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Desert New Urbanism: testing for comfort in downtown Tempe, Arizona

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ABSTRACT
Outdoor human comfort is determined for the remodelled downtown of Tempe, Arizona, USA, an acclaimed example of New Urbanist infill. The authors desired to know whether changes were accompanied by more comfortable conditions, especially in hot, dry summer months. The physiological equivalent temperature provided an assessment of year-round outdoor human comfort. Building compactness and tree shade that became part of the changes in the downtown provided more overall daytime human comfort than open nearby streets; however some downtown sites were less comfortable at night, but below 40°C, a threshold for human comfort in this desert environment.

Introduction

Since the 1990s, a number of cities in the Phoenix metropolitan area have sought to strengthen their downtowns with higher building densities. The aims have been to create compact walkable environments, reduce commuting and improve local economies (Frank 2006; Ewing and Handy 2009). Fresh incentives have added momentum to this drive, such as the Valley Metro transit system initiative since 2007, and pressures to protect the vanishing Sonoran desert (Ewan, Ewan, and Burke 2004; Martin 2008). Design strategies are by now highly recognizable and follow original New Urbanist models of Calthorpe (1996) or (Duany and Plater-Zyberk 1991). Medium-sized buildings flank narrowed main streets, sidewalks are widened and parking is either on-street or in small lots to the rear. Floor area ratios are considerably higher than before.

Unfortunately, there is limited understanding of the heat impacts from higher building densities in the Southwestern United States. While New Urbanist developments have been widely tested for their health and economic benefits (Frank 2006; Handy 2007; Ewing and Handy 2009; Forsyth and Krizek 2009), these have not been systematically evaluated for climate impacts in hot cities. Planners should be alerted by reports of dangerous heat levels in some Southwestern cities (Garfin et al. 2013), plus growing evidence that building densities in desert cities can trap night-time heat, particularly in street canyons (e.g. Pearlmutter 1998; Pearlmutter and Berliner 2000; Ali-Toudert et al. 2005; Stone, Hess, and Frumpkin 2010; Chow, Brennan, and Brazel 2012; Yahia and Johansson 2012). Moreover, local planners have few

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Figure 1. Aerial view of renovated Mill Avenue site with field site numbers.

examples of compact settlements to learn from in the Phoenix area, since low-density lifestyles have been a traditional norm since the early years of Southwestern cities (Gober 2010).

City leaders of the City of Tempe, AZ, a city in the Phoenix Metropolitan Area, have created a vibrant downtown, desiring to enhance circulation and encouragement of outdoor activity (City of Tempe Community Development Department 2006, see Figure 1). The project has been celebrated as a model of urban infill, with the central Mill Avenue acclaimed by the American Planning Association in 2008 as one of America's 'Great Streets' (American Planning Association 2008).

Using climate data gathered on selected days representative of the four main seasons from October 2014 to June 2015, diurnal variations of microclimate are converted to comfort levels along seven walkways throughout the renovated Mill Avenue and its periphery (Figure 2). Five measurement sites are located in Mill's compact urban development, and two sites are on the lower density periphery more typical of Phoenix. A readily available comfort model (RayMan, e.g. Matzarakis, Rutz, and Mayer 2007, 2010), illustrates the degree

Figure 2. Study map of downtown Tempe within Phoenix Metropolitan area in Southwest USA with numbered sites.

to which modifications to the downtown, including overhangs, walkthroughs and vegetation placement have altered human comfort. Using a model, questions can be addressed, such as: what is the variation in human comfort along walkways throughout the day and early evening? How do enclosed streetscapes compare with open, and what are the impacts of seasonal change?

Inputs were measured or determined for the RayMan model, such as fisheye lens camera images for sites, latitude, time of year and day and weather data, including parameters of air temperature, humidity and wind speed (see Matzarakis, Rutz, and Mayer 2007 for details of model constructs). The model provides outputs of several features of a given site along streets – solar radiation, mean radiant temperature and the physiological equivalent temperature (these are measures of comfort commonly studied by human comfort researchers; Matzarakis, Rutz, and Mayer 2010).

Researching city densities: a literature review

Overall, the literature of urban design and planning is positive about compact densities (see for example Calthorpe and Fulton 2001; Carmona et al. 2003; Punter 2003; Talen and G. Knaap 2005; Talen 2011). Urban compactness can improve access to services and activities (e.g. Lathey and Guhathakurta 2009). Higher densities are found to increase mobility choices and reduce traffic time and pollution, while property values can escalate around transit lines in compact cities (Cervero 2007; Cervero and Kockelman 2007). The walkability associated with compact developments can improve health and physical fitness, enhance use of one's environment, and improve access to housing (Handy 2007; Forsyth and Krizek 2009). User perception studies have in particular shown preferences for compact streets and plazas in higher density environments. When questioned about their outdoor surroundings, survey respondents have regularly noted greater psychological comfort in enclosed places, particularly from overhanging facades, safety barriers and reduced glare (Givoni and Noguchi, 2000; Ewing and Handy 2009; Ewing and Clemente 2010).

