STUDY OF THERMAL COMFORT DETERMINANTS IN THE URBAN STREET DESIGN IN HOT AND ARID CLIMATE : ROLE OF MATERIALS

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Statement by The Author

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CONTENTS

Calle de la Silleria, Toledo, Spain, Photography by Youngsoo Kim

Rua do Vilar, Santiago de Compostela, Spain, photograph by Youngsoo Kim

0.0 INTRO TO RESEARCH

Preliminary bioclimatic design principles that are related to thermal comfort level of the urban street environment in hot and arid climate region were searched in this research. As methods of investigation included: literature reviews, empirical studies and case studies. In hot and arid climate region, most of physically unpleasant conditions in the street environment are found during summer time. However, street design standards and typologies on the basis of mere dichotomy of access and movement don't reflect diversity of existing streets and their bioclimatic requirements to provide physical comfort within them. Thermal comfort was used as a criterion to evaluate the physical condition of the street environment in the research and determinants of thermal comfort in the street environment were researched. The preliminary literature reviews conclude that the reflectivity and the emissivity of materials are two main determinants of thermal performance. Field research were conducted for the numerical comparison of the ambient and the surface temperature by surrounding materials in the street environment. Paseo del Prado in Madrid Spain and Univeristy boulevard in Tucson, Arizona, United States are the measured streets. It is found that there is clear difference in the ambient temperature by surrounding material. Simultaneously, critical role of shades was revealed to decrease both ambient and surface temperature in the street environment. The ambient temperature measured in the shade maintained 20.0 F lower than non-shaded environments. Further investigations on urban climatology show crucial relationship of the street geometry, e.g. street orientation and building height to street width ratio (H/W) with thermal comfort in the street environment. Street case studies provide supplementary solutions for the street design such as vegetations and shading devices. Material uses, geometry, vegetation and shading devices are organized as a preliminary design recommendations in conclusion.

1.0 INTRODUCTION


La Rambla, Barcelona, Spain, photograph by Youngsoo Kim

1.0 INTRODUCTION

> "If we can develop and design streets so that they are wonderful, fulfilling places to be, community building places, attractive public spaces for all people of cities and neighborhoods, then we will have successfully designed about one-half of the city directly and will have had an immense impact on the rest."
>
> **Allan Jacobs, Great Streets, 1993**

Most of authors agree that streets are one of the most important public elements in the city consisting of both social activities and physical characteristics. They perform as intrinsic venue of communal activities while it works as a system for vehicular movement as well as people and public transit. Since Camillo Sitte's research of traditional streets and its conflicts with modern engineering and standards (Collins 1965), the role and importance of streets have been challenging by many problems in western contemporary cities. When suburbia emerged rapidly from 1950's in many cities, motorized vehicles started to occupy more and more portion of public space (Southworth, Ben-Joseph 2003). Both social and physical condition of streets has deteriorated, but it didn't take long time to bring reaction of this decaying public realm of city. In her significant work, 'The death and life of great American cities', Jane Jacobs brought importance of street and since then, scholars and designers like Kevin Lynch, Donald Appleyard and Alan Jacobs brought important arguments in defense of public space.

Rua de Santa Clara, Porto, Portugal, photograph by Youngsoo Kim

From the sustainability point of view, measuring the street or public environment has been very difficult, since our understanding of social and physical aspects of sustainability are still vague to define. From this broad conception of sustainability, more specified concept of livability arouse. Today, many social and physical indicators have been established by different organizations as such city government of Seattle, Portland, to measure livability of cities (San Martin, 2006). Nevertheless principles applicable to streets design have still been in slow pace. From these reasons, this study will focus on physical design principles and design applications for physical street in relationship with human comfort level. As a building consists of various elements like envelope, structure, mechanical system, and etc, streets also have various components within them such as Pedestrian sidewalks, vehicular roads, landscapings, street furniture and buildings, all of which are related to human comfort level . For instance, the different pavement material of sidewalks will perform differently on heat radiation with different height of buildings and different time duration of shades on the streets, all of which are related to thermal comfort on streets. Unlike buildings, the outdoor environment is very difficult to adjust its physical settings once it is built. In this sense, there must be sensitive considerations when streets are designed.

2.0 HYPOTHESIS

4th Avenue, Tucson, AZ, USA, photograph by Youngsoo Kim

2.0 HYPOTHESIS

In the contemporary urban environment, streets and roads occupy more than 30% of the land (Metro 2003). Simultaneously, in terms of social activities in t he urban environment, streets are thresholds where private and public realms interface and interact to each other. Also, social interactions are deeply influenced by physical settings and design of the streets (Gehl, 1987). In this sense, providing sound physical conditions of the street environment must be one of the premises to accommodate healthier social activities. In other words, as an important public space, physical comfort must be provided by the street environment. Physical comfort of the outdoor environments like streets is mostly dependent on the regional climatic factors (Olgyay, 1963). Accordingly, it is critical reflecting regional climatic characteristics into the street design. Adaptation of specific design strategies becomes critical to mitigate the given climatic condition in the street environment. Various types of design strategy have developed since Victor Olgyay's renown work 'Design with Climate (1963)'. For example, by changing orientation or building height of the street, exposure of the street to the solar radiation can be increased or decreased to ameliorate given climatic condition in the street environment. Yet, changing properties such as orientation and geometry of the street entails complex procedures. Instead, this thesis focuses on role of materials in determining physical comfort level in the street environment. Different material selections of horizontal and vertical surface of the street environment and its performance on thermal comfort in comparison with the other design strategies are researched in this thesis.

3.0 RESEARCH

3.0 RESEARCH METHOD AND THESIS STRUCTURE

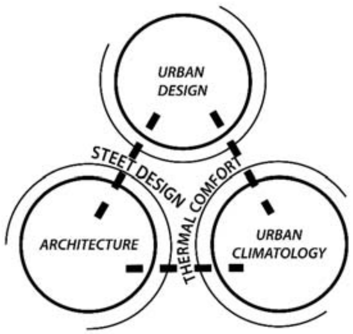


Figure 3-0-1 Integrated Fields

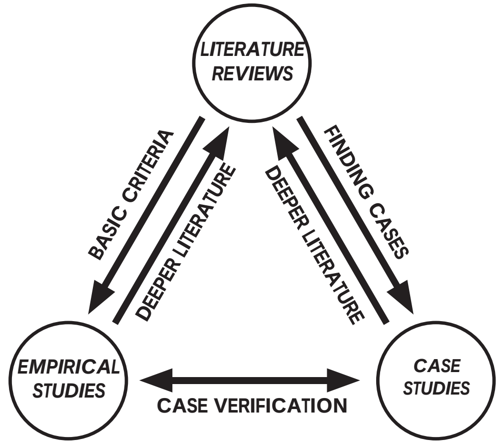


Figure 2-0-2 Research Methods

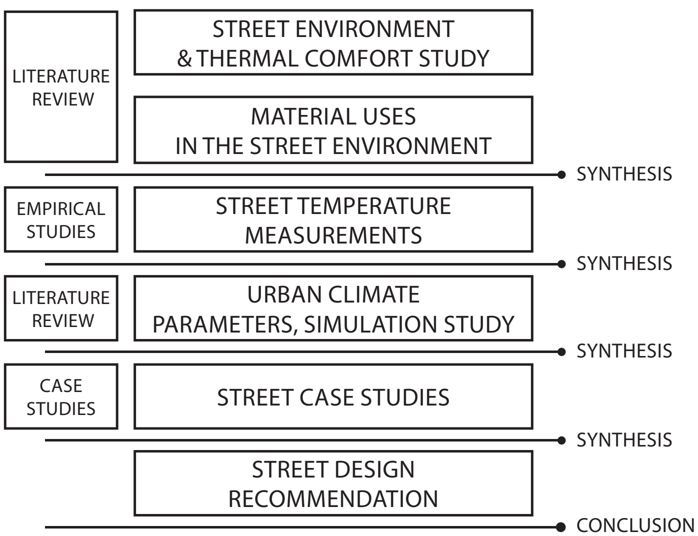


Figure 3-0-3 Thesis Structure

The structure of this thesis is the end result of a process of learning by reading and researching for methods of integrating related fields to street design and thermal comfort, applicable to urban design, and urban climatology, Figure 3-0-1. As such, this thesis is rest on the penduline supported by three types of research investigations: literature review, empirical studies and case studies. As seen in the diagram Figure 3-0-2 and 3-0-3, each research method has interacted to each other in the process of thesis development. Survey was initially of literature on streets environment and outdoor thermal comfort studies. Physical components of the street environment were outlined and became the basis for additional research on material of street surfaces. Basic literature review was conducted to find cases of street design and materials uses of it. Additional temperature measurements were conducted to verify performance of each material in the street environment. After this evaluative process, human comfort was specified to variations of material uses, street orientation, and geometry where included. These investigations opened the door for further literature reviews on urban climate studies based on computer simulation method in urban microclimate.

3.1 LITERATURE REVIEW

YEAR	ORGANIZATION	STANDARD
1935	FHA (Federal Housing Association)	Subdivision Development
1947	ULI (Urban Land Institute)	The Community Builders Handbook
1965	ITE (Institute of Transportation Engineers)	Recommended Practices for Subdivision Streets
1974	ULI (Urban Land Institute)	Residential Streets
1984	ITE (Institute of Transportation Engineers)	Recommended Guidelines for Subdivision Streets
1994	ITE (Institute of Transportation Engineers)	Traffic Engineering for Neotraditional Neighborhood Design
2000	ODT/ODLCD (Oregon Department of Transportation, Department of Land Conservation and Development)	Neighborhood Street Design Guide-lines: An Oregon guide for reducing street width

Fig 3-1-1 Development of street standards

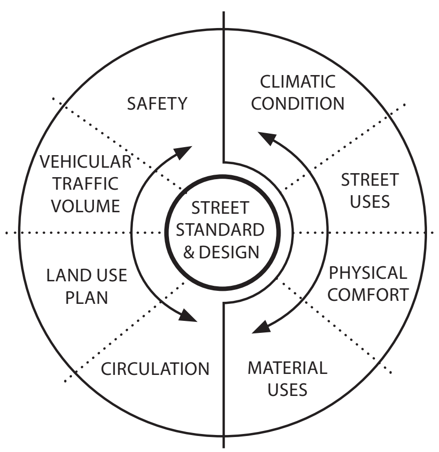


Fig 3-1-2 Separated principles of street standards and design

(Streets and the shapings of towns and cities, Michael Southworth, Eran Ben-Joseph)

3.1.1 STREET STANDARDS: FROM SEPARATION TO INTEGRATION

Since the focus of this thesis lies on the physical setting of streets, it is critical to understand some of the current determinants of street design. In architecture, for instance, there is a building code that determines general physical parameters of the building. Not unlike the building design, there are street standards that delineate the basic physical settings of streets. For example, street width and side walks are determined by the street standards and it is a framework of street design. It seems that street standards control mere dimensions of streets but, these simple numbers can change the total behavior of streets in the city. Over time, the design of streets have been determined by evolving street standards and they have been developed by different entities. Amongst them, most influential standards are from FHA, ITE and ULI as seen in the Fig 3-1-1. FHA's first standard in 1935 introduced rationalized principles based on precise dimensions and this standard led to postwar suburban street pattern (Southworth, Ben-Joseph 2003). ITE's standard in 1965 also followed this line by rigid regulations on the basis of safety, volume of vehicular traffic, land use plan and circulation system within the subdivision development. Yet, these principles separated the other determinants of street design such as physical comfort of pedestrians, multiple street uses, regional climate condition and material uses (Fig 3-1-2).

Fig 3-1-3
Elm street
Tucson, AZ

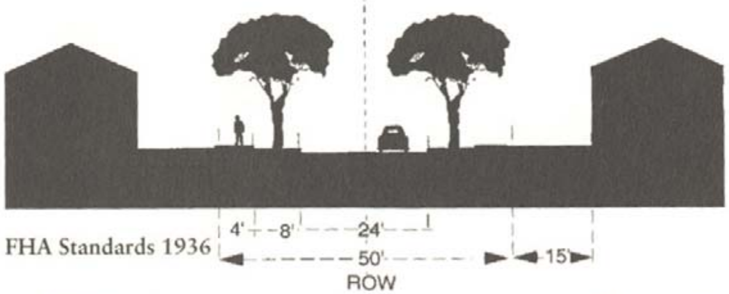


Fig 3-1-4
1936 FHA Standard
(Streets and the shapings of towns and cities, Michael Southworth, Eran Ben-Joseph)

Fig 3-1-5
Park avenue
Tucson, AZ

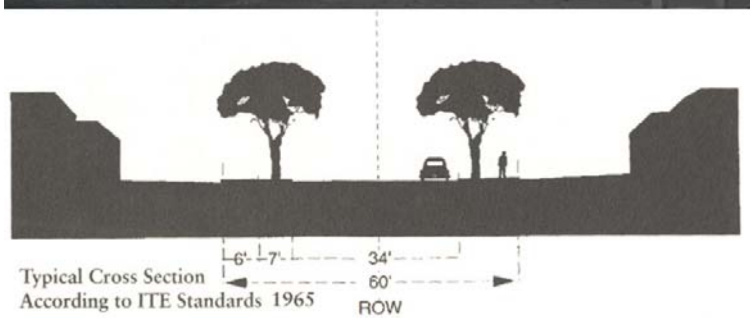


Fig 3-1-6
1965 ITE Standard
(Streets and the shapings of towns and cities, Michael Southworth, Eran Ben-Joseph)

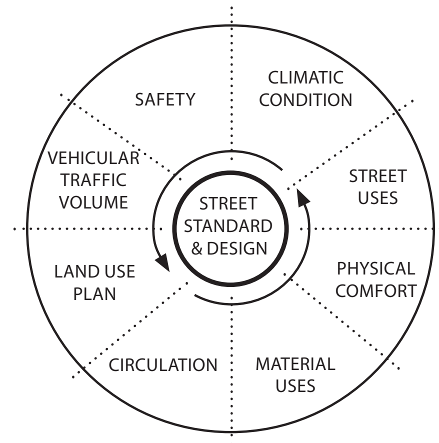


Fig 3-1-7 Integrated principles of street standard and design

Results of the separation in principles are shown in Fig 3-1-2,3,4,5. Typical street cross sections by FHA and ITE standards and their examples. As seen in photos, it is found that streets and their surrounding environment of street are not well integrated into each other. This is also a representation of simple but powerful street standards (Southworth, Ben-Joseph 2003). To avoid problems from limited principles and rigid standards, non profit organizations and local government such as ULI and ODT introduced street design recommendations based on flexible and integrated principles (Fig 3-1-7). In this sense, there must be not only quantitative but also qualitative consideration in the street design. Instead of monotonous street scape, how diverse street typologies have been and are possible with integration of street design principles will be discussed in the following section.

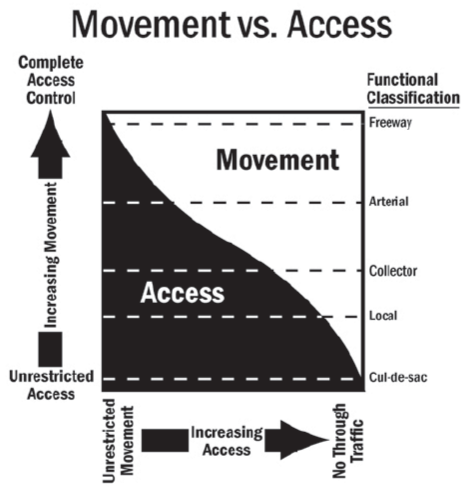


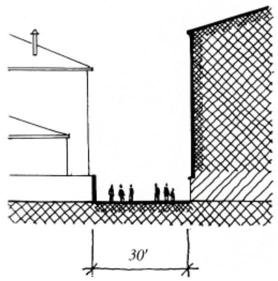
Figure 3-1-8 Hierarchy of Roads (Tucson Department of Transportation)

STREET TYPOLOGY	DESCRIPTION
Lane, Path	Alle, Alley, Path
Streets	Strada, Strasse, Multiple systems, In principle a space for movement, including vehicular, service merchandise, and people
Avenue	A wide street designed for access or attainment to and from a place. Often well landscaped with trees
Gallery	An internal commercially specialize and covered street
Terrace	lat.terraceus, a platform, the top of an elevated surface. Residential street following at the top of a surface
Rambla	Bed, channel, river course, converted into a boulevard
Parkway	Broad thoroughfare, with a dividing strip, planted with trees and shrubs and with planted side walks
Boulevard	Along or on top of a fortification i.e. bulwark. Borrowed by the French modernize by Haussmann in Paris and since then with similar design intent as Parkway but often with larger and well landscaped medians
Freeway, Highway Expressway	Mortorway connecting cities and towns

Figure 3-1-9 Street Typologies (Ignacio San Martin, 2007)

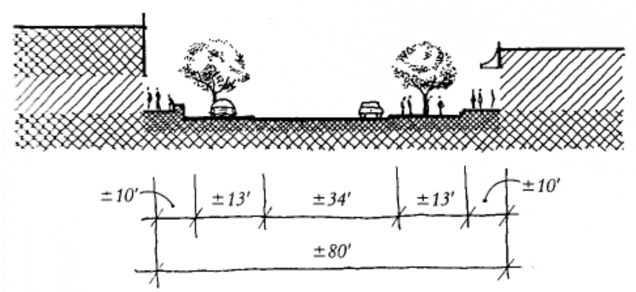
3.1.2 STREET TYPOLOGY

This section was structured to emphasize diverse typologies of street environment that cannot be supported by current street standards. In his book 'Streets & Patterns', Stephen Marshall presents that streets can be classified by numerous different parameters (Marshall 2005). Thus, this section focuses only on the street typology that relates to the definition of the 'street environment'. Figure 3-1-8 shows conventional hierarchy of streets in the United States (City of Tucson, department of transportation). Stephen Marshall points out problems of this hierarchy system in reality. This hierarchy is based on artificial relationship of access and movement, even those two variables are independent to each other (Marshall 2005). Further more, two independent variables that are presented together in inverse relationship cannot represent the street that does not fit into this hierarchy in the built environment (Marshall 2005). For example, streets like La Rambla in Barcelona, Spain which is traditional arterial and it has both higher access and traffic movement. Streets with various types of transportation are also not possible to categorize with this conventional hierarchy system. Instead of this hierarchy system, Ignacio San Martin suggests wider range of street typologies that are found in cities (Figure 3-1-9, San Martin 2007). Since design strategies for the street environment are diverse, it is critical to understand various types and scale of street environment. Definition of each type is explained with examples in following pages.



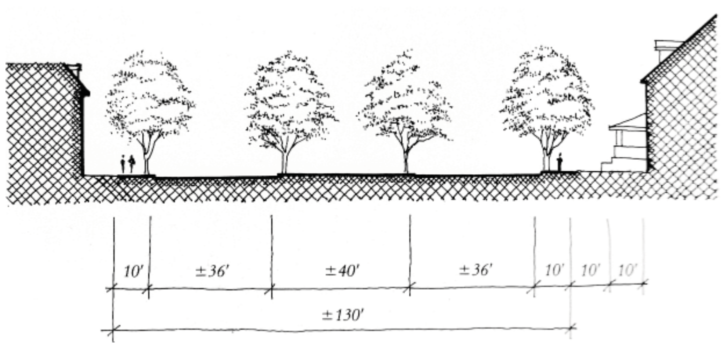
(Figure 3-1-10 Section of Alley, Strada Nuova Venice, Italy, Allan Jacobs, Great Streets, 1993)

Alley: Alley is a narrow street; especially : a thoroughfare through the middle of a block giving access to the rear of lots or buildings. In Europe, alleys are easily found as narrow pedestrian only streets. It is considered one of the narrowest scale streets. It is occupied mainly by pedestrians but there traffics are also allowed in modern alleys. Typical European Alley is shown in Figure 3-1-10.



(Figure 3-1-11 Section of Street, Castro Street, Mountain View, CA, Allan Jacobs, Great Streets, 1993)

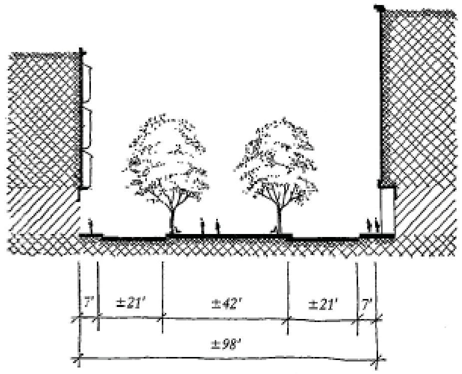
Street: Etymology of street is from the Latin strata (meaning "paved road"). Meaning of street includes stratifications of different movement in it. Spread out and, if constructed, paved surface of public use. Also with the intended reference to movement and as connector between specific points with the specific objective of providing circulation and access (San Martin, 2007). In terms of classification of street, street includes both pedestrian and vehicular movement within it. Street parking is also found along side vehicular traffics (Figure 3-1-11).



(Figure 3-1-12 Section of Avenue, Monument Avenue, Virginia, Allan Jacobs, Great streets, 1993)

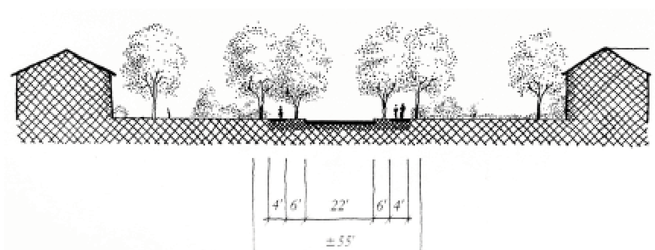
Avenue: From Latin word advenire to French avenir, meaning to come to, Avenue is defined as the principal walk or driveway to a house situated off a main road or a broad passageway bordered by trees (Figure 3-1-12). As it is described in definition, in modern urban settings, it is used as secondary collector street from or to major arterials. Streets are also used for naming the avenues to distinguish the directions.

Rambla: Etymology of rambla is from Arabian word 'ramla' meaning dry stream. In Catalan and Spanish, it means an intermittent water flow. Best known type of it is, La Rambla in Barcelona, Spain. Indeed, till late 18th century, rambla was a stream for sewer and towards the end of 18th century it was converted into wide street with lined trees (Figure 3-1-13).



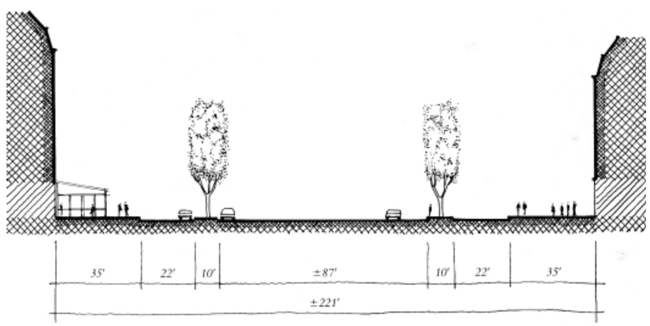
(Figure 3-1-13 Section of Rambla, La Rambla, Barcelona, Allan Jacobs, Great Streets, 1993)

Parkway: Frederick Law Olmsted designed the first parkway in U.S in the 19th century. In his design, pedestrian and vehicular movement were separated. Eastern Parkway and Ocean Parkway in Brooklyn, NY are examples of his work. Parkway generally includes rich landscape of trees and vegetations in the median and alongside sidewalks providing pastoral experience of walking and driving (Figure 3-1-14).



(Figure 3-1-14 Section of Parkway, Roxboro Road, Tutor Road, OH, Allan Jacobs, Great Streets, 1993)

Boulevard: Originated from Dutch, Bolwark, meaning bastion, introduced to French in 15th century, Boulevard is defined in dictionary (Merriam-Webster 2007), as a broad often landscaped thoroughfare. It is often divided by medians in the middle with trees and has parking lanes on each side. Boulevard means flat summit of a rampart in French. It is well known by French civic planner Baron Haussmann in his reshaping plan of Paris from 1853 to 1870. Champs Élysées in Paris is one of the most famous of its kind (Figure 3-1-15).



