BIKERACK	Presence of bike racks at or near the stop	Binary
STRUCTURE	Presence of transit stop shade structure	Binary
VRT_GREEN	Presence of vertical greenery on stop structure	Binary
NEAR_COOL	Nearest public building that may provide air conditioning or act as a potential cooling center. Distance in feet rounded to nearest 10 feet.	Integer

1.2.4 GEOSPATIAL ANALYSIS

Geospatial analysis was performed to determine spatial linkages between various datasets obtained from Valley Metro, scientific literature and transit stop classification created by team members from photographic evidence for the purpose of in-depth analysis of bus stop amenities and infrastructure characteristics.

Data types and sources used for geospatial analysis:

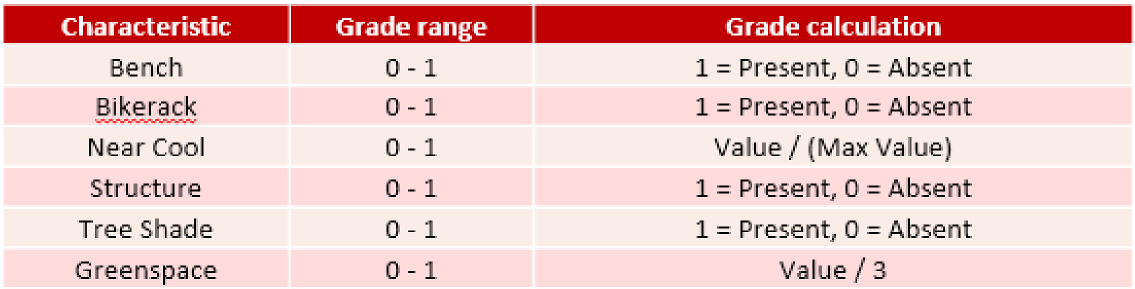
- Valley Metro bus and light rail stops locations and average daily ridership (2015-2016)
- Wait times estimates based on the Valley Metro schedule (Fraser and Chester, 2016)
- Vegetation estimates based on the stop photographs (sourced from Valley Metro GeoCenter database, 2017) characterization
- Shade level based on the stop photographs (sourced from Valley Metro GeoCenter database, 2017) characterization

Geospatial analysis included walk time to the nearest transit stop, average daily ridership, average wait time, vegetation and shade level for each stop.

1.2.5 HEAT VULNERABILITY INDEX

The next phase in the analysis of transit infrastructure and people's behavior regarding transit in the context of extreme heat was to develop a heat vulnerability index of all transit stops in the investigated region. This index combines the data obtained from the transit stop characterization and the transit survey to determine the degree of heat vulnerability at each transit stop. The goal of this index is to rank all transit stops based on their heat vulnerability to determine which stops are the most vulnerable to extreme heat. The stops were quantitatively rated based on the characteristics described in Section 2.3. For the vulnerability index, some characteristics studied in the stop characterization process earlier were determined to be irrelevant or difficult to account for. For example, the characteristic "pavement type" was excluded from this study because it was difficult to evaluate the impact of one particular material, since they are often used near each other. The characteristic "VRT Green" was omitted from the index because it was not mentioned in the transit rider survey, which prevented understanding ridership perspectives on this feature at transit stops. Table 2 lists each characteristic used and its associated rating range for stop vulnerability evaluation. As displayed below, in Table 2, all values range from 0 to 1. The acceptable ranges were purposely normalized to ensure that all characteristics have the same impact on overall stop vulnerability rating before incorporation of a weighting scheme to provide value to each characteristic. The normalization of results is very important for characteristics such as "Near Cool", which was scored based on distance to nearest cool location (in feet), which would have produced complications if the characteristic remained on a scale of 0-2080 ft, with 2080 feet being the longest distance to the nearest public cooling relief location. The characteristic "Greenspace" was slightly modified for the same reason. Tree shade and structure were separate characteristics that were created out of the characteristic "shading". The purpose of this was to better represent the types of questions presented in the survey to better represent transit rider values in the upcoming weighting scheme.

Table 2 - Characteristic grading scale for stop vulnerability index.



Characteristic	Grade range	Grade calculation
Bench	0 - 1	1 = Present, 0 = Absent
Bikerack	0 - 1	1 = Present, 0 = Absent
Near Cool	0 - 1	Value / (Max Value)
Structure	0 - 1	1 = Present, 0 = Absent
Tree Shade	0 - 1	1 = Present, 0 = Absent
Greenspace	0 - 1	Value / 3

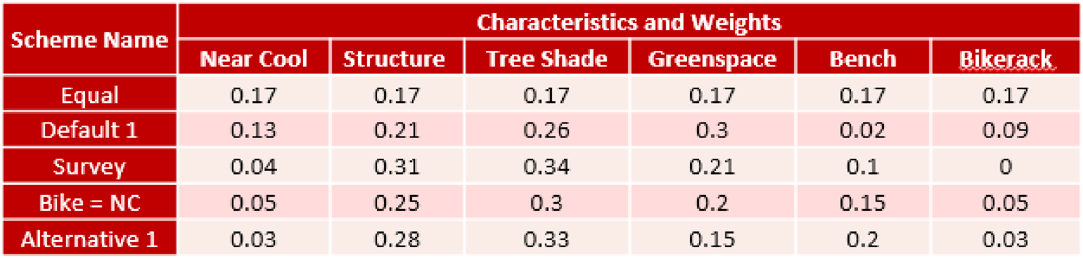
Several weighting schemes were developed to represent different perspectives and values on heat vulnerability. Each weighting scheme assigned a level of importance to each characteristic such that characteristics of greater importance have a larger impact on the vulnerability score of that stop. The objective of implementing multiple weighting schemes is to provide stop vulnerability rankings that are specific to different attitudes and thermal comfort perceptions on heat vulnerability. In addition, analyzing stop vulnerability form multiple perspectives will create more defensible results due to the variety of perspectives being considered. These results have the potential to be even more compelling if a set of stops are determined to be highly vulnerable, moderately vulnerable or not vulnerable under all weighting circumstances.

In order to calculate stop vulnerability rank, the stop characteristic grading scale and weighting schemes were combined is as follows:

- Establish grading scale for each characteristic (between 0 and 1).
- Multiply characteristic score by weighting value from given weighting scheme, summing. all categories for an overall score.
- Perform 1-result to determine most vulnerable stops.
- The higher the result, the less vulnerable it is.
- Repeat for each scheme to obtain ratings based on different perspectives.

Table 3 displays the five weighting schemes used to rank stop vulnerability. The scheme "Equal" gave an equal weight to all characteristics, so that each characteristic had an equal impact on stop vulnerability. The next scheme, titled "Default 1" was developed by the team members on what they collectively thought was most valuable for reducing heat vulnerability, which included high priority to green space and tree shade (for the urban heat island reduction abilities of plants) and very little importance on benches and near cool. The scheme "Survey" created a weighting scheme that reflected the results of transit rider survey performed by the entire class. The scheme "Bike = NC" was another scheme developed by the team in which they gave bike racks and distance to near cool an equally low weight and high value placed on shading mechanisms. The last scale, titled “Alternative 1” was another attempt by the team to create an alternative weighting that varied and could be compared to the previous schemes.

Table 3 – Final weighting schemes developed by the team members.



Scheme Name	Characteristics and Weights					
	Near Cool	Structure	Tree Shade	Greenspace	Bench	Bikerack
Equal	0.17	0.17	0.17	0.17	0.17	0.17
Default 1	0.13	0.21	0.26	0.3	0.02	0.09
Survey	0.04	0.31	0.34	0.21	0.1	0
Bike = NC	0.05	0.25	0.3	0.2	0.15	0.05
Alternative 1	0.03	0.28	0.33	0.15	0.2	0.03

1.3 RESULTS AND DISCUSSION

1.3.1 TRANSIT SURVEY RESULTS

One question from the Tempe transit survey was identifying transit stop characteristics that are perceived more favorably for cooling ability by transit riders. Specifically identifying which characteristics are of higher priority for keeping cool is important to justify further focuses in the analysis. Figure 4 shows a summary which elements were reported by transit riders as keeping them cool. Specifically, respondents favored shade structures and nearby trees heavily. Respondents were less likely to report benches, nearby grass, and nearby water as keeping them cool. These findings provide useful insight of which transit stop characteristics are important to the perceived thermal comfort and preference of transit riders. In other words, shade is very important specifically when provided directly by shade structures or tress, or when nearby trees offer shade. This is an important component that helps inform which characteristics may be influential in altering transit behavior.

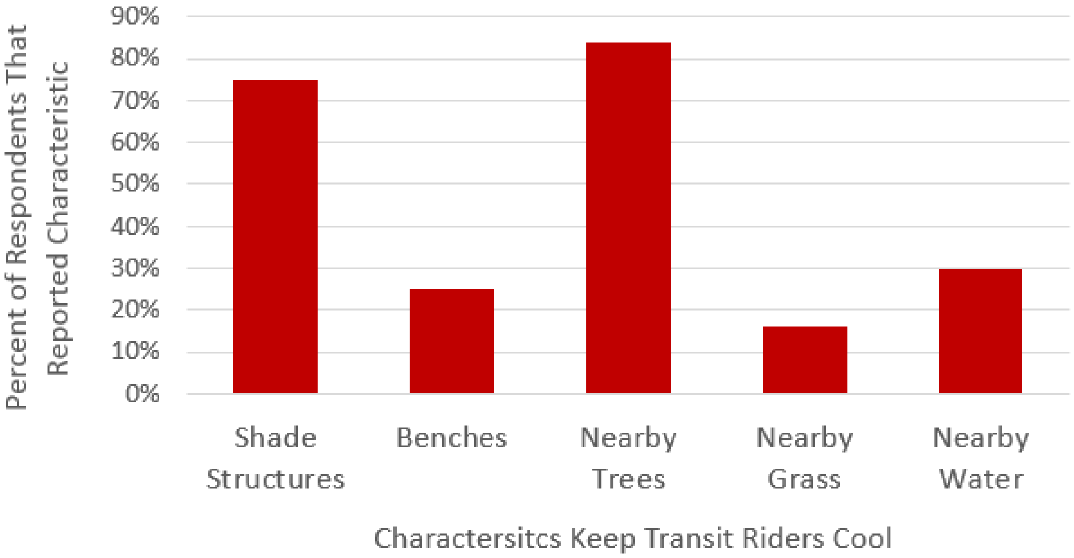


Figure 4 - Elements that Tempe Transit Rider Respondents Indicated Made Them Cooler. Note that respondents were allowed to choose as many elements as they felt kept them cool.

1.3.1.1 STUDY REGION WALK AND WAIT TIMES

To understand riders' heat exposure and travel behavior, walk times and wait times were analyzed. First, this was done by examining details of walking and wait times from the previously discussed Tempe transit survey. Table 4 shows walk and wait times in a matrix from the survey. Interestingly, 23 respondents had a combined walk plus wait time of 17-30 minutes and 6 respondents had a walk plus wait time of 22 minutes, minimum (Table 4 boxes outlined in red). Although this survey was conducted in over mid 80°F days in March 2017, the questions asked how long these activities typically took, therefore these behaviors may continue during extreme heat periods. Specifically, 8 respondents in these 17-minute minimum walk plus wait time category also indicated that they do not change behavior at all under extreme heat (while most others said they wait in shade, bring water, bring umbrellas, etc.). Through these results, it is clear that transit riders in Tempe – and potentially the greater Maricopa region – could be vulnerable to extreme heat due to high walk plus wait times to access transit.

Table 4 - Walk and wait times from Tempe transit survey.
Note that not all transit stops in Tempe or all stops within the study region were sampled.
Stops outlined by the red box are N = 88 total samples.

		Walk Time			
		1-5 minutes	6-10 minutes	11-20 minutes	Over 20 minutes
Wait Time	1-5 minutes	7	3	3	-
	6-10 minutes	23	8	6	1
	11-20 minutes	13	17	3	-
	Over 20 minutes	-	2	-	-

Walk time analysis for the whole study region was done to spatially identify regions that are potentially more isolated than others. This geospatial analysis assumed an average walk time of roughly 3 miles per hour (MPH) and assumed transit riders walking to a bus stop would follow along the road network. Figure 5 shows the spatial distribution of walk times to the nearest bus stop in the Tempe study region. Comparing the walk times to the nearest stop to the previously reported survey walk times shows that people report walk times much larger than the greatest times needed to walk from any point in the study region to a bus stop. In some cases (about 11 of the 88 respondents), their walk times to a Tempe bus stop were over double the longest walk time to the nearest stop estimated by Figure 5 (max of 5 minutes in the figure compared to at least 11 minutes for some in the survey). This indicates that transit riders are not commonly walking to the closest bus stop from their origin or perceive their walk to be longer than it actually is. Regardless of the actual reason why (and the likely possibility that both are contributing factors to higher reported walk times), this indicates that transit riders accessing stations are either vulnerable or not comfortable during hot periods of the day.

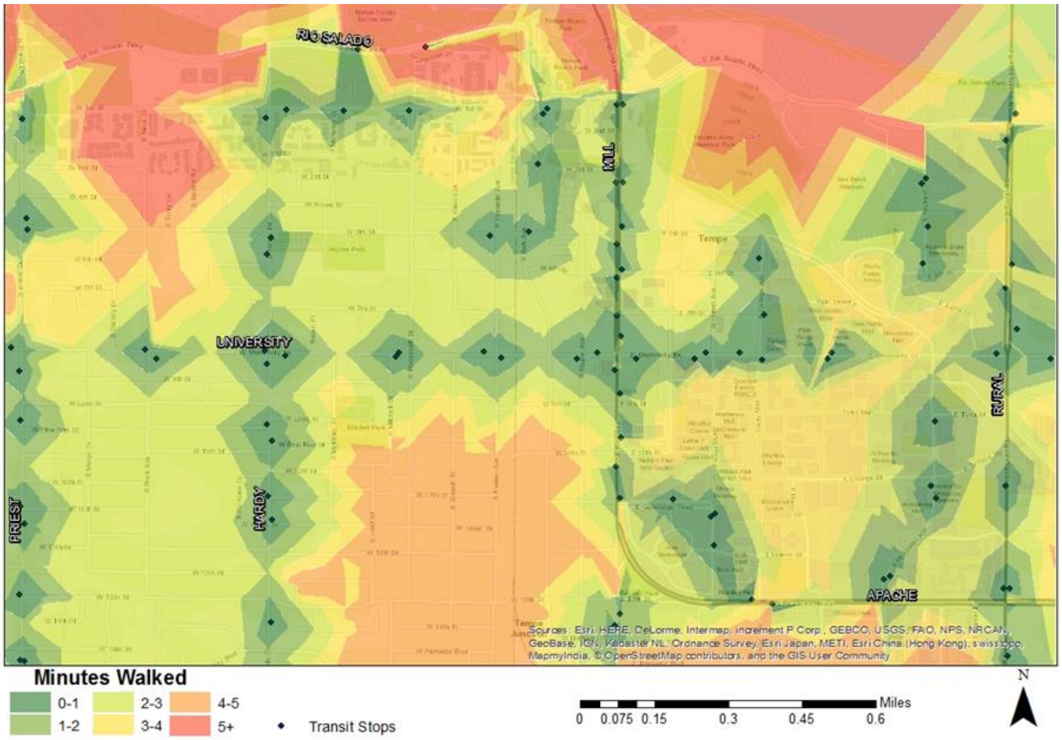


Figure 5 - Minimum Walk Time to Nearest Bus Stop in Tempe Study Region.
Note walk times are assumed to be ~3 MPH and follow road networks only (no shortcuts).

To examine wait times further, estimated wait time data from Fraser and Chester (2016) was combined with ridership data from Valley Metro in a geospatial analysis to assess if any stops may be more vulnerable due to high ridership and high wait times. Figure 6 shows the nexus of ridership and wait times at bus stops in the study region. There are no obviously high ridership stops with long average wait times. This is not surprising due to the fact that transit planning aims to serve high volume stops with more frequent vehicle headways. Although there are not any clearly vulnerable stops apparent in Figure 6, there are stops that have long wait times that may be more isolated when considering walk time access (Figure 5)

Specifically stops on W Rio Salado Pkwy, stops on University Dr near Beck Ave, Farmer Ave, and Maple Ave, and a stop at Priest Dr and 13th St. may be slightly more vulnerable due to moderate ridership and some longer than average wait times. However, the bus stops with the longest average wait times have among the lowest average ridership.