However, climatologists have noted that while compact urban densities may be cooled by shade during the day, night-time temperatures may be elevated through heat trapping. As early as the 1980s, Oke (1981) found night-time heat retention between medium-sized concentrated buildings in hot climates in the US. Since the 1990s, Pearlmutter and others have noted heat retention between compact buildings in housing estates in Israel, attributable to reduced albedo, restricted air currents and diminished night sky (Pearlmutter 1998; Stone and Rodgers 2001; Erell, Pearlmutter, and Williamson 2011; Erell 2014). It is noted that compact urban settings are hard to measure for climate, given their characteristic tight spaces, varied building materials and range of activities. Givoni and Noguchi (2000) discuss the challenge of gauging air temperatures and wind speeds in dense public spaces, particularly older downtowns. Ali Toudert et al. (2005) note the unpredictable heating effects from varied combinations of street paving and building materials at high densities. For these reasons, many climate studies have used modelling to analyze dense environments. For example, Ali-Toudert and Mayer (2006) used the three-dimensional ENVI-met to test cooling from buildings in the Algerian town of Ghazia, as have Emmanuel and Johansson (2006) in Fez, Morocco. In their studies of dense urban areas in Taiwan, Hwang, Lin, and Matzarakis (2011) use the RayMan model to analyze PET levels based on wind change, wind speed and solar radiation.

Site context

This study encompasses the renovated stretch of Mill Avenue between University and Rio Salado Avenues, and includes a half-mile of dense building on either side of Mill (Figure 2). The new layout includes groupings of three- to four-storey office and commercial buildings enclosing small courtyards and plazas accessed by narrow pedestrian corridors.

As the project's 'signature' street, Mill Avenue connects with Arizona State University to the south and new office and commercial development to the north, accommodating moderately heavy vehicle traffic and commercial functions. Tempe's *General Plan 2030* and *Design Guidelines* (City of Tempe Community Development Department 2006) outlines the importance of enclosure for encouraging outdoor activities and allows autos to participate but not to dominate (Design Guidelines 2006, 8). Mill Avenue has been narrowed from four lanes

Table 1. Study site characteristics.

Site# / Labels	Orientation/shading	Sky view factor	Vegetation %	Albedo
North-south sidewalks				
1. Ash Ave	NS exposed walk	0.92	5	13
2. Mill Ave	NS shaded walk	0.19	18	14
East-west sidewalks				
3. Arcade	EW shaded walk	0.05	9	12
4. University Ave	EW exposed walk	0.78	17	23
5. Overhang	EW shaded walk partial	0.21	12	12
Corridors				
6. Arbor Walk	EW corridor shaded	0.13	39	22
7. Tunnel	EW corridor shaded	0.03	16	22

to two. The tree-lined sidewalks are wider than before, and flanked by a solid 'street wall' of stores and businesses. Cross streets are kept narrow to preserve the continuity of the main street. In visible contrast, the two wide arterial streets bounding the site, Ash Avenue to the west and University Avenue to the south, are bordered by parking lots and low structures giving lower height/width ratios. Table 1 notes design and site locations of study. Narrow interconnecting corridors (a feature of the Mill Avenue Development) are widely used in dense inner cities since they provide auto-free access between buildings to inner courtyards (Punter 2003). Note that sky view factors (the extent of sky observed from a point as a proportion of the total possible sky hemisphere) range from 0.03 to 0.92.

Study areas and methods

Two north-south and three east-west sidewalks were chosen for measurement, plus two east-west corridor walkways (Figures 3, 4 and 5). All represent recurring design treatments of walkways in the Phoenix area. The two north-south sites (Figure 3) offer contrasting approaches, from the widely exposed Ash Avenue typical of Southwestern towns from the 1950s (Site 1), to the heavily canopied Mill Avenue sidewalk on Site 2, commonly found in renovated downtowns. The east-west sites represent recurring sidewalks in the Southwest from the semi-covered 'Mexican-style' arcade to the light (and low-cost) overhang structure commonly used to shade building entries (Figure 4). The wide east-west arterial University Avenue resembles Ash Avenue. The two corridor walkways are common in dense inner cities, with the Arbor Walk partially protected by tree shade, and the Tunnel fully covered by building (Figure 5). Sites represent north-south orientations and east-west. North-south walkways can experience sun exposure at times depending on the placement of shading on either side. However, east-west walkways (particularly south-facing) may suffer prolonged radiation due to unmitigated exposure, particularly in summer (e.g. Pearlmutter 1998; Erell, Pearlmutter, and Williamson 2011).

Data in Table 1 were determined through the use of the RayMan model, remote sensing and on-site instrument observations: sky view factor (calculated from fisheye photography), vegetation cover (5–39%, with access to MODIS/ASTER Simulator MASTER data) and albedo (12–23% with a spectrometer, discussed below). The fieldwork of this study was conducted on four selected clear days representing seasonal changes in the Phoenix area: February, March, July and October. While July represents the height of summer, a potentially dangerous time for heat exposure, the months of March and October represent the 'wings' of the

Figure 3. North/South sidewalks, Mill and Ash Avenues (right to left numbers are site numbers).

Figure 4. East/West sidewalks, Arcade, University Avenue, and Overhang (left to right).

Figure 5. Arbor Walk and Tunnel walkthrough (left to right).

summer and pose critical opportunities and challenges for outdoor design. February, on the other hand, is a key winter month for tourism in Arizona, where optimal use of the mild sun is encouraged. Data were collected for selected calm days in July and October 2014, through to February and March 2015 – calm days with low humidity to reflect prevailing norms in metropolitan Phoenix. Air temperature, relative humidity, wind speed and global temperatures were recorded at each site from 6 am to 11 pm on a 3-hourly basis. Data and site information were used to initiate the RayMan calculation of Mean Radiant Temperature (Tmrt) and PET. Tmrt accounts for all short wave and long wave radiation fluxes reaching the human body. Measurement times reflect regular travel patterns to work, daytime business hours and night-time socializing. Site measurements were conducted on foot with each walk completed within half an hour. Walking was necessary as no equipment could be left at sites, and equipment was limited. Hand-held sensors were used to measure the weather data. Table 1 summarizes the site information contributing to calculations.