(Figure 3-1-15 Section of Boulevard, Champs Elysees, Paris, France, Allan Jacobs, Great streets, 1993)

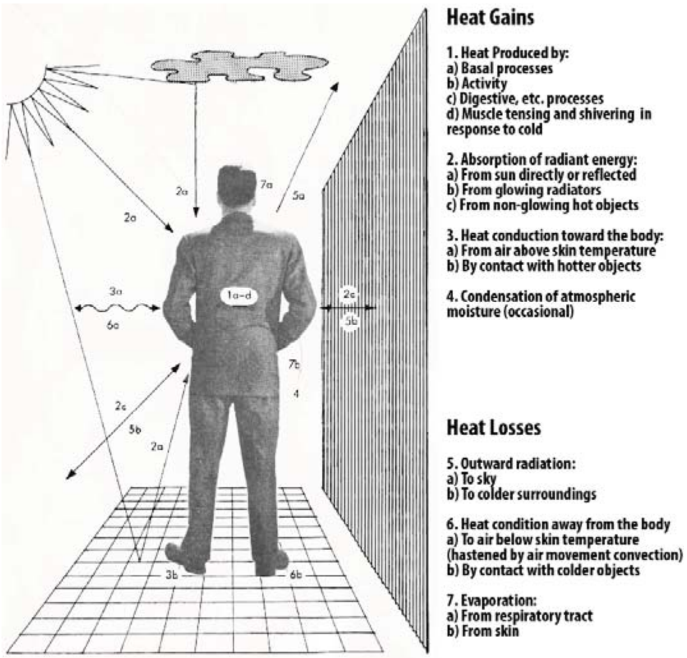


Figure 3-4-1 Heat exchange between man and surraundings (Victor Olygay, 1963, Design with Climate)

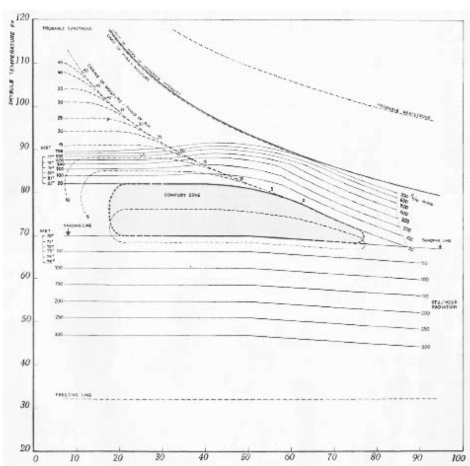


Fig 3-4-2 Bioclimatic Chart and Analysis of Phoenix, (Victor Olygay, 1963, Design with Climate)

3.4 THERMAL COMFORT AND THERMAL COMFORT INDICATORS

The main purpose of this thesis is to find some design applications to increase the physical comfort in the street environment to invigorate outdoor activities in hot and arid climate. For this study, thermal comfort will be used as the critical measurement method of human comfort level in the street environment. Humans exchange their heat with their surroundings and try to achieve thermal comfort by balancing heat gains and looses, Fig 3-4-1. Various reactions to different climatic conditions represent the effort to achieve thermal comfort. For instance, people change their clothes when temperature changes to increase thermal comfort level. In most of the cases, reaction to the thermal condition is related to the sense of entire body. In this sense, thermal comfort can be defined as conditions at which humans consume minimum energy to adjust themselves to their environment (Olgyay 1963). According to the Architect's Council of Europe, thermal comfort is defined as 'Thermal comfort is sense of well-being with respect to temperature. It depends on achieving a balance between the heat being produced by the body and the loss of heat to the surroundings.' (Green Vitruvius, 1999). As thermal comfort is influenced by the climate, climatic variables become critical such as solar radiation, air temperature, relative humidity and wind speed. Victor Olgyay brought the idea of thermal comfort zone defined by relatively simple variables of dry bulb temperature and relative humidity, Fig 3-4-2.

Thermal Comfort Indicator	Scholars/ Year	Description
Operative Temperature (OP)	Winslow, Herrington, Gagge (1937)	Arithmetic average of air temperature and mean radiant temperature that is including solar and infrared radiant fluxes weighted by exchange coefficients.
Index of Thermal Stress (ITS)	Giovoni (1976)	Assumes that within the range of conditions where it is possible to maintain thermal equilibrium, sweat is secreted at sufficient rate to achieve evaporative cooling.
Predicted Mean Vote (PMV)	Fanger (1982)	PMV expresses the variance on a scale from -3 to+3 from a balanced human heat budget. Clothing and activity are variables.
Physiological Equivalent Temperature (PET)	Mayer, Höppe (1987)	Temperature at which in a typical indoor setting: $T_{mrt} = T_A$; VP = 12h Pa ; v = 0.1 ms^{-1}, the heat balance of the human body (light activity, 0.9clo) is maintained with core and skin temperature equal to those under actual conditions, unity °C.

Figure 3-4-3 Selected thermal comfort indices for outdoors (Ali-Toudert F, 2005)

Since not only climate but also surroundings have impacts on thermal comfort, there have been efforts to develop thermal comfort indicators for last decades.There are various elements related to climate that are influencing outdoor thermal comfort. Climate elements in the urban settings are *solar radiation, wind, precipitation, air temperature and relative humidity* (Hough 1995). These elements are reflected in the Olgyay's bioclimatic chart limitedly. *Operative Temperature* by Winslow, Herrington and Gagge (1937) has been used but, because it didn't reflect more complex parameters of outdoor urban environment, various evaluation models were developed by urban climatologist. Focused on hot climate, *Index of Thermal Stress* (ITS) was developed by Givoni (1976). There is also a comfort prediction model including human's empirical response by Fanger, *Predicted Mean Vote* (PMV) (1982). A model allowing assessment of comfort in both hot and cold climate, *Physiological Equivalent Temperature* (PET) was developed by Mayer and Höppe (1987). Figure 3-4-3 is a summary of thermal comfort indicators. These models give clues what parameters can be critical for design of streets. In the following sections it will be discussed that how each element street environment is related to these variables and indicators of outdoor thermal comfort. Further climatic parameters will be discussed in the section 4.1.

3.1.4 SYNTHESIS- STREET AS A PHYSICAL ENVIRONMENT

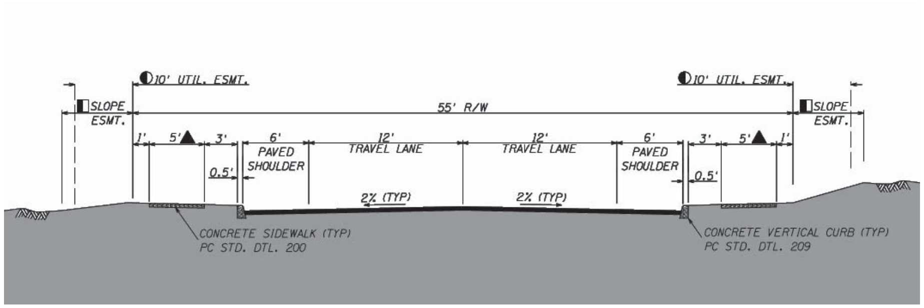


Figure 3-1-16 Street standard for collector commercial or industrial subdivision (Pima county department of transportation)

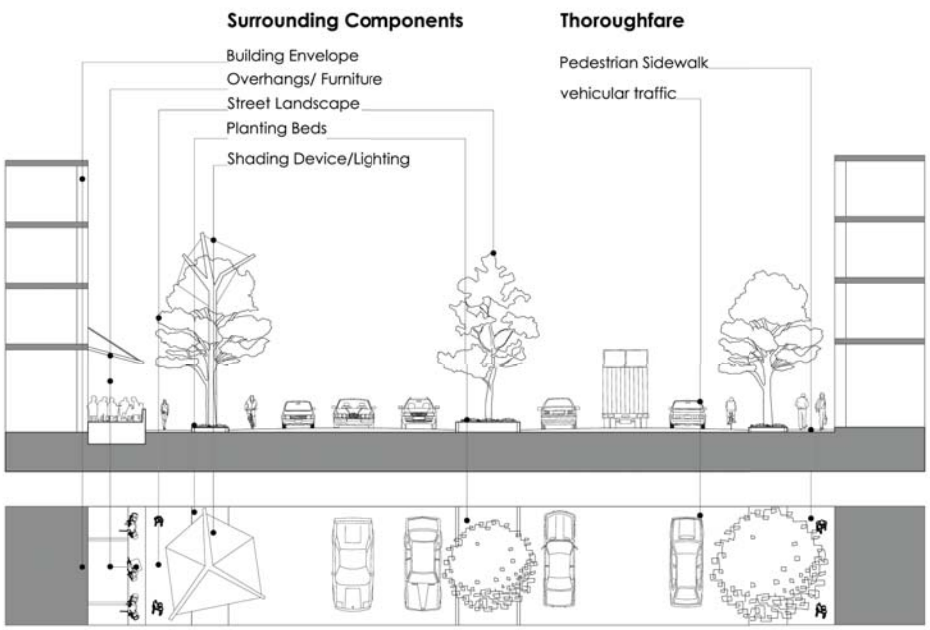


Figure 3-1-17 Street environment and its components

As stated in the statement, streets are one of the most critical outdoor built environments in the city. To have more precise understanding of streets as physical environment and its material use, analysis of streets is critical. However, depending on focus of study, streets have broad and wide definition and typology, thus it is also important to narrow down that of streets. From this point of view, in this study, physical aspects of streets need more emphasis than social ones in definition. In Merriam-Webster dictionary 2007, the word street is originated from Late Latin strata which means *paved road and street is* defined as *'a thoroughfare especially in a city, town, or village that is wider than an alley or lane and that usually includes sidewalks'*. This definition explains function, scale of streets as both for traffics and walking environments in urban built environments but it is still wide and unclear definition as physical environment for this study. Since the focus of this study is based on design of streets and its influence on human physical comfort, components like building facades, landscaping and shading devices must be added in the definition. Current street standards don't reflect various components of the street, Figure 3-1-16. Instead, the street can be redefined as 'street environment' consisting of vehicular traffic road and pedestrian sidewalk and its surrounding components including building facades, overhangs and street furniture, street landscape, planting beds, shading devices, paving materials and lighting, Figure 3-1-17.

3.2 INVESTIGATIONS IN URBAN CLIMATOLOGY

Climatic factors	Urban Design Factors	Individual Factors
Air temperature	Street geometry	Metabolic rate
Solar Radiation	Street orientation	Clothing type
Wind speed	Material use	Adaptation
Relative Humidity	Vegetations	
	Shading Devices	

Figure 3-2-1 Determinants of outdoor thermal comfort

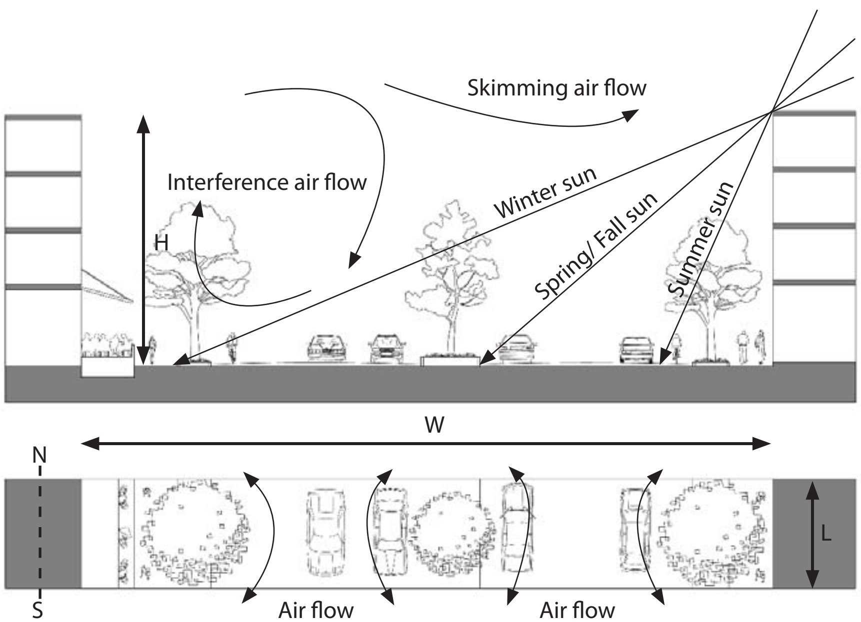


Figure 3-2-2 Sun and wind reaction to H/W ratio and orientation

3.2.1 INVESTIGATIONS IN URBAN CLIMATOLOGY

The field of urban climatology, focuses its research by testing specific factors of street environments responsible for influencing the comfort level of the street environment. Figure 3-2-1 shows the most common parameters from their point of view, that have impact on thermal comfort in the outdoor urban environment (Swaid et al, 1992).

Climatic factors: The European research project RUROS (Rediscovering the Urban Realm and Open Spaces) is primarily on the basis of microclimatic monitoring by weather stations and annual field survey including 10,000 interviews covering 14 cities in 5 countries in Europe according to Nikolopoulou, Lykoudis, 2005. People reacted more sensitively to air temperature and solar radiation than relative humidity and wind speed variables.

Urban Design Factors: For streets are considered as *Urban Canyons: UC* having specific geometries such as building height to streets width (H/W) and specific orientation, Figure 3-2-2. The length (L) of building is six times longer than the height in definition(Oke, 1988). H/W ratio and street orientation can influence ambient temperature, solar radiation and wind speed of the street environment.

Individual Factors: This research also discusses individual factors such as human adaptation. In terms of thermal comfort, adaptation can be defined as a process that humans experience to improve their comfort within their environments. (Nikolopoulou, Lykoudis, 2005). This research, psychosomatic categories of adaptation including: psychological, reactive, interactive and physical adaptation. With these factors climatologists have tried to develop evaluation methods over last decades. Difference of each method and outcome will be compared in the next section.

3.2.2 LITERATURE REVIEW
-THERMAL COMFORT EVALUATION METHODS

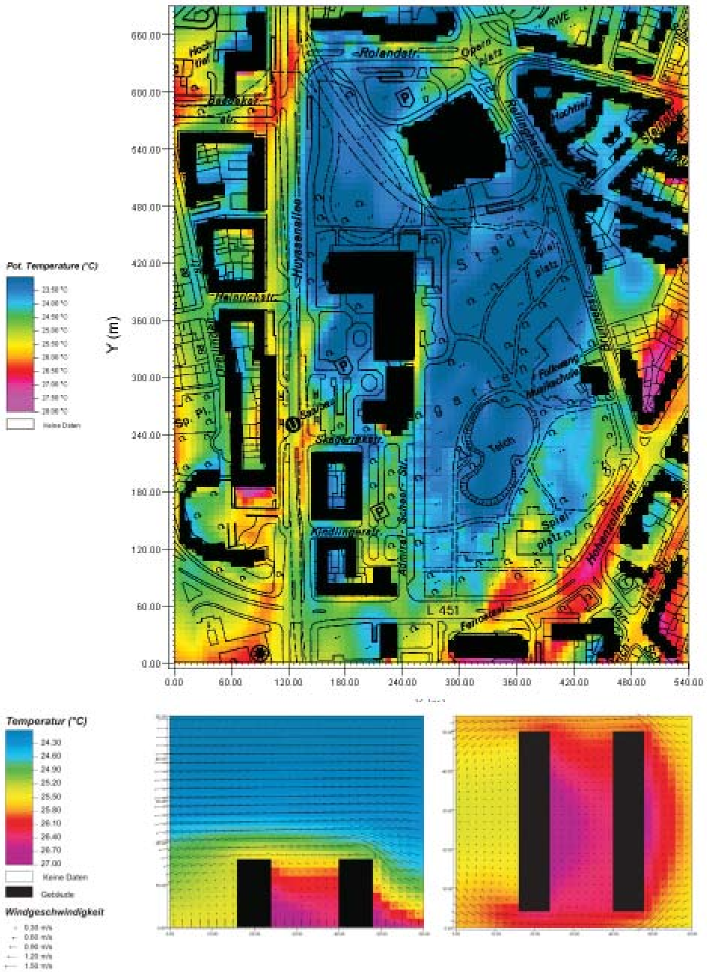


Figure 3-2-3 Thermal analysis map produced by Envi-met 3.0 (Bruse, 2004)

Research of numerous variables and their impact on thermal comfort in the street environment have explored in the last two decades (Arnfield 2001). Researches have inclined toward development of thermal comfort evaluation method. There are groups of people who have researched different variables and their impact on thermal comfort in the street environment. Early studies conducted by Timothy Oke (1988) provided design recommendations based on the performance of street geometry such as building height to streets width ratio (H/W) and the orientation of the urban canyon. However, simplicity of geometry and two dimensional aspects of this study leaded to further quantitate researches. Number of parameters by which thermal comfort is influenced increased as studies evolved. From mere consideration of air temperature, humidity and wind speed, more complex parameters such as mean radiant temperature (T_{mrt}) started to involve into. As studies of solar radiation in the street environment, comparison of long and short wave radiation from the vertical and horizontal surface of the streets were studied, (Arnfield 1990). Influences of different materials on thermal radiation were also researched (Asaeda et al 1992). These numerous variables and complex processes in the urban stimulated combining the field study and simulation models (Arens, Bosselmann 1990). Computer models also developed such as Envi-Met by Bruse, Figure 3-2-3 (2004). Also, RUROS project took individual factors into consideration (2004). These evolving methods can be summarized as following Figure 3-2-4.

Research Group/Field/ Research Paper	Research Focus	Research Outcomes
Timothy Oke/ Atmospheric Science (University of British Columbia) / Street design and urban canopy layer climate	Geometry Density Wind flow	• Geometry of the street must be compatible for seasonal changes. • Compatible range of H/W ratio is 0.4 - 0.6. • For better wind flow, building density (Floor area ratio) is suggested to be 0.2 - 0.4
John Arnfield/ Atmospheric Science (Ohio State University) / Street design and urban canyon solar access	Geometry Solar Access, Solar Radiation	• Solar access indices were proposed. • Horizontal surface absorbs more radiation than vertical surface of the street. • H/W ratio is critical determines the quantity of radiation received on urban surfaces.
Takashi Asaeda/ Environmental Science (Saitama University) / Heat storage of pavement and its effect on the lower atmosphere	Pavement Materials	• Asphalt emit more radiation than bare soil surface. • Evaporation of water from the soil beneath the pavement helps lowering surface temperature. • Thicker ground surface material increases surface temperature.
Peter Bosselmann/ Urban Design (University of California, Berkeley) / Wind, sun and temperature-Predicting the thermal comfort of people in outdoor spaces	Solar Access, Wind Speed, Temperature, Geometry	• Comfort prediction procedure based on climate record and simulation of physical model was proposed. • Solar radiation influence more to thermal comfort in San Francisco Climate than wind speed.
Michael Bruse/ Climatology (University of Bochum) / Modelling and strategies for improved urban climates	Simulation Methods	• Computer simulation program based on physiological equivalent temperature Envi-met was proposed.
RUROS (Rediscovering the Urban Realm and Open Spaces)	Psychological Effect	• People in the area who have decided to expose themselves to certain conditions by their own choice are more tolerant to the thermal environment, as they can terminate such exposure by leaving, as opposed to being dependent on external factors.

Figure 3-2-4 Comparison of thermal comfort evaluation methods

3.2.3 LITERATURE REVIEW -SIMULATION CASE STUDIES BY ENVI-MET 3.0

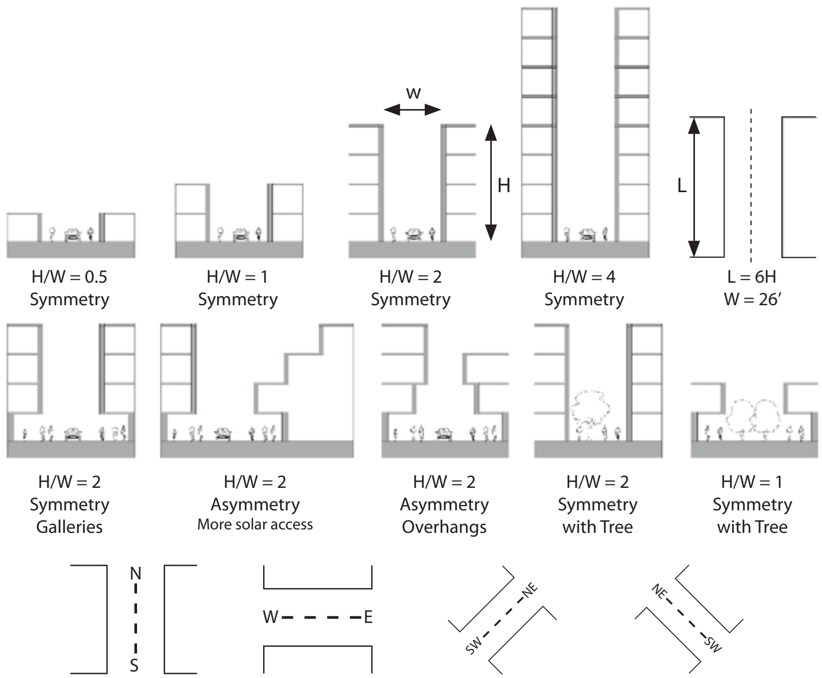


Figure 3-2-5 Variations of H/W ratio and orientation for simulation (Ali-Toudert, Mayer, 2005, 2006)

Only few studies regarding effects of street geometry and orientation on thermal comfort have conducted in the field of urban climatology that are providing information which can be utilized by designers effectively. One of them is numerical studies conducted by Fazia Ali-Toudert and Helmut Mayer (2005, 2006). These studies provide preliminary evaluations of street geometry and orientation and some aspects of vegetation. Temporal and spatial variation of physiological equivalent temperature (PET) were presented in graphics as seen in Figure 3-2-5, 6. Envi-met simulations have conducted on the basis of hot and arid climatic condition of Ghardaia, Algeria, 32°13' N, 3°80' E. It is on the similar latitude of Tucson. Date and time duration were also set as mid summer day of Aug 1 and diurnal time from 7:00 to 20:00.

Summary: Literature review raises the critical role of mean radiant temperature that is influenced by short and long wave radiations from surroundings. This study recommends shades created by geometry and orientation of streets as effective instruments reducing mean radiant temperature. E-W oriented streets show most heat stress even with H/W=4 condition. N-S orientation with H/W=4 case provides most thermal comfort but it causes less solar access in winter. NE-SW and NW-SE orientation provide interim comfort level between E-W and N-S, but comprises with better solar access in winter. Galleries work effectively for E-W oriented streets for pedestrians as horizontal shading structure. The higher H/W ratio results higher effects of galleries. For NE-SW, NW-SE orientation, galleries works better for wider streets. Asymmetrical geometry also increases heat stress but has faster heat release in summer and more solar access in winter. Vegetation works most effectively for lower H/W ratio and E-W oriented streets. It decreases PET up to 24.