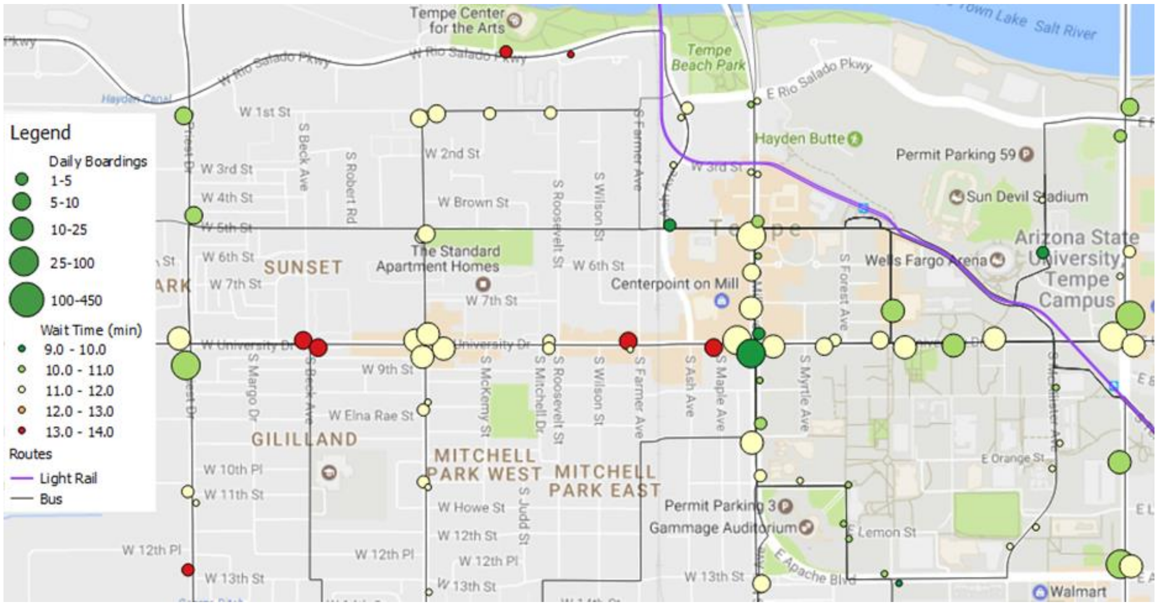
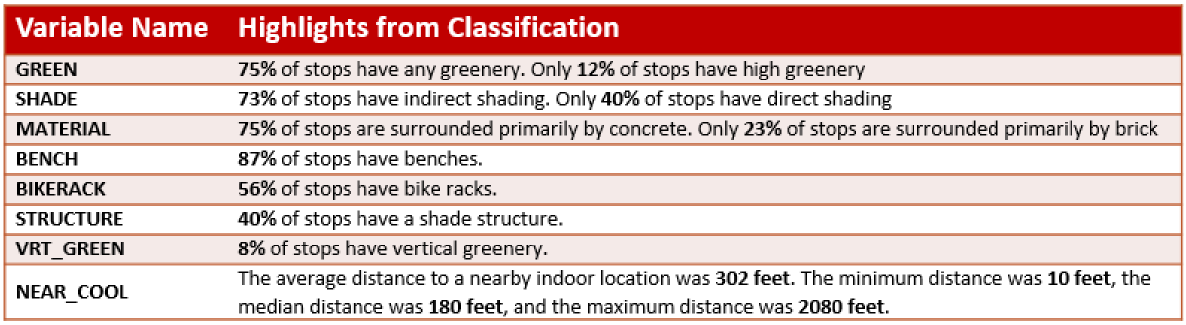


Figure 6 – Daily Bus Stop Ridership versus Average Daily Estimated Wait Time. Daily ridership correlates to the size of each bus stop node (note the scaling is non-linear due to the high variance in daily ridership within the region) and wait times correlate to the color intensity of the nodes (red is high wait time, yellow around average wait time, and green is low wait time).

1.3.1.2 VALLEY METRO BUS STOP CHARACTERIZATION CLASSIFICATION RESULTS

A summary of Tempe Transit stops amenities is summarized in Table 5. From these 124 transit stops, 75% stops are adjacent to some greenery whereas the remaining 12% provide little to no greenery, which may be concerning since vegetation is known to alleviate ambient temperatures. The analysis also found that about 27% transit stops lack significant shading (either absence of shade structure, canopy shade or indirect shading from nearby structures/buildings) based on the classification method. Table 5 indicates that concrete is the most common material used at transit stops, followed by brick and asphalt. Although concrete might be the primary material, a transit stop may lie in the center of a highly urbanized space where asphalt may intensify the ambient heat. Most transit stops within the study region have benches and 56% of stops had nearby bike parking. Table 5 also conveys the distribution of distance to the nearest indoor space that may serve as a cooling refuge. The average distance to a public space is 302 feet (0.06 miles), with a minimum and maximum of 10 feet and 2080 feet (0.4 miles) respectively. Thus, transit stops within the study region tend to be less than 0.5 miles away from a public cooling space. However, the study area focuses mostly on Downtown Tempe and ASU Tempe, which is considered denser than the rest of Tempe in terms of public facilities. Moreover, the accessibility of some of these public spaces may change with the season as campus buildings, stores, restaurants etc. change hours in response to students leaving in summer.

Table 5 - Highlights of Tempe Study Region Transit Stop Characteristics and Amenities.
Only Tempe transit stops in the study region were classified with these variables.



Variable Name	Highlights from Classification
GREEN	**75%** of stops have any greenery. Only **12%** of stops have high greenery
SHADE	**73%** of stops have indirect shading. Only **40%** of stops have direct shading
MATERIAL	**75%** of stops are surrounded primarily by concrete. Only **23%** of stops are surrounded primarily by brick
BENCH	**87%** of stops have benches.
BIKERACK	**56%** of stops have bike racks.
STRUCTURE	**40%** of stops have a shade structure.
VRT_GREEN	**8%** of stops have vertical greenery.
NEAR_COOL	The average distance to a nearby indoor location was **302 feet.** The minimum distance was **10 feet**, the median distance was **180 feet**, and the maximum distance was **2080 feet.**

1.3.1.3 VALLEY METRO RIDERSHIP AND BUS STOP CHARACTERISTICS

To determine if any stops may be classified as vulnerable due to the combination of high volume of passengers per day and the lack of thermal comfort characteristics, two more geospatial analysis were done similar to the analysis in Figure 6. Based on the survey results, nearby trees and shade structures were the most commonly favored characteristics to keep riders cool. Additionally, according to the field thermal imaging by other members in this study, trees and shade structures also provide the highest level of surface temperature heat relief. As such, the two characteristics "level of greenery" and "level of shade" at each stop was compared with daily ridership for each bus stop in the study region to understand the relationships and potentially identify if any stops my be more vulnerable. In Figure 7, daily bus ridership is shown versus level of greenery for each stop in similar fashion to Figure 6. Many of the stops with the highest ridership also have medium to very high nearby vegetation. When looking for specific stops that lack greenery with higher ridership, there are no obvious stops to hone in on (similar to Figure 6). It is clear that most bus stops near ASU campus have moderate to high greenery surrounding them. However, there are stops that lack greenery, and they commonly intersect with stops that also have higher wait times. All stops on W Rio Salado Pwky have no greenery nearby, and many stops on the south side of Priest Dr and Hardy Dr also lack greenery. In Figure 8, daily bus ridership is displayed with level of shade for each bus stop in the study region. Following similar trends as Figure 6 and Figure **7**, the highest ridership stops are most likely to have direct or at least indirect shade. Yet again, many low ridership stops also commonly have indirect and no shade, and many of these stops also were previously identified to commonly lack greenery and have higher wait times. All stops on W Rio Salado lack shade, and the same group of stops mentioned above on the south side of Priest Dr and Hardy Dr also lack shade.

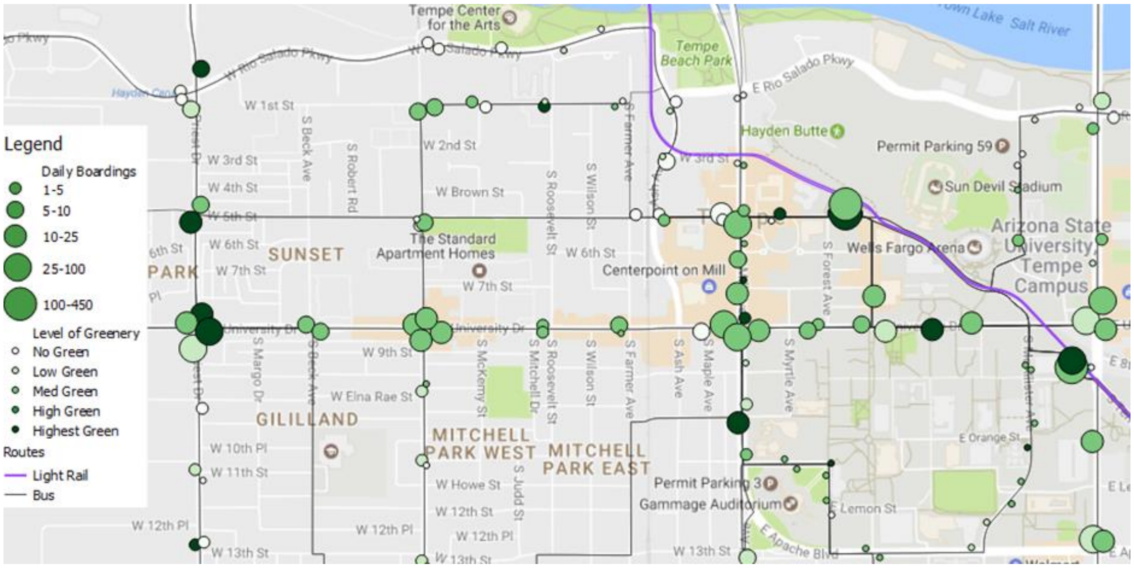


Figure 7 – Daily Bus Stop Ridership versus Level of Greenery.
Daily ridership correlates to the size of each bus stop node (note the scaling is non-linear due to the high variance in daily ridership within the region) and level of greenery correlates to the color intensity of the nodes (off-white is no greenery, and dark green is the highest greenery).

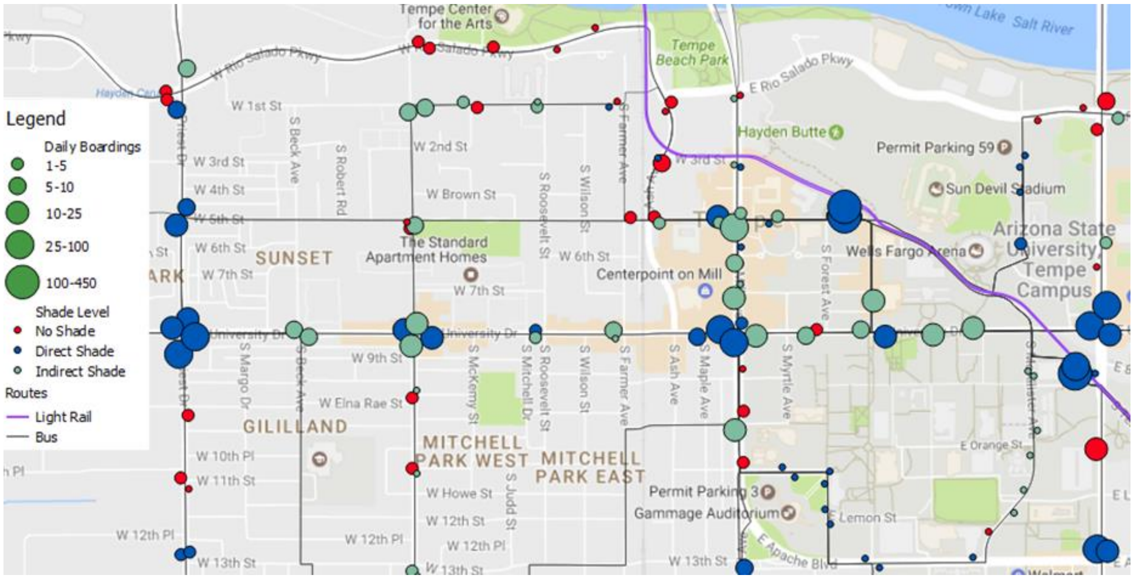


Figure 8 – Daily Bus Stop Ridership versus Level of Shading.
Daily ridership correlates to the size of each bus stop node (note the scaling is non-linear due to the high variance in daily ridership within the region) and level of shading correlates to the color of the nodes (no shade is red, indirect shade is gray, and direct shade is blue). Direct shade is defined shade from a shade structure or trees directly at the stop.

Although it is apparent that the Tempe study region has high transit coverage—many stops with adequate shading, greenery, and wait times—there are many stops that lack all three of these crucial characteristics. Stops such as those on W Rio Salado, South Priest Dr, South Hardy Dr, and some stops on University Dr are stops that have higher vulnerability to extreme heat, however, they also serve a lower volume of passengers. The specific stops identified as potentially more vulnerable from the geospatial ridership analysis are highlighted in Figure 9.

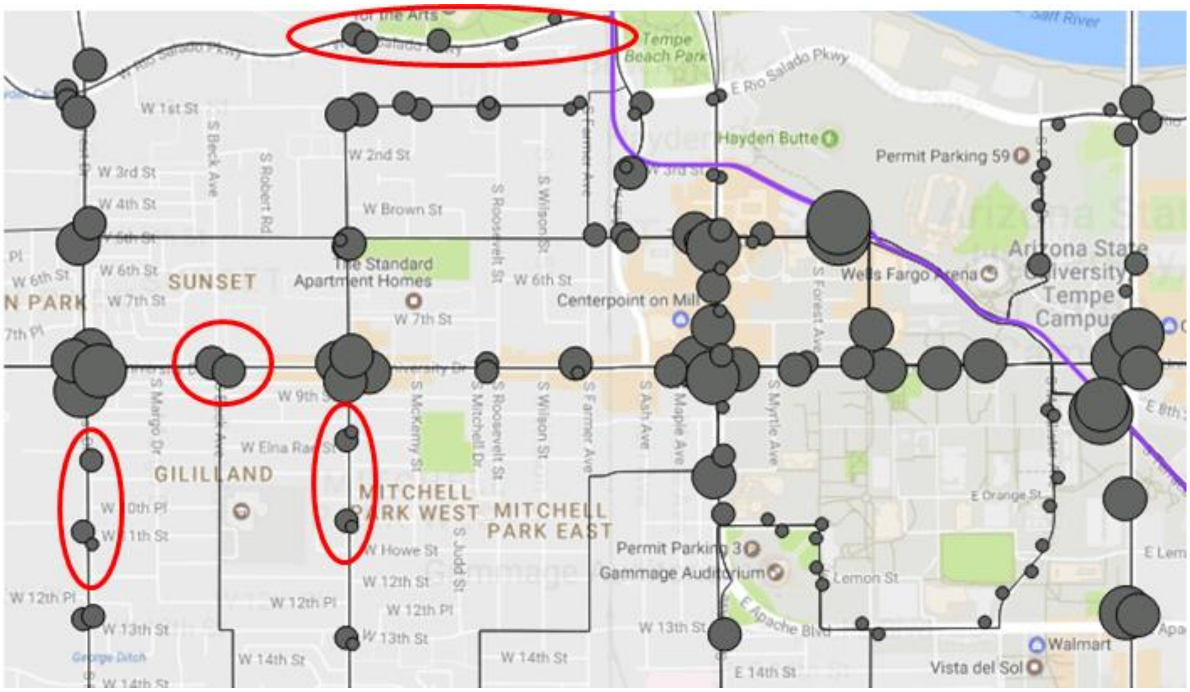
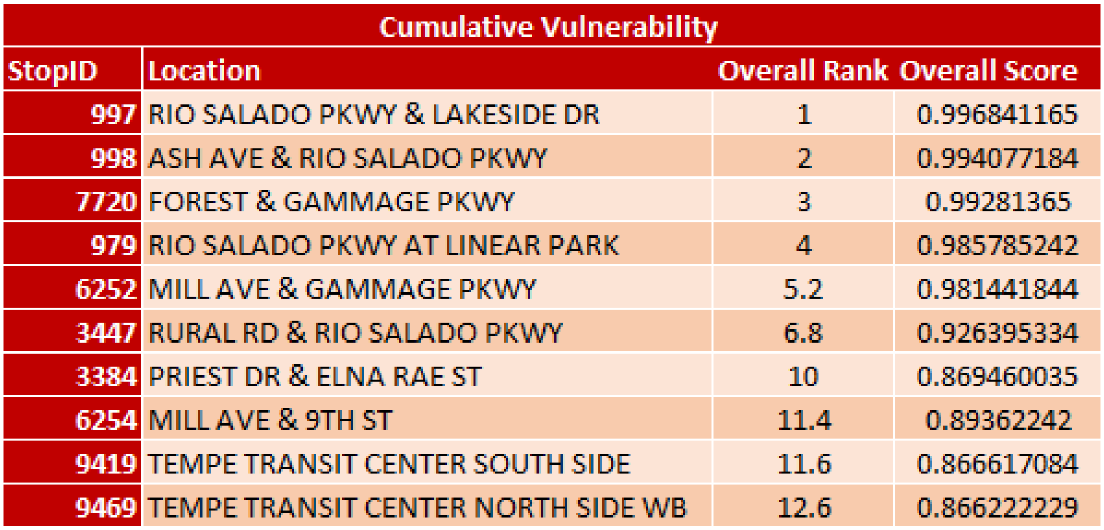


Figure 9 – Stops Identified as Potentially More Vulnerable Due to Lack of Thermal Comfort Characteristics.
No legend is included but note that the same legend from the previous three figures still applies except the color schemes.

1.3.2 HEAT VULNERABILITY INDEX

Table 3 outlines the rankings of transit stops under the various weighting schemes developed for this index. The creation of multiple weighting schemes was an attempt at performing a sensitivity analysis of stop vulnerabilities to extreme heat. It was determined that some form of sensitivity analysis was necessary to produce stop vulnerability results that were defensible. The sensitivity analysis or creation of a heat vulnerability index was necessary given that none of the team members were experts in perceived or actual heat vulnerability. By analyzing transit stop vulnerability from multiple perspectives, it enables the reader to isolate results that align with their values (for instance, Valley Metro's perspectives on potential transit stop improvements). More importantly though, combining the stop rankings from multiple schemes has the potential to provide even more powerful results in the event that certain stops score either very poorly, very highly or average across all weighting schemes. As it turned out, this was the case. There were a handful of stops that scored extremely vulnerable across all ranking schemes. These stops are Rio Salado Pkwy & Lakeside Dr, Ash Ave & Rio Salado Pkwy, Forest & Gammage Pkwy, Rio Salado pkwy at Linear Parl, Mill Ave & Gammage Pkwy. Ten stops with highest vulnerability score across all weighting schemes are identified in the Table 6 below. Table 7 shows 10 most vulnerable stops per each weighting scheme.

Table 6 Ten stops with highest vulnerability score across five weighting schemes.