Comfort variations were investigated through the common comfort index abbreviated as PET (Physiological Equivalent Temperature). PET is defined as the air temperature at which, in a typical indoor setting, the heat budget of the human body is balanced and compared with thermal outdoor conditions (Matzarakis, Mayer, and Iziomon 1999). PET levels include multiple outdoor comfort factors such as on-site radiation, humidity and wind, and are widely used in evaluating heat in cities for the purposes of tourism and public health risks. For this study, PET values were calculated through the use of the RayMan model (Matzarakis, Rutz, and Mayer 2007). Ongoing radiation levels are calculated through sky view factors (SVFs) or sun diagrams to estimate the hours of sunlight for each site throughout all seasons. The simulations were for a person of average height and weight, with clothing appropriate for respective seasons, and a person in a walking position.

Instruments for the study included hand held Kestrel 4400 Heat Stress Tracker devices with digital readout, which measured air temperature, wind speed, relative humidity and global temperature (GT). The latter reading took some 5 min to equilibrate, as suggested by Kestrel specifications and pioneering researchers (e.g. Thorsson et al. 2007). Sensors metrics included: wind resolution of 0.l m/s with accuracy to 0.4 m/s; temperature accuracy of 0.5°C; resolution 0.1°C. Sensors provided a global temperature accurate within 1.4°C, resolution 0.1°C; RH accuracy of 3%, resolution 0.1%. A Flir i3 IR sensor 'thermal' camera was used to record surface temperatures. Resolution was at 60 x 60 pixels, or 3600 pixels per scene with a declared thermal sensitivity < 0.15°C, accuracy of 2% or 2°C, and field of view of 12.5° by 12.5°. Ground reflectance spectral measurements were taken using an ASD FieldSpec-4 Wide-Res spectrometer that measures reflectance at the visible and near infrared wavelength range (350–2500 nm) over 50 nm wavebands.

Sky view fisheye lens photographs were taken of all sites using a camera at 1.5 m height on a tripod. A fisheye lens was used that captures a 180 degree field of view along its diagonal. For each site six images were taken of the horizon with the camera lens facing upwards, rotating the camera 60 degrees around its nodal point after each shot (to avoid parallax errors). Images were then stitched together in Corel Photopaint to create the circular bitmap images required of the RayMan software that covers 180 hemispherical degrees per site. The bitmaps were rotated to reflect true north, flipped horizontally to correct west-east orientation, then imported in RayMan and converted to black and white. Based on bitmaps, RayMan facilitates sky view factor calculations that incorporate shading from built structures.

Authors of the RayMan model acknowledge potential simplifications of the greater radiant environment as experienced by humans, especially in complex urban settings. The model's key parameter is Tmrt.

> The procedure for determining Tmrt experimentally is very complex, time-intensive and expensive. This is due to the combination of pyranometer and pyrgeometer, which have to be orientated in six directions (4 cardinal directions, upwards, downwards) to measure the complete short- and long-wave radiation fluxes which are significant for a person in the 3D environment…. Due to its clear structure, the RayMan model can be applied not only by experts in human-biometeorology, but also by people with less experience in this field of science …(Matzarakis, Rutz and Mayer 2007, 324)

Kruger, Minella, and Matzarakis (2014) show alternative methods for calculating Tmrt through RayMan, the most accurate of which is to observe radiation fluxes from cardinal directions at sites to account for local effects from surroundings (this was not possible in this study). A second method involves using solar radiation data from a nearby weather station, determining a site's sky view factor with a fisheye camera approach, and then running RayMan to obtain Tmrt. A third method is to allow RayMan to estimate incoming solar radiation based on sky view factors and the local geometry of sites (for example, using an imported fisheye photo). The second and third approaches were used in this study. Given an absence of obstructions at Sites 1 and 4, 5-min interval solar radiation data from a utility real time weather station (archived at http://mesowest.utah.edu/) some 4.4 km to the south-east were used to test RayMan's solar calculations. Estimates were carried forward in the model per Kruger et al.'s method 3 allowing RayMan to process sky view factors and solar paths for a given date, and thus resolving further the Tmrt.

RayMan output was compared to global temperature readings, solar data from a nearby site, thermal infrared camera surface temperatures (Ts), and on-site albedo readings. For example, global temperature readings (under no wind conditions at 0.0 m/s) were compared to Tmrt values from the model; and Ts from the Flir camera were compared to RayMan's Ts output using similar emissivity from images and model estimates. Finally, the model was run comparing on-site albedos and assumed RayMan default values.