PET = Physiological Equivalent Temperature (Thermal comfort indicator)

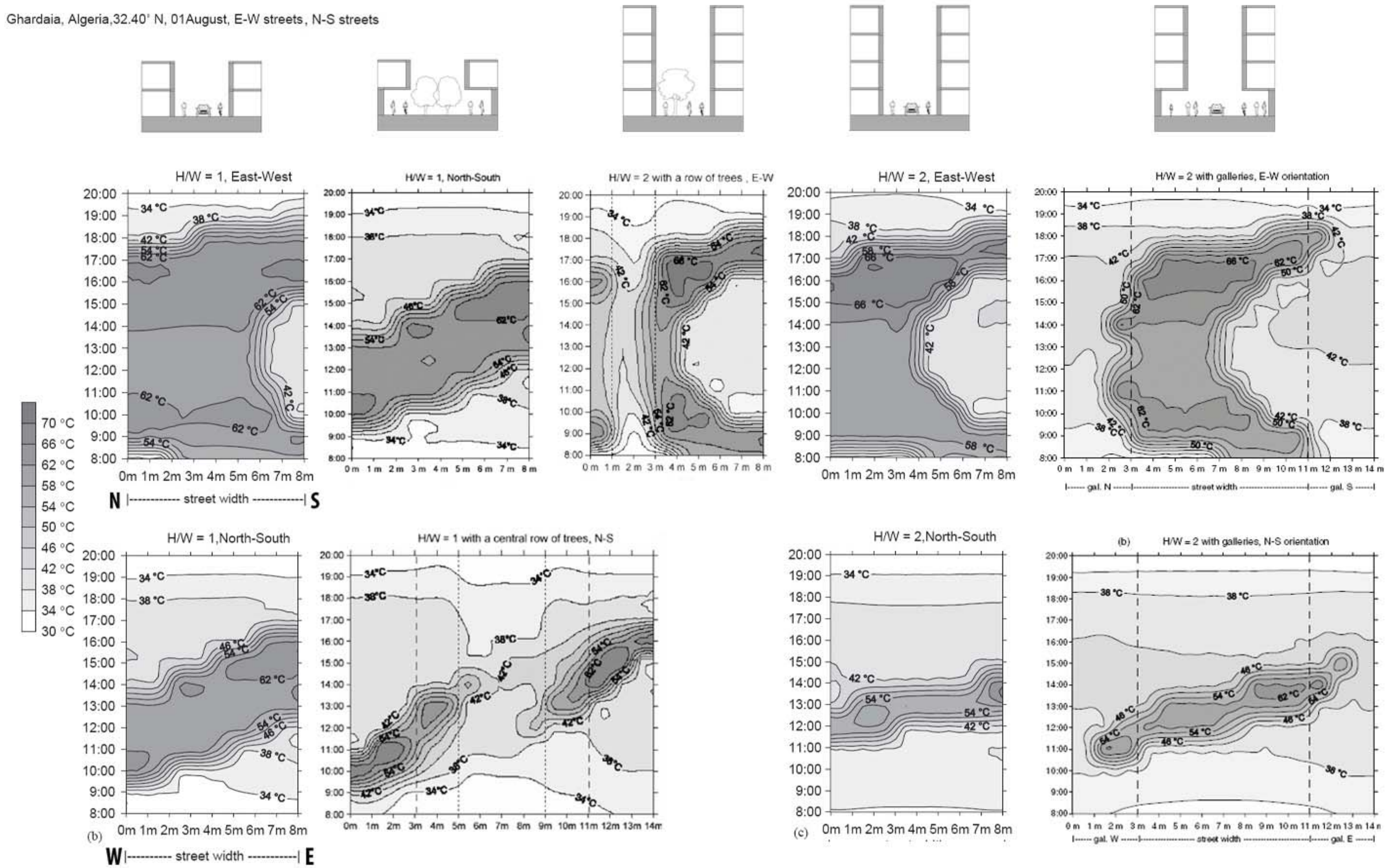


Figure 3-2-6 Spatial and temporal variation of PET at 4' above the ground by geometry and orientation of the street (Ali-Toudert, Mayer, 2005)

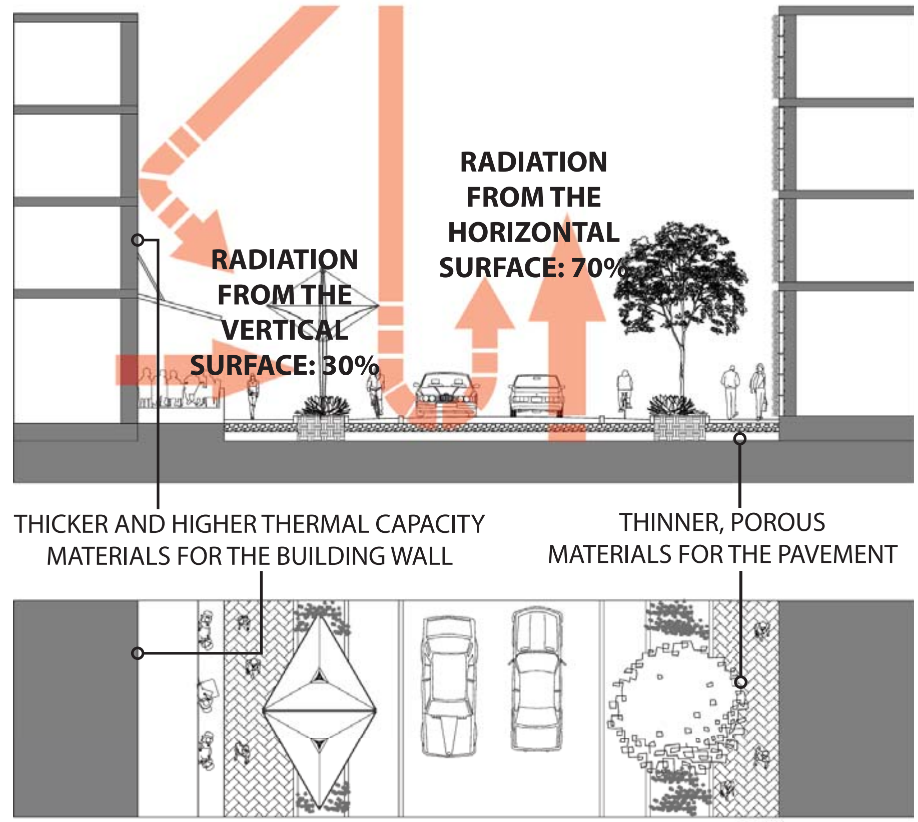


Figure 3-2-7 Vertical and horizontal radiations in the street environment and recommended material uses

Albedo (Reflectivity) : White (1) Black (0)
Greater Albedo = Greater Reflectivity

Emissivity : Black Body (ε=1) > Grey (ε<1)
Greater Emissivity = Greater Heat Radiation

Figure 3-2-8 Determinants of thermal performance of materials (Olgyay, 1963, L.Doulos et al. 2004)

3.2.4 SYNTHESIS

Street section of Fig 3-2-7 shows influences of the vertical and horizontal surfaces of the street environment and recommended use of materials. First one is albedo to short wave radiation which indicates reflectivity and second one is the emissivity to long wave radiation which represents ability to radiate absorbed energy, Figure 3-2-8, (Olgyay, 1963, L.Doulos et al., 2004). From empirical case studies and literature reviews of urban climatology, following chart of Figure 3-2-9 provides preliminary description of thermal comfort conditions in the street environment by each orientation and geometry. Fig 3-2-10 shows comparison of climatic determinants of thermal comfort.

Street Orientation	H/W ratio	Thermal Comfort Description
N - S	H/W≥2 H/W=1 H/W≤0.5	Most preferable condition Mitigation at sunrise and sunset Less stressful than H/W≤2, E-W street
NE - SW / SW - NE	H/W≥2 H/W=1 H/W≤0.5	Less stressful than E-W orientation More stressful than S-N orientation
W - E	H/W≥2 H/W=1 H/W≤0.5	Less stressful in the north facing side No significant heat stress mitigation Least preferable condition

Figure 3-2-9 Design recommendations for the street environment for each orientation and H/W ratio

Solar Radiation	≥	Air Temperature	≥	Wind Speed	≥	Humidity

Figure 3-2-10 Comparison of climatic factors of thermal comfort

3.3 EMPIRICAL STUDIES

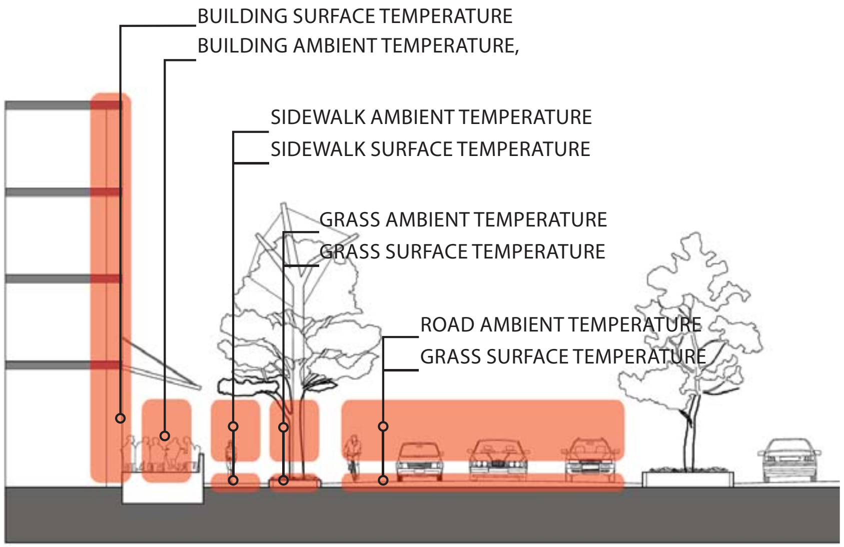


Figure 3-3-1 Temperature measurement points in the street environment

Figure 3-3-2 Temperature measurement Instrument, Infrared surface thermometer, relative hygrometer, ambient thermometer

3.3 EMPIRICAL STUDIES-
SURFACE AND AMBIENT TEMPERATURE MEASUREMENTS

Surface temperature and ambient temperature of street environment were measured for empirical studies. Surface temperature of building facade and sidewalk pavement were measured. Ambient temperature was measured 3-1/2' above the ground surface and from the vertical surface as seen in Figure 3-3-1. Two streets were selected in hot and arid climate regions. One is Paseo del Prado in Madrid, Spain and the other is University Boulevard in Tucson, Arizona. Each street was measured in diurnal summer time in between 10:00 and 20:00 in June and September. Measurement conducted for a week long of clear day with similar range of air temperature and similar range of humidity fluctuation. Recordings were made using three different instruments, Figure 3-3-2. Average temperature displayed in each instrument was used. For ambient temperature, measured temperature after 5 minutes of standing on the spot was used.

Figure 3-3-3 Paseo del Prado (Satellite Photo from Google Earth and Visual Earth)

3.3.1 PASEO DEL PRADO, MADRID, SPAIN
40° 26', N/ 3° 42', W -JUN 16-22, 2008

Paseo del Prado in Madrid is one of the most important streets in Madrid traversing north and south of the city. As shown in the Figure 3-3-3, Paseo del Prado is surrounded by two contrasting types of urban setting. The west side of street is facing group of buildings with high density and the Royal botanic garden with densely planted trees on the east side. Paseo del Prado can be divided into three pedestrian walks and two vehicular traffic thoroughfares in between them, Figure 3-3-4. Two pedestrian walks are on each side and only one on the east side has lined trees. Medians are as wide as vehicular roads and also have tree canopies. Various materials are used for pavements and building surfaces. Recently completed project of La Caixa Forum designed by Herzog & de Meuron and a vertical garden facade by Patrick Blanc (2008) provided opportunity to compare contemporary use of materials to conventional use of materials in the street environment. nine different surface materials' temperature and six different ambient temperature were catalogued and compared.

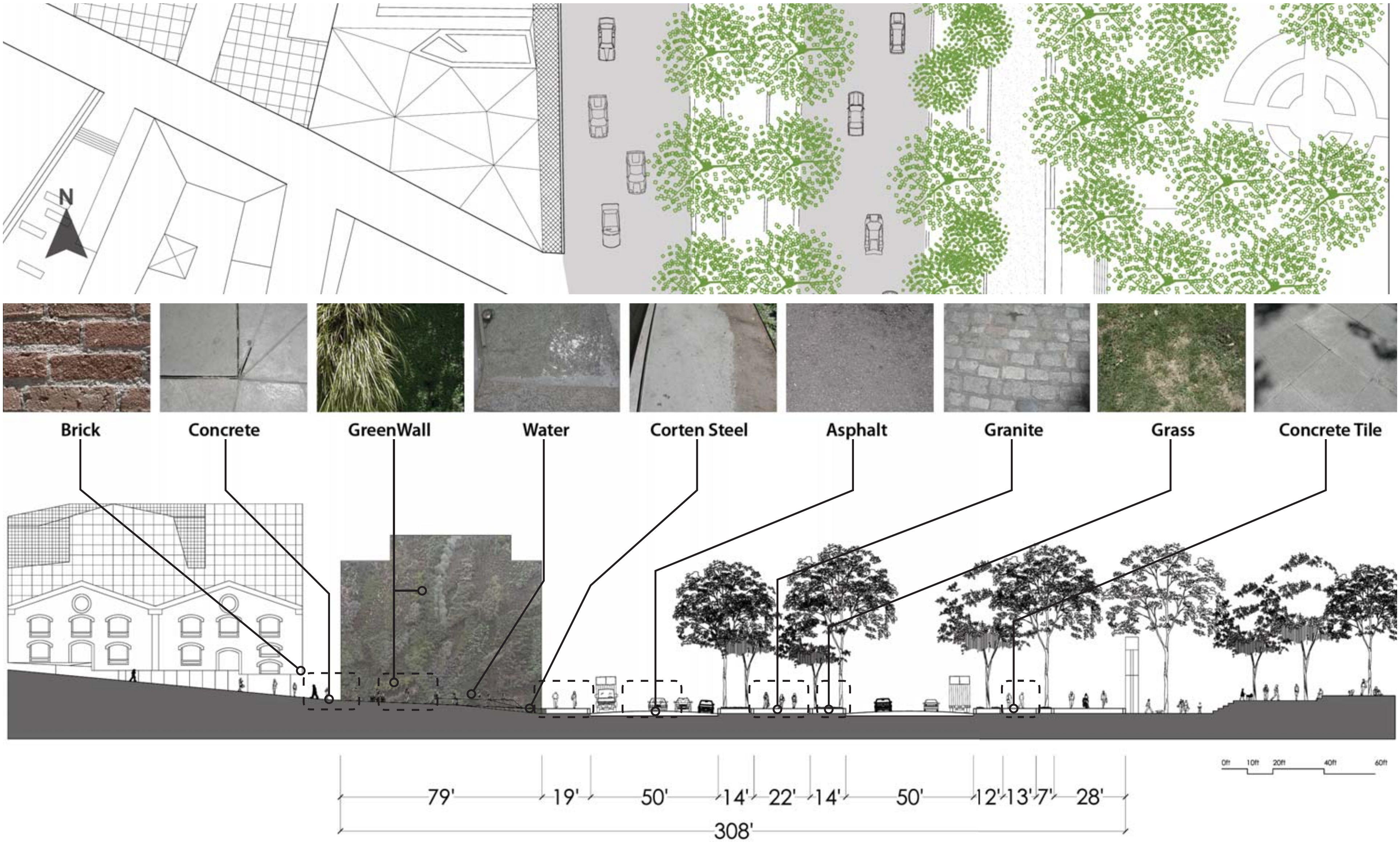
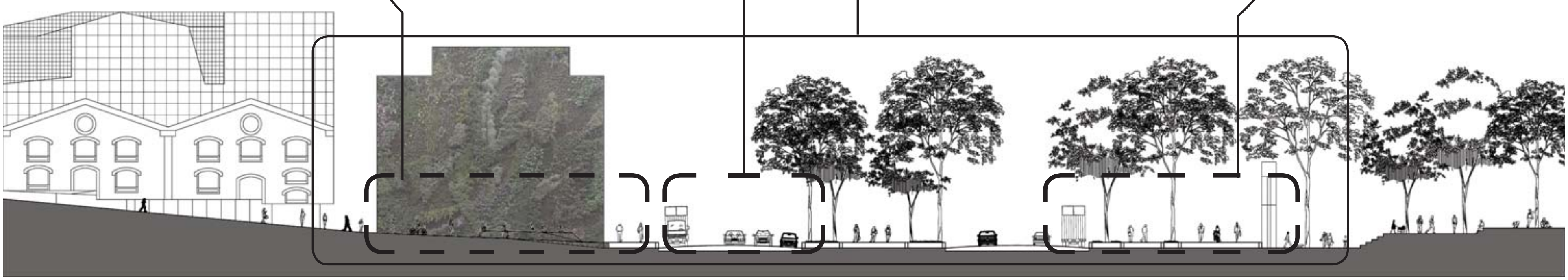


Figure 3-3-4 Plan, section and material uses

View points in Paseo del Prado, Madrid, Spain, photograph by Youngsoo Kim



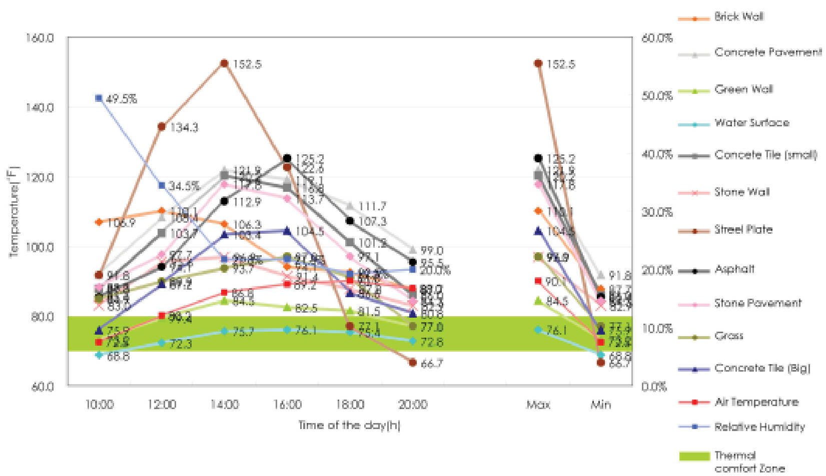


Figure 3-3-5 Surface temperature comparison

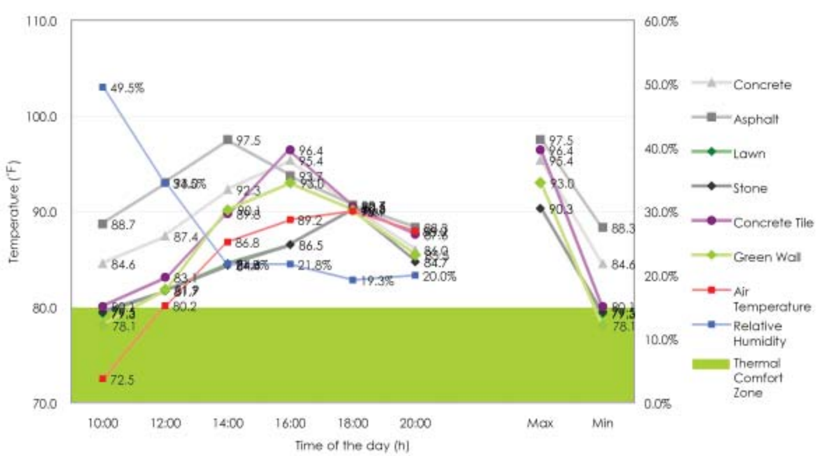


Figure 3-3-6 Ambient temperature

Surface temperature comparison:

Diurnal temperatures for each surface material was recorded to be outside the comfort zone, Figure 3-3-5. Only water surface temperature maintained consistent temperature within comfort zone. Plants on the green wall had temperature closer to the comfort zone while steel fluctuated most amongst measured materials. There was 90.0 °F difference between the highest and the lowest surface temperature of steel plate while there was only 7.3 °F and 8.0 °F for water surface and plant surface. This is attributable to its reflectivity and emissivity balance. Concrete as monolithic pavement and tile pavement performs differently when it cools down because of thickness. Thicker pavement cannot utilize soil as thermal mass and this aspects brings higher surface temperature. Surface temperature of tiled concrete cools 10.0 °F more rapidly within same time duration. As thickness of tile decreases, surface temperature decreases more. Asphalt pavement stays cooler than monolithic concrete pavement except around 16:00 after which it cools slower than concrete tile pavement.

Difference between surface and ambient temperature:

While the monolithic concrete pavement maintains the highest surface temperature, except steel, ambient temperature above asphalt pavement keeps the highest temperature. Ambient temperature above concrete tile pavement maintains lower temperature than that of the monolithic concrete pavement except around 16:00. This is attributable to two reasons. First, monolithic pavement was exposed more to the direct solar radiation. Second, thinner pavement mobilizes thermal capacity of soil beneath. Ambient temperature difference between concrete pavements of 5.0 °F. The stone pavement maintains lowest ambient temperature above it except after 18:00 hour of the day. Around 18:00, all measured ambient temperature converges into almost same temperature of 90.5 °F (Figure 3-3-6).

3.3.2 UNIVERSITY BOULEVARD, TUCSON, AZ, USA, 32° 13' N/ 110° 58' W-SEP 1-7, 2008

Figure 3-3-7 University Boulevard (Satellite Photo from Google Earth and Visual Earth)

University Boulevard is one of the most vibrant streets in the city of Tucson. It is east and west oriented street with low-rise buildings street side with planted trees, Figure 3-3-7. It has sidewalks on both side and vehicular roads with trams running on the median. Angled surface parking between sidewalks and roads is present. Compared to Paseo del Prado, it has less density of planted trees on the side walks. Instead, overhangs are used on the wall of the buildings on the north side but these were not casting effective shades on the sidewalks while it is protecting buildings from the strong south sun during diurnal time of the day. Eight different material's temperature and six ambient temperatures were measured for comparison, Figure 3-3-8. Ambient temperature of the sidewalks was measured under both conditions of with and without the building shades. Also, ambient temperature of the promenade with turf grass and lined trees alongside it was measured for the comparison.

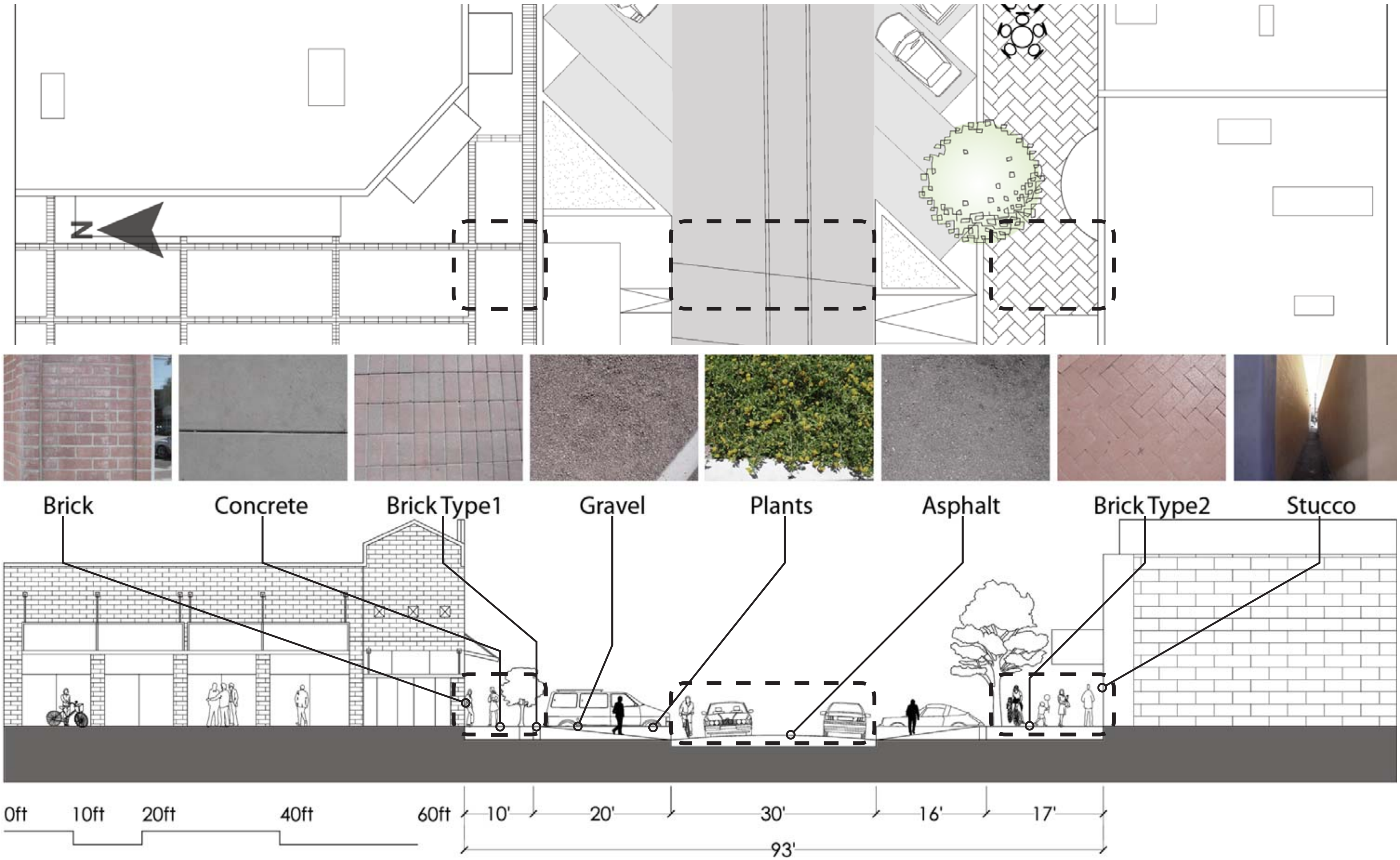
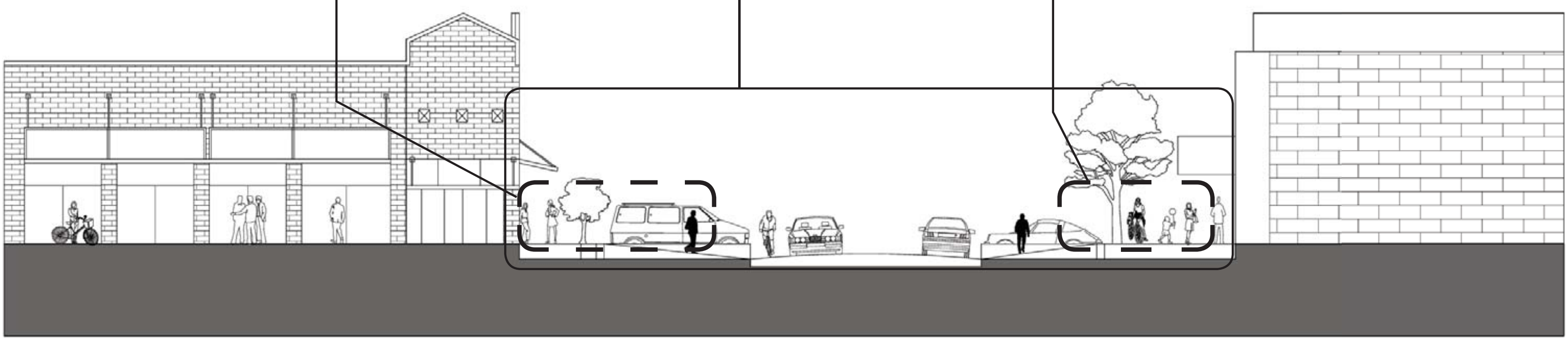