Cumulative Vulnerability			
StopID	Location	Overall Rank	Overall Score
997	RIO SALADO PKWY & LAKESIDE DR	1	0.996841165
998	ASH AVE & RIO SALADO PKWY	2	0.994077184
7720	FOREST & GAMMAGE PKWY	3	0.99281365
979	RIO SALADO PKWY AT LINEAR PARK	4	0.985785242
6252	MILL AVE & GAMMAGE PKWY	5.2	0.981441844
3447	RURAL RD & RIO SALADO PKWY	6.8	0.926395334
3384	PRIEST DR & ELNA RAE ST	10	0.869460035
6254	MILL AVE & 9TH ST	11.4	0.89362242
9419	TEMPE TRANSIT CENTER SOUTH SIDE	11.6	0.866617084
9469	TEMPE TRANSIT CENTER NORTH SIDE WB	12.6	0.866222229

Table 7– Ten stops with highest vulnerability score per each weighting scheme.

Equal			
Rank	StopID	Location	Score
1	997	RIO SALADO PKWY & LAKESIDE DR	0.99359
2	998	ASH AVE & RIO SALADO PKWY	0.987981
3	7720	FOREST & GAMMAGE PKWY	0.985417
4	979	RIO SALADO PKWY AT LINEAR PARK	0.971154
5	6252	MILL AVE & GAMMAGE PKWY	0.96234
6	3447	RURAL RD & RIO SALADO PKWY	0.933226
7	3327	PRIEST DR & UNIVERSITY DR	0.887687
8	5196	1ST ST & HARDY DR	0.886405
9	6091	MILL AVE & UNIVERSITY DR	0.877831
10	7607	MILL AVE & 5TH ST	0.871261

Default 1			
Rank	StopID	Location	Score
1	997	RIO SALADO PKWY & LAKESIDE DR	0.99509
2	998	ASH AVE & RIO SALADO PKWY	0.990794
3	7720	FOREST & GAMMAGE PKWY	0.98883
4	979	RIO SALADO PKWY AT LINEAR PARK	0.977905
5	3384	PRIEST DR & ELNA RAE ST	0.975164
6	6252	MILL AVE & GAMMAGE PKWY	0.971154
7	9419	TEMPE TRANSIT CENTER SOUTH SIDE	0.970745
8	9469	TEMPE TRANSIT CENTER NORTH SIDE WB	0.970131
9	3468	UNIVERSITY DR & PALO VERDE DORMS	0.952332
10	3447	RURAL RD & RIO SALADO PKWY	0.892117

Table 7– Continues

Survey

Rank	StopID	Location	Score
1	997	RIO SALADO PKWY & LAKESIDE DR	0.998411
2	998	ASH AVE & RIO SALADO PKWY	0.99702
3	7720	FOREST & GAMMAGE PKWY	0.996384
4	979	RIO SALADO PKWY AT LINEAR PARK	0.992848
5	6252	MILL AVE & GAMMAGE PKWY	0.990663
6	3447	RURAL RD & RIO SALADO PKWY	0.928348
7	6254	MILL AVE & 9TH ST	0.911859
8	3384	PRIEST DR & ELNA RAE ST	0.895542
9	5194	UNIVERSITY DR & COLLEGE AVE	0.895105
10	3511	UNIVERSITY DR & MILL AVE	0.894708

Bike = NC

Rank	StopID	Location	Score
1	997	RIO SALADO PKWY & LAKESIDE DR	0.998077
2	998	ASH AVE & RIO SALADO PKWY	0.996394
3	7720	FOREST & GAMMAGE PKWY	0.995625
4	979	RIO SALADO PKWY AT LINEAR PARK	0.991346
5	6252	MILL AVE & GAMMAGE PKWY	0.988702
6	3447	RURAL RD & RIO SALADO PKWY	0.929968
7	6254	MILL AVE & 9TH ST	0.910016
8	3327	PRIEST DR & UNIVERSITY DR	0.866306
9	5196	1ST ST & HARDY DR	0.865921
10	6091	MILL AVE & UNIVERSITY DR	0.863349

Alternative 1

Rank	StopID	Location	Score
1	997	RIO SALADO PKWY & LAKESIDE DR	0.999038
2	998	ASH AVE & RIO SALADO PKWY	0.998197
3	7720	FOREST & GAMMAGE PKWY	0.997813
4	979	RIO SALADO PKWY AT LINEAR PARK	0.995673
5	6252	MILL AVE & GAMMAGE PKWY	0.994351
6	3447	RURAL RD & RIO SALADO PKWY	0.948317
7	6254	MILL AVE & 9TH ST	0.938341
8	3327	PRIEST DR & UNIVERSITY DR	0.89982
9	5196	1ST ST & HARDY DR	0.899627
10	6091	MILL AVE & UNIVERSITY DR	0.898341

1.4 CONCLUSION

This research investigated infrastructure characteristics of public transit stops, availability of shading, wait and walk times to determine the average heat vulnerability of stops and to identify the stops that are at higher risk than others. Several quantitative and spatial analysis methods were used to verify the results.

Results showed that majority of the stops have direct or indirect shade and they are also the stops with higher daily ridership located at intersections. Unshaded stops are located in-between the intersections with daily ridership not exceeding 10 people, with the exception of the stop at Rural Rd & Terrace Rd with up to 22 riders a day. Similarly, stops with higher ridership and shade availability have medium to high level of greenery and are also associated with shorter wait times. There is not enough information to determine the direction of causality between ridership at stops and the presence of preferred amenities. It seems intuitive that Valley Metro and the City of Tempe would prioritize developing (or initially providing) amenities at stops that have (or are predicted to have) high ridership. Spatial analysis of walk times showed that majority of the stops are within 5 min reach. However, 13% of surveyed transit riders reported their walk time to be twice as long. Considering this difference in walk times, it is certainly plausible that riders could choose a stop with more amenities, or even plan their trips such that they are more commonly at better shaded or cooled stops. Future research should aim to confidently identify the direction of causality between ridership and stop amenities for regions with extreme temperatures, which likely also would require higher temporally resolute data.

It is apparent that stops along W Rio Salado Pwky, Priest Dr and Hardy Dr are more vulnerable based on the infrastructure and wait time characteristics. However, these stops have low ridership level which means that fewer people would get exposed overall. The limitations of this study did not allow to establish route and cause relationships between ridership, wait times and available infrastructure, thus, it is recommended to further investigate this stops and identify the need for improvement.

2 CHAPTER II: EXPOSURE

Extreme heat events are associated with increased morbidity and mortality. This is especially concerning as all climate models indicate the Earth's temperature will continue to rise and as the temperature increases, extreme heat events will become more frequent, more severe, and longer lasting. This poses an issue specifically in Maricopa County due to its location in the arid southwest and the additional issues associated with heavy urbanization such as the urban heat island effect. The heightened temperatures leave a large portion of the citizens in the county vulnerable to heat related illnesses and deaths. In particular, during the summer months, non-automotive transit users in the Phoenix metro area are especially vulnerable to heat. In combination with a lack of regional connectivity and disjointed planning of transportation networks, transit and transportation users are likely to have major parts of their travel experiences that require non-voluntary exposure to heat. Building from previous as well as new research, this paper quantifies the thermal dynamics and characteristics of transit stops and transit stop components of the Valley Metro bus system. This was accomplished through field-based observations of surface and air temperatures of Valley Metro transit stops in Tempe, AZ. It was found that green infrastructure paired with shaded structures provided the greatest protection from the heat.

2.1 INTRODUCTION

More than half of the world's population lives in cities, where the combined effect of urban heat island and summer time extreme heat events exacerbate already high levels of heat related morbidly and mortality. Extreme heat is a leading cause of weather related human mortality in the United States. Heat exposure is a complex problem for major urban areas. In the arid southwest, extreme atmospheric heat combined with phenomena like the urban heat island effect can produce challenges for urban planners and city managers. In particular, during the summer months non-automotive transit/transportation users in the Phoenix metro area are especially vulnerable to heat. This is due in part to the absence of extensive cooling or shade features or corridors in the Phoenix region. In combination with a lack of regional connectivity and disjointed planning of transportation networks, transit and transportation users are likely to have major parts of their travel experiences that require exposure to heat.

There are several previous studies on extreme heat and human health that have estimated threshold temperatures where negative health outcomes become prevalent (Hajat et al., 2006, McGregor et al., 2007), as well as developed heat preparation plans (EPA 2006), and identify vulnerable groups within the population (Harlan et al., 2013). While these approaches offer useful information about the geographic distribution of potentially vulnerable 'hot spots' in a study region, they are limited in specifying what components of transit infrastructure mitigate or exacerbate heat exposure. Karner et al. (2015) illustrates the heat exposure risk for pedestrians in the Bay area giving some insight into conditions that urban transit users might be more generally experiencing. Additionally, links between extreme heat and adverse health outcomes (morbidity or mortality) are well documented in the literature (Hartmann et al. 2013, similar studies). An analysis performed by Mills et al. reveals that mortality from weather related illnesses are projected to increase due to extreme weather events increasing in frequency and number (Mills et. al., 2015). Further, there is an important equity dimension to heat vulnerability and heat exposure– populations (often low socioeconomic status, elderly age along with isolation, or non-vegetated areas) that are most vulnerable to heat are also most likely to need to rely on non-automotive transit for their travel behavior (Harlan et al., 2013). As such, non-automotive transit experiences are likely the represent the most significant amount of non-voluntary heat exposure for many urban residents, particularly those from more vulnerable demographics.

A key step in generating solutions to the problems of heat, health, and transit-necessitated heat exposure is to understand what the actual thermal characteristics of transit experiences are. In reviewing previous research to date, efforts by ASU researchers and ValleyMetro were found to be largely focused on modeling or simulation approaches (ASU College of Design). However, these are insufficient as heat experiences are often a combination of a number of context- or site-specific environmental and psychological variables not adequately captured in modeled approaches. Additionally, other research to date in Phoenix has shown that research about infrastructure or city functioning such as transit systems in other major US or world cities may not translate well due to the unique arid land climactic conditions of this region (Weller et al. 2016). As an example, the Tres Rios Tertiary Wastewater Treatment Wetlands has been demonstrated by researchers in the Central Arizona Phoenix Long Term Ecological Research (CAP LTER) program to exhibit unique hydrologic processes relative to other treatment wetlands in more traditional, mesic settings (Weller et al., 2015). Importantly, these unique processes are driven by the incredibly hot, arid climate (Bois et al., 2017). The need to understand the unique contributions of Phoenix's climate to person-based heat experiences during transit use is especially pressing given that climate change will likely exacerbate existing issues related to heat morbidity and mortality (Transportation Research Board, 2008; Hondula et al., 2015).

2.1.1 RESEARCH QUESTIONS

As such, the primary goal in conducting this research is to advance the resolution of the scientific community's understanding of the thermal characteristics of transit infrastructure. Specifically, this study sought to quantify surface and air temperatures of transit stops and transit stop components in the Phoenix metro area. Further, it seeks to understand the relationship between perceived and actual temperatures at transit stops. The corresponding research questions are as follows:

1. What are the surface and air temperatures of transit stops and transit stop components in the Valley Metro bus system?
2. What are the impacts of heat mitigation features (e.g. shade) on the surface and air temperatures of transit stops and transit stop components?
3. What are the differences between the perceived and actual heat relief provided by heat mitigation features at transit stops?

To answer these questions, a field-based approach was proposed in order to quantify thermal characteristics of transit stops and transit stop components. The use of instrumentation in the field will allow for a better approximation of the exact conditions that transit users will experience during transit-related travel activities.

2.1.2 EXPERIMENTAL DESIGN

Field measurements of different types of surfaces and the air temperatures of Valley Metro stops were taken for better understanding of personal heat exposure. The study region is bounded by S Priest Drive and Dorsey Lane to the west and east respectively, and Rio Salado Dr and Apache

Blvd to the north and south, respectively. A geographic representation of the study area can be seen in Figure 10.

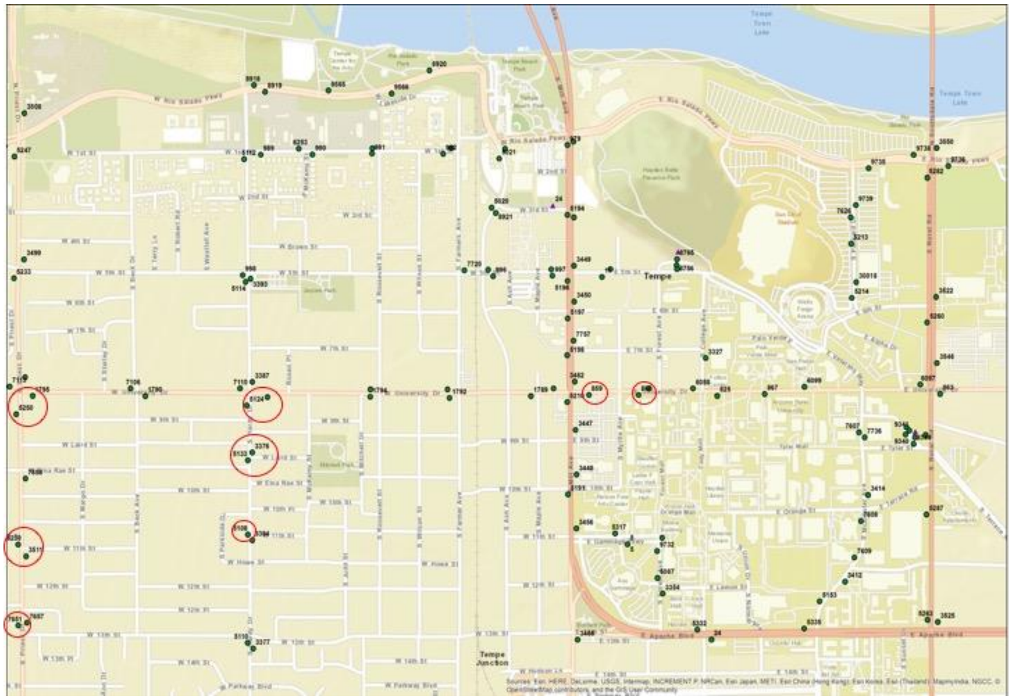


Figure 10 Map of study region. Green dots represent ValleyMetro stops contained within the study region.
Red circles denote the 13 stops analyzed in this research.

The study area contained approximately 120 Valley Metro transit stops. However, within the scope of this project, bus stops were specifically focused on. Within the study area, 13 bus stops were identified which represent every possible configuration of transit stop features and components in the Valley Metro transit system. These include unshaded bus stops, bus stops with "gray" shade infrastructures (e.g. metal roof), bus stops with "green" shade infrastructure (e.g. trees), and so on. In addition, these 13 stops overlap with stops that were identified as vulnerable or needing particular attention by the Travel Behavior researchers in this course. While earlier iterations of this research proposed more spatially-oriented analytical approaches (e.g. transect-based surveys), a site-based approach was utilized instead. Importantly, this decision was made in order to prioritize the capture of all possible transit component configurations at a select number of stops. This will allow the data and analysis to be broadly applicable and scalable to any bus transit stop in the Valley Metro system that features stop components observed in this study. Field research was conducted during Spring 2017. Specifically, all field observations were made during March and April 2017. Further, field observations were taken between 1PM and 4PM to capture peak daytime temperatures.

One of the issues with the given sampling season is that the impacts of maximum annual temperatures or extreme heat events were unable to be analyzed. The data and analysis is constrained to this time frame. However, since data were collected during peak daytime temperatures, it can be further analyzed for extreme summer temperatures. The 13 stops were then categorized using a variety of different metrics to classify the stops components based on the materials, presence and absence and percent coverage. Further, each of the 13 stops were identified by the unique 5-digit stop site ID numbers determined by Valley Metro to ensure consistency in site identification between all project groups of the UIA class. After identifying the stops, the thermal imaging photos and temperatures were taken in March and April 2017 during peak hours for better representation of summer time using infrared imaging (FLIR Exx Series Infrared Camera) at a consistent distant (3m radius) from each transit configuration to capture the overall range of these stops as well as each component’s temperatures.

2.2 METHODS

To address research questions 1 and 2, field-based approaches were utilized to quantify the various thermal dynamics of transit stops identified in the experimental design. To address research question 3, the field data was analyzed in conjunction with data gathered via the course travel survey (as explained and identified by other project groups) to understand what heat mitigation techniques are most effective.

- *Travel Survey Methods*

UIA researchers administered travel surveys at different bus stops within the scope of the project. There were ten questions that were asked. In order to receive responses free of any bias, each of the survey takers were able to fill out the form on their own using a pen. This data was then further organized using Google forms where all of the responses were consolidated by the UIA researchers. The survey and its associated questions can be seen in Appendix A and Appendix B.

- *Field Methods*

Field surveys of the 13 transit sub-sites identified previously in the experimental design were conducted. During field surveys, the goal was to capture three primary types of data: metadata, thermal data, and classifications of stop features. The metadata consisted of data that would help situate and provide context for the field measurements and thermal images in time and space: these included timestamps, locations, transit stop ID's, and other relevant information collected at the time of sampling. The thermal data consisted of thermal characteristics of transit stops as captured by two field instruments: a FLIR Exx Series Infrared Camera, and a NCEon SMART Environmental Meter (further known as environmental meter). Finally, in order to relate thermal data to configurations of transit stops, the features of each transit stop were classified. This classification scheme was designed similarly to the scheme utilized by Group 1 (Travel Behavior) to strengthen synergies between the datasets. Transit stop components were classified based on material, presence/absence, and/or percent coverage dependent on the particular component in question. See Table 8 for details. Importantly, this schema was extended to all features within a 3m radius of the centermost point of the stop. Distances were measured in the field using a Keson 165ft/50.2m fiberglass measuring tape. This was done to ensure that the data and surveys captured the transit stop features that are most likely to have a direct impact on heat experiences of transit users at the stop.

Table 8 – Classification scheme for transit stop components and materials.