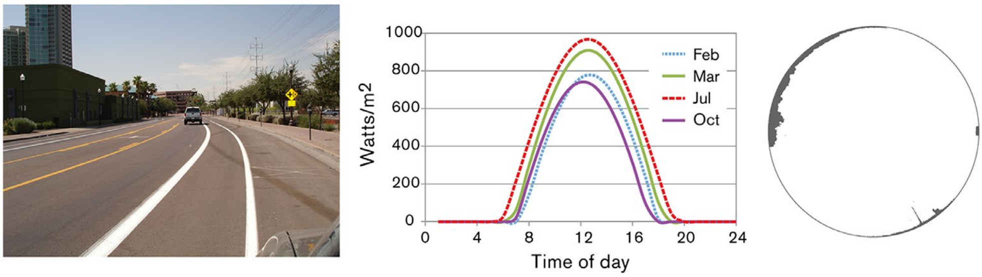
The initial findings revealed a solar radiation estimate for exposed sites within 5% of measured values from the nearby weather station recording at 5-min intervals. A root mean square error (rmse) statistical approach after (Willmott et al. 1985) was followed comparing RayMan default runs with observations. For all observation data during calm winds, the Tmrt from RayMan had a root mean unsystematic square error (rmuse) within 6°C (over a range of Tmrt from near zero to upwards of 70°C across seasons) with a tendency for model values lower than GT in the lower Tmrt range of values; and model values higher than GT readings in the upper part of the range (the Willmott index of agreement was -0.83, on a scale of 0.0 to 1.0). This compares well with other verification studies (e.g. Matzarakis et al. 2007 and 2010).

There are well-known potential limitations of global temperature readings (e.g. Pearlmutter, Jino, and Garb 2014), however, the Kestrel instrument was the only one available in this study to compare to RayMan's model Tmrt values. Observations converted to Tmrt using air temperature, wind speed plus GT yielded unrealistic estimates of Tmrt for wind values ca.>2 m/s (see e.g. Thorsson et al. 2007 for the equation used). The errors are clearly wind-sensitive. Matzarakis, Rutz, and Mayer (2010) compared Tmrt values to a six-sensor radiometer array and resultant Tmrt calculation (a more exacting test) and found a good relation to model output. However, although it was found that there was a statistically significant relation of GT converted to Tmrt vs RayMan's Tmrt values overall, it is cautioned that specification of PET and comfort values from this model remain a central issue versus other measures of comfort such as the Index of Thermal Stress or other measures (e.g. Pearlmutter, Jino, and Garb 2014). Details of these comparisons are ongoing (e.g. Wagner et al. 2016) and are the topic of a more detailed paper forthcoming on testing the RayMan model and using ENVI met for various locales in the Phoenix area.

Analyzing site radiation through the SVF's

Figures 6, 7 and 8 show solar curves, and black and white fisheye images for all seasons using the RayMan model. As revealed, the hours of sunlight differ substantially for each site and season. For example, the open site on Ash Avenue has day-long heat exposure, while the tree-lined Mill Avenue (Site 2) shows periods of heat exposure attributable to gaps in the tree canopy. Wide exposure for University Avenue (Site 4) is noted, with maximum hours of sunlight year-round with some moderate wind potential. Not surprisingly, the study's exposed sites of Ash and University (Sites 1 and 4) were generally cooler before sun up, warmer during the day, and also showed cooler evening temperatures than in obstructed downtown sites. Partially sheltered north sides of east-west streets (Sites 3 and 5), unlike the north-south sites, streets have a potential for prolonged radiation throughout the day particularly in summer months (e.g. Pearlmutter 1998), while the covered south-facing arcade (Site 3) offers year-round shelter from heavy columns, and the 'overhang' (Site 5) shows consistent sun exposure for March, July and October. Wind potential was lower in the covered sites. The Walkthrough Tunnel (Site 7) is fully shaded by building year-round. The Arbor Walk

Site1: Ash Avenue



Site 2: West Mill Sidewalk PF Chang

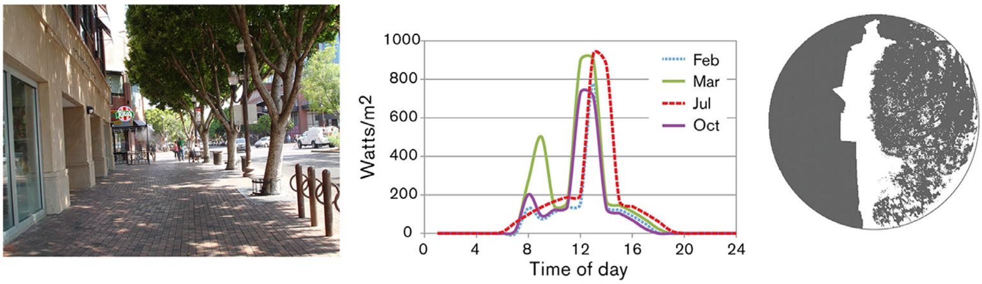
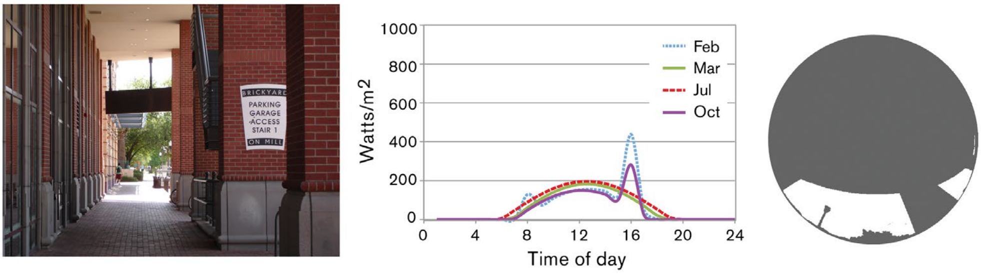
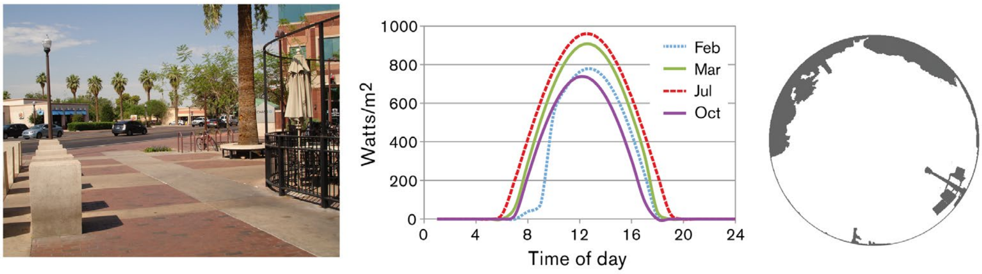


Figure 6. North/South sites showing fisheye diagram and solar curves for measurement days.