Figure 3-3-8 Plan, section and material uses

View points in University Boulevard, Tucson, AZ, photograph by Youngsoo Kim



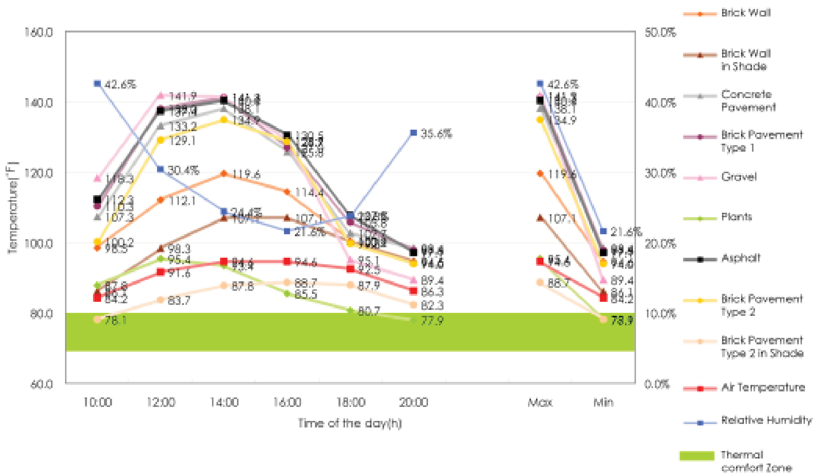


Figure 3-3-9 Surface temperature comparison

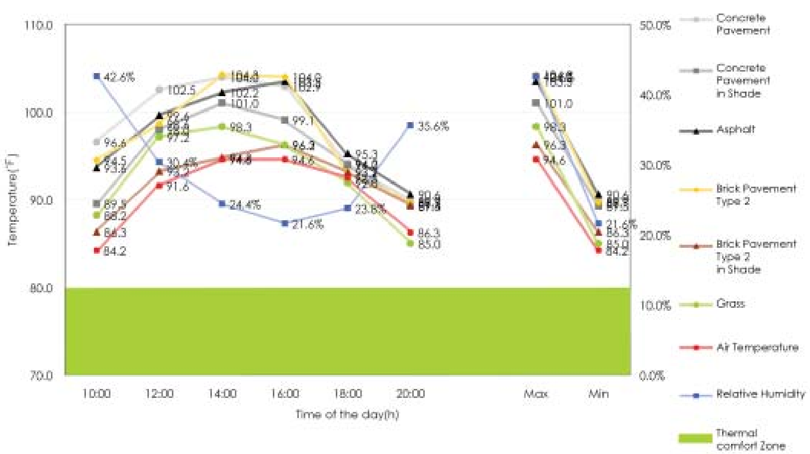


Figure 3-3-10 Ambient temperature

__Surface temperature comparison:__

The surface temperature of gravel fluctuates the most among measured materials while that of plants maintains the lowest and reaches comfort zone after 18:00, Figure 3-3-9. Temperature difference between these materials is 37.9 °F. All of measured surface temperatures except that of plants and brick pavements in shades, are higher than air temperature of the day. Brick wall keeps its surface temperature 18.5 °F lower than the concrete pavement and it is attributable to the difference of solar radiation angle between the vertical and the horizontal surface. Gravel, asphalt, concrete and brick pavement have similar temperature changes within range of 10.0 °F but these materials can be categorized into the group of higher surface temperature.

__Difference between surface and ambient temperature:__

During the time duration of measurement, none of the compared ambient temperature reached the comfort zone. However, there was 10.0 °F difference between measurements. Evenly, ambient temperature above the concrete pavement kept the highest ambient temperature while brick type 2 pavement kept the lowest. Before 18:00, it maintains more and less of 10.0 °F. Similar to the surface temperature, the ambient temperature also converges to similar temperature at 18:00, Figure 3-3-10. Role of shades revealed more clearly in the case of University Boulevard than that of Paseo del Prado. As seen in Figure 3-3-10, the concrete pavement, one of the materials in higher surface and ambient temperature group, maintains averagely 20.0 °F cooler surface temperature with shades.

3.1.3 SYNTHESIS-PASEO DEL PRADO, MADRID, SPAIN, 40° 26', N/ 3° 42', W -JUN 16-22, 2008

Figure 3-3-11 Material Surface Temperature in Paseo del Prado

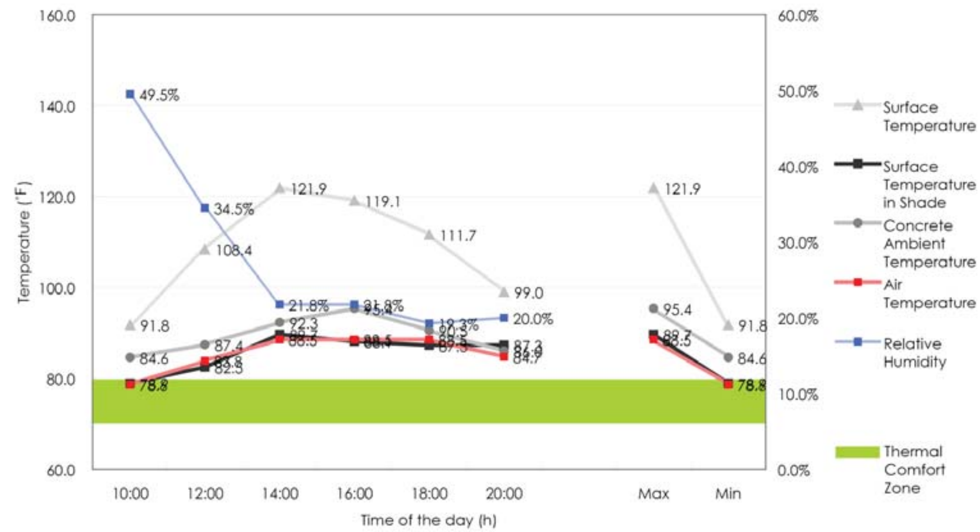


Figure 3-3-12 Comparison of concrete ambient temperature with shades

Role of shade: Outside reflectivity and emissivity of material itself, shade plays critical role decreasing both surface and ambient temperatures. Shade effectively drops the surface temperature, for instance: surface temperature of concrete pavement is averagely 20.0 °F lower when it is in the shade. Measurements of surface temperature in the shade have lower readings than ambient temperature above the concrete pavement, Figure 4-1-12.

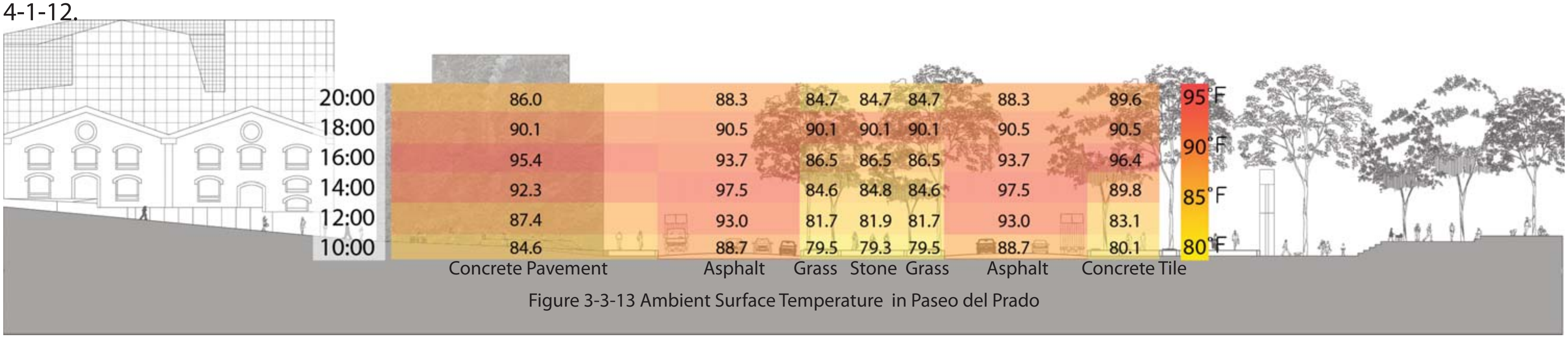


Figure 3-3-13 Ambient Surface Temperature in Paseo del Prado

UNIVERSITY BOULEVARD, TUCSON, AZ, USA, 32° 13' N/ 110° 58' W-SEP 1-7, 2008

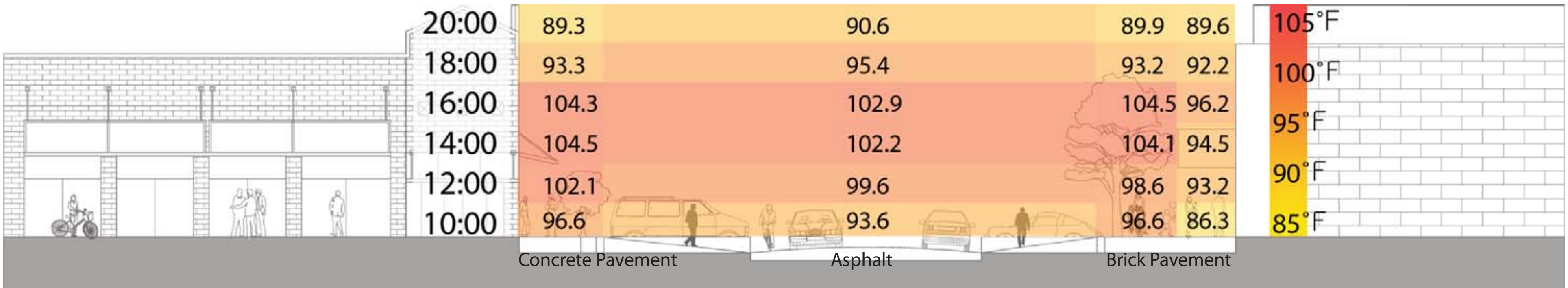


Figure 3-3-14 Temporal Ambient Temperature Comparison in University Boulevard

Findings: Two empirical studies provided preliminary research basis for design variables that influence thermal comfort in the street environment. It started from material performance comparison but ended with inquiries for those design variables such as shade and pavement types. Figure 3-3-13 and 3-3-14 represent temporal ambient temperature changes depending on different surface materials. Findings from measurements can be summarized as follows:

- Shade plays critical role for reducing surface and ambient temperature.
- Thinner ground surface pavement recorded lower surface and ambient temperature.
- Thicker or insulated building facade recorded lower surface and ambient temperature
- Vegetations on both horizontal and vertical surface of the street remarkably decrease surface and temperature.
- When street is wider than the range of shade provided by buildings, landscaping can be an alternative way for shade.

4.0 SYNTHESIS OF RESEARCH

4.0 SYNTHESIS OF RESEARCH

Material's influence found in the preliminary researches can be summarized as shown in Fig 4-0-1. This chart provides inquiries for further researches on the role of materials in the street environment. Victor Olgyay's work provides in-depth knowledge regarding thermal effect of materials to the indoor environment. Research on the material's influence in the outdoor environment has developed but applicable design principles are very limited, Fig 4-0-2. Nevertheless, research result provides preliminary information regarding two critical determinants of material performance in the outdoor environment. One is thermal property of material such as reflectivity and the other is design factor such as thickness. Since the thermal property of a material is related to heat transfer in the outdoor environment, it is critical to understand heat transfer mechanism in order to utilize thermal property of material. As shown in Fig 4-0-3, there are three main modes of heat transfer: conduction, convection and radiation (Addington, Schodek, 2005). Each mode is influenced by certain thermal properties of material. As discussed in the previous, since solar radiation is the most influential climactic factor in the street environment, thermal properties that are related to radiation become critical. Amongst them, properties such as emissivity, reflectivity and specific heat can be indicators for material selection. Emissivity is the measure of material's ability to emit absorbed thermal radiation relative to that of ideal black body and it is expressed as a unitless ratio from 0 to 1. Reflectivity is ratio of the reflected thermal radiation relative to total radiation and it is expressed as albedo with unitless measure from 0 to1. Specific Heat Capacity is the measure of the heat energy required to increase the temperature of substance in a certain condition.

Author	Book	Research Focus	Role of Material
Allan Jacobs	Great Streets	Physical design of streets	Design of building facades or street pavements can contribute to delight walk experience.
Michael Southworth, Eran Ben-Joseph	Streets and the shaping of towns and cities	Street Standards	Change of pavement types can influence vehicular traffic speed in a certain street environment.
Victor Olgyay	Design with Climate	Bioclimatic design strategies	Different material usages and material properties of building surface can influence indoor thermal comfort level.

Figure 4-0-1 Summary of preliminary literature review

Author	Research	Research Focus	Research Result
Takashi Asaeda et al	Heat storage of pavement and its effect on the lower atmosphere.	Effect of pavement material and design on ambient temperature	• Asphalt emit more radiation than bare soil surface. • Evaporation from the soil beneath the pavement decreases surface temperature. • Thicker ground surface material increases surface temperature.
Doulos, L., Santamouris, M., Livada, I.	Passive cooling of outdoor urban spaces. The role of materials	Ambient and surface temperature changes by different materials	• Using materials with higher reflectivity and less emissivity can reduce surface temperature. • Lighter color and smoother surface increases reflectivity.

Figure 4-0-2 Summary of literature reviews on material influences in the outdoor environment

	Heat Transfer Modes		
	Conduction	Convection	Radiation
Material Thermal Properties	Thermal Conductivity	Specific Heat Viscosity	Emissivity Absorptivity Reflectivity Transmissivity

Figure 4-0-3 Heat transfer modes and their determining material properties

	Water	Grass	Soil	Granite	Concrete	Asphalt	Steel
Emissivity	0.95	0.76	0.80	0.45	0.94	0.93	0.79
Reflectivity	0.05	0.23	0.17	0.36	0.30	0.10	0.04
Specific Heat	4.186	-	0.80	0.79	0.88	0.92	0.50

Figure 4-0-4 Reflectivity and emissivity of different materials
(Addington, Michell and Schodek, Daniel,
Smart Materials and Technologies for the architecture and design professions, 2005)
(Haider Taha, David Sailor, Hashem Akbari,
High-Albedo Materials for Reducing Building Cooling Energy Use, 1992)

	Design Factors		
	Thickness	Surface Roughness	Surface Color
Thermal Performance	Thermal Capacity Emissivity	Emissivity Reflectivity	Reflectivity

Figure 4-0-5 Design factors that have influences on thermal performance of material

		Thermal Properties of Material			Design Factors		
		Emissivity	Reflectivity	Specific Heat	Thickness	Surface Roughness	Surface Color
Considerations for Surface of the Street Environment	Ground Surface	Higher	Higher	Higher	Thinner	Smoother	Lighter
	Vertical Surface	Higher	Higher	Higher	Thicker	Smoother	Lighter

Figure 4-0-6 Considerations of material properties and design for the street environment

Emissivity is an independent property from the others while absorptivity, reflectivity and transmissivity are proportionally related to each other as follows: absorptivity+reflectivity+transmissivity = 1, (Addington, Schodek, 2005).When a certain material has higher specific heat capacity, it means that it requires more energy to raise its temperature. For example, water has higher thermal capacity than steel and it takes more heat energy to heat water than steel. Each property can result higher or lower surface and ambient temperature in the outdoor environment. In this respect, when the other design factors are limited, selection of materials with different thermal property and design for the pavement and building facades of the street environment can have an influence on mitigating the given solar radiation. Fig 4-0-4 shows materials that were surveyed in the empirical study section and their reflectivity, emissivity and specific heat capacity. Higher emissivity, higher reflectivity and higher capacity can be criteria of the material selection for the street environment, but as seen in Fig 4-0-5 and empirical study, cooler surface of water can be explained not by its low emissivity or reflectivity but by its high thermal capacity. In this sense, each thermal property must be considered as complementary to each other. From the research, three design factors that have influences on thermal performance of material are found: thickness, surface roughness and color, Fig 4-0-3. For the ground surface, thinner material use can decrease surface temperature by utilizing soil beneath it as thermal mass while thicker material is needed for vertical surface as thermal mass. Since design factors such as thickness, surface roughness and color also have influence on thermal performance of material, it must be integrated with thermal properties of material use for vertical and horizontal surface of the street environment, Fig 4-0-6.

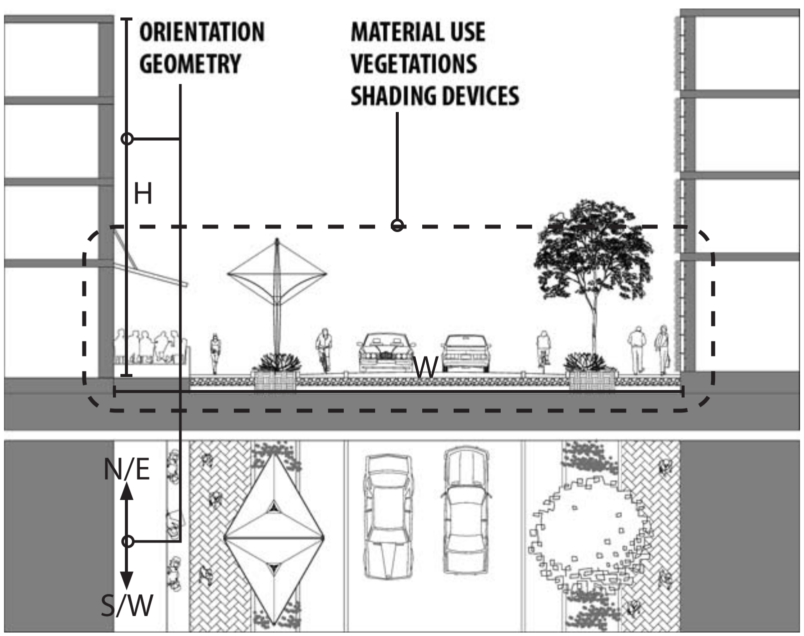
5.0 CONCLUSION

5.0 CONCLUSION

(O = Influence, X= No Influence, Δ= Potential Influence)

		Urban Design Factors				
		Factors for Preliminary Design		Factors for Modification		
		Street Orientation	Street Geometry	Material Use	Vegetations	Shading Devices
Climatic Factors	Air Temperature	O	O	O	O	O
	Solar Radiation	O	O	O	O	O
	Wind Speed	O	O	Δ	O	O
	Relative Humidity	X	X	O	O	X

5-0-1 Design factors as climate mitigator



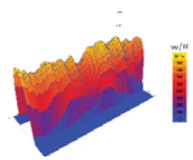
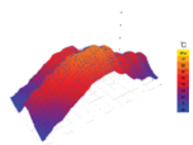
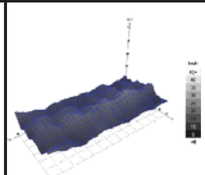
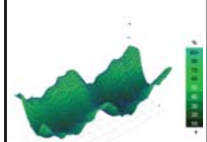
5-0-2 Street environment components as design variables

Thermal comfort level in the street environment is influenced by numerous factors. Climatic, design and individual factors are the most common ones among them. To increase thermal comfort level, the given factor, climatic condition can be mitigated by design factors. As seen in the Fig 5-0-1 and Fig 5-0-2, urban design factors can be sub-categorized. Factors such as orientation and geometry play critical role in the initiative street design process while surface materials, shading devices and vegetations become decisive for the purpose of modification to increase thermal comfort in the street environment. Shading devices and vegetations increase thermal comfort mainly by providing shades in hot and arid climate condition. Materials also can decrease surface temperature not by providing shade but by controlling solar radiation. Nevertheless, material is scarcely reflected in the design strategies or processes while shading devices and vegetations are taken into consideration as sources of shade. As discussed in the previous sections, since radiation is one of the most influential climatic factors, performance of materials in the street environment becomes crucial. Yet, as shown in Fig 5-0-1 and empirical research, single design factor is always not enough to mitigate given climatic factors. In this respect, as design of the street environment requires comprehensive approaches, all of the urban design factors must be integrated into design considerations to provide optimized thermal comfort level in the given climatic condition. Possible design applications are proposed in the following section.