Stop Component	**Classification**
Pavement	Concrete, brick, asphalt
Seats	Concrete, metal, plastic
Landscaping	Xeric (rocks/dirt), mesic (grass)
Shading	Shade structure, direct tree shading, indirect tree shading

Protocol for a typical sampling of one of the sub-sites would look as follows. Upon arrival to the site, researchers power on all equipment and field instruments. During instrument warm-up, researchers would conduct the classification of stop features, writing down observations in a field notebook. The environmental meter was held by a researcher at the centermost location of the transit stop (defined as the location of the signpost denoting stop location and information). Ambient air conditions (air temperature, relative humidity) would then be recorded in the field notebook as observed through the environmental meter. Finally, a series of infrared photos were taken using the FLIR camera. The first photo of each stop was an overview shot, taken while standing approximately 10m from the stop. This would ensure that all features of the stop would be captured in one image. Subsequent photos are then taken of each individual component of the transit stop (pavement, seats, trees, grass, etc.). These feature-specific photos were taken from much closer distances that allowed the crosshairs on the FLIR camera to target the feature directly to capture the surface temperatures. If a feature was present in both open sunlight some form of shade, then each variation (shaded/unshaded) was captured independently. Finally, the FLIR camera produces two images simultaneously upon pulling the trigger – a normal photo and an infrared thermal image. As each photo was taken, the image IDs were recorded as metadata in the field notebook to provide context and ease of identification for both the normal and corresponding thermal images.

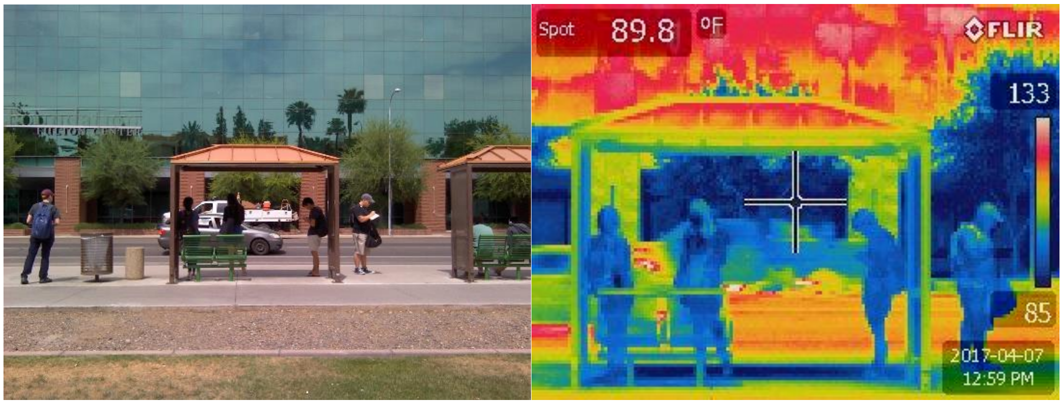


Figure 11 - Example of thermal image + corresponding normal image.
Taken with FLIR Exx Series Infrared Camera.

A proposed component of the field analysis involved the use of iButtons to capture the impacts of transit infrastructure interactions on personal heat experiences. This data collected by Spring 2017 UIA course students was initially proposed to be utilized. These iButtons would have provided air temperature and relatively humidity measurements recorded at 5 minute intervals throughout transit interactions. In addition, students also recorded corresponding information about location, activity, and heat-related factors that provided context for raw iButton data. However, a significant challenge encountered was from an informal survey of course members (and a review of personal data of members of this group) it became apparent that very few transit interactions were recorded by iButtons or in corresponding travel diaries. As such, this sample size was deemed too small to be considered useful. A second challenge encountered was that microclimate data (i.e. air temperature and relatively humidity) were not consistently recorded during each site visit. As such, the data for microclimate at each transit stop were relatively limited compared to other field measurements.

- *Data Analysis*

Data collected in the field were promptly entered into a spreadsheet for archival and analysis. Field data and observations recorded in field notebooks were transcribed into this spreadsheet. Thermal images were extracted from the FLIR camera via USB, categorized by the subject of the image (overview, seat, pavement), and stored into corresponding folders. This choice to organize photos by image subject was done as an extension of the experimental design – by compiling photos that all feature the same stop components, a database was created of thermal images and thermal data for a variety of stop components in a variety of conditions and configurations.

After data transcription, extraction, and QAQC, data were analyzed using a variety of tests, statistical analyses, and graphical renderings. To answer Research Question 1, observations were sorted by stop component, then by shade type, and then averaged all surface temperature readings for observations with the same component and shade type. Standard error was also calculated. This created a dataset of average surface temperatures for each stop feature as they existed in each of the four shade classifications utilized. To answer Research Question 2, multiple linear regression models were run utilizing the R statistical package (CRAN 2017). The regression models were set up so that surface temperature was tested against each of the factors recorded in the classification of travel stops, such as stop shade type, percent green cover, etc., as well as combinations of these factors. These models were designed to tease apart the significant and/or dominant drivers of the variation in temperatures measured. Finally, to answer Research Question 3, data was extracted from the travel survey responses which captured transit users perceptions related to heat experiences at transit stops. Specifically, responses to the travel survey questions 6 and 7 were investigated for the purposes of this study. Question 6 asked, "Is there a temperature at which you would be uncomfortable waiting at or traveling to a transit stop, and if so what is it?" Questions 7 asked, "Do any of these elements make you feel cooler? Select all that apply." The question then listed out a number of options such as, nearby trees, nearby grass, shade structure, nearby water, nearby shrubs, or cool breeze. Respondents' answers were binned based on similarities in answers and then number of responses for each answer type was evaluated as a percent of all total survey responses for that specific question.

2.3 RESULTS AND DISCUSSION

- Thermal Imaging Database

All of the thermal images taken for this project were organized in a thermal image database created by the Exposure Team. Thermal images were classified and organized according to the particular feature (seating, shade structures, etc.) that is the subject of the photo, and about which the camera captured thermal image. This database is currently located within the UIA course Box folder, however, these images will be made into a publicly accessible repository in the future. This database of thermal images has been structured to allow future work, both within and beyond the scope of this particular UIA course section, to expand on these initial results.

- Climate & Heat Dataset

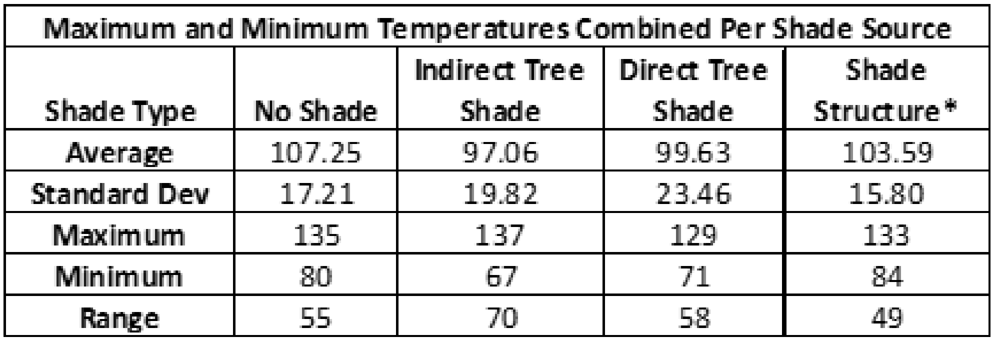
A dataset of temperatures extracted from raw thermal imaging files, along with corresponding time, location, and climate data were collected for each of the bus stops explored. The metadata identifies when the photo was taken, the researchers who were involved in taking the photo, the transit mode that the stop represents, the unique image ID and thermal image id, and what the subject of the photo is. Each photo in the thermal imaging database has been given an individual sample ID number. All of the sample ID's are easily identified by other observers/researchers for their respective stops and attributes due to that each sample ID has a corresponding Stop ID and NextRide ID that have been cross-referenced from Valley Metro's database of stops.

Within the thermal image, there was a timestamp, as well as readings of image subject surface temperature (°F), and a range of minimum and maximum temperatures within the photo (°F). At the time of the images being taken, the existence of shade as well as the type of shade was recorded. Each thermal image taken in the field was organized in categories based on the transit feature that is subject of each photo. These include the following possible subjects: overview shots, pavement/flooring, grass, stop structures (walls, poles, etc.), and heat mitigation features (built or green shade components). This was done to ensure that current and future research would be able to analyze the comparative surface temperatures of various transit components (overview photos), in addition to the variability in surface temperature profiles of individual stop features (various other subject photos). In addition to photo-specific data, an catalog was created of heat-related stop features at each sampling site (e.g. transit stop) where images were taken. Importantly, the classification scheme for this catalog was designed to align with the stop classification scheme utilized by UIA Spring 2017 Group 1, enabling potential synergies between the biophysical data and the behavioral data. See Appendix B for a complete metadata package.

2.3.1 EXPOSURE – RESEARCH QUESTION 1

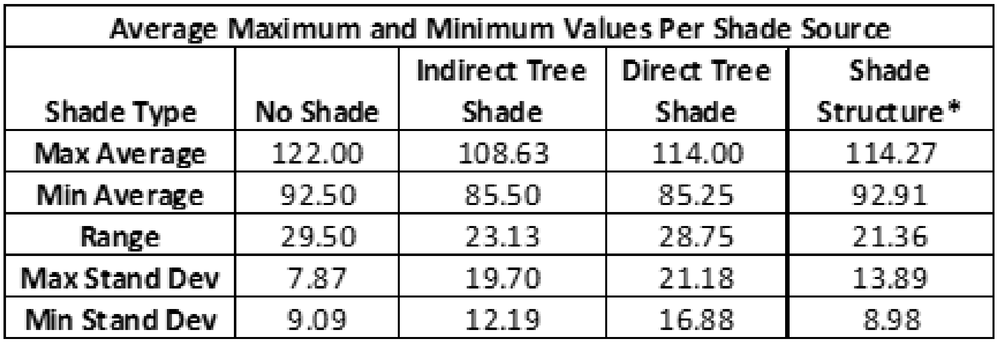
Figure 11 above is an example of a thermal image taken in the field, and represents the primary method utilized for measuring surface temperatures at transit stops. A key feature of this image is that it captured a range in surface temperatures of 48°F. This large range in surface temperatures was fairly representative of what was found throughout the study: surface temperatures of transit components varied greatly. This variation was seen both across various components (e.g. pavement vs chairs). As an example, the shaded areas of pavement at a transit stop came in at around 85°F, while pavement areas just outside of that shade showed a extreme increase to 110°F. This quickly guided the analysis to be broken down by shaded vs. unshaded components, as well as looking at each component separately. Tables 8 and 9 display some summary statistics about the thermal data collected. Following the tables, Figures 12 and 13 show a visual representation of the data collected. From these results, it is clear that shade has a noticeable affect on the surface temperatures, but more importantly, it is clear that tree shade has the greatest effect.

Table 8 - Summary Statistics of Thermal Imaging Data



Maximum and Minimum Temperatures Combined Per Shade Source				
Shade Type	No Shade	Indirect Tree Shade	Direct Tree Shade	Shade Structure*
Average	107.25	97.06	99.63	103.59
Standard Dev	17.21	19.82	23.46	15.80
Maximum	135	137	129	133
Minimum	80	67	71	84
Range	55	70	58	49

Table 9 - Average Values of Thermal Imaging Data



Average Maximum and Minimum Values Per Shade Source				
Shade Type	No Shade	Indirect Tree Shade	Direct Tree Shade	Shade Structure*
Max Average	122.00	108.63	114.00	114.27
Min Average	92.50	85.50	85.25	92.91
Range	29.50	23.13	28.75	21.36
Max Stand Dev	7.87	19.70	21.18	13.89
Min Stand Dev	9.09	12.19	16.88	8.98

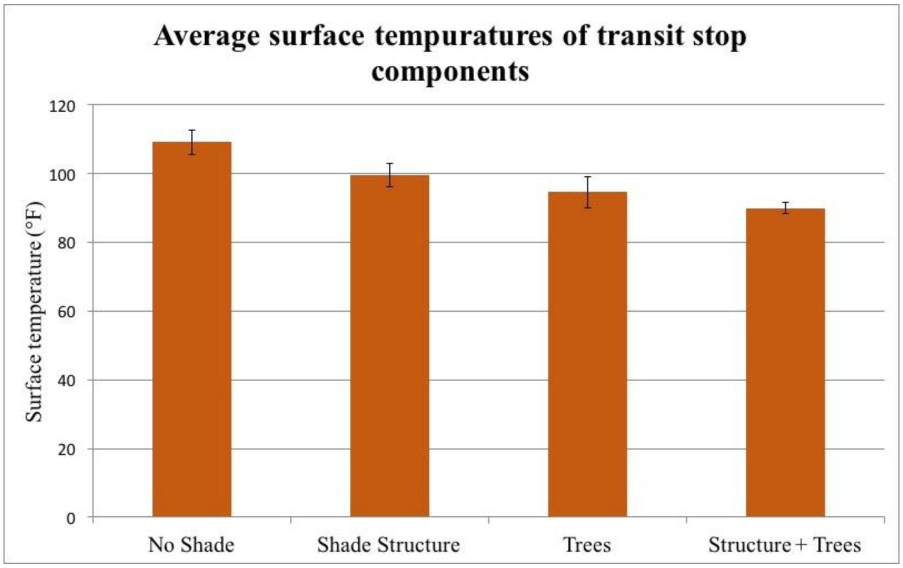


Figure 12 - Average surface temperatures for various configurations of shade

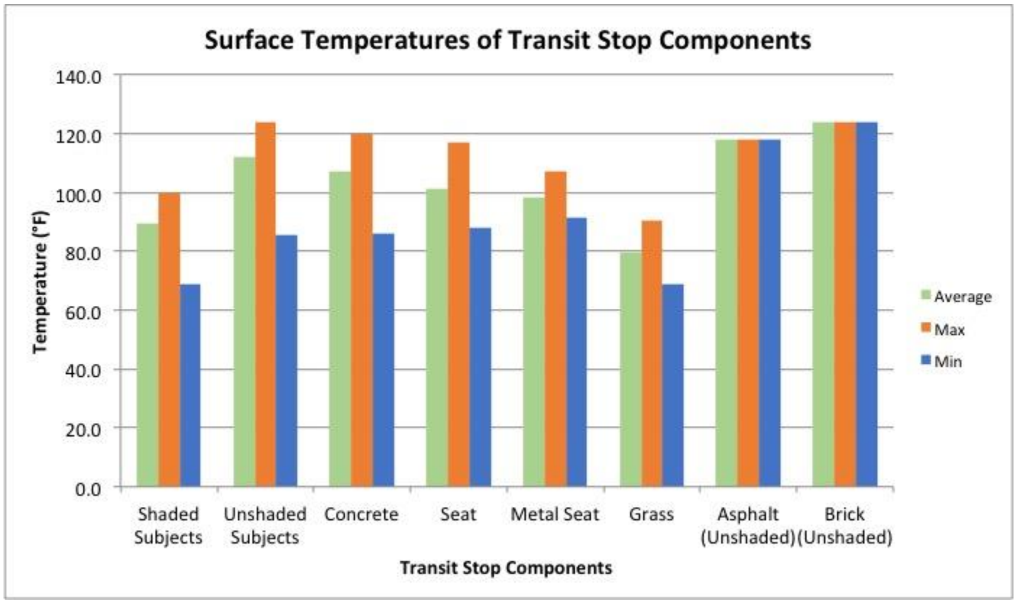
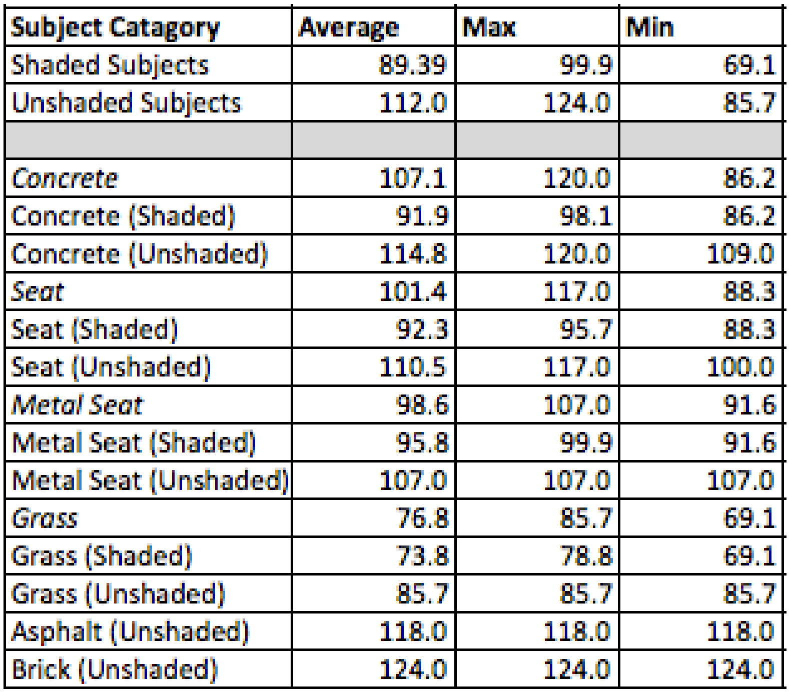


Figure 13 - Surface temperatures of transit stop components.
Note large differences between minimum and maximum temperatures both within and between different transit components.