Site 3: Arcade East West Oriented



Site 4: Corner University & Mill Ave



Site 5: East West Overhang near Arcade

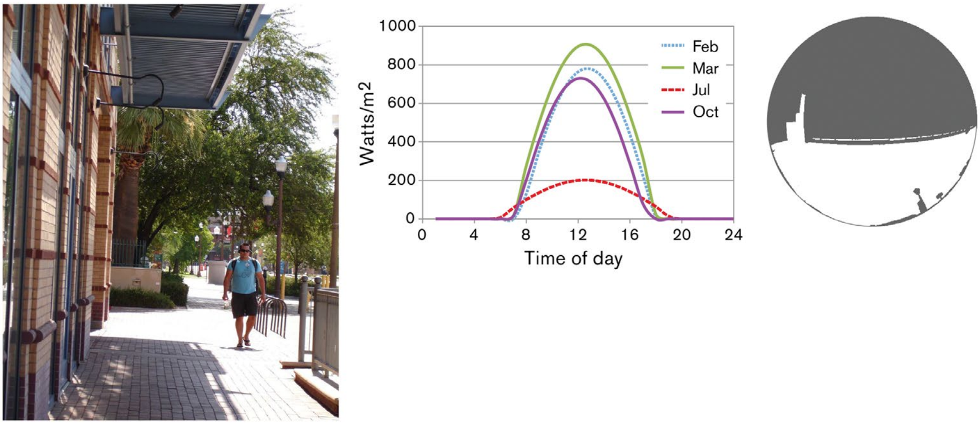


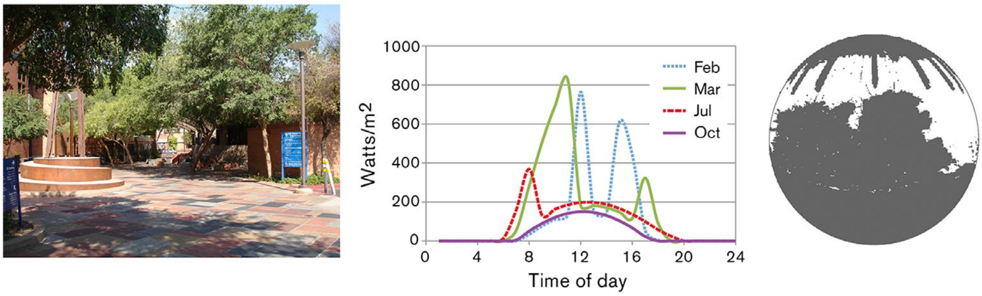
Figure 7. East/West sites showing fisheye diagram and solar curves for all measurement days.

(Site 6) is shaded by deciduous trees, producing full shade in summer with diminished shade for March and October, explained by leaf-drop.

Findings: site readings

The following summarizes recorded summer and winter temperature ranges. In July exposed temperatures ranged from early morning lows of 29.7°C to highs of 41.9°C at noon, while shaded sites ranged from lows of 28.6°C to highs of 40.4°C at noon. February temperatures ranged from early morning lows of 11.7°C (exposed) and 12.8°C (shaded) to noontime highs

Site 6: East West Oriented Breezeway from Mill to Plaza Trellis



Site 7: Walkthrough Tunnel from Mill to DCDC plaza

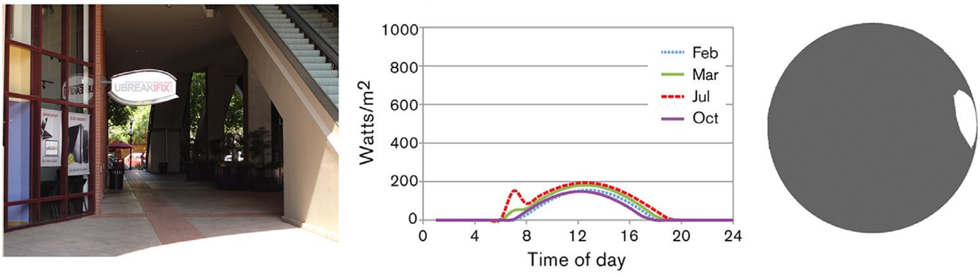


Figure 8. Arbor Walk and Tunnel sites showing fisheye diagram and solar curves for all measurement days.

of 25.8°C (exposed) and 20.7°C (shaded). Comparable differences persisted through the transitional months of October and March.