5.1 DESIGN APPLICATIONS

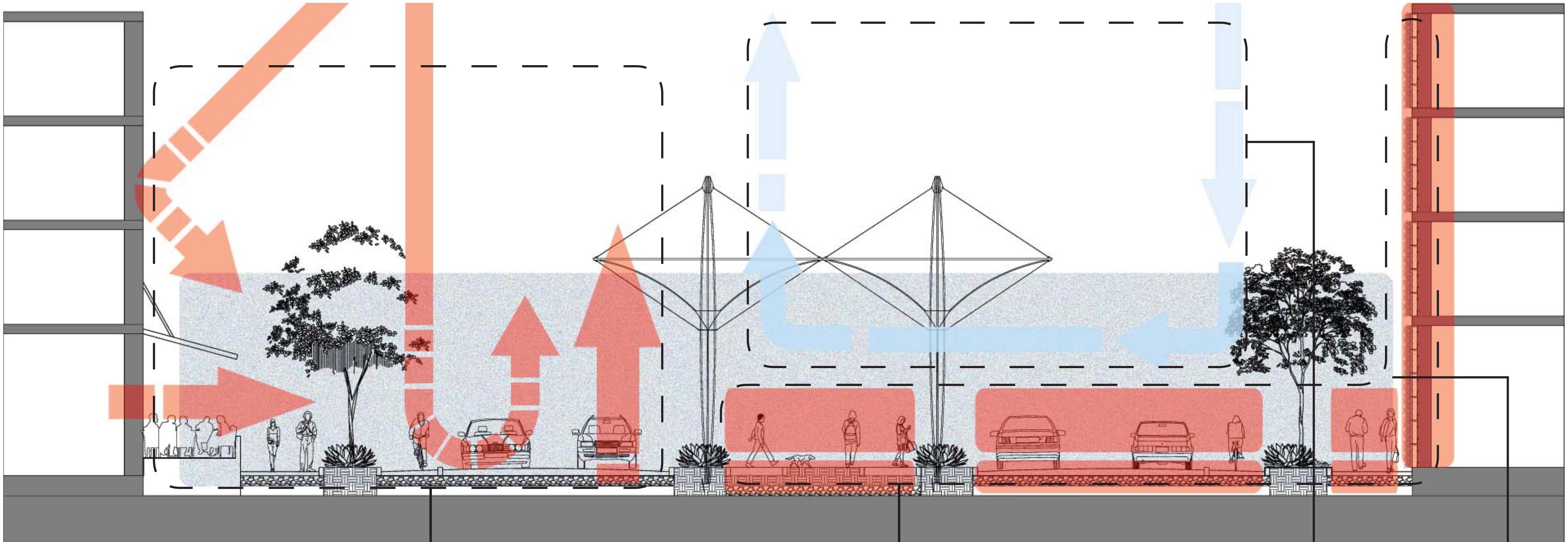
5.1 DESIGN APPLICATIONS

CLIMATIC DETERMINANTS OF THERMAL COMFORT IN HOT AND ARID CLIMATE AND CHARACTERISTICS AND DESIGN OBJECTIVES OF SUMMER AND WINTER

DETERMINANTS		SUB-DETERMINANTS		SUMMER		WINTER	
				CHARACTERISTICS	DESIGN OBJECTIVES	CHARACTERISTICS	DESIGN OBJECTIVES
Solar Radiation		Direct/Diffuse radiation		High (2000 - 3000 Btu/ft^2)	Decrease	Relatively Moderate (500 - 1200 Btu/ft^2)	Increase
		Indirect radiation	Emmissive radiation (Long wave)		Decrease		Increase
			Reflective radiation (Short wave)		Decrease		Increase
Air Temperature		Ambient Temperature		High (85 - 110 °F)	Decrease	Relatively Moderate (25 - 45 °F)	Increase
		Mean Radiant Temperature			Decrease		Increase
Wind Speed		Parallel Wind		Relatively highly Influential	Increase	Relatively lowly Influential	Maintain
		Perpendicular Wind		Relatively lowly Influential	Increase		Maintain
Humidity		Relative Humidity		Low (10 - 40 %)	Increase	Relatively Moderate (30 - 70 %)	Maintain

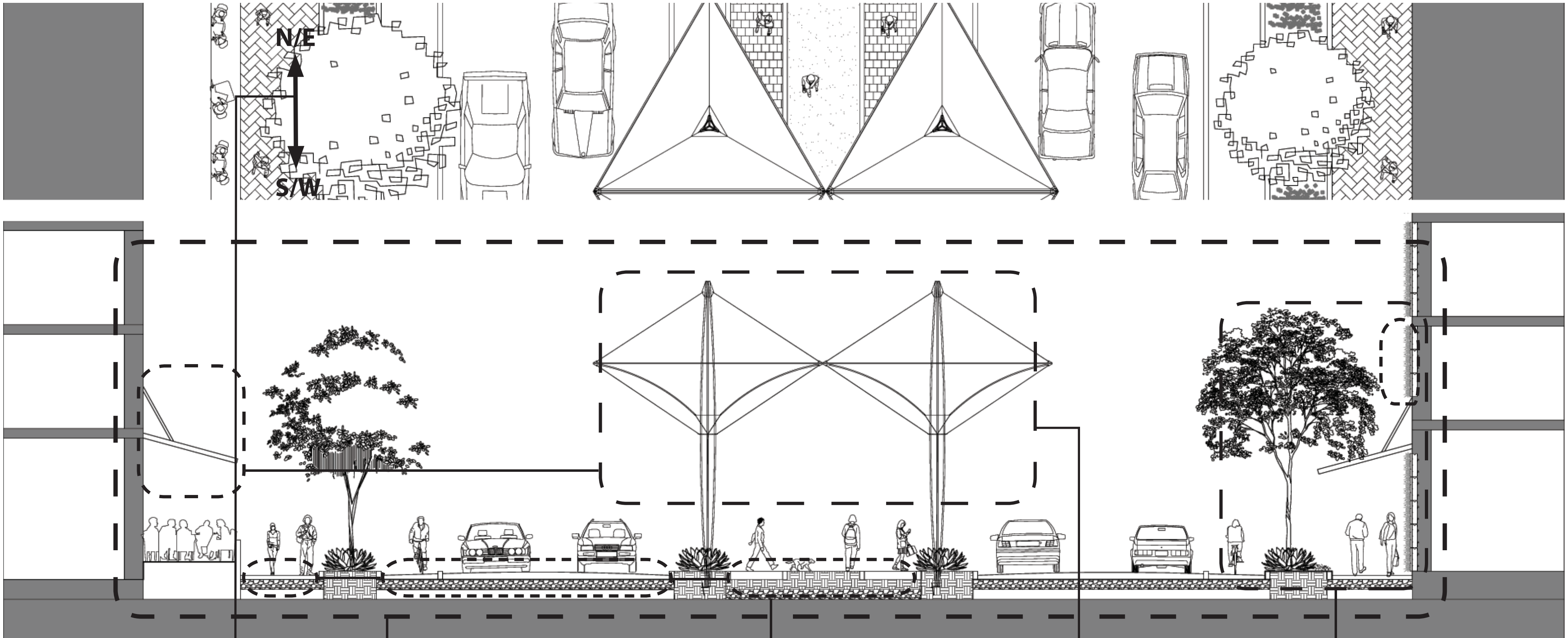
GRAPHIC REFERENCE: ECOTECT, WEATHER MANAGER BY UNIVERSITY OF CARDIFF, SQUARE ONE

CLIMATIC DETERMINANTS OF THERMAL COMFORT IN THE STREET ENVIRONMENT AND POSSIBLE DESIGN VARIABLES



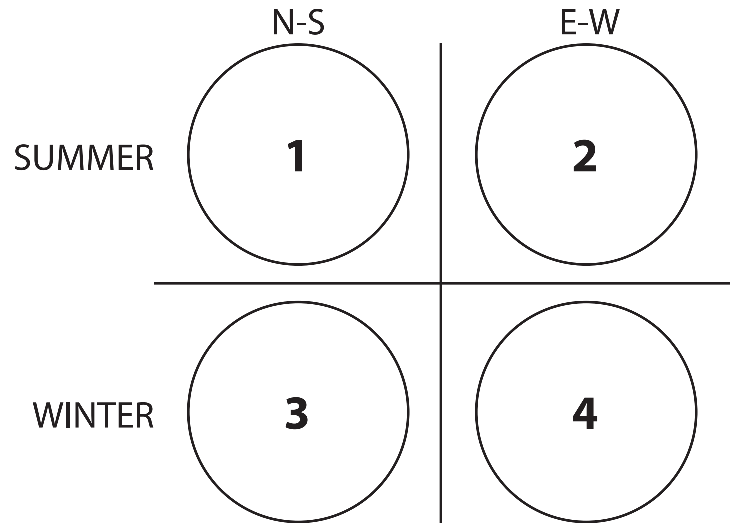
DETERMINANTS	SOLAR RADIATION			AIR TEMPERATURE		WIND SPEED		HUMIDITY
		Indirect radiation						
SUB-DETERMINANTS	Direct/Diffuse radiation	Emmissive radiation (Long wave)	Reflective radiation (Short wave)	Ambient Temperature	Mean Radiant Temperature	Parallel Wind	Perpendicular Wind	Relative Humidity
USEFUL DESIGN CONSIDERATION	Orientation Geometry Vegetation Shading Devices	Orientation Geometry Material Use Vegetation Shading Devices	Orientation Geometry Material Use Vegetation Shading Devices	Orientation Geometry Material Use Vegetation Shading Devices	Orientation Geometry Material Use Vegetation Shading Devices	Orientation Geometry Vegetation	Orientation Geometry Vegetation	Evaporation

GENERAL APPLICABLE DESIGN CONSIDERATION OF DESIGN VARIABLES FOR THE STREET DESIGN IN HOT AND ARID CLIMATE



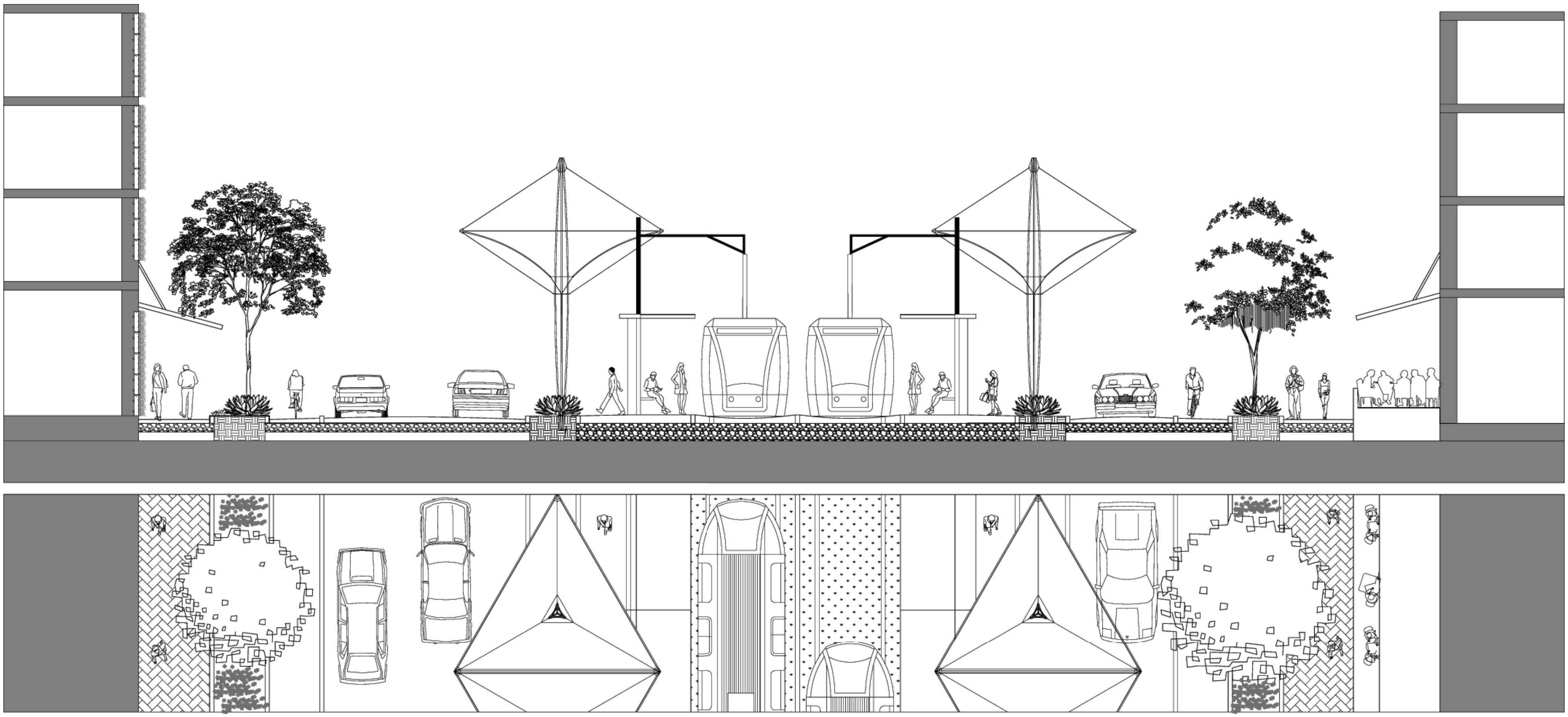
DESIGN VARIABLES	Orientation	Geometry (Building Height-Street Width Ratio)	Material Use		Shading Devices		Vegetation		Evaporation
			Pavement Material	Building Material	Street Shading Device	Building Shading Device	Horizontal Vegetation	Vertical Vegetation	
USEFUL DESIGN CONSIDERATION	-N-S is most preferable -E-W needs most heat protection	-H/W ≥ 2 is preferred for summer -H/W ≤ 2 is preferred for winter in E-W	-Material with higher albedo -Material with smoother surface -Thinner and porous material use	-Material with higher albedo -Material with smoother surface -Material with higher thermal capacity	-Pedestrian walk with H/W ≤ 1 -Sidewalk with H/W ≤ 1 in E-W streets -Movable device for N-S streets	-Surface shading devices to reduce heat radiation	-Trees along side pedestrian walk -Vegetation use on the pavement	-Vertical gardens on the building wall	-Vegetation and soil evaporation -Evaporative cooling for summer

APPLICABLE DESIGN CONSIDERATION FOR SUMMER AND WINTER IN ORTHOGONAL STREET LAYOUT



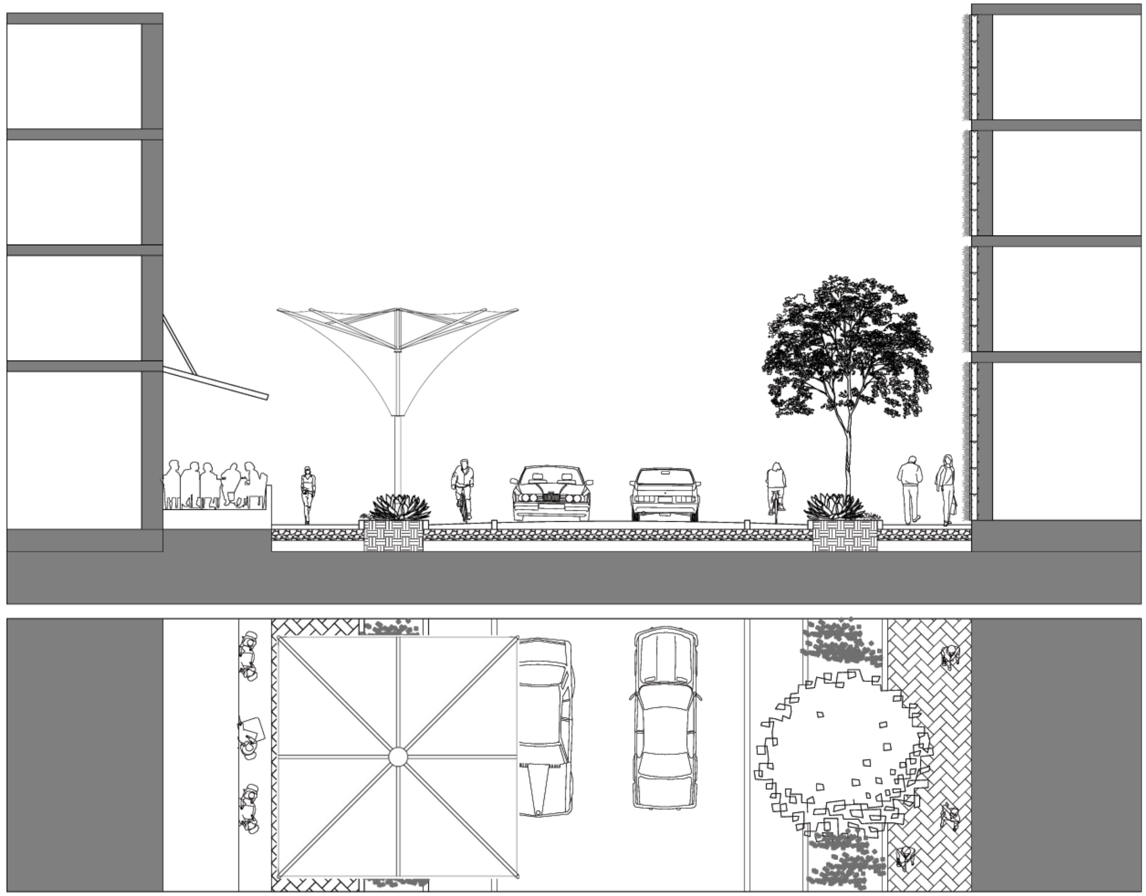
Design Variables	Geometry	Shading Devices	Material	Vegetation
1	Higher H/W Ratio (H/W ≥ 2) is preferable	Shading devices for both east and west side	Thinner pavement combined with vegetation is preferable for east and west side	Trees with bigger crown is preferable for east and west side
2	Higher H/W Ratio (H/W ≥ 2) is preferable	Shading devices is critical for north side	Thicker wall is preferable for south facing wall	Trees with bigger crown is preferable for north side
3	Moderate H/W Ratio (H/W ≤ 2) is preferable	Shading device needs to be folded for both east and wset side	Materials with too low emissivity must be avoided	Deciduous tree is needed for both east and west side
4	Moderate H/W Ratio (H/W ≤ 2) is preferable	Shading device need to be folded for north side	Thicker pavement for south side and thicker wall for north facing facade is preferable	Deciduous tree is needed for both north and south side

DESIGN RECOMMENDATIONS BY DIFFERENT CONDITIONS OF STREET ENVIRONMENT



GIVEN DESIGN CONDITIONS	Orientation	Geometry	DESIGN VARIABLES	Material Use		Shading Devices		Vegetation		Evaporation
				Pavement Material	Building Material	Street Shading Devices	Building Shading Devices	Horizontal Vegetation	Vertical Vegetation	
	E-W Orientation	$H/W \leq 1$	USEFUL DESIGN CONSIDERATION	Thin & porous pavement on the south fac-ing side walk	Higher thermal capacity ma-terials for the south facing wall	Shading device covering the south facing sidewalk	Shading device covering south facing wall	Plant trees and vegetations for south facing side	Greenwalls possible for the south facing wall	Evapora-tive cooling device for both side of sidewalk

DESIGN RECOMMENDATIONS BY DIFFERENT CONDITIONS OF STREET ENVIRONMENT



GIVEN DESIGN CONDITIONS	Orientation	Geometry	DESIGN VARIABLES	Material Use		Shading Devices		Vegetation		Evaporation
				Pavement Material	Building Material	Street Shading Devices	Building Shading Devices	Horizontal Vegetation	Vertical Vegetation	
	N-S Orientation	$H/W \geq 1$	DESIGN RECOMMENDATIONS	Thin & porous pavement on the pedestrian walk	Higher thermal capacity wall materials	Operable shading structures for pedestrian walk	Shading device covering street level	Plant trees and vegetations for pedestrians	Vertical gardens	Evaporative cooling device for both side of sidewalk

5.2 FURTHER CONSIDERATIONS ON RESEARCH

Type of Smart Materials	Input	Output
Type 1 Property Changing		
Thermochromics	Temperature Difference	Color Change
Photochromics	Radiation (Light)	Color Change
Type 2 Energy Exchanging		
Photoluminescents	Radiation	Light
Thermoluminescents	Temperature Difference	Light
Photovoltaic	Radiation (Light)	Electric Potential Difference
Type 2 Energy Exchanging (reversible)		
Pyroelectric	Temperature Difference	Electric Potential Difference
Thermoelectric	Temperature Difference	Electric Potential Difference

5-2-1 Smart Material Types
(Smart Materials and Technologies for the architecture and design professions, Addington, Michelle and Schodek, Daniel, 2005)

Two inquiries raised regarding: utilizing vegetations integrated into building envelope or pavement system, utilizing smart materials for similar purpose. As a design strategies for the urban street environment, green walls or green pavement can play critical role as thermal comfort mitigator. Even several wall or pavement systems have developed, methods combining regional vegetations with certain construction materials reflecting regional climate is still in slow pace. Certain materials and their properties provide opportunities for further investigations to increase thermal comfort level in the street environment, Fig 5-2-1 (Addington, Schodek, 2005). Thermochromics and Photochromics and have potential to optimize reflectivity of materials by different seasons, e.g. lighter color for summer to increase and darker color for winter to decrease. Further more, energy exchangeable materials such as photoluminescents and thermoluminescents have potentials in transforming solar radiation and temperature changes into light. For example, part of walls or pavement can be part of street lighting system. Other materials such as photovoltaics are well known as materials for solar cells and pyroelectric and thermoelectric also have potentials of usages in the street environment mobilizing temperature difference.

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APPENDIX

A. STREET CASE STUDIES

A. CASE STUDIES

Two case studies of recent design to modify the street environment were selected for evaluating in this section. First case is Avinguda Diagonal in Barcelona, Spain and the other is Eco Boulevard in Madrid in the same country. Design solutions for thermal comfort in the street environment were also explored.

Avinguda Diagonal, Barcelona, Spain, photograph by Youngsoo Kim

Eco Boulevard, Madrid, Spain, photograph by Youngsoo Kim

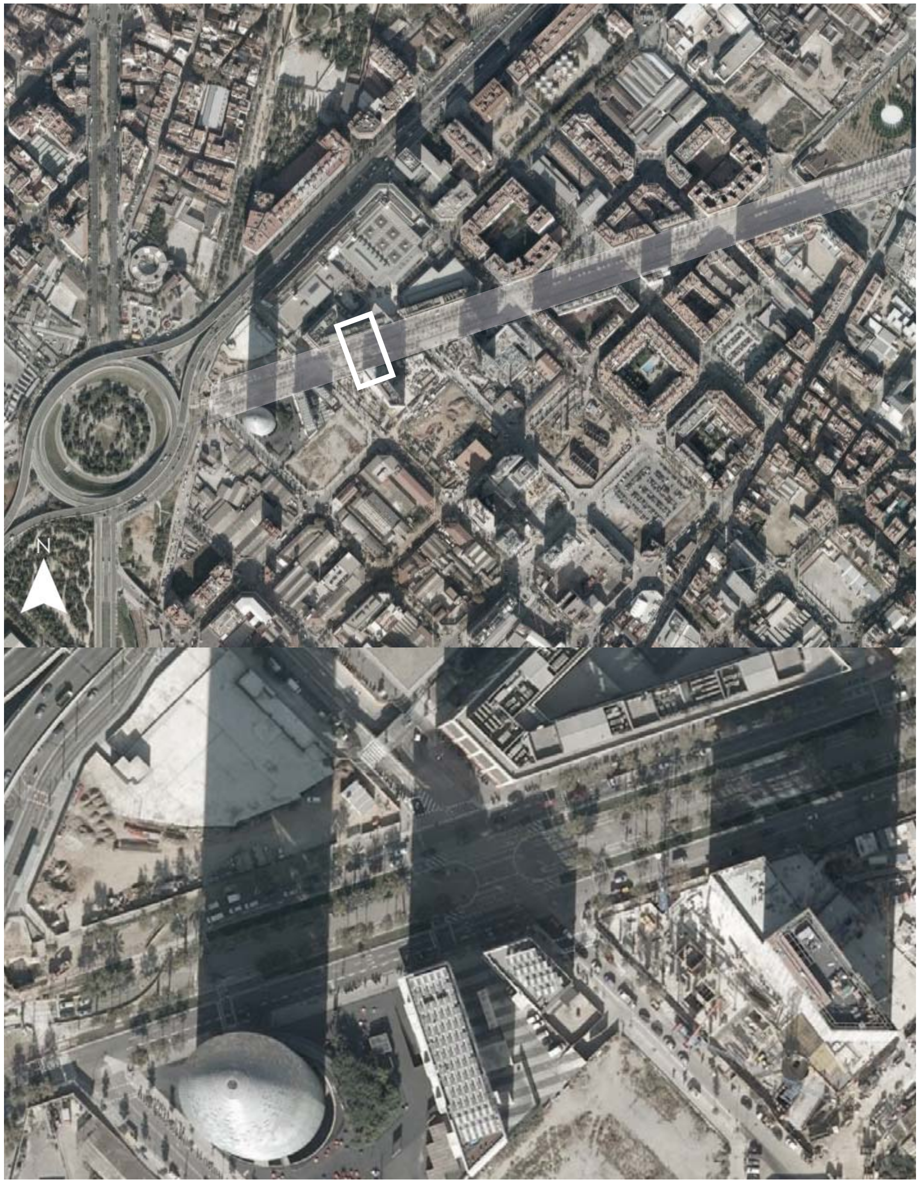


Figure A-1-1 Avinguda Diagonal (Satellite Photo from Google Earth and Visual Earth)

A.1 AVINGUDA DIAGONAL, BARCELONA, SPAIN 41° 23', N/ 2° 11', E

As stated in its name, Aviguda Diagonal is the street that is diagonally crossing orthogonal city grid of Barcelona. According to the plan of Innovation District, Avinguda Diagonal became an axial street of the development (Busquets 2006). From 1996 to 1999, the street was redesigned to expand the city to the new water front of Barcelona. Now Avinguda Diagonal includes three pedestrian sidewalks, two lanes of light rail, two bicycle lanes and six of vehicle traffic. Along side, tall buildings with mixed use and high density, including Torre Agbar by Jean Nouvel. Street width is 163 feet and it is divided into 9 movement sections (Figure A-1-2,3,4). Each mode of movement is clearly distinguished by a line of trees parallel to it and each line of trees provide shades on relatively wide pedestrian walks in the median. Material uses on the street are relatively simple compared to the case of Paseo del Prado in Madrid. Pedestrian sidewalks on each side of the street has concrete tile block and light rail lanes are covered with turf grass. Asphalt pavement is used for vehicular traffic lanes, pedestrian walk and bicycle lanes.