Figure 12 breaks down transit stops by components and shows the average, maximum, and minimum temperatures of those separate components. The first point to be made of the data collected is that the components had a range from 69.1°F to 124°F.This 54.9°F difference made it evident that the components used at and around the stop are extremely important when it comes to heat mitigation. Another interesting point drawn from this table, is that grassy areas had the lowest average temperature at 79.5°F. This temperature was 19.1°F cooler than the next lowest component, making this by far the coolest component at any of the transit stops. One outlier of data, 90.3°F when shaded, could be removed from this analysis of grass. This outlier was high because this specific grassy area was more patchy than most and had only about 40% grass coverage. As such, this particular thermal image sample was found to capture a surface temperature that was not representative of what actual surface temperatures likely were. The results thus changed Grass & Shaded Subjects to 76.8°F average, 85.7°F max for Grass & 89.39°F average for Shaded Subjects. This new data is shown in Table 10. This would increase the gap from grass to the next coolest component to a change of 21.8°F. As it pertains to shade the average temperature changed from a manageable 89.4°F average for shaded components to a extreme 112.0°F average for unshaded ones, yielding a temperature change of 22.6°F, which brought shade into first place as the leading transit stop cooling characteristic. This did not distinguish between green or grey shade though.

Table 10 - Statistical analysis with outlier removed



Subject Catagory	**Average**	**Max**	**Min**
Shaded Subjects	89.39	99.9	69.1
Unshaded Subjects	112.0	124.0	85.7
Concrete	107.1	120.0	86.2
Concrete (Shaded)	91.9	98.1	86.2
Concrete (Unshaded)	114.8	120.0	109.0
Seat	101.4	117.0	88.3
Seat (Shaded)	92.3	95.7	88.3
Seat (Unshaded)	110.5	117.0	100.0
Metal Seat	98.6	107.0	91.6
Metal Seat (Shaded)	95.8	99.9	91.6
Metal Seat (Unshaded)	107.0	107.0	107.0
Grass	76.8	85.7	69.1
Grass (Shaded)	73.8	78.8	69.1
Grass (Unshaded)	85.7	85.7	85.7
Asphalt (Unshaded)	118.0	118.0	118.0
Brick (Unshaded)	124.0	124.0	124.0

2.3.2 EXPOSURE – RESEARCH QUESTION 2

According to the results, the stops with the largest difference in temperature were stop 860 (50°F difference) and stop 859 (61°F difference). Taking this into consideration, it is clear the temperature differences varied by feature/surface material. As the research indicates, the stops had variable amounts of shade to consider in regards to temperature (no shading, direct shading from transit, structure (awning, etc.), indirect tree shade, direct tree shade). Areas that were concrete and shaded showed little difference in gap temperatures compared to those areas that were concrete and unshaded. For example, the shaded concrete area at bus stop 825 had a range of 37°F while the unshaded concrete area at stop 860 had a range of 38°F. However, seats that were shaded had a more substantial range than those that were unshaded. For example, the shaded seats at stop 859 had a range of 44°F while the unshaded seats at stop 3376 had a difference of only 41°F.Another factor that considered in the data was the grass at each stop. The grass in the shaded area at stop 859 had a range of 54°F while the grass in the unshaded area at the same stop had a range of only 47°F. Overall, the areas that were under shaded conditions showed a larger gap in the temperatures than those that were unshaded.

To more broadly analyze the relationship between transit stop features and surface temperatures, multiple regression analysis as utilized. Measured surface temperature data were regressed against transit stop classifications (e.g. presence/absence of shade, percent green cover). Of all variables tested, only shade type was significantly related to surface temperatures ($p < .001$). Shade type included the categories of: no shade, built shade, direct or indirect tree shade. Further, shade type explained the majority of the variance in our surface temperature data ($r^2 = 0.69$). There were not any significant correlations or relationships with air temperature data. This is likely due to the smaller than anticipated sample size, as many of the field data did not feature complete or adequate microclimate data.

2.3.3 EXPOSURE – RESEARCH QUESTION 3

A portion of the field data was compared to the heat perception gathered by the transit surveys. One question proposed by the survey was, "What transit stop elements make you feel cooler?" The responses are displayed in Figure 14 below. 84% of the survey respondents perceived that nearby trees provided significant heat relief. And 74% of respondents replied that shade structures provide heat relief and a large portion of respondents said both provided heat relief. The field data measurements were explored to see if this perception was true. It indicated that tree shading provided on average greater heat mitigation versus built shade structures. Grey shade structures averaged about 100°F, tree shaded areas averaged about 95°F, and a combination of the two brought the temperature down to about 90°F. This reinforced the perception of the surveyed public, potentially guiding any mitigation strategies. These comparisons are also important as heat stress and heat-related health outcomes are a combination of context- and site-specific environmental and psychological conditions/stressors.

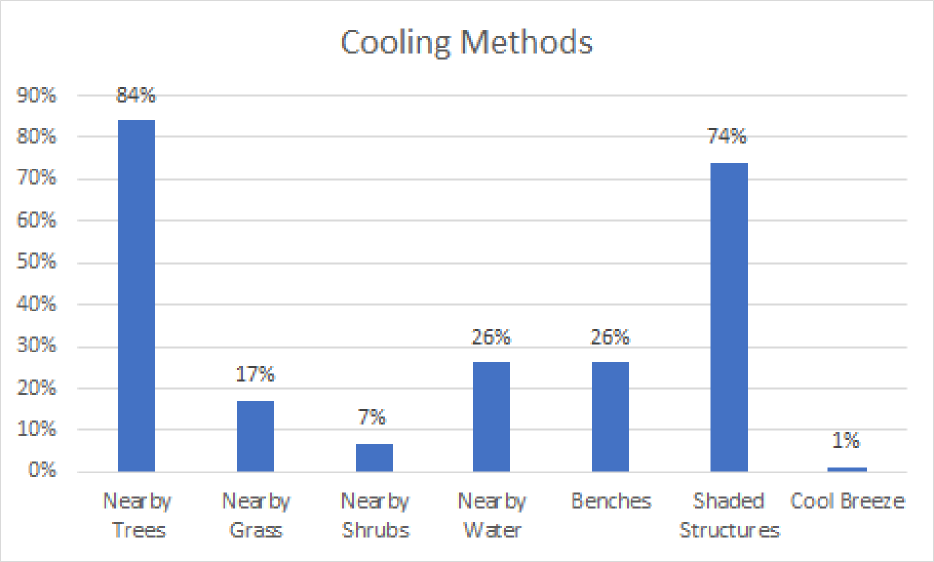


Figure 14 - Best Cooling Methods from Survey Responses

The results of Figure 14 and the thermal data collected are important to consider, especially as it relates to the survey results for the question, "Is there a temperature at which you would be uncomfortable traveling to or waiting at a transit stop?" This question sought to see at what temperature transit users behavior changed. Based on the results shown in Figure 15, a large portion of transit users begin feeling uncomfortable at about 90 degrees and a portion of the transit users do not have a choice and must continue using transit no matter what the temperature. While the temperature data presented here is limited to surface temperatures, these can be used as a proxy for general heat conditions at transit stops. It is well known that for a large portion of the year, the Arizona temperatures exceed these temperatures respondents chose. Additionally, many of the surface temperatures measured here during Spring are already exceeding these thresholds. This means that a large majority of transit users are uncomfortable or stop using transit when the temperatures thresholds are exceeded, therefore, it is important to find the best ways to help mitigate heat at these stops in order to help make the rider experience not only more bearable, but safer.

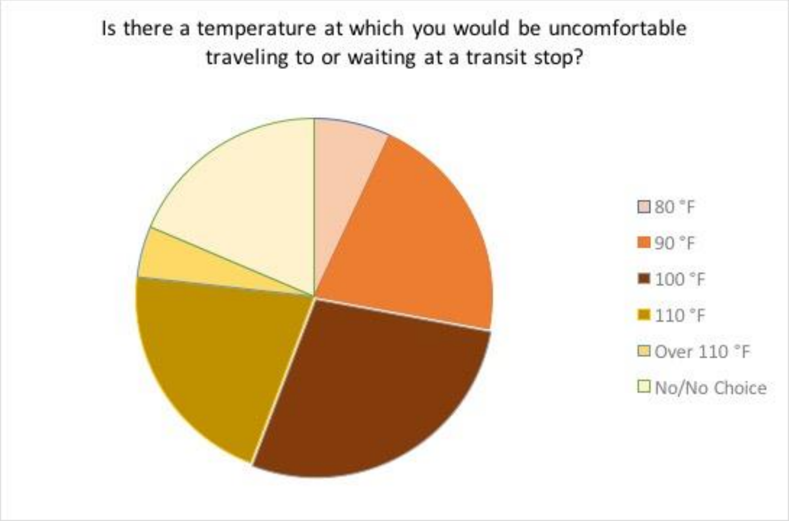


Figure 15 - Survey responses regarding transit behavior change based on temperature

2.4 BROADER IMPACTS

- *Scientific*

Despite the desire to provide a wide-ranging understanding of how infrastructural thermal characteristics affect human travel, the scope of this study is too limited. As such, the data and results were formatted in line with data management best practices to facilitate future research into this topic. Specifically, the data and metadata are formatted for compatibility with the Central Arizona Phoenix Long Term Ecological Research (CAP LTER) database. The hope is that further research can continue to expand upon the thermal image and heat databases to provide a more comprehensive overview of the thermal characteristics of transportation infrastructure. In particular, this research would be most relevant to decision makers and practitioners if data from summer seasons were able to be collected and analyzed to better highlight how the findings here relate to the performance of these infrastructure components during extreme heat events. With this in mind, extensive metadata has been included in the report to ensure the dataset is easily accessible, reproducible, and expandable.

- *Societal*

Considering the drastically changing climate and the corresponding effect it will have on temperatures in the Phoenix-metro area, this study sets a powerful baseline for residents and municipal leaders looking to improve transit-related infrastructure. With the recent trend of locally funding transportation projects through voter initiatives, citizens across the nation are becoming a more integral part in the transportation planning process (Goldman et al, 2001). Furthermore, many municipalities implementing these locally funded projects are required to present a complete list of features and plans before the funding initiative can go for a vote. As such, local governments and transit agencies are becoming more cognizant of providing features that appeal directly to the users, lest the initiative fail. By empowering the community with the information contained in this report, residents will be able to demand certain materials or features be present in the transportation plan before it becomes fully implemented.

2.5 CONCLUSION

Research to date has demonstrated the growing concerns and impacts related to heat exposure in urban areas. In particular, negative health outcomes (i.e. morbidity, mortality) related to heat have been shown to be the predominant weather-related health stressor in Maricopa County. One of the most common non-voluntary sources of heat exposure for people in urban areas is transit use. Not coincidentally, people that are dependent on transit often are also demographic categories that recent research has identified as vulnerable. The thermal dynamics, characteristics, and processes of transit experiences that create health outcomes are not well understood or quantified. To create a better resolution of this information, a field-based approach was utilized to quantify surface temperatures of transit stops and transit stop components in the Phoenix metro area. Field observations at 13 bus stops in the City of Tempe yielded data on the surface temperatures ranges of entire transit stop assemblies, as well as more detailed information on the thermal characteristics and dynamics of specific transit stop components.

Transit stop features were classified by presence/absence, type, and material. Statistical and regression analyses revealed that, among all variables measured, shade type provided that greatest and most significant explanation for variance observed in surface temperature data. Specifically, tree shade (both direct and indirect) were found to have a stronger cooling effect than built shade structures. Generally though, a combination of both built and tree shade resulted in the most dramatic cooling effects, with temperatures ranges at some stops as great as 55°F. Although this study was conducted during the relatively mild climate conditions of Spring, they provide valuable insight into the broader thermal dynamics and interactions at play at transit stops. Importantly, these results and data are generally applicable to nearly all transit stops in the ValleyMetro network, as stops surveyed in this study contained all possible combinations of bus stop components.

3 CHAPTER III: MITIGATION

3.1 INTRODUCTION

Group 1 (Transport) and Group 2 (Exposure) identified and assessed the effects of heat exposure on the behavior of users of mass transit in urban environments by focusing on a geographical area in Tempe, Arizona bounded on the north by Rio Salado Parkway; on the east by Rural Road; on the South by 13th Street/Apache Boulevard; and on the West by Priest Drive. Figure 16 show, a map of the study area follows:

Figure 16 - *Study Area*

Group 3 (Mitigation) reviewed the findings of Group 1 (Transport) and Group 2 (Exposure) and prepared this chapter that describes the findings and proposed recommendations to reduce the impact of heat exposure on mass transit riders.

3.1.1 ASSESSING VULNERABILITY TO HEAT EXPOSURE

O'Brien et al. (2007) distinguish between "outcome vulnerability" and "contextual vulnerability" in the discourse surrounding climate change. These two interpretations frame vulnerability in very different ways. Outcome vulnerability frames issues around science; contextual vulnerability assesses climate change from a human and security point of view. Outcome vulnerability focuses on future climate change; contextual vulnerability privileges current climate variability. Outcome vulnerability suggests quantitative methods like dose response models while contextual interpretation looks to qualitative methods like case studies and surveys.

The tool provided by O'Brien et al. (2007) includes possible responses to the following dimensions located on a spectrum: prioritized questions, focal points, methods, identified results, and policy responses. Applying the tool to Eisenman et al. (2016) and Jenerette, et al. (2011) provides a useful way to frame vulnerability to heat exposure.

3.1.2   CONTEXTUAL VULNERABILITY

Eisenman et al. (2016) uses weather data from 2005-2010 in Maricopa County to analyze the mortality of four groups that exhibit tendencies that have been shown "to contribute to social vulnerability during heat waves" (91). Eisenman et al. (2016) considered "access to public cooled spaces, home air-conditioning and thermal protection of residential buildings" as "infrastructural variables." Eisenman et al. (2016) defines heat events "summertime temperatures that are substantially hotter and/or more humid than the historic average for that location at that time of year" (p. 92).

The study produced a "data set of 49,394 census-tract/days … [and] yielded 1584 deaths from all-internal causes (814 on heat days and 770 on control days) and 40 deaths from heat-related illness (35 on heat days and 5 on control days)" (93). Eisenman et al. (2016) extracted four factors that "explained 77% of the variability in the dataset" (p. 93).

1. Socioeconomic vulnerability based no health insurance, working outdoors in construction, and female headed households.

2. Renters living alone without a vehicle.
3. Older aged female living alone.
4. Agriculture or extraction industries (p. 93)

The approach of Eisenman et al. (2016) is consistent with contextual vulnerability as defined by O'Brien et al. (2007) because it focuses on human and security aspects related to the mortality of four socially vulnerable groups caused by the interaction of extreme heat and infrastructure. In addition, Eisenman (2016) address the following issues in ways that are consistent with O'Brien et al. (2007):

1. Prioritizes questions related to a region (Maricopa County) and special social groups (the socially vulnerable);
2. Focuses on current climate variability based on historic weather data in Maricopa County from 2005-2010, not future projections;
3. Identifies institutional and socio-economic constraints on local responses by modeling the availability of the three infrastructural variables to the socially vulnerable;
4. Describes policy responses including local constraints (e.g. access to cooled spaces); and
5. Concludes that the identified "adaptive resources to extreme heat" had "mixed results" (p. 98).

3.2 VULNERABILITY OUTCOME

Jenerette, et al. (2011) offers a perspective more consistent with outcome vulnerability as described by O'Brien et al. (2007). Consistent with the prioritized question of the outcome vulnerability, Jenerette, et al. (2011) analyzed "three decades (1970–2000) of land surface characteristics and residential segregation by income in the Phoenix" to assess whether human modification of urban vegetation affected ecosystem cooling services (2637) and, in turn, exacerbates climate change. Jenerette, et al. (2011) asserts that vegetation may cool surfaces by 25 degrees C and the loss of habitat now may contribute to higher temperatures in the future.

Jenerette, et al. (2011) develop a forward-looking approach called the "urban heat riskscape," which is an integrated assessment model that shows "spatial variation in risk exposure and potential human vulnerability to extreme heat" (2637). "Urban heat riskscape" measures gains and losses associated with identified results of outcome vulnerability. Further, the article asserts that in order to "to alleviate neighborhood inequality in risks from extreme heat through increased vegetation and evaporative cooling, large increases in regional water use would be required" (2637); this provides a metric to assess whether the increased demand on scarce regional water resources would constitute an inappropriate action under the outcome interpretation.

By advocating "a systems evaluation of the benefits, costs, spatial structure, and temporal trajectory for the use of ecosystem services to moderate climate extremes" (2637) and suggesting that "increasing vegetation is one strategy for moderating regional climate changes in urban areas and simultaneously providing multiple ecosystem services" (2637), Jenerette, et al. (2011) assume an evenhanded, forward-looking orientation associated with outcome vulnerability.

Because this project focuses on the effects of heat on the average user of transit stops, it is more consistent with the outcome vulnerability described above. In this vein, Group 3 (Mitigation) evaluated strategies to mitigate the heat exposure of transit stops and recommends that Valley Metro plant more vegetation, especially trees, near transit stops. However, Group 3 (Mitigation) believes that the project should be extended to assess issues having to do with contextual vulnerability in ways calculated to reduce the impact of heat on vulnerable populations like the elderly, children, or homeless who are most likely to use the transit system during extreme heat events and suffer poor or tragic outcomes.

3.2.1 OVERVIEW OF THE MASS TRANSIT SYSTEM

In 2004, voters approved Proposition 400, which authorized continuing for another 20 years a half-cent sales tax to fund improvements to freeways, streets, and the mass transit system in Maricopa County as part of the Regional Transportation Plan (RTP) (Sjoberg Evashenk Consultants, 2016, p. 1).

Pursuant to Proposition 400 and state law, Sjoberg Evashenk Consultants submitted an audit in November 2016 entitled, *Performance Audit: Maricopa Association of Governments Regional Transportation Plan*. The information contained in the audit is reliable due to the high standards that auditors must meet. Although the project only addresses a small, bounded area in northern Tempe, it is important to understand the broad context in which the transit system operates.

Partners in the RTP are:

- Maricopa Association of Governments (MAG);
- Arizona Department of Transportation (ADOT);
- Valley Metro Regional Public Transportation Authority (RPTA);
- Sixteen local jurisdictions including Phoenix, Scottsdale, and Tempe, 11 towns, and three Native American Communities;
- Maricopa County; and
- Valley Metro Rail, Inc. (Sjoberg Evashenk Consultants, 2016, p. 8)

RPTA "is a political subdivision of the State of Arizona" and is "responsible for short-term planning and the operation of the regional bus transit system in Maricopa County" (Sjoberg Evashenk Consultants, 2016, p. 8).