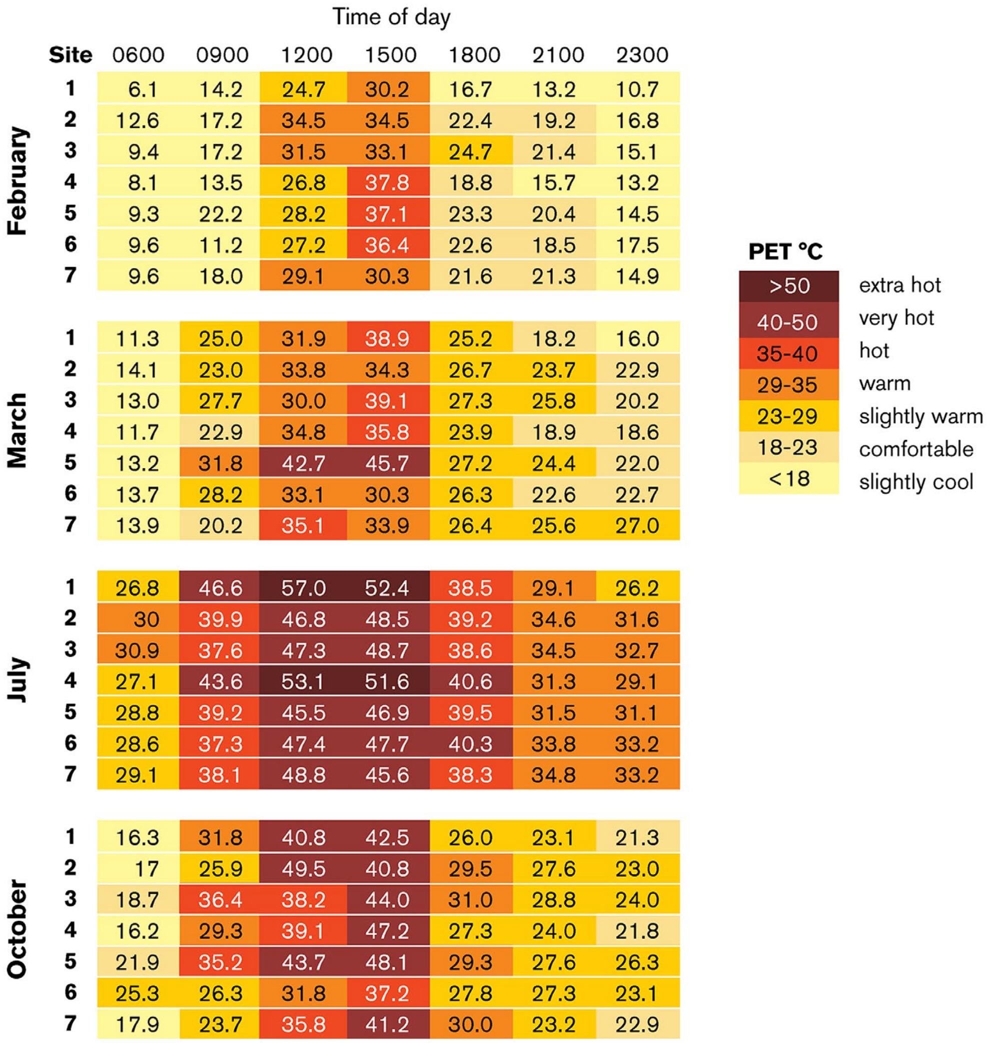
Global temperature mostly closely followed ground temperature readings, but showed a few examples of extremely high readings in July. While in February global temperatures ranged from 10.0°C for early morning (exposed) and 13.1°C (sheltered), July temperatures ranged from early morning lows of 34.5°C (exposed) and 35.7°C sheltered, to extremely hot noontime temperatures of 56–55°C (exposed) and to 53.5° C (sheltered). Global temperatures for February resembled physical temperatures more closely, from 10.0°–11.9°C (exposed), and 11.8–13.1°C (sheltered) in the early morning, and a noontime range from 35.4–31.5 °C exposed and 21.5–32.9°C (shaded). For summer, global temperatures ranged from early morning lows of 35.7–34.5°C (exposed) and 28.2–30.9°C (shaded). At noon, however, very high global temperatures were recorded at 56–55°C (exposed) and 42.1–53.5°C (shaded).

Wind and humidity readings were low throughout the study; 34% of all wind observations recorded less than 0.4 m/s., with the highest recorded wind speed at 5.1 m/s in February at the exposed site of Ash. Winds were slightly higher for exposed sites in July. Humidity was low across all seasons, never exceeding 40% during daytime in February and less than 20% in July.

Findings: PET and comfort

Figure 9 shows PET temperatures for the four measurement periods. PET levels are shown on the horizontal axis, with sites on the vertical axis. Pale shades represent cooler PET values; dark shades are hotter, with black as extremely hot. Findings are discussed in relation to the estimated 40°C threshold of human comfort outdoors (Middel et al. 2016) above which humans may experience dangerous heat effects.

Throughout the summer and transition months, daytime PET temperatures were extremely high at key periods, frequently well above the 30–40°C comfort zone indicated in Figure 9. In July, all sites were extremely high from noon to 3 pm, with extreme heat persisting until 6 pm. There was slight overall cooling by 11 pm. In July, Ash and University Avenue (Sites 1 and 4) PET rapidly climbed by 9 am, and both remained very high through the afternoon. Ash Avenue attained the study's highest PET temperature of 57°C at noon. The transition month of October showed nine extremely hot readings, while March had two such readings.