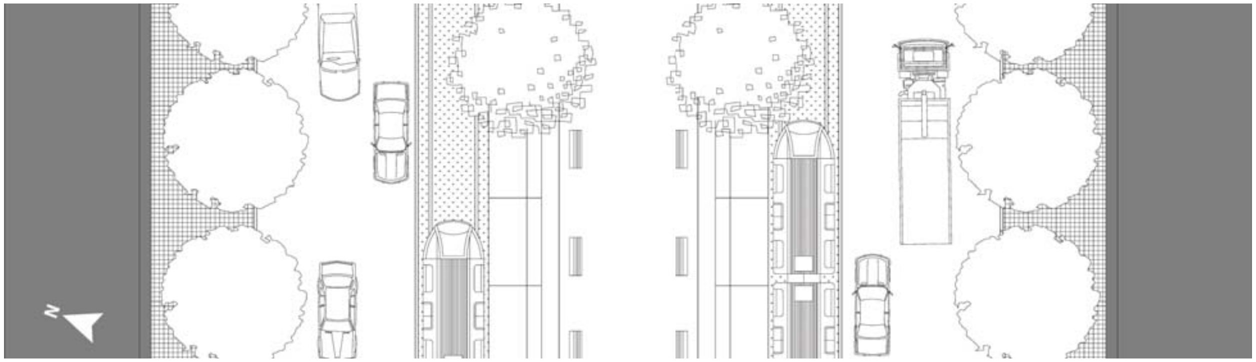


Figure A-1-2 Avinguda Diagonal, Plan

Figure A-1-3 Avinguda Diagonal, Photography by Youngsoo Kim

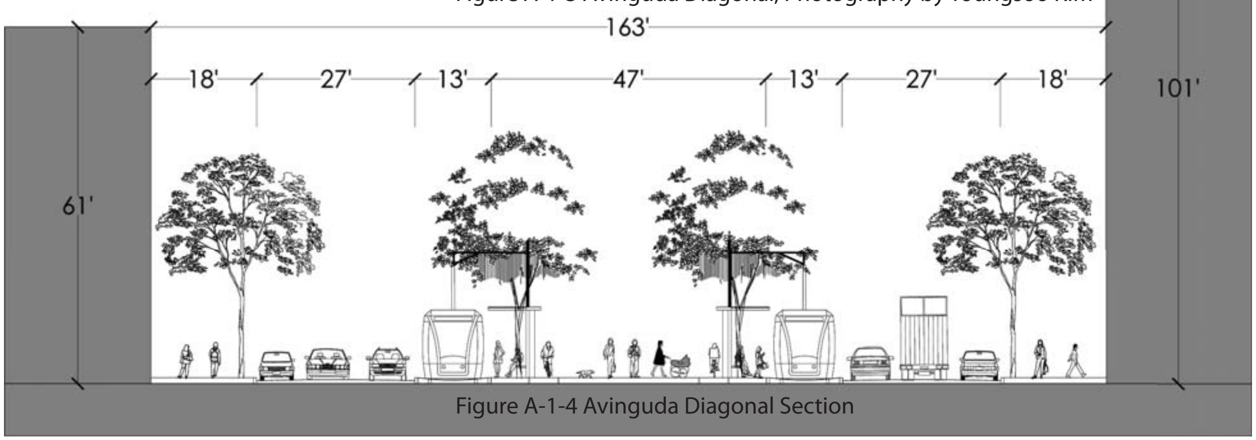
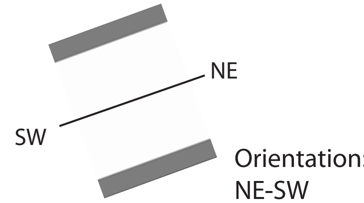
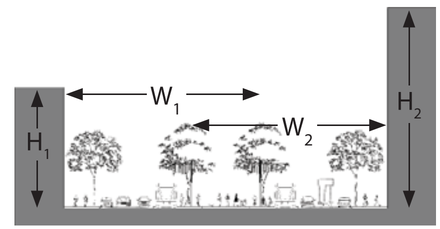


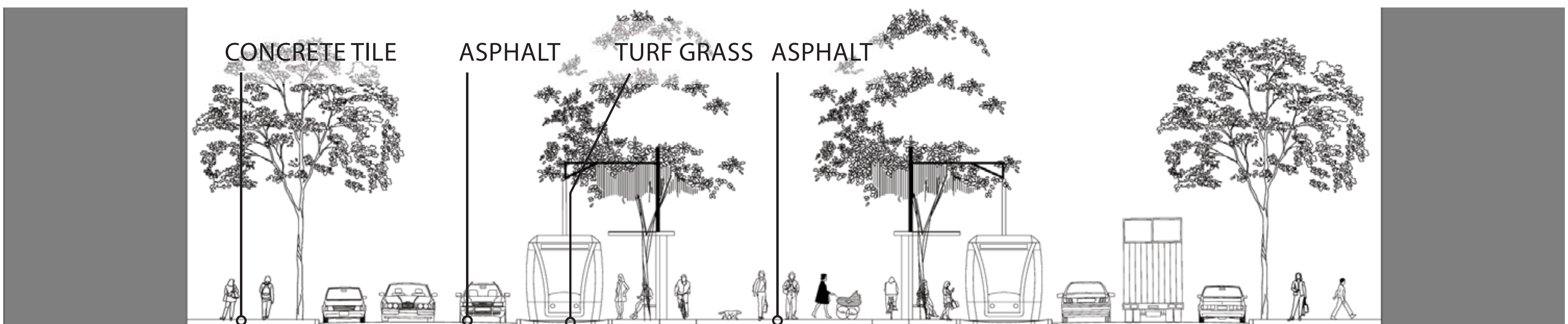
Figure A-1-4 Avinguda Diagonal Section



H/W Ratio:
$H_1/W \approx 0.4$
$H_2/W \approx 0.6$



H/W Ratio:
$H_1/W_1 \approx 0.6$
$H_2/W \approx 1$



View points in Avinguda Diagonal, Barcelona, Spain, photograph by Youngsoo Kim

Figure A-2-1 Eco Boulevard (Satellite Photo from Google Earth and Visual Earth)

A.2 ECO BOULEVARD, VALLECAS, SPAIN
40° 26', N/ 3° 42', W

Eco Boulevard is located in the town of Vallecas in the south of the city of Madrid. Needing an urban park, the Madrid Municipal Housing Corporation's Residential Innovation Office (with support from the EU LIFE Program) sponsored an architectural competition in 2004. and Ecosistema Urbano's proposal was selected because it provided different design approaches to the urban park (Kottas, 2007). The project envisions long term return of the design effect in the street environment. While planted trees are growing over 10 to 20 years, shade will be mostly provided by a new "air-tree" system installed in the middle of the street. (Figure A-2-2,3,4) Air-tree is a cylindrical steel structure with a diameter of 65 feet that allows green walls with planted vines combined with solar panels located on the top of the structure. It also planned to work as an urban social space in the neighborhood. The idea is that, in the long term, when planted trees meet the shading requirements in the street, it can be dismantled and recycled in different streets. (Figure A-2-5,6,7) Air-trees located in the middle of the crossroads also implement higher H/W ratio in the street. Less heat radiation is expected from the surface materials the structure.

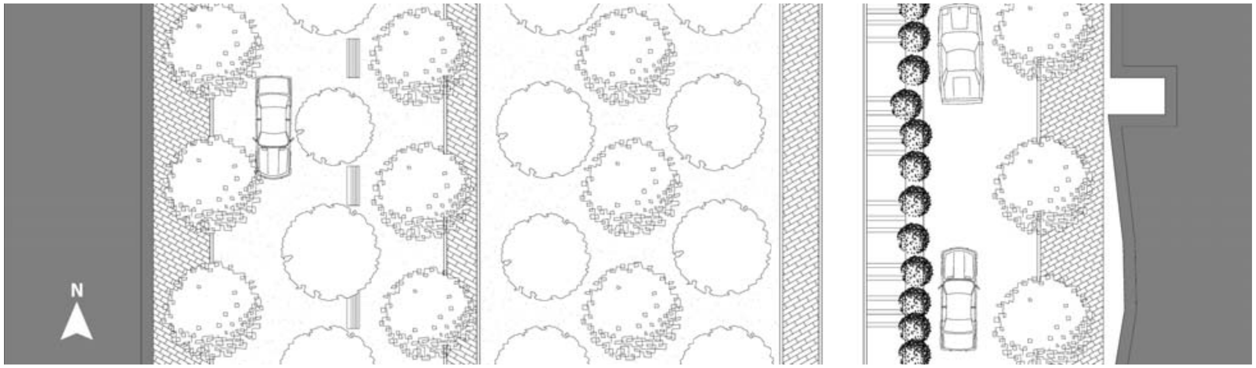


Figure A-2-2 Eco Boulevard, Plan1

Figure A-2-3 Eco Boulevard, Photography by Youngsoo Kim

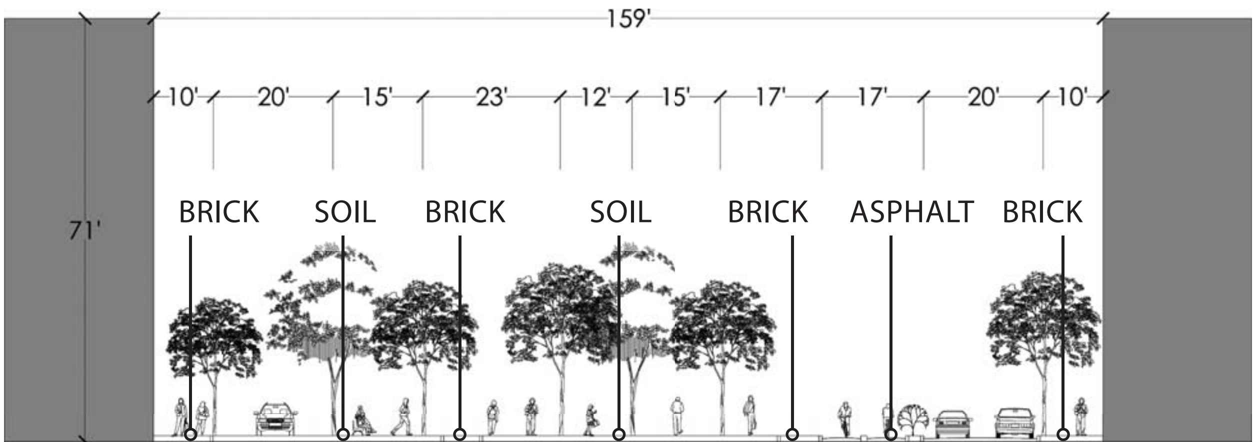
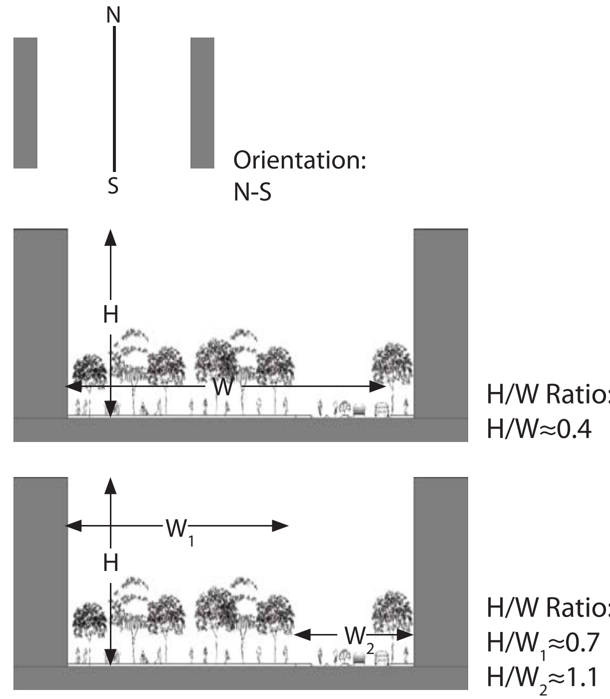
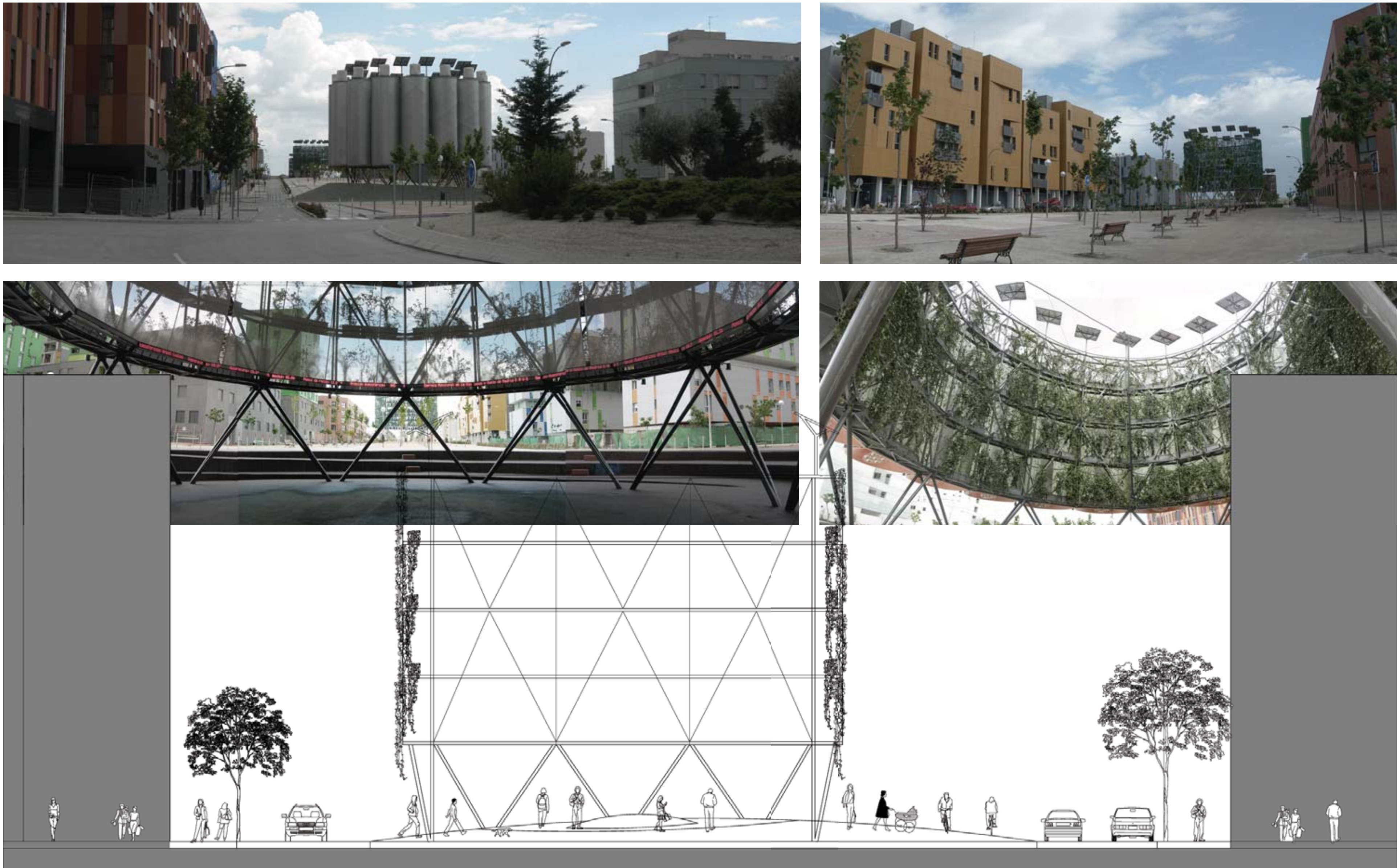


Figure A-2-4 Eco Boulevard, Section1





View points in Eco Boulevard, Vallecas, Spain, photograph by Youngsoo Kim

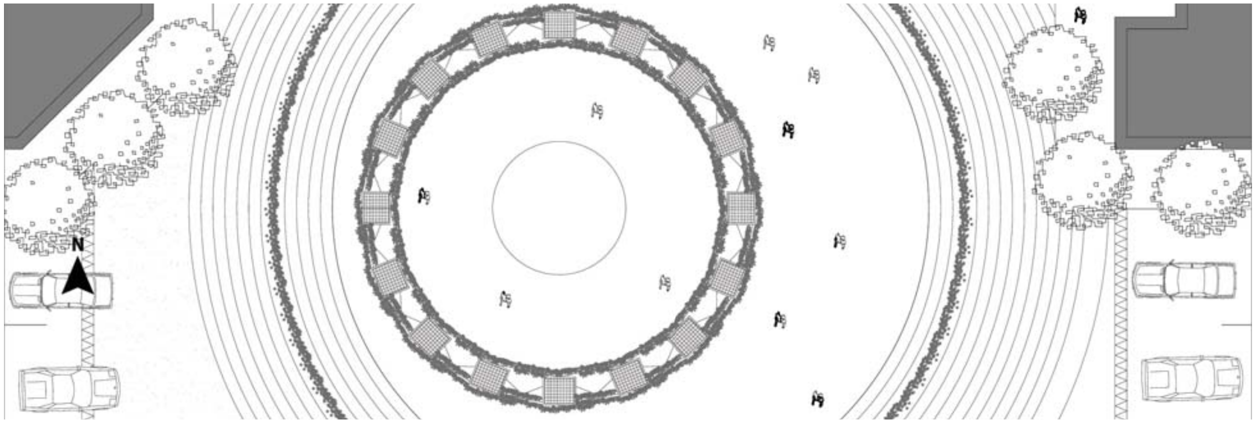


Figure A-2-2-5 Eco Boulevard, Plan2

Figure A-2-6 Eco Boulevard, Photography by Youngsoo Kim

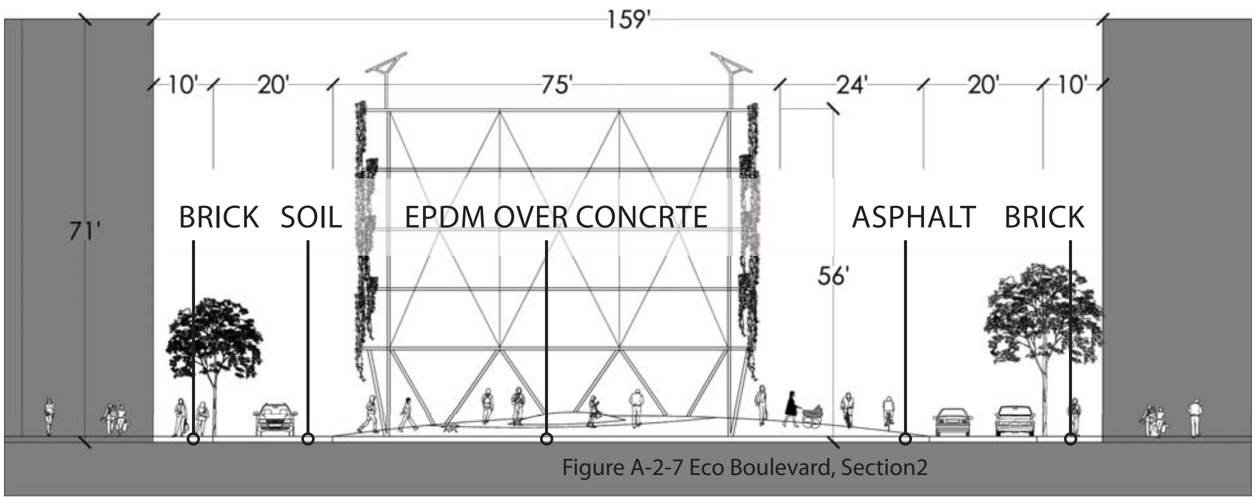
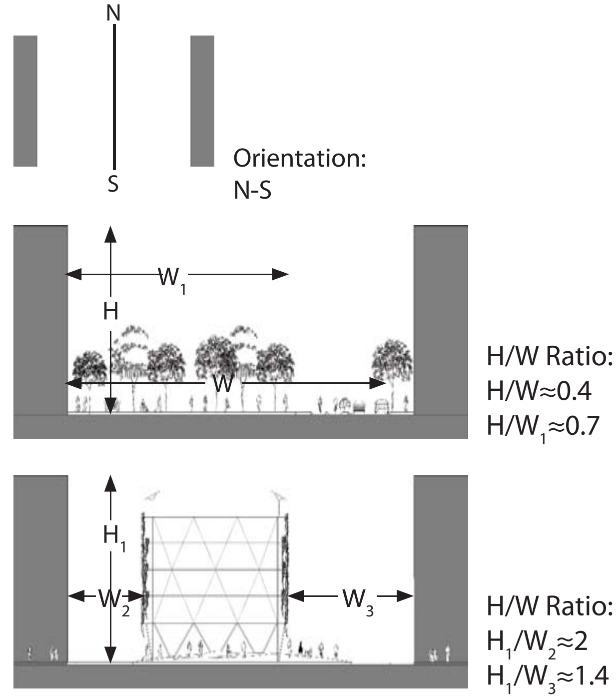


Figure A-2-7 Eco Boulevard, Section2



Photography from Ecosistema Urbano

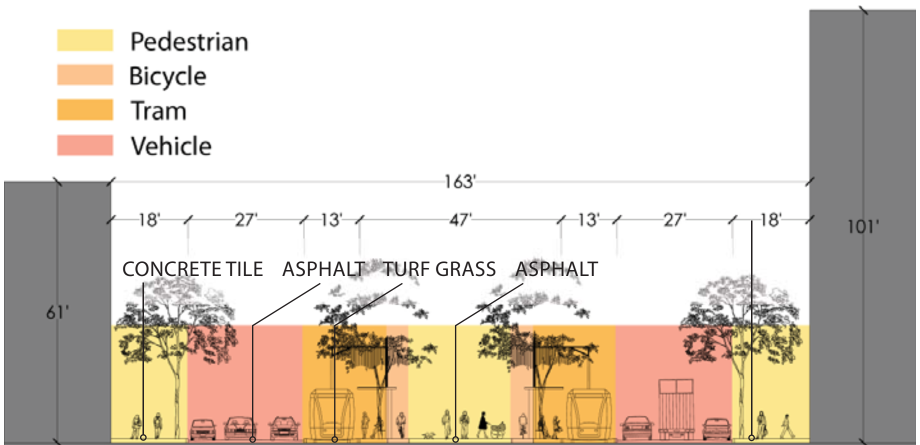


Figure A-2-8 Width comparison of each movement system in Avinguda Diagonal section

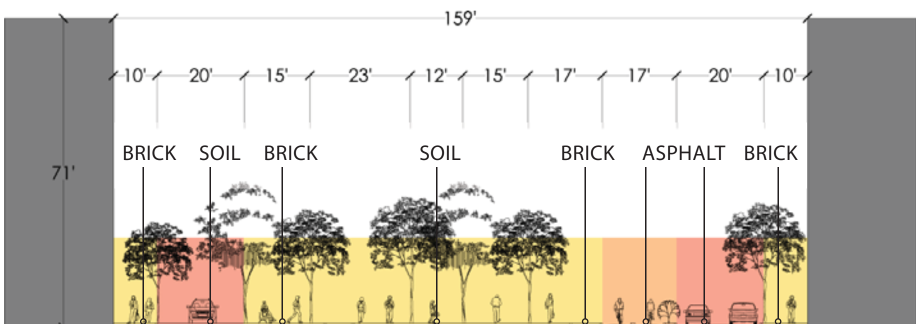


Figure A-2-9 Width comparison of each movement system in Eco Boulevard section 1

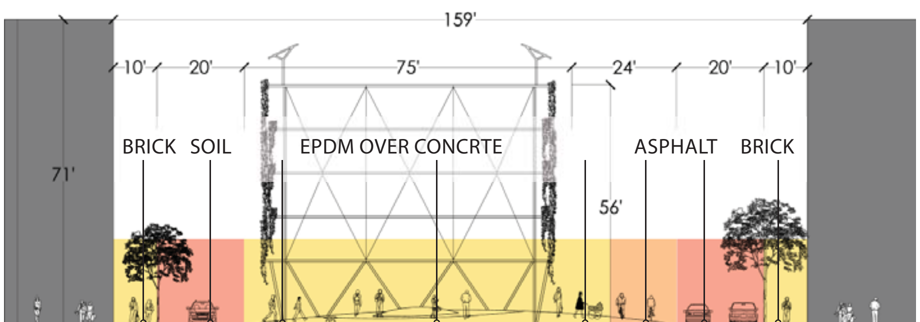


Figure A-2-10 Width comparison of each movement system in Eco Boulevard section 2

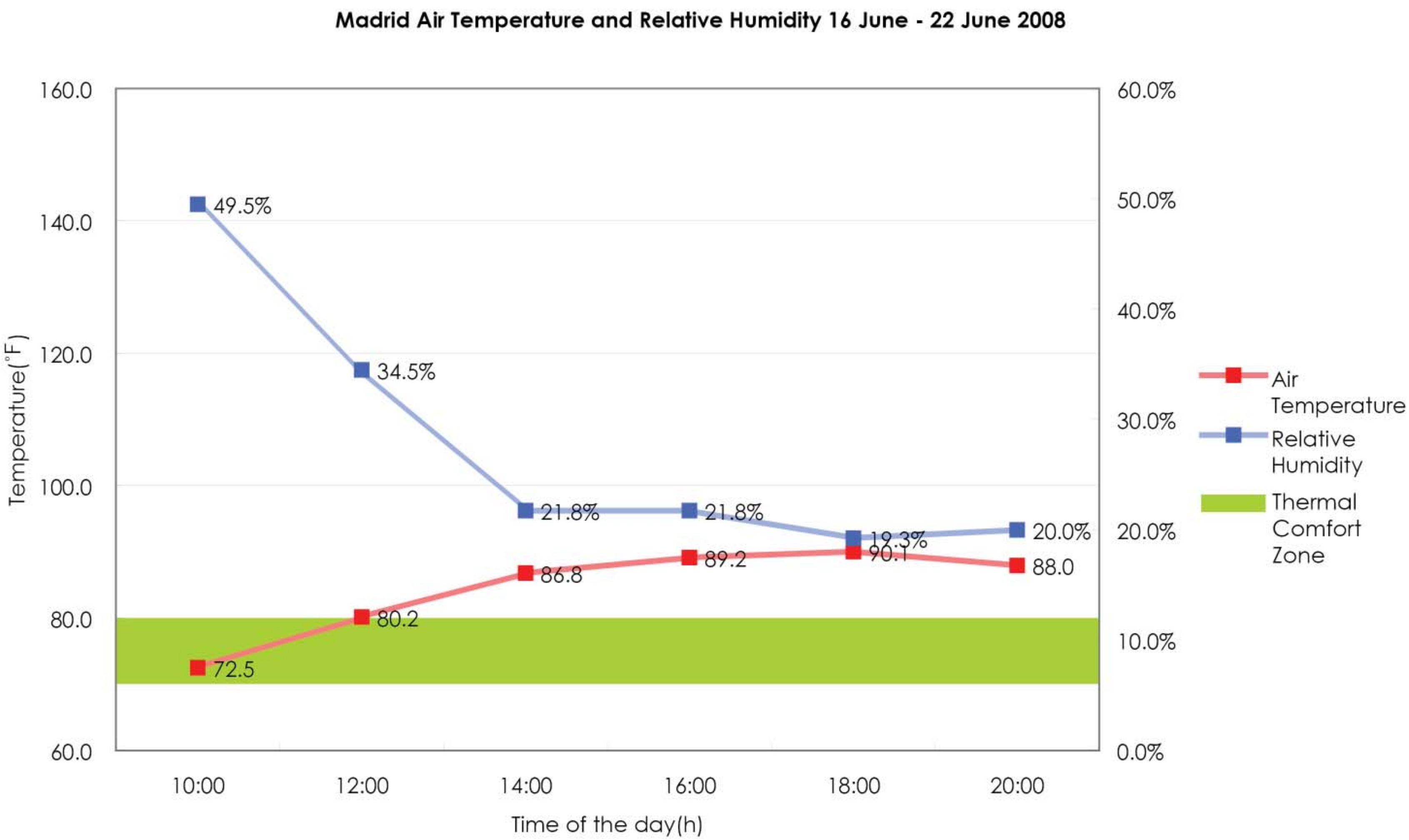
A.3 SYNTHESIS

Different design approaches were found from the case study. In both case, orientation and geometry of the street were determined mainly by land use, density and transportation. Design proposals were adapted as modifications of existing conditions. Summary of each design approach can be summarized as follows.