Valley Metro Rail, Inc. is "a non-profit, public corporation formed by the cities of Glendale, Mesa, Phoenix, Tempe, and Chandler" and is "responsible for the design, construction, and operation of the light rail system in Maricopa County" (Sjoberg Evashenk Consultants, 2016, p. 8).

Valley Metro Rail, Inc. was "administratively combined" with RPTA under single Chief Executive Officer. Together Valley Metro Rail, Inc. and RPTA are known as Valley Metro (Sjoberg Evashenk Consultants, p. 8). In the rest of this report, Group 3 (Mitigation) will use the term "Valley Metro" to identify the entity that manages the light rail and bus systems. Most of transit stops within the study area are bus stops although a short segment of the light rail system is included on the northern boundary of the study area.

Valley Metro manages the following relevant transit services:

- Fixed Route: Bus service provided on a repetitive, fixed schedule basis along a specific route.
- Bus Rapid Transit (BRT): Fixed route bus mode where a majority of each line operates in a separated right-of-way dedicated for public transportation use during peak periods and includes features that emulate services provided by rail, such as defined stations and traffic signal priority.
- Express / RAPID: Bus service intended to run faster than normal bus services between specific commuter or destination points.
- Supergrid: Bus service providing frequent local service throughout the day and evening.

- Light rail/high capacity: Urban rail system that uses light rail vehicles on fixed rails in a dedicated right-of-way space.
- Paratransit (dial-a-ride): Transit service that is more flexible than conventional fixed route service, including dial-a-ride services throughout Maricopa County. These services provide Americans with Disabilities Act paratransit service to individuals with disabilities that cannot access the fixed route bus and rail system (Sjoberg Evashenk Consultants, 2016, p. 60).

Valley Metro light rail outperformed the six-peer average for four of the five categories including:

- Operating Cost per Revenue Mile;
- Boardings per Revenue Mile;
- Farebox Recovery;
- Operating Cost per Boarding; and
- Subsidy per Boarding.

In 2014, the subsidy per boarding was 84 percent below six peers (Sjoberg Evashenk Consultants, 2016, p. 62). The six peers were: Dallas, Denver, Houston, Sacramento, San Diego, and Utah (Sjoberg Evashenk Consultants, 2016, p. 90).

As regards light rail, Sjoberg Evashenk Consultants (2016) found:

With the exception of on-time performance, we found favorable trends across each of the performance metrics. For instance, total boardings increased by nearly 12 percent from fiscal year 2010-2011 to fiscal year 2014-2015, from nearly 12.8 million boardings to 14.3 million boardings. While total boardings increased over the audit period, boardings have remained fairly constant over the last three years. Other performance measures indicate the strength and operation of the system, such as the farebox recovery that shows the portion of total operating expenses covered by passenger fares. In Maricopa County, the light rail system's farebox recovery increased by more than 24 percent over the five-year audit period from nearly 33 percent in fiscal year 2010-2011 to 41 percent in fiscal year 2014-2015 (p. 63).

As regards fixed route bus transit, Sjoberg Evashenk Consultants (2016) found:

Between fiscal years 2010-2011 and 2014-2015, fixed route bus system performance showed improvements in certain areas and slight decreases in performance in other areas …. For instance, we noted improvements in five of the 12 metrics reviewed – total boardings, boardings per revenue mile, safety incidents, security incidents, and mechanical failures. While fixed route bus service outperformed peers as discussed earlier in this chapter, metrics related to service efficiency such as operating cost per revenue mile and operating cost per boarding showed an increase between fiscal years 2010-2011 and 2014-2015. With costs increasing and the average fare remaining relatively consistent, the farebox recovery declined by nearly 7 percent and the subsidy per boarding increased by more than 10 percent (p. 65).

3.3 RESULTS AND DISCUSSION

3.3.1 FINDINGS RELEVANT TO VULNERABILITY OUTCOME

Sjoberg Evashenk Consultants (2016) made the following findings that are relevant to mitigation of heat exposure and associated outcome vulnerability:

- Congestion trends on freeways and arterial streets has generally increased between calendar years 2011 and 2014, although average speeds have slightly increased on freeways and slowed on arterial streets – nonetheless, these trends are better than those reported nationally (p. 2).

- Light rail and bus transit continue to outperform peer agencies in terms of boardings, farebox recovery, and operating costs; transit vehicles were on-time at least 92 percent of the time or higher between fiscal years 2010-2011 and 2013-2014 and mechanical failures have been decreasing over the same timeframe [citations omitted] (p. 3).
- Some active traffic management tools, such as traffic signal synchronization and transit signal priority, are in place to enhance mobility. However, the region is still moving toward more active real-time monitoring and dynamic, proactive adjustment of the system to meet traffic conditions on a 24-hour a day basis (p. 3).

Systemwide ridership was five percent higher in fiscal year 2014-2015 than in fiscal year 2010-2011; however, it "declined from a high of 73.4 million boardings in fiscal year 2012-2013 to nearly 70.8 million boardings in fiscal year 2014-2015, a decrease of more than 2.6 million boardings or nearly 4 percent" (Sjoberg Evashenk Consultants, 2016, p. 60). The decline was attributed to:

- A better economy and lower prices for gas, and
- A declining number of students from Arizona State University. The number of annual passes decreased by 55 percent from 18,000 in 2009-2010 to 8,000 in 2013-2014, which translates into 15,000 student trips per day. Valley Metro attributes the decline to online courses, free shuttles, increased prices for passes, and more student housing near campus. (Sjoberg Evashenk Consultants, 2016, p. 60).

A survey of riders in 2014 showed that although 75 percent of riders expected to continue usinging the transit system, the satisfaction rate slipped slightly to 70 percent. Reasons cited by riders for decreased satisfaction included the "need for increased service frequency or longer hours of operation, lack of on-time performance, and rude or unprofessional drivers" (Sjoberg Evashenk Consultants, 2016, p. 60). Riders did not cite exposure to heat or lack of features intended to reduce the exposure to excessive heat as reasons for dissatisfaction.

Funds from Proposition 400 are "dedicated to projects approved and proposed as part of the original 2003 RTP" including:

- 344 total miles of new or improved freeways and highways;
- 275 miles of new or improved streets;
- 34 major intersections;
- 27.7 new miles of light rail; and
- 40 enhanced or new bus routes (Sjoberg Evashenk Consultants, 2016, p. 5-6).

Funds collected pursuant to Proposition 400 must be spent as follows:

- Freeway: 56.2 percent for freeways including capital expense and maintenance.
- Arterial: 10.5 percent for major arterial street and intersection improvements.
- Transit: 33.3 percent for capital construction, maintenance, and operation of public transportation as well as for capital construction costs associated with a light rail system (Sjoberg Evashenk Consultants, 2016, p. 6).

About two-thirds of the funds generated by Proposition 400 are earmarked for freeways and streets with the remaining third devoted to transit. The open question is whether this is an appropriate allocation.

Efforts to reduce the effect of extreme heat on transit riders could be enhanced if the political will existed to change the proportion spent on transit.

When Proposition 400 passed in 2004, projections anticipated that $14.3 billion would be generated over twenty years from 2006 to 2026; however, the economic recession from 2007 to 2009 reduced projected sales tax revenues to $8.6 billion, or 40 less than the amount originally projected. A shortfall of this magnitude constrains the options and resources that Valley Metro can devote to efforts intended to reduce the effects of extreme heat on transit riders.

Group 3 (Mitigation) finds it intriguing that in an audit comprising 129 pages, no mention of extreme heat or climate change or global warming could be found by electronic searches. Based on this finding and the conversation with a representative of Valley Metro, heat and its effects on riders and infrastructure may not be a high priority. Group 3 (Mitigation) believes that outcome vulnerability of Valley Metro has increased due to decreased ridership, less satisfied riders, misallocation of tax revenue that favors construction of roads over transit, and declining revenue that has not met expectations that arose around the passage of Proposition 400.

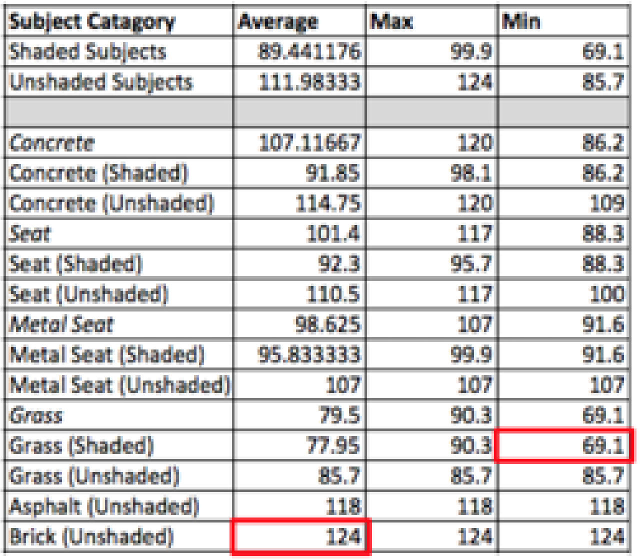
3.3.2 HEAT RISK ASSESSMENT

The purpose of the Heat Risk Assessment is to determine which Valley Metro bus stops in the study area are in the greatest need of heat mitigation intervention. Heat mitigation strategies include shading, cool or green pavement, and cool or green roofs. To recommend where to install heat mitigation strategies, Group 3 (Mitigation) devised a tool that uses data from the Transit Survey and measurements from thermal images.

Member of Group 1 (Transport), Group 2 (Exposure), and Group 3 (Mitigation) administered the Transit Survey throughout the study area. The survey asked questions regarding the travel behavior of riders including perceptions of heat exposure. Two principal findings from the survey are addressed in the Heat Risk Assessment: average walk time and average wait time. On the survey, respondents were asked, “how long do you typically wait at a transit stop?” and given four options: ‘*1-5 minutes*,’ ‘*6-10 minutes*,’ ‘*11-20 minutes*,’ or ‘*over 20 minutes*.’ Respondents were also asked, “how long did it take you to reach this transit stop?” and were given the same four options, plus a ‘*I transferred to another line*’ option.

Thermal images were collected by Group 2 (Exposure) at thirteen transit stops in the study area. The images recorded the surface temperatures of the following infrastructure elements at the stops: shaded concrete, un-shaded concrete, shaded seats, un-shaded seats, shaded metal seats, un-shaded metal seats, shaded grass, un-shaded grass, un-shaded asphalt, and un-shaded brick. Some of the results are embodied in table 11, which shows the average, maximum, and minimum surface temperature readings of the infrastructure element at the thirteen stops.

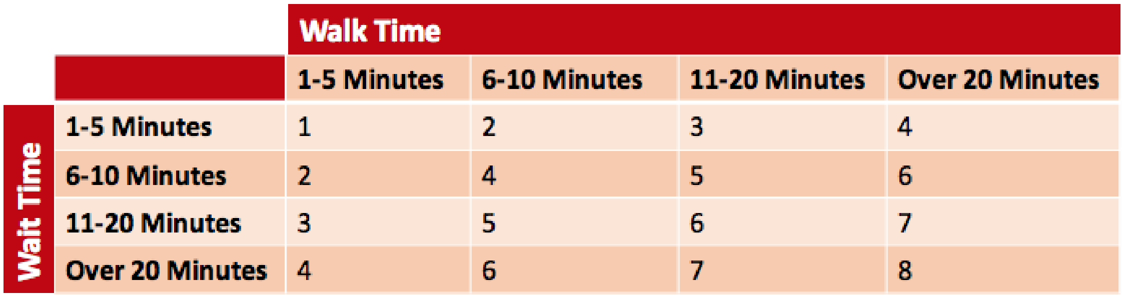
Table 11 – Impacts of Shade type on surface Temperature



Subject Catagory	**Average**	**Max**	**Min**
Shaded Subjects	89.441176	99.9	69.1
Unshaded Subjects	111.98333	124	85.7
Concrete	107.11667	120	86.2
Concrete (Shaded)	91.85	98.1	86.2
Concrete (Unshaded)	114.75	120	109
Seat	101.4	117	88.3
Seat (Shaded)	92.3	95.7	88.3
Seat (Unshaded)	110.5	117	100
Metal Seat	98.625	107	91.6
Metal Seat (Shaded)	95.833333	99.9	91.6
Metal Seat (Unshaded)	107	107	107
Grass	79.5	90.3	69.1
Grass (Shaded)	77.95	90.3	69.1
Grass (Unshaded)	85.7	85.7	85.7
Asphalt (Unshaded)	118	118	118
Brick (Unshaded)	124	124	124

The Heat Risk Assessment combines the Transit Survey Results with data from the thermal images; however, the measurements are not expressed in the same units. The Transit Survey measures time and the thermal images measure temperature. To address this inconsistency, the measurements were converted to four-level Likert scales. Because the average walk and wait times were already divided into four response categories, they were converted to a Likert scale with values from one through four categories on a spectrum from '*1-5 minutes*' to '*over 20 minutes*.' The Transit Survey Likert scale matrix is presented in table 12.

Table 12: Transit Survey Likert Scale Matrix

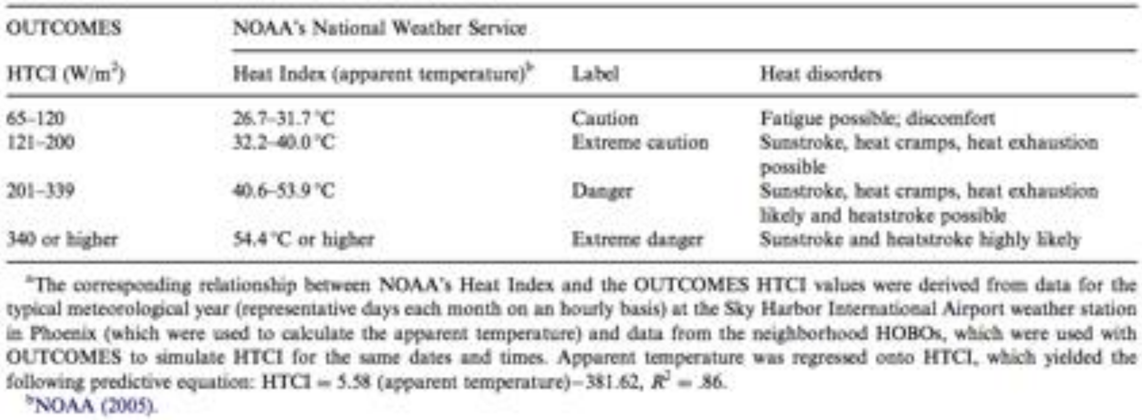


		Walk Time			
		1-5 Minutes	**6-10 Minutes**	**11-20 Minutes**	**Over 20 Minutes**
Wait Time	**1-5 Minutes**	1	2	3	4
	6-10 Minutes	2	4	5	6
	11-20 Minutes	3	5	6	7
	Over 20 Minutes	4	6	7	8

As a test case, Group 3 (Mitigation) chose to analyze the transit stop at the intersection of University Drive and College Avenue (UDCA). According to the Transit Survey data, the average walk time the UDCA stop was '11-20 minutes,' and the average wait time was '11-20 minutes.' Therefore, by using the Transit Survey Likert Scale Matrix, the UDCA stop scored a six. To keep the values on a four-level Likert scale, six was divided by the number of values (n = 2) to calculate an overall score of 3 out of 4.

To convert the thermal image data to a four-level Likert scale, the average measured temperatures of each of the infrastructure elements was applied to a Heat Index prepared by the National Oceanic and Atmospheric Administration (NOAA). The NOAA Heat Index presents four different temperature ranges associated with different levels of caution/danger and heat disorders. To convert these temperature ranges to a four-level Likert scale, the values one through four were assigned to each temperature range respectively, with one being equal to the 26.7 - 31.7℃ range and four being equal to the 54.4℃ or higher, please refer to table 13. The NOAA Heat Index Likert Scale Matrix is presented below. An extra category with a Likert value equal to zero was also added for temperatures of less than 26℃

Table 13 – Relationship between Human thermal Comfort Index and NOAA Heat Index



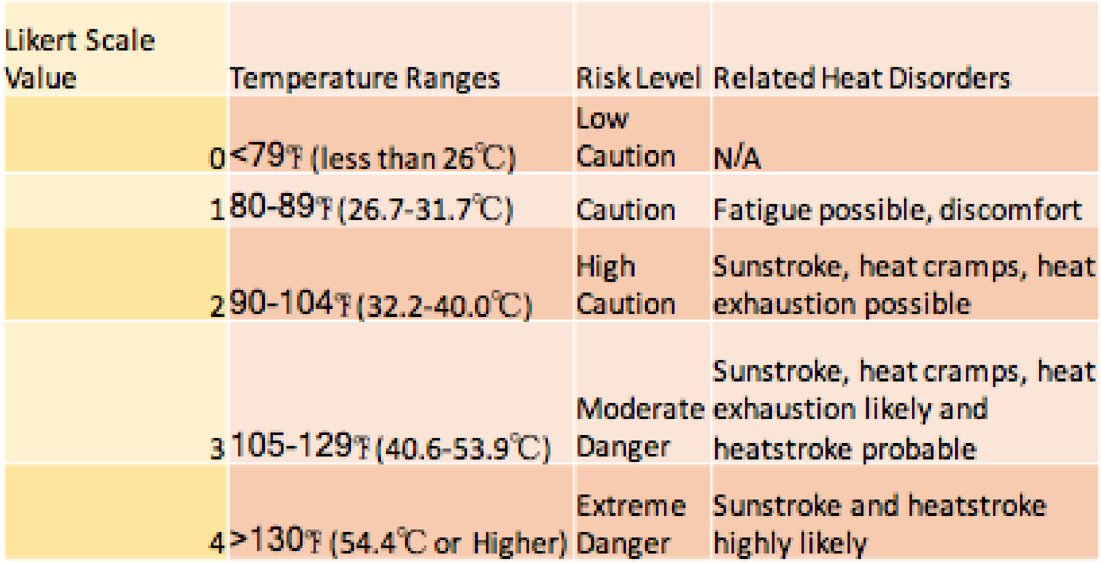
OUTCOMES	NOAA's National Weather Service		
HTCI (W/m^2)	Heat Index (apparent temperature)[b]	Label	Heat disorders
65–120	26.7–31.7 °C	Caution	Fatigue possible; discomfort
121–200	32.2–40.0 °C	Extreme caution	Sunstroke, heat cramps, heat exhaustion possible
201–339	40.6–53.9 °C	Danger	Sunstroke, heat cramps, heat exhaustion likely and heatstroke possible
340 or higher	54.4 °C or higher	Extreme danger	Sunstroke and heatstroke highly likely

[a] The corresponding relationship between NOAA's Heat Index and the OUTCOMES HTCI values were derived from data for the typical meteorological year (representative days each month on an hourly basis) at the Sky Harbor International Airport weather station in Phoenix (which were used to calculate the apparent temperature) and data from the neighborhood HOBOs, which were used with OUTCOMES to simulate HTCI for the same dates and times. Apparent temperature was regressed onto HTCI, which yielded the following predictive equation: HTCI = 5.58 (apparent temperature)−381.62, R^2 = .86.