Time of day

	Site	0600	0900	1200	1500	1800	2100	2300
February	**1**	6.1	14.2	24.7	30.2	16.7	13.2	10.7
	2	12.6	17.2	34.5	34.5	22.4	19.2	16.8
	3	9.4	17.2	31.5	33.1	24.7	21.4	15.1
	4	8.1	13.5	26.8	37.8	18.8	15.7	13.2
	5	9.3	22.2	28.2	37.1	23.3	20.4	14.5
	6	9.6	11.2	27.2	36.4	22.6	18.5	17.5
	7	9.6	18.0	29.1	30.3	21.6	21.3	14.9
March	**1**	11.3	25.0	31.9	38.9	25.2	18.2	16.0
	2	14.1	23.0	33.8	34.3	26.7	23.7	22.9
	3	13.0	27.7	30.0	39.1	27.3	25.8	20.2
	4	11.7	22.9	34.8	35.8	23.9	18.9	18.6
	5	13.2	31.8	42.7	45.7	27.2	24.4	22.0
	6	13.7	28.2	33.1	30.3	26.3	22.6	22.7
	7	13.9	20.2	35.1	33.9	26.4	25.6	27.0
July	**1**	26.8	46.6	57.0	52.4	38.5	29.1	26.2
	2	30	39.9	46.8	48.5	39.2	34.6	31.6
	3	30.9	37.6	47.3	48.7	38.6	34.5	32.7
	4	27.1	43.6	53.1	51.6	40.6	31.3	29.1
	5	28.8	39.2	45.5	46.9	39.5	31.5	31.1
	6	28.6	37.3	47.4	47.7	40.3	33.8	33.2
	7	29.1	38.1	48.8	45.6	38.3	34.8	33.2
October	**1**	16.3	31.8	40.8	42.5	26.0	23.1	21.3
	2	17	25.9	49.5	40.8	29.5	27.6	23.0
	3	18.7	36.4	38.2	44.0	31.0	28.8	24.0
	4	16.2	29.3	39.1	47.2	27.3	24.0	21.8
	5	21.9	35.2	43.7	48.1	29.3	27.6	26.3
	6	25.3	26.3	31.8	37.2	27.8	27.3	23.1
	7	17.9	23.7	35.8	41.2	30.0	23.2	22.9

PET °C	
>50	extra hot
40-50	very hot
35-40	hot
29-35	warm
23-29	slightly warm
18-23	comfortable
<18	slightly cool

Figure 9. PET (Physiological Equivalent Temperatures) for all measurement periods and times of observations during days; values in °C. Values shaded by our descriptors of general comfort categories modified after Matzarakis, Rutz and Mayer (2006) and the research of Middel et al. (2016).

Exposed sites also showed greater reductions in PET at the extremes of the day. Although the two wide avenues of Ash and University attained exceedingly high daytime values, they cooled faster at night and remained cooler early in the morning, in spite of low albedo asphalt. Winter PET levels ranged from cool in the early mornings to comfortably warm around noon and early afternoon, to significantly cooler by 11 pm.

A few shaded sites showed heat trapping in late afternoons and early evenings, although not during periods of extreme heat. For July and October, the tree-lined Mill Avenue did not heat up as rapidly as the open site of Ash Avenue, but later in the day illustrated higher PETs than more open sites. By 6 pm in July and October, the heavily shaded Mill Avenue was hotter than Ash, and proved the hottest site at 11 pm. However, this heat was not excessive. The Arbor Walk showed more marked heat trapping than Mill Avenue, proving the hottest of all sites at 6 pm in July. When full canopied in July, the Arbor Walk exhibited marked characteristics of urban heat trapping. The site was cool during the day but showed relatively high PET temperatures at 11 pm, and was hottest among all sites.

While observed global temperatures under no wind conditions yielded lower Tmrt values than RayMan for higher PET ranges, it is acknowledged that the model may yield higher PET values than in reality. On the high end in summer PET values may be some 5–10°C too high, as suggested by RayMan. However, PET values were nevertheless well over the comfort 40°C threshold.

Surprises and no surprises

Table 2 shows study sites in relation to expected and unexpected findings; these are grouped according to conditions at site level: street orientation, vegetation and on-site design. Many of the findings were as expected, including cooling from shade during summer and hot periods of fall and spring, and night-time heat retention attributable to sheltered conditions. Comfortable winter conditions were also predictable. However, there were some surprises. A few shaded sites were extremely hot, not only in July but in March and October, hotter at times than the Ash or University more open sites. The solar curves and sky horizon charts provide a nuanced explanation of site readings, particularly for distinct and apparently anomalous warm spots.

Overhang: The SVF suggests only a partially shaded 'Overhang' location having a shallow awning that shields the sun in July but not in the spring or fall. In March the Overhang site proved extremely hot around noon and was the only site to reach 'extreme' heat for the 3 pm measurement. In October, Overhang temperatures were comparable to the exposed sites of Ash and University. This extreme heat may be explained by its north side of street, east-west prolonged exposure to sun.

The Arcade, on the other hand, shows the benefits of a solid yet arched building structure along an east-west sidewalk. The heavy columns (common design practice in the Southwest) provide protection against the direct sun while admitting oblique sun when desirable. Arcade temperatures, although high in July, did not reach the heat of the exposed sites, neither was the heat retained in the early evening. In October the Arcade site was cooler than the adjacent Overhang, except for the 3 pm reading when temperatures were equally hot. The Arcade was also relatively cool in March, but in winter proved receptive to the sun, when it is needed. Figure 7 shows some spiky behaviour in February and October with low sun.

Table 2. Expected and unusual findings with site characteristics.