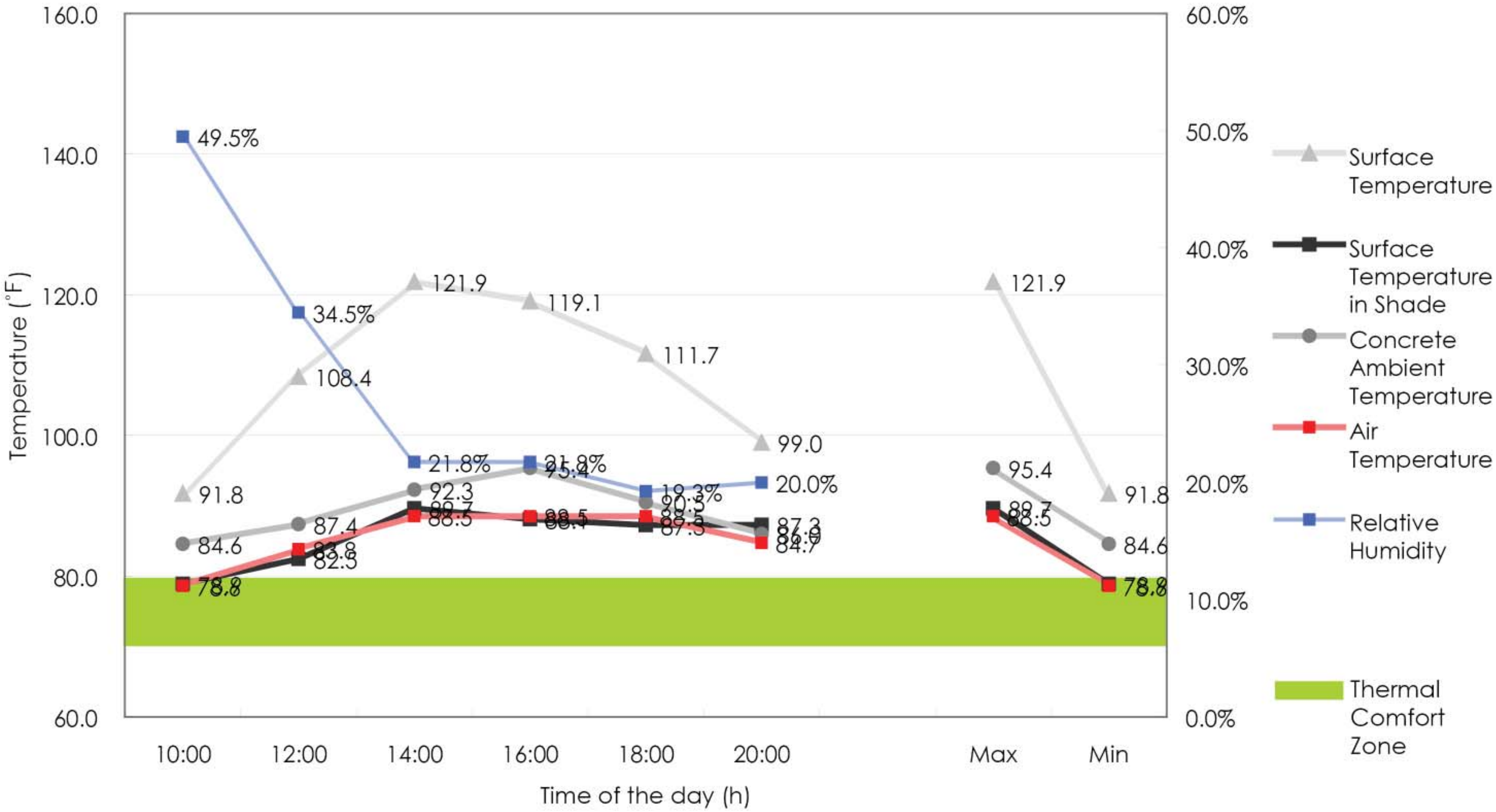
Street	Design Approach
Avinguda Diagonal	• Four lines of trees divide the street symmetrical by different type of movement system: Pedestrian, Tram, Bicycle, Car • Width proportion- Sidewalk : Car : Tram : Bicycle : Median = 1 : 2.5 : 1.5 : 0.5 : 1.5 • Each lines of trees help increasing H/W ratio from 0.4 to 0.6 and from 0.6 to 1. • Asphalt is used for both median and vehicular traffic.
Eco Boulevard (1)	• Seven lines of trees divide the street asymmetrically with three types of movement system: Pedestrian, Bicycle, Car • Width proportion- Sidewalk : Car : Median : Bicycle : Car : Sidewalk = 1 : 2 : 8 : 1.5 : 2 : 1 • Pedestrian movement is concentrated on the east side • Various materials are used for the pavement. Combination of earth and brick pavement is used for median.
Eco Boulevard (2)	• "Air tree" structure divides the street asymmetrically by providing open space in the middle. • Width proportion- Sidewalk : Open Space : Bicycle : Car : Sidewalk = 1 : 2 : 8 : 1.5 : 2 : 1 • Material used for the pavement under the air tree is EPDM (Ethylene, Propylene, Non-conjugated Diene) pavement and it is not durable and not porous.

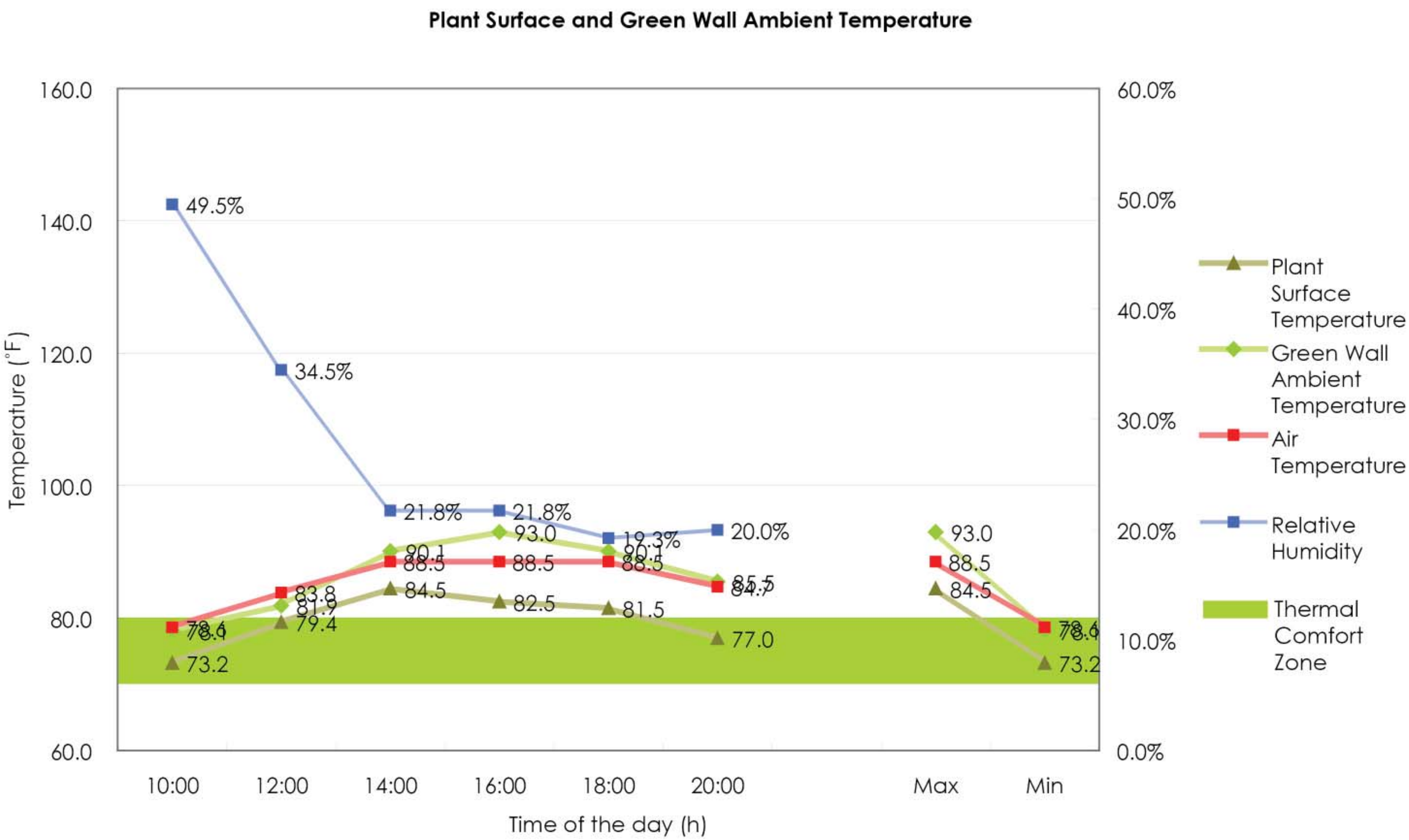
B. TEMPERATURE MEASUREMENT DATA

TEMPERATURE MEASUREMENT DATA OF PASEO DEL PRADO, MADRID, SPAIN



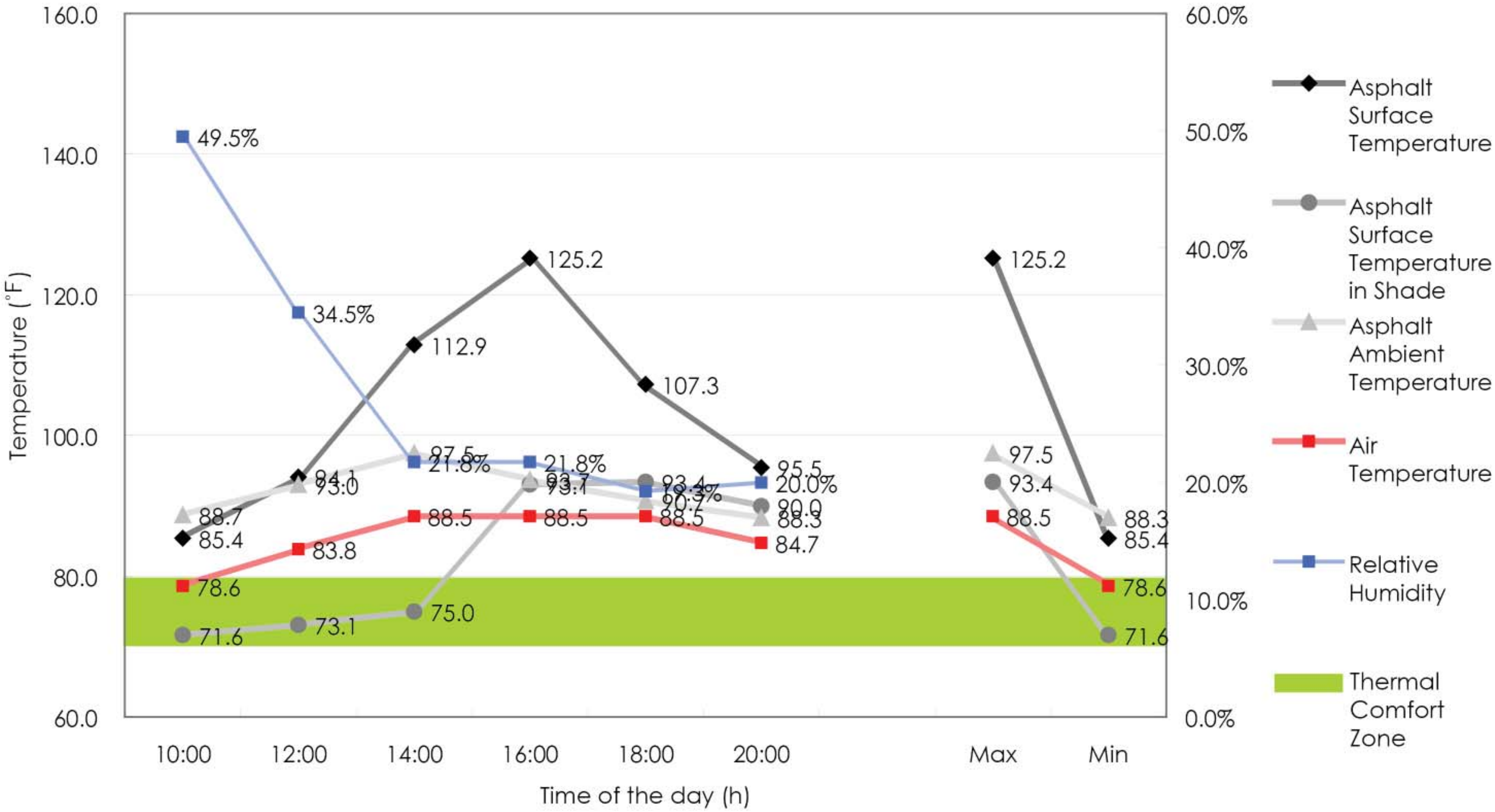
Concrete Pavement Surface and Ambient Temperature

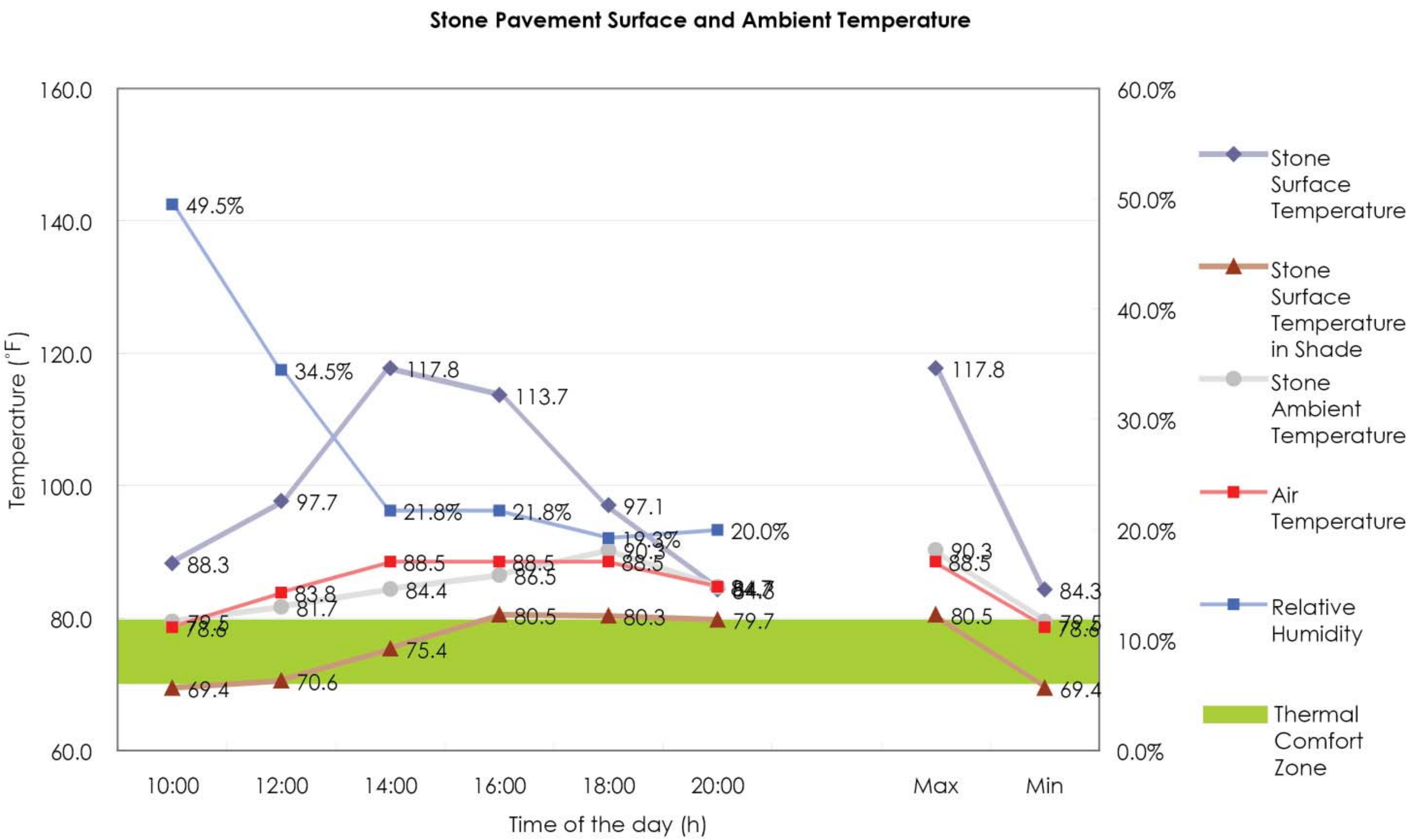


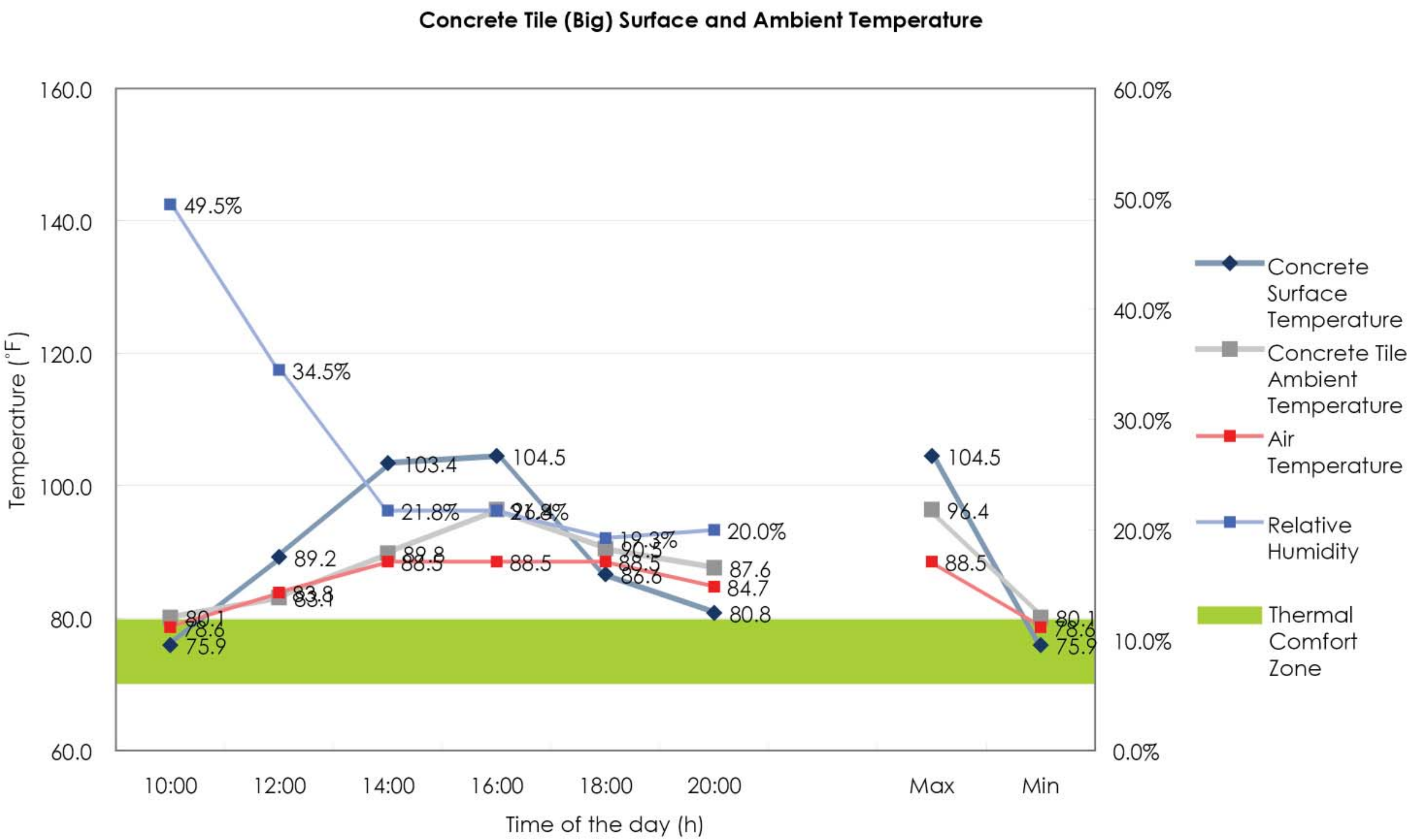


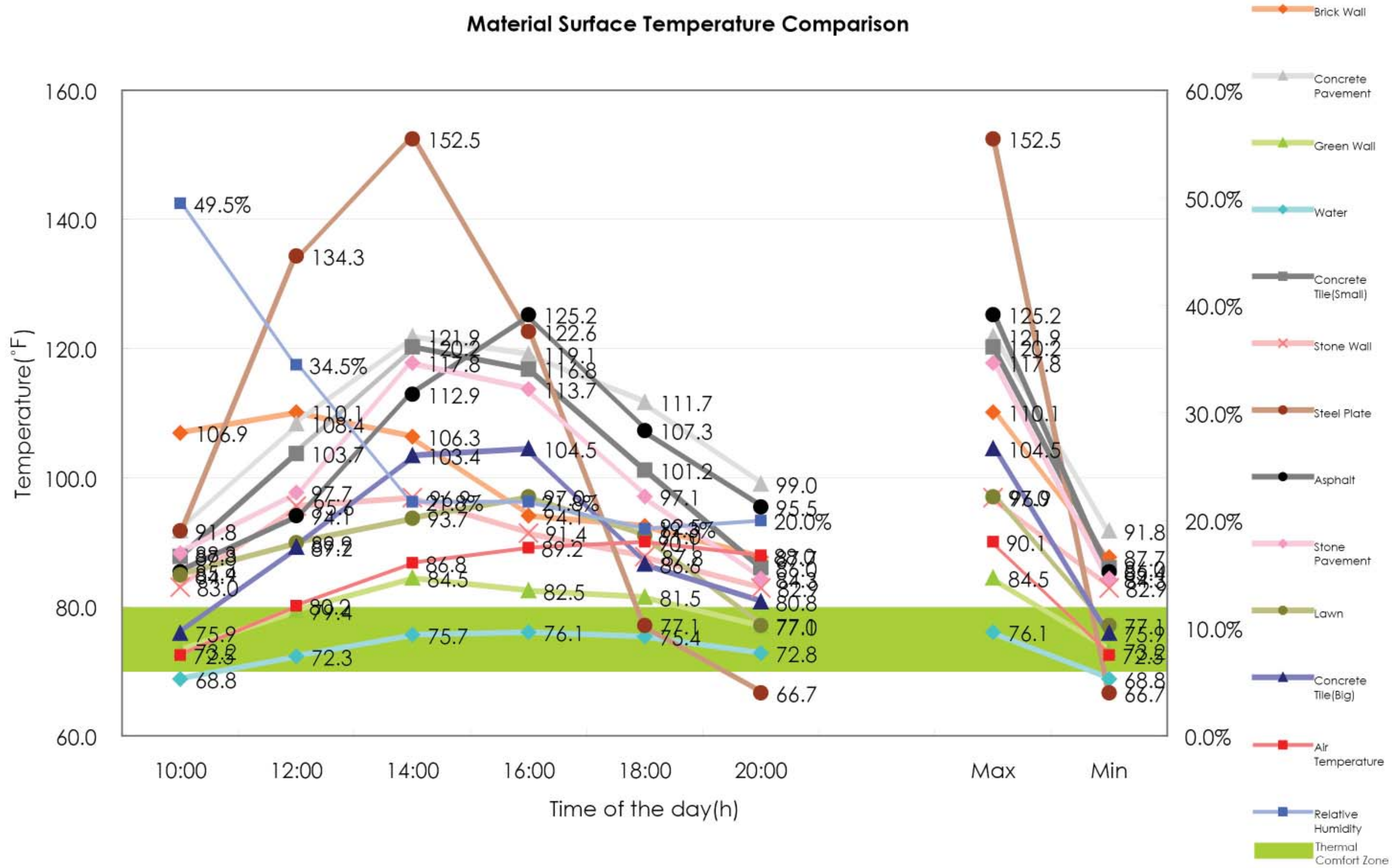
Plant Surface and Green Wall Ambient Temperature
160.0
140.0
120.0
100.0
80.0
60.0
Temperature (°F)
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
49.5%
34.5%
21.8%
21.8%
19.3%
20.0%
93.0
90.1
88.5
88.5
90.1
88.5
85.5
84.7
83.8
81.9
84.5
82.5
81.5
77.0
78.4
79.4
73.2
93.0
88.5
84.5
78.4
73.2
10:00
12:00
14:00
16:00
18:00
20:00
Max
Min
Time of the day (h)
Plant Surface Temperature
Green Wall Ambient Temperature
Air Temperature
Relative Humidity
Thermal Comfort Zone

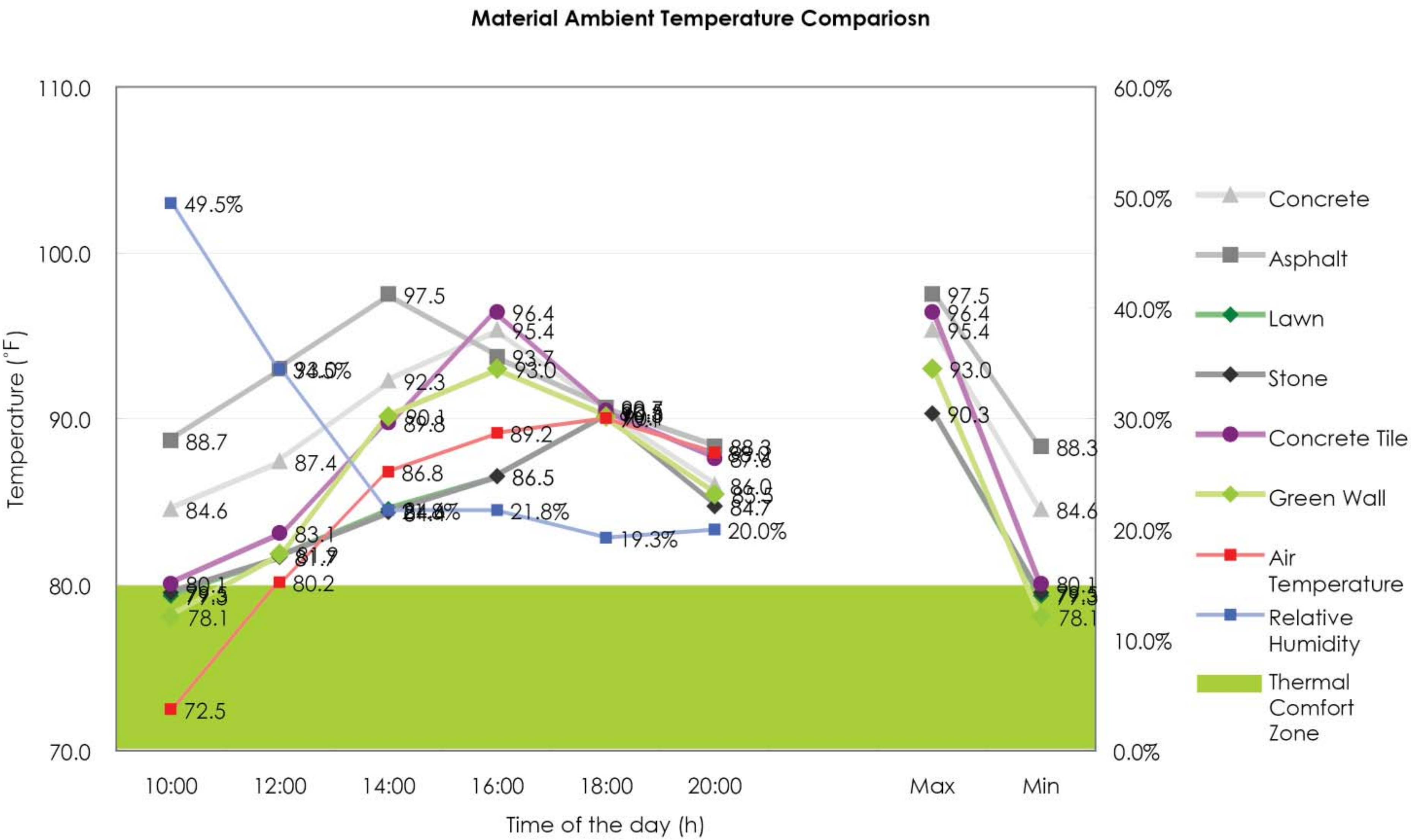
Asphalt Surface and Ambient Temperature



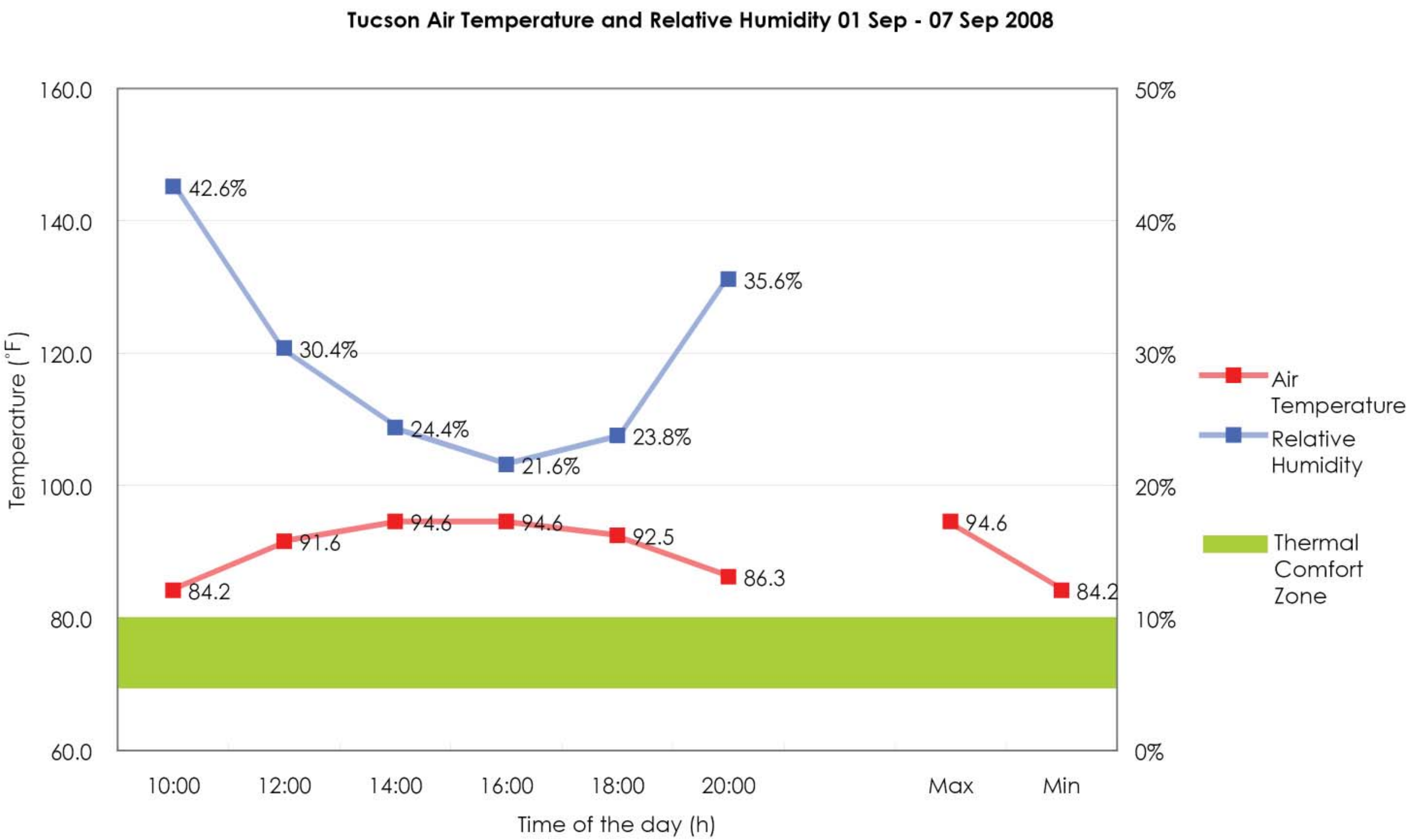

Stone Pavement Surface and Ambient Temperature
160.0
140.0
120.0
100.0
80.0
60.0
Temperature (°F)
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
49.5%
34.5%
21.8%
21.8%
19.3%
20.0%
88.3
97.7
117.8
113.7
97.1
84.3
117.8
84.3
83.8
88.5
88.5
88.5
84.7
88.5
78.6
79.5
81.7
84.4
86.5
90.3
90.3
69.4
70.6
75.4
80.5
80.3
79.7
80.5
69.4
10:00
12:00
14:00
16:00
18:00
20:00
Max
Min
Time of the day (h)
Stone Surface Temperature
Stone Surface Temperature in Shade
Stone Ambient Temperature
Air Temperature
Relative Humidity
Thermal Comfort Zone

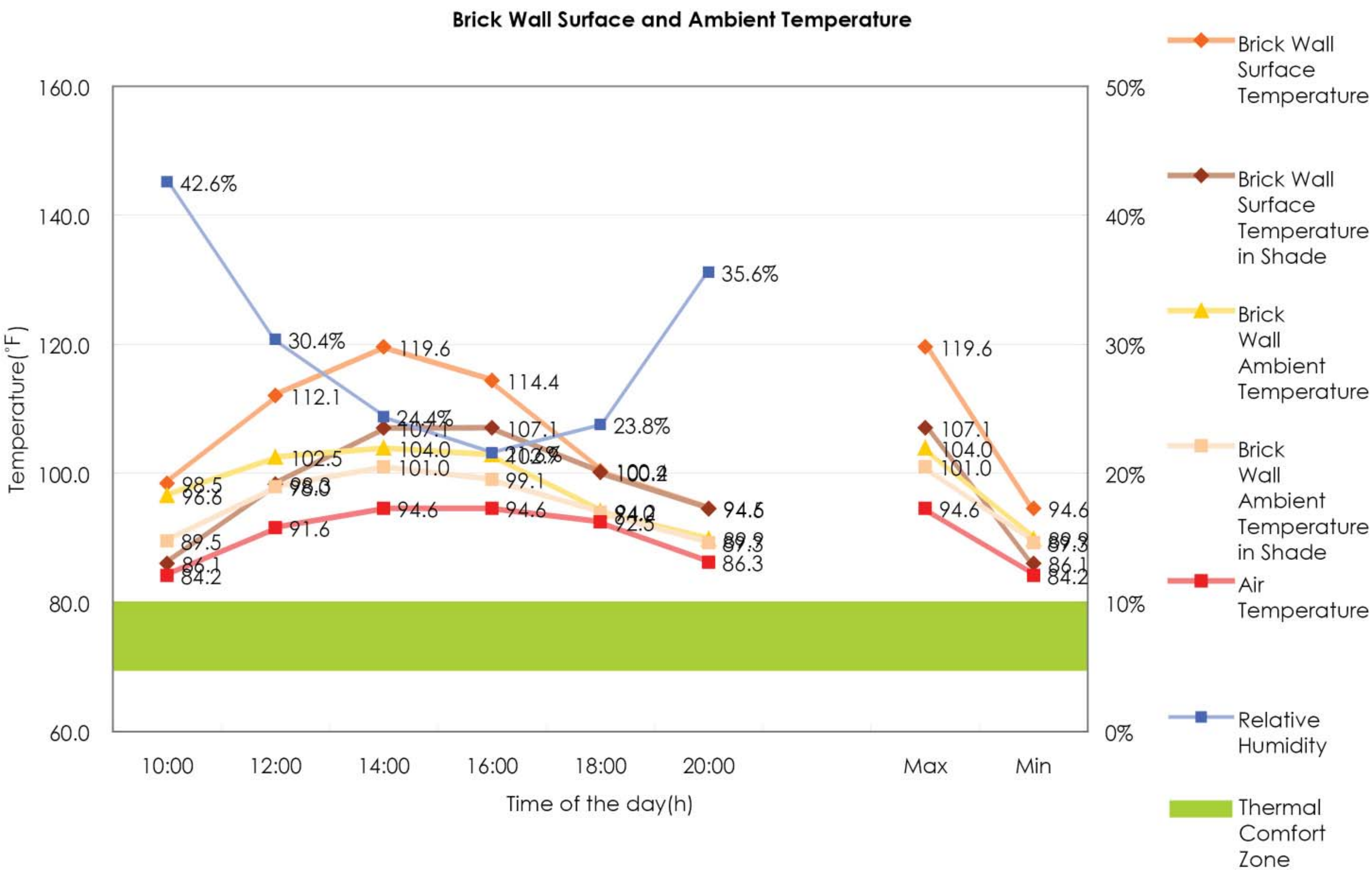

Concrete Tile (Big) Surface and Ambient Temperature
Temperature (°F)
160.0
140.0
120.0
100.0
80.0
60.0
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
10:00
12:00
14:00
16:00
18:00
20:00
Max
Min
Time of the day (h)
49.5%
34.5%
21.8%
20.0%
103.4
104.5
89.2
87.6
84.7
80.8
96.4
88.5
75.9
Concrete Surface Temperature
Concrete Tile Ambient Temperature
Air Temperature
Relative Humidity
Thermal Comfort Zone


Material Surface Temperature Comparison
Temperature(˚F)
Time of the day(h)
10:00
12:00
14:00
16:00
18:00
20:00
Max
Min
160.0
140.0
120.0
100.0
80.0
60.0
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Brick Wall
Concrete Pavement
Green Wall
Water
Concrete Tile(Small)
Stone Wall
Steel Plate
Asphalt
Stone Pavement
Lawn
Concrete Tile(Big)
Air Temperature
Relative Humidity
Thermal Comfort Zone

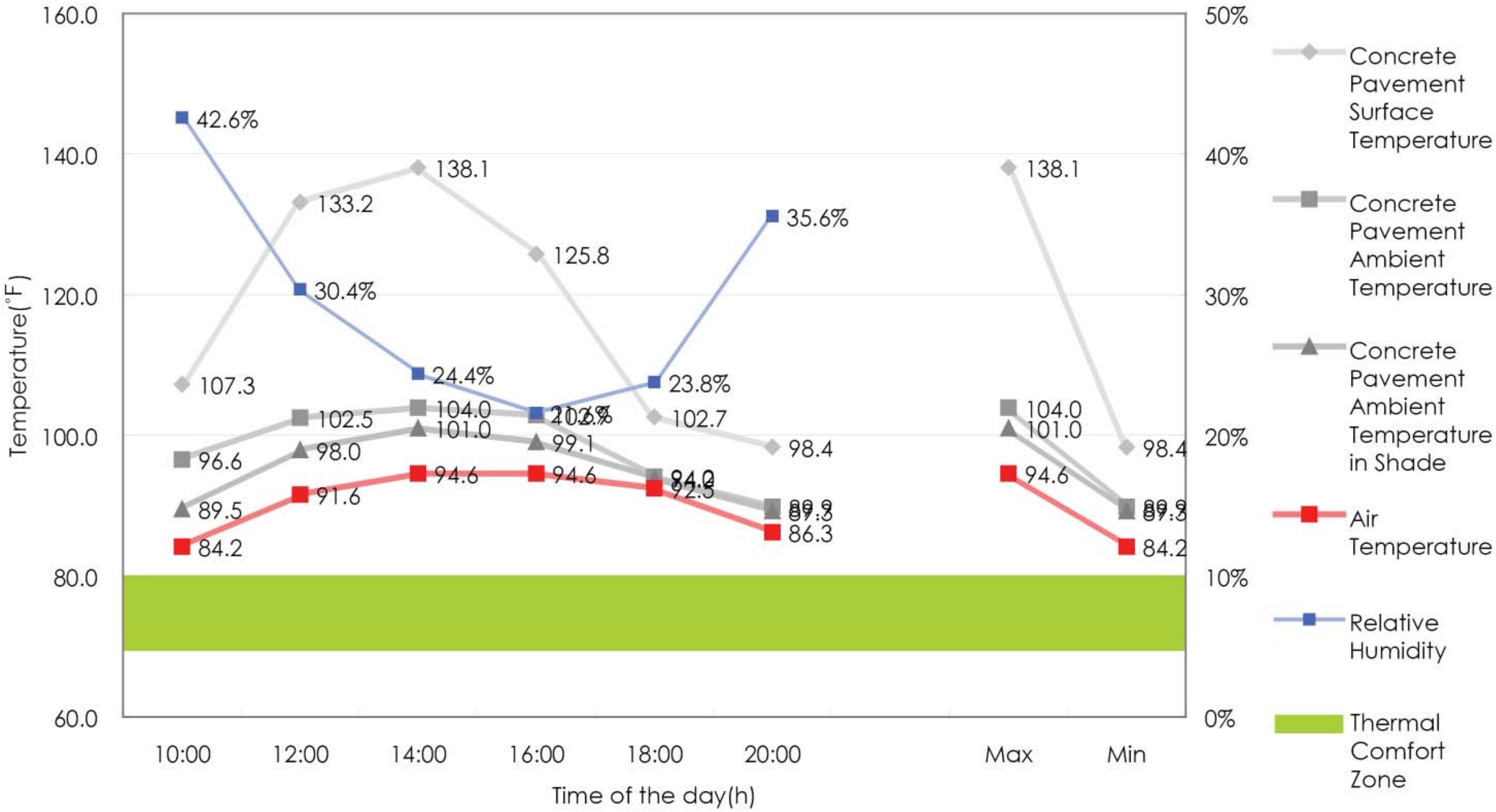

Material Ambient Temperature Compariosn
Temperature (˚F)
Time of the day (h)
10:00
12:00
14:00
16:00
18:00
20:00
Max
Min
110.0
100.0
90.0
80.0
70.0
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Concrete
Asphalt
Lawn
Stone
Concrete Tile
Green Wall
Air Temperature
Relative Humidity
Thermal Comfort Zone

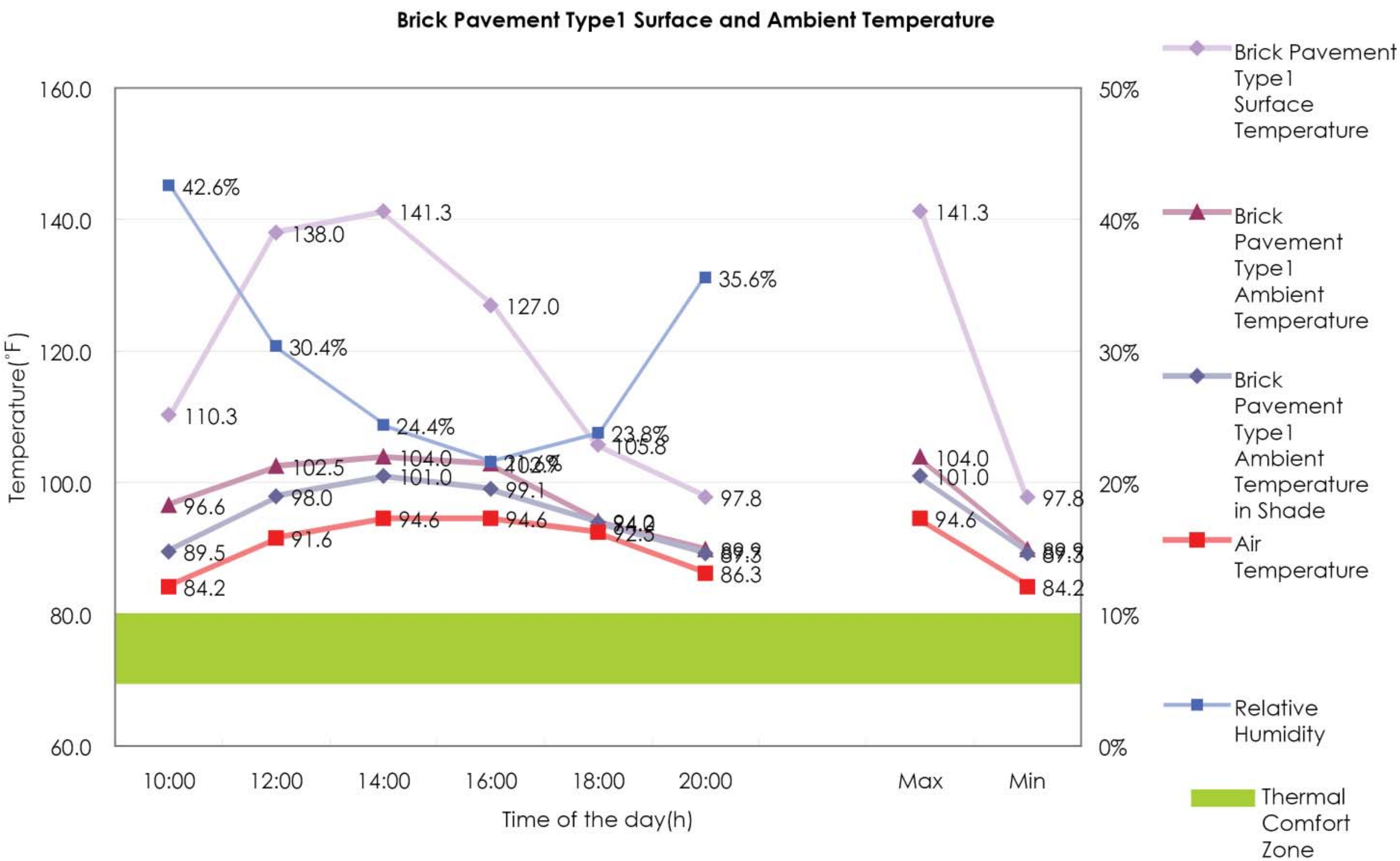
TEMPERATURE MEASUREMENT DATA OF UNIVERSITY BOULEVARD, TUCSON, AZ, USA