[b] NOAA (2005).

(Harlan 2006)

NOAA Heat Index Likert Scale Matrix



Likert Scale Value	Temperature Ranges	Risk Level	Related Heat Disorders
0	<79℉ (less than 26℃)	Low Caution	N/A
1	80-89℉ (26.7-31.7℃)	Caution	Fatigue possible, discomfort
2	90-104℉ (32.2-40.0℃)	High Caution	Sunstroke, heat cramps, heat exhaustion possible
3	105-129℉ (40.6-53.9℃)	Moderate Danger	Sunstroke, heat cramps, heat exhaustion likely and heatstroke probable
4	>130℉ (54.4℃ or Higher)	Extreme Danger	Sunstroke and heatstroke highly likely

(Harlan 2006)

At the UDCA stop, the Group 2 (Exposure) found shaded concrete, unshaded concrete, and an unshaded seat present. Using the NOAA Heat Index Likert Scale Matrix, these infrastructure elements have a combined Likert scale value of seven. To keep the values on a four-level Likert scale, seven was divided by the number of values (n = 3) to calculate an overall score of 2.33 out of 4. To find the Heat Risk Assessment for the UDCA stop 3 out of 4 is added to 2.33 out of 4 with the result totaling 5.33 out of 8.

Group 3 (Mitigation) recommends that Valley Metro expand the Transit Survey to its entire service area and take thermal images of all stops so that Valley Metro can calculate the Heat Risk Assessment for all transit stops that it operates. Using the Heat Risk Assessment tool to calculate the scores for all transit stops will allow Valley Metro to identify to most "at risk" stops. Depending on the availability of funds, Valley Metro should create a plan to retrofit the most "at risk" transit stops with appropriate mitigation strategies. These steps would allow Valley Metro to reduce the outcome vulnerability of its system and provide a better experience for its riders.

3.3.3 GENERAL MITIGATION STRATEGIES

Although changing urban form will provide some relief to transit riders over the long term as they walk to and from stops, most of the strategies that reduce or eliminate urban heat islands will not bring immediate relief to transit riders sweltering at increasingly hot transit stops in Phoenix. Yamamoto (2006), for instance, includes a comprehensive list of mitigation strategies relevant to urban heat island (UHI) at all levels and scales, but most are not relevant to transit stops. Mitigation strategies intended to reduce the causes and effects of urban heat islands involve significant modification to the urban form; however, the responses are implemented at scales larger than transit stops and over extended periods of time – years, if not, decades – and do not address the immediate discomfort of riders.

Group 3 (Mitigation) considered many possible mitigation strategies, but believes that only a few are achievable or feasible within the financial, regulatory, maintenance, or operational constraints that inhibit the actions of Valley Metro. For instance, regulations addressing sightlines and visibility of citizen driving cars interfere with the ability of Valley Metro to plant trees or shrubs at many stops. Further, Valley Metro may not be able to install plants or devices that use water like water fountains or misters at light rail stops because of adjacent high voltage electricity lines. In addition, many strategies are not feasible due to budget or maintenance constraints.

Using the categories defined by Connors et al. (2013), Group 3 (Mitigation) categorized mitigation strategies most relevant to the users of Valley Metro transit system in Tempe. The unit costs of chosen strategies summarized in the third column below and the benefits of the strategies are addressed in the next section.

Table 14 – Urban Heat Island Causes and Mitigation Strategies

Intra-Urban Variation	*Mitigation Strategies*	*Unit Cost or Notes*
Urban fabric	Cool pavement	\$2~2.5 per sqft
Urban fabric	Green pavement	\$1.5~5.74 per sqft
Urban cover	Cool roofs	Not priced
Urban cover	Green roofs	\$10 per sqft

Urban cover	Green walls	$90~135 per sqft
Urban cover	Solar panels	Material: $2.87~3.85 per watt; Labor: $0.44 per watt
Urban cover	Grass	Material: $0.05 per sqft; Labor: $ 30 per hour
Urban cover	Shrubs	Material: $10~16.65 per gallon; Planting: $106~2423 per tree
Urban cover	Trees	Material: $7.58~28 per gallon; Planting: $106~2423 per trees
Urban cover	Parks	Not applicable
Urban cover	Water detention ponds	Not applicable
Urban cover	Wetlands	Not applicable
Urban metabolism	Air conditioning	Not feasible now, but may be in the future as temperatures increase
Urban metabolism	Fans	Not feasible now, but may be in the future as temperatures increase
Urban metabolism	Misting systems	Not feasible now, but may be in the future as temperatures increase. Cannot be installed at light rail stops.
Urban metabolism	Water fountains / coolers	Material: $60~180 each Labor: $320~520 each Excavation: $0.047~2.28 per sqft
Urban metabolism	Public chilled water system	Not relevant

Urban metabolism	Cooling centers	Not subject to unit pricing
Urban metabolism	Altered transit schedules in response to extreme heat events	Variable
Urban metabolism	Combined cooling, heat, and power or co-generation systems for transit centers	Depends on the needs assessment and size
Urban metabolism	Community-based outreach program	Depends on size and type of program
Urban metabolism	Enhanced transit connectivity	Depends on scale and scope
Urban metabolism	Hot weather warning systems	Variable
Urban metabolism	Improved transit maps	No additional costs anticipated
Urban metabolism	Intelligent signage	Variable
Urban metabolism	Pedestrian amenities	Depends on type of amenity
Urban metabolism	Restructuring traffic and transportation	Unknown
Urban metabolism	Transit apps	Valley Metro is working on
Urban metabolism	Using renewable energy and energy saving appliances and equipment	Not applicable
Urban structure	Complete Streets	Not applicable

3.3.4 COSTS OF RECOMMENDED HEAT MITIGATION STRATEGIES

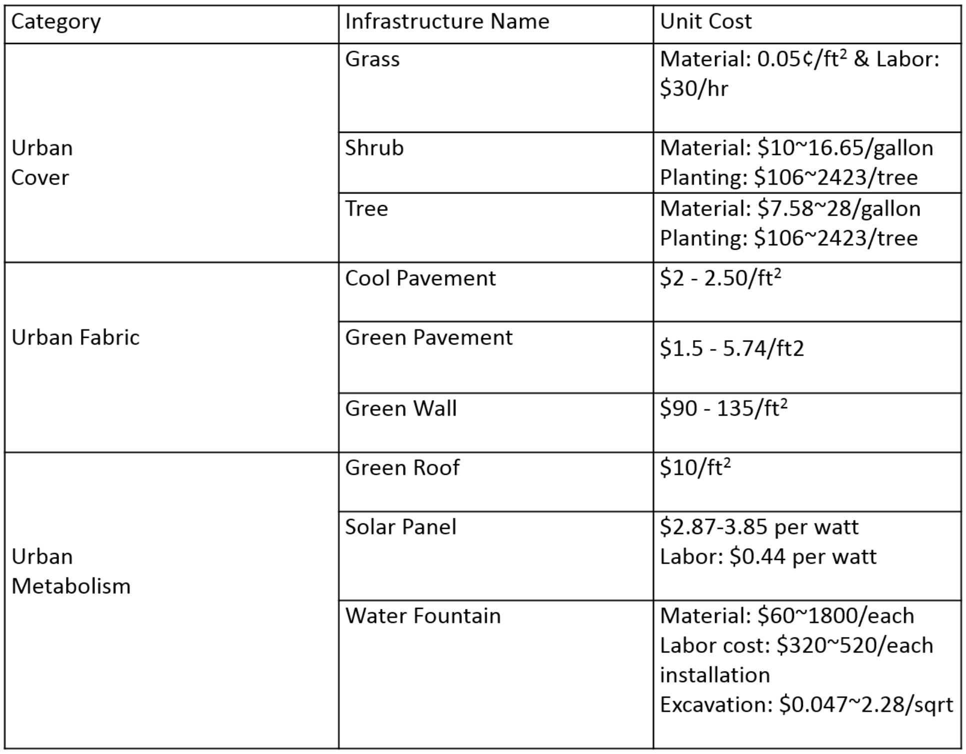
The most cost effective and sustainable strategy to mitigate heat exposure associated with users of the Valley Metro transit system is vegetation – especially trees. Trees have many advantages. They reduce urban heat island and absorb greenhouse gasses. They not only improve the aesthetic experience of the urban environment but also contribute to both physical and psychological health. Other strategies include:

- Solar panels, which provide shade and clean energy, which could be potentially used to run air conditioners or fans at the transit stops;
- Cool pavement, which reflects solar radiation and absorbs less heat while requiring less maintenance.
- Green roofs and green pavements that reduce temperatures and improve comfort.
- Water fountains that allow transit riders to stay hydrated, but may be prohibited at light rail stops to the presence of high voltage electrical wires and concerns about homeless people taking "bird baths."
- Of the strategies that might help alleviate the suffering of transit riders, green walls and the water fountains are the most expensive.
- The most cost effective are cool and green pavement.

Unit costs for mitigation strategies that Group 3 (Mitigation) believes are feasible for transit stops operated by Valley Metro are included in Table 15 below under the categories of Urban Cover, Urban Fabric and Urban Metabolism from Table 14 above. Costs are subject to change depending upon the type of materials used and methods employed for installation.

As an example of a possible mitigation strategy that might be effective at transit stops, a member of Group 3 (Mitigation) measured the footprint of the UDCA stop at six feet by ten feet. One possible way to reduce the exposure of riders to heat would be to install green roofs on shelters. According to the Table 15 below, green roof costs about \$10 per square foot, or about \$600 for a 60-square foot roof. Therefore, the cost of materials would be relatively modest but the lifecycle cost of maintaining green roofs on many transit stops would be substantial and perhaps prohibitive. Current bus stop shelters could not accommodate green roofs. For an idea of how much Valley Metro would be willing to pay for shelters, the 2008 Bus Stop Design Guidelines shows allowances for bus stops in four levels with associated components. At the low end, the cost of a bus stop sign is limited to \$150. At the high end, the cost for an enhanced Level 4 shelter is capped at is \$23,200 (Bus Stop Design Guidelines, p. 9).

Table 15 - Costs of Feasible Mitigation Strategies



Category	Infrastructure Name	Unit Cost
Urban Cover	Grass	Material: 0.05¢/ft^2 & Labor: \$30/hr
	Shrub	Material: \$10~16.65/gallon Planting: \$106~2423/tree
	Tree	Material: \$7.58~28/gallon Planting: \$106~2423/tree
Urban Fabric	Cool Pavement	\$2 - 2.50/ft^2
	Green Pavement	\$1.5 - 5.74/ft2
	Green Wall	\$90 - 135/ft^2
Urban Metabolism	Green Roof	\$10/ft^2
	Solar Panel	\$2.87-3.85 per watt Labor: \$0.44 per watt
	Water Fountain	Material: \$60~1800/each Labor cost: \$320~520/each installation Excavation: \$0.047~2.28/sqrt

Descriptions of benefits associated with the selected mitigation strategies follow.

3.3.4.1 VEGETATION

The temperature of urban surface areas may be decreased through evapotranspiration by planting trees and vegetation. Shade provided by trees and vegetation in public spaces mitigate the effect of heat exposure. In addition, trees and vegetation reduce storm water runoff and protect soil from erosion. Group 3 (Mitigation) gathered data on costs of from multiple sources, including vendor websites and technical reports. Group 3 (Mitigation) included only cost data for shade trees and plants that can survive Arizona's harsh weather conditions.

3.3.4.2 COOL AND GREEN PAVEMENT

Cool pavements reflect solar radiation, lower the surface temperatures, and reduce the amount of heat absorbed into the pavement so that they stay cooler than the traditional pavements. Cool pavements use reflective aggregate, reflective clear binder, or a reflective surface coatings. The many benefits include energy savings, emission reductions, improved comfort and health, increased driver safety, improved air quality, reduced street lighting cost, reduced power plant emissions, improved water quality and slowed climate change. The properties of solar reflectance, thermal emittance, and permeability play significant roles. If pavement reflectance throughout a city were increased from 10 percent to 35 percent, the air temperature could potentially be reduced by 1 degree Fahrenheit °F (0.6 degrees Celsius (Pomerantz, Pon, Akbari, & Chang, 2000). There are many types of cool pavements including:

- Conventional asphalt or concrete;
- Vegetated and non-vegetated permeable; and

- Other reflective types like resin based and colored asphalt and colored concrete.

Costs depend on the region, climate, contractor, time of year, accessibility of a site, underlying soils, project size, expected traffic, and desired the life of the pavement (Ferguson et al., 2008). The benefits of cool pavements include:

- Increased water percolation, improved stormwater management and reduced water runoff due to permeability (Booth & Leavitt, 1999);
- Decreased air temperatures thereby enhancing outdoor comfort and public health (Pomerantz et al., 2000);
- Increased energy savings, reduced formation of ground-level ozone, and reduced greenhouse gases;
- Increased driver safety and reduced need for street lighting due to improved solar reflectance
- Increased durability due absorbing less solar energy over time
- Less damage to local watersheds due to solar reflectance and permeability (James & Shahin, 1998)
- Mitigation of urban heat island (Qin, 2015)
- ***Sunlight reflectance:*** Instead of absorbing 80~90% of sunlight as tradition pavement does and heating the material to temperature between 120-150°F (48–67°C), cool pavement stays cooler because it reflects sunlight.
- ***Reduced storm water runoff:*** Cool pavement is permeable, which allows water to soak into the ground, reducing runoff and filtering pollutants and prevent thermal shock to plants.

- ***Energy saving from air conditioning:*** Cool pavement lowers the outdoor temperature, leading to reduce energy bills for air conditioning needed to cool buildings.
- ***Reduced street light cost:*** Cool pavement could increase the solar reflectance of roads, reducing the energy required for street lighting at night.
- ***Reduced power plant emissions:*** Reduced energy demand reduces emissions from power plant operation.
- ***Improved air quality:*** Cool pavement reduces outside air temperature, improving the comfort and reducing heat-related illness. Cooler temperature could reduce smog, which is formed by the reaction of sunlight and carbon-hydrocarbons and nitrogen oxides in the air and could affect people's respirations.
- ***Improved local comfort:*** Cool pavements in parking lots or other areas where people congregate or children play can provide a more comfortable environment.
- ***Slowed climate change:*** Cool pavement could reduce earth surface temperature and consequently air temperature due to solar reflectance, which may offset the global warming caused by greenhouse gas in atmosphere.

3.3.4.3 GREEN WALLS

Green walls are covered with vegetation usually supported by an integrated water delivery system. They keep the wall comparatively cooler especially when exposed to heat or sun. They can be of great help in the urban environments and improve the aesthetics of the area. Green walls can be used at the transit stops to prevent direct heat exposure and keep the waiting area cooler from all the sides caused by evapotranspiration and reflective properties.

3.3.4.4 GREEN ROOFS

Green roofs or rooftop gardens reduce the heat exposure of the occupants. They not only help in reduce heat exposure but also contribute to improved human health. They help to reduce the urban heat island effect and reduce the greenhouse gases. They can be efficiently applied at the transit stops to reduce the temperature underneath.

3.3.4.5 SOLAR PANELS

Solar panels can be used to generate electricity and provide shade. The electricity generated through the panels can be used to power lights, fans, and cell phone chargers at transit stops. Solar panels are especially attractive in Phoenix because of the abundance of sunlight.

3.3.4.6 WATER FOUNTAINS

The human body depends on water to survive. Every cell, tissue and organ in the body needs water to work properly. The body uses water to maintain the temperature, remove waste, and lubricate the joints. Dehydration is a danger for people living and working outdoors in Arizona during the summer. Widely installed water fountains could increase access to the water at transit stops, where people are vulnerable to the heat while waiting. Drinking water is the most effective way to reduce body temperature and to prevent people from suffering from heat-related illness or death

3.3.4.7 FUTURE INNOVATION

When exploring current possibilities, it is easy to leave out what may be possible in the future. For instance, in the future it is possible that transit entities will invent new ways to communicate with users so that transit systems can quickly transition from passively protecting users to actively moving people to cooler and safer locations.

One strategy that has already been implemented by some transit agencies like SFMTA, King Country Metro, but not all is the transit frequency map. Transit consulting planner Jarrett Walker (2010) proposed this style of map as a response to what he perceived as misleading transit maps. By giving all lines equal weighting on the system-wide map, it is difficult to see which buses run less frequently than others. He asserts that the way the transit system looks to the layperson is the most important factor in the system.

In Phoenix, this innovation might be even more critical. By giving all lines equal weights, it is difficult to know what kind of service is being run. For instance, on the current (April 2017) map, the graphic representation for Route 72, a bus line that has headways of 10 minutes at peak hours is given the same representation as Route 251, which runs at an hour frequency throughout the week. For casual transit users, this can be misleading, and might encourage waiting for a bus that might be infrequent despite the fact that the width of the route on the map shows graphically that it has the same frequency.

3.3.5 FISCAL POLICY (FINDINGS AND RECOMMENDATIONS)

Most people do not think of a policy as being part of a city’s infrastructure. However, almost all physical forms of infrastructure in a city are results of policies and codes. In fact, the built environment is a direct manifestation of various local, state, and other municipal policies, regulations, and codes. While policies usually have good intentions they also may carry unintended consequences that may negatively impact a person's experience with urban infrastructure. For example, a building setback may make sense for safety and visibility reasons for automobiles, but might unintentionally reduce the amount of shade provided to transit users by buildings when they are built right next to lot lines. It is important to identify policies that may be barriers to adapting to climate change and to design new policies in ways that are flexible and easily adaptable to outcome vulnerabilities associated the climate change.

The goal of Group 3 (Mitigation) was to investigate and understand the policies most relevant to the creation of the built environment within the study area as well as identifying possible policy proposals in order to improve people's experience with infrastructure related to heat exposure in the future.

Group 3 (Mitigation) understands the complex nature of the policies and regulations that have produced the infrastructures. We followed a three-pronged approach to achieving our goal. First, we identified the most relevant policies and governing bodies that create some of the conditions that are reported by Group 1 (Transport) and Group 2 (Exposure). Second, Group 3 (Mitigation) reviewed these policies and made necessary updated proposals. Third, Group 3 (Mitigation) devised additional policies to help mitigate major infrastructure deficiencies identified by the other groups on the project team.

Finding: City of Tempe has codified shade infrastructure in two discrete ways. First, they have used the General Plan as the major touchstone for the priorities of the city and this has noticeably changed over the last iteration of the plan. The 2030 version, enacted by the City of Tempe in 2003, did not mention shade or shade mitigation. The 2040 version enacted in 2014 mentioned shade 21 times. The primary framing behind improving the shade of the city is pedestrian friendliness in a traditional New Urbanist/Complete streets model. There are no noticeable SMART strategies, which is understandable from the perspective of quantitative evidence.

Recommendation: While it is encouraging that the City of Tempe now acknowledges the importance of including shade in general and zoning plans, additional improvements can be made. The 2040 version of the General Plan includes shade from a quality of life perspective. While this is not necessarily a deficiency it is important that future iterations of the general plan acknowledge the important role that shade plays in reducing personal heat exposure during extreme heat events.

Group 3 (Mitigation) recommends that the Tempe start including shading requirements for developments that are adjacent to bus stops. This will help reduce the cost to the city for provide shade at bus stops and will perhaps help this strategy be implemented quicker than if it were up to just the city to get it done through its own funding sources. Similar requirements to this have been proven to be effective. A local example is the City of Phoenix's Walkable Urban Code that requires 75% shade cover over sidewalks.

Finding: No Boards & Committees exist that exclusively deal with heat although the Sustainability Commission & Transportation Commission might interested in the topic.

Recommendation: First, the Sustainability and Transportation Commissions should each be introduced to the concepts of individual heat exposure as a result of interactions with infrastructure during extreme heat events. In the short term, there should be cooperation between these two boards on tackling these issues. While both of these boards should always keep heat exposure in mind when considering issues within the city, our long-term proposal is that the City creates a new commission explicitly focused on the issue of heat exposure. We feel that the issue is important enough to warrant its own commission. There should be cooperation between the existing two commissions and the future commission when tackling these issues.

Finding: Maricopa County is in a unique position as the governing body directly above most of the municipalities in the Phoenix region. Maricopa County has influence and money available that could be used to help guide and direct municipalities by funding studies, creating best practice guides, and further assisting cities with heat mitigation. However, Maricopa County does not currently provide much support for heat mitigation.

Recommendation: Maricopa County needs to take advantage of its hierarchal position over the local municipal governments and take charge on issues related to personal heat exposure. This includes providing municipalities with best practice solutions, providing a forum for cities to exchange resources and ideas, and providing funding opportunities for cities to take advantage of to speed up the implementation process.

Finding: In 2015 Maricopa County released a comprehensive Multi-Jurisdictional Hazard Mitigation Plan. The plan focused on environmental and climate change hazards. While extreme heat is one of the hazards mentioned in the plan, there was not nearly as much focus on it as would be expected from city built in the desert. The plan lays out the following four heat-related goals:

- Identify, stock, and communicate locations within the community that can serve as cooling stations during times of extreme heat.
- Perform a public information campaign at the onset of the extreme heat season to help educate the public on ways to remain safe during periods of extreme heat.

- Partner with non-governmental organizations like The Salvation Army, church organizations, and homeless shelters to provide respite care and hydration stations during extreme temperature events.
- Investigate and develop an implementation strategy for using "cool roofs" on any new or major roof rehabilitation projects of tribal/county/city/town owned buildings to lower the urban heat island effects.

Recommendation: While these goals are all good, it is a very basic framework. It can be used as a starting point but by no means should this be used as the four-point plan moving forward. We recommend that the county expand upon this list, providing more specific goals. These goals should be:

- Upgrading bus stops until 90% of all stops in the county meet a set shade standard;
- Identify and map all cooling stations in the county;
- Create funding opportunities specifically for personal heat exposure mitigation.

Finding: There are no grants offered by the City of Tempe, Maricopa County, Maricopa Association of Governments, or the State of Arizona that directly relate to heat mitigation strategies. The Federal Transit Authority offers grants that could potentially be used for heat mitigation strategies at bus stops. The most relevant of these offered grants is the Buses and Bus Facilities Grant No. 5339. The function of this grant is to provide funds to municipalities to improve buses and related facilities, including bus stops. While this could be used to mitigate heat exposure at bus stops, that is not its focus. In 2016, the FTA awarded 63 grants under the program totally about $211 million. Out of these grants, only three of them went to projects other than bus fleet upgrades. Two of the projects were upgrading transit centers and one was to update a bus repair shop. None of the grants were used to upgrade bus stops or to mitigate heat exposure in any way. Regardless, this program still appears to be one of the better funding mechanisms for heat exposure mitigation projects.

The lack of specific funding mechanisms is especially telling for several reasons. First, it reflects the general lag in combating heat exposure, even in hotter regions in the United States. There are plenty of funding opportunities for climate change mitigation strategies but heat has not been included in the discussions. It is important to implement mitigation strategies because many cities in Maricopa County have acknowledged that personal heat exposure is of concern but lack the funds to implement effective mitigation strategies.

Recommendation: New methods of funding must be found to implement the mitigation strategies. Traditionally, funding systems are biased in favor of initial investment in new infrastructure projects. Maintenance costs are usually unpredictable and therefore are not emphasized. It is also worth noting that given the change in climate, conditions in Phoenix will become more extreme, so the same should be assumed of maintenance. For instance, felled trees may change monsoon patterns change. The ability of Valley Metro to plant storm resistant trees and increase the resilience of trees is a good method to reduce the costs of maintenance.

The cost of climate change in relation to personal heat exposure to Valley Metro is also liable to rise. As the number of heat related health incidents rise, litigants will target Valley Metro. More information is needed to conduct a proper cost-benefit analysis, but Group 3 (Mitigation) expects litigation to increase.

3.4 LIMITATIONS

The scope of this study was limited to the area between Rio Salado Pkwy, S. Rural Rd, E.Apache Blvd, and S Priest Dr This area contains ASU Tempe Campus and Downtown Tempe which means that results of this study are highly influenced by the student population and cannot be generalized for the whole city. Additionally, the survey conducted during this research is a small sample size of the Tempe population, and was skewed towards the younger population (likely students as indicated above). Also, we surveyed transit riders in the month of April which is significantly cooler than summer in the study area (compare 85°F to 110°F in summer).

There are some limitations associated with data availability and resolution. Daily ridership data per transit stop was not available (outside averages for each season) to conduct sensitivity analyses between ridership and extreme heat days. Without daily, weekly, or possibly even monthly ridership data, it is hard to tease out the relationship between historical temperature and ridership behavior. Transit authorities that wish to identify how extreme heat may influence ridership should start by comparing historical temperature data with highly resolute ridership data.

The wait time data used (Figure 6) was estimated based on Valley Metro service frequency and does not reflect actual arrival times and schedule delays. Therefore, actual rider wait times likely vary day-to-day from the presented averages.

This study did not include socio-economic characteristics as they were deemed outside the scope of the analysis. Future work would benefit taking into account where vulnerable populations are located in a study region to identify not only characteristics of transit service that may be vulnerable, but also the dynamic of vulnerable riders who interact with vulnerable transit service characteristics.

3.5 CONCLUSION

Transportation infrastructures will be challenged in the future by more extreme heat events, increased overall temperatures, and more riders due to increasing populations. Extreme heat exposure is both a health risk for riders and threat to the operations of Valley Metro. To increase resilience of its transit system, Valley Metro must deploy robust mitigation strategies that decrease outcome vulnerability caused climate change and prepare to mitigate the consequences of more extreme heat events that will damage transportation infrastructures. At the same time, all of levels of government should begin to address contextual vulnerability at risk groups of riders like the elderly and homeless who have no choice but to use transit regardless of the heat exposure.

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5 APPENDIX:

5.1 APPENDIX A: TEMPE TRANSIT SURVEY FOR STUDY REGION

TEMPE TRANSIT SURVEY

ASU Students request your help in understanding transit riders' experiences of heat at Tempe transit stops. Please complete the following questions to the best of your ability. Thank you for your time.

1. *How did you reach this transit stop?*

☐ Walk ☐ Bike ☐ Skateboard ☐ Car
☐ I transferred from another line ☐ Other: ________________

2. *How long do you typically wait at a transit stop?*

☐ 1 – 5 minutes ☐ 6 – 10 minutes ☐ 11 – 20 minutes ☐ Over 20 minutes

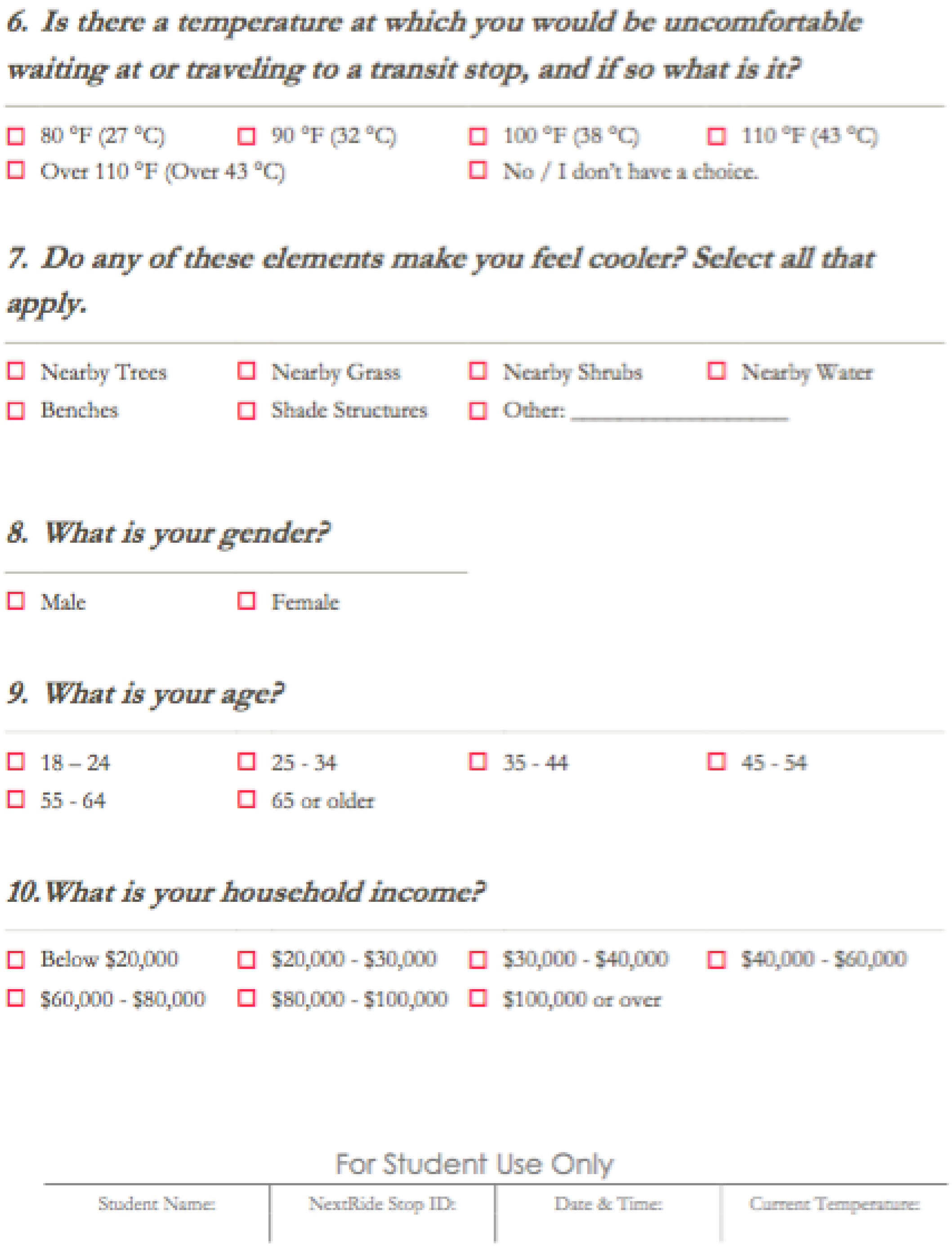
3. *How long did it take you to reach this transit stop?*

☐ 1 – 5 minutes ☐ 6 – 10 minutes ☐ 11 – 20 minutes ☐ Over 20 minutes
☐ I transferred from another line

4. *Do you change the way you travel when it gets hot?*

☐ Don't change behavior ☐ Earlier/later travel ☐ Being umbrella ☐ Bring water or bring more water
☐ I try to get cover in shade on the way ☐ Go to another stop that is more shaded ☐ Other: ________________

5. *How do you keep cool while you wait?*



6. Is there a temperature at which you would be uncomfortable waiting at or traveling to a transit stop, and if so what is it?

☐ 80 °F (27 °C)
☐ 90 °F (32 °C)
☐ 100 °F (38 °C)
☐ 110 °F (43 °C)
☐ Over 110 °F (Over 43 °C)
☐ No / I don't have a choice.

7. Do any of these elements make you feel cooler? Select all that apply.

☐ Nearby Trees
☐ Nearby Grass
☐ Nearby Shrubs
☐ Nearby Water
☐ Benches
☐ Shade Structures
☐ Other: ________________

8. What is your gender?

☐ Male
☐ Female

9. What is your age?

☐ 18 – 24
☐ 25 - 34
☐ 35 - 44
☐ 45 - 54
☐ 55 - 64
☐ 65 or older

10. What is your household income?

☐ Below $20,000
☐ $20,000 - $30,000
☐ $30,000 - $40,000
☐ $40,000 - $60,000
☐ $60,000 - $80,000
☐ $80,000 - $100,000
☐ $100,000 or over

For Student Use Only

Student Name:	NextRide Stop ID:	Date & Time:	Current Temperature:

5.2 APPENDIX B: STANDARDIZED CAP LTER METADATA PACKAGE ASSOCIATED WITH THIS PROJECT DATA.

For future compatibility with CAP LTER or other database for data publication purposes. Project data available upon request.

Attribute Name	Attribute Description	Units	Unit definition/details	Other notes
sample_id	Observation number	integer	Sequential	
date	Date of observation	dd/mm/yy		
researchers	Researchers present	text		
stop_id	ValleyMetro stop ID	Integer		
nextride_id	ValleyMetro NextRide ID	Integer		
location	Closest major crossroads	Text		
transit_mode	Transit mode utilizing stop	Text	Bus or light rail	
timestamp	Classification of observed bird activity at time of observation	Text	Time in 24 hour format based on MST	
image_id	Corresponding database file number	Integer	File number of normal camera image in thermal image database	
thermal_image_id	Corresponding database file number	Integer	File number of thermal camera image in thermal image database	
image_subject	Transit stop component	Text	Component of transit stop infrastructure that is subject of image	Overview, seats, pavement, grass,
surface_temp_f	Surface temperature	Degrees fahrenheit	Temperature of image subject as captured by FLIR camera	
air_temp_f	Air temperature	Degrees fahrenheit	Temperature of air 1m from ground at center of transit stop	
relative_humidity_%	Relative humidity	%		
min_temp_f	Minimum temperature	Degrees fahrenheit	Minimum temperature captured in thermal image	
max_temp_f	Maximum temperature	Degrees fahrenheit	Maximum temperature captured in thermal image	
temp_range_f	Temperature range	Degrees fahrenheit	Difference between minimum and maximum temperatures in thermal image	
subject_shade	Shading of image subject	Integer	Indicates whether subject was located in shade	0 = not shaded, 1 = shaded

material	Dominant pavement material	Integer	Dominant pavement material within 3m of transit stop	1 = concrete, 2 = asphault, 3 =brick
%green_space	Amount of green land cover	%	Amount of green landcover within 3m of transit stop	25% increments
stop_shade	Stop shade features	Integer	Indicates which shade features stop has	0 = no shading 1 = direct shading from transit structure (awning, etc.) 2 = indirect tree shade 3 = direct tree shade
seating	Stop seating features	Integer	Indicates if stop has seating features	0 = no seating 1 = seating