	Ash	Mill	Arcade	University	Overhang	Arbor	Tunnel
No surprises	Wide PET swings from day to night	Lower PET than exposed sites in summer	Lower PET than expected, gaps in tree canopy	Similar to Ash	Lowers PET in summer?	Lower PET than exposed with full summer canopy	Flattens seasonal extremes
Unusual		Higher midday PET than expected	Swing seasons higher pet due to sun penetration & pavement heating		High PET not accounted for by overhang; admits high sun	Higher PET than expected, heat retention at night	Higher PET than expected on summer days; lack of ventilation
Orientation influence	N/S street, orientation of little consequence	West sidewalk on N/S streets protects afternoon PET	North side of E/W street, lower sun heating	Orientation of little value	North side of E/W street, high PET values	E/W narrow walk-through; canopy helps buffer high sun	Minimal
Vegetation effects	None	Tree canopy on sidewalk shades year round	None	None	None	Open SVF winter, full in summer	None
Design features	Open street and sidewalk, no shade: surprise night cooling in spite of asphalt	Cooling from evergreen tree canopy spaced evenly	Classical arcade allows winter sun & summer shade	Similar to Ash	Shallow overhang allows sun to hit pedestrians much of day	Air trapping from summer shade; Welcome winter sun after leaf-drop	Covered walk-through extremely hot in summer

Leaf Cover. Some anomalies were attributable to gaps in tree cover, including leaf shedding from deciduous trees. In March and February the Arbor Walk had no leaf cover and showed increased radiation, with cooling resulting from adjacent buildings and woody branches only. Sky horizons reveal change in canopy cover from bare branches in February and March, to heavy canopy in October and July. Comfortably sunny conditions were found in March and February as sun penetrates into the Arbor Walk (see Figure 8). In October the Arbor Walk provided cooling.

Sky view diagrams also helped explain the relatively high PET readings that were found at the Mill Ave location in July around midday and early afternoon (Figure 6). This could be explained by a gap in the tree cover seen in the sky diagrams, allowing radiation to penetrate the sidewalk in mid-afternoon from directly overhead, and causing a raised PET value during the highest sun period. The Mill Avenue tree canopy understandably does not fully cover the sidewalk in the morning hours on this west side of the main street. This causes solar penetration to the pavement, although the canopy and building shields the sun in the hot afternoon period. These short periods of full sun exposure are typical of north-south streets (see for example Pearlmutter, Berliner and Shaviv 2006).

Conclusions and recommendations

Findings from this study point to predictable comfort enhancement through increased building height and tree shade. However, orientation was important. While north-south sidewalks showed direct response to periods of sun exposure throughout the day (cooling from shade, warming from sun), the east-west sidewalks showed prolonged and severe radiation at times throughout the day (confirming findings, for example, by Ali-Toudert and Mayer 2006). Sites with little wind proved liable to significant night-time heat trapping, while the two wide streets showed significant cooling at night, attributable to openness and more exposure to gusts of wind. For daytime hours, it is likely that the rehabilitated and redeveloped streets were cooler and more comfortable than the open streets that existed in the 1960s. During that time there were lower building heights and no median or street sidewalk trees, unlike today. Using RayMan to make PET estimates for 1960s vs now, daytime excess PET in 1960s could have been ~15°C higher in July, 6°C in October, 7°C in March and 3°C higher in February. However, night conditions now could be 5°C higher than in 1960 in July, 4°C higher in October, 5°C higher in February, and 6°C higher in March – so somewhere between 4–6°C higher PET at night. The rehabilitation and redevelopment has flattened out the extremes to cooler during the day but warmer at night, but the main conclusion is a sought-after more comfortable use of the downtown during daytime.

The call for generalizable findings is growing among urban designers, given the need to encourage use of outdoor spaces (see for example, Ewing and Handy 2009; Talen 2011). In the case of Tempe, city leaders have expressed their intention to encourage pedestrian activity around Mill Avenue for the area's economic and social benefits. Leaders might take further note of urban design strategies for maximum street comfort in dense downtowns in the Southwest.

- Consider land uses appropriate to daytime and night-time cool periods. While daytime shade might be desirable for many business and recreation areas, streets programmed for heavy night-time use and entertainment might be positioned in relation to wind.
- Full-canopied trees are desirable for maximum daytime cooling, although they can trap night-time heat. Deciduous trees can ensure sun during transitional months. Urban designers should consider the effectiveness of tree species in urban cooling (e.g. Bowler et al. 2010; Hwang, Lin, and Matzarakis 2011).
- Street orientation is important. Designers might note the potential of east-west streets to suffer prolonged southern exposure, while north-south streets can experience shorter periods of heat vulnerability.
- Consider building structures that provide shade as needed, yet offer diffuse radiation in March and July. Use modelling to anticipate the effects from buildings and walls; such features need further assessment in models.
- Shallow awnings should be used with caution, potentially leaving a site vulnerable to full sun unless assessed in detail.
- Designers should consider strategies to take advantage of the prevailing wind systems to increase cooling in the late evening. In the case of Tempe, allow east-west orientations to take advantage of cool night-time drainage from easterly directions.A number of critical comfort issues are identified within the desert city of Phoenix Arizona and its satellite communities such as Tempe, Arizona. Some relevant cautions and solutions are applicable not only to Phoenix but to growing desert cities worldwide. However,

accurate predictions of outdoor comfort levels will require further detailed modelling. The ENVI met model (Bruse and Fleer 1998 and now in version 4) goes far in addressing energy balances of micro-environments by including building height, materials and spacing at a fine scale to anticipate outdoor comfort results. The RayMan model offers valuable estimates of PET to identify comfort variations outdoors. However, both are works in progress, and are part of a surge of ongoing initiatives to analyze downtown environments within metropolitan regions. As pressures increase for comfortable outdoor urban environments, so does the need for accurate predictions that can apply to specific locations and new situations.

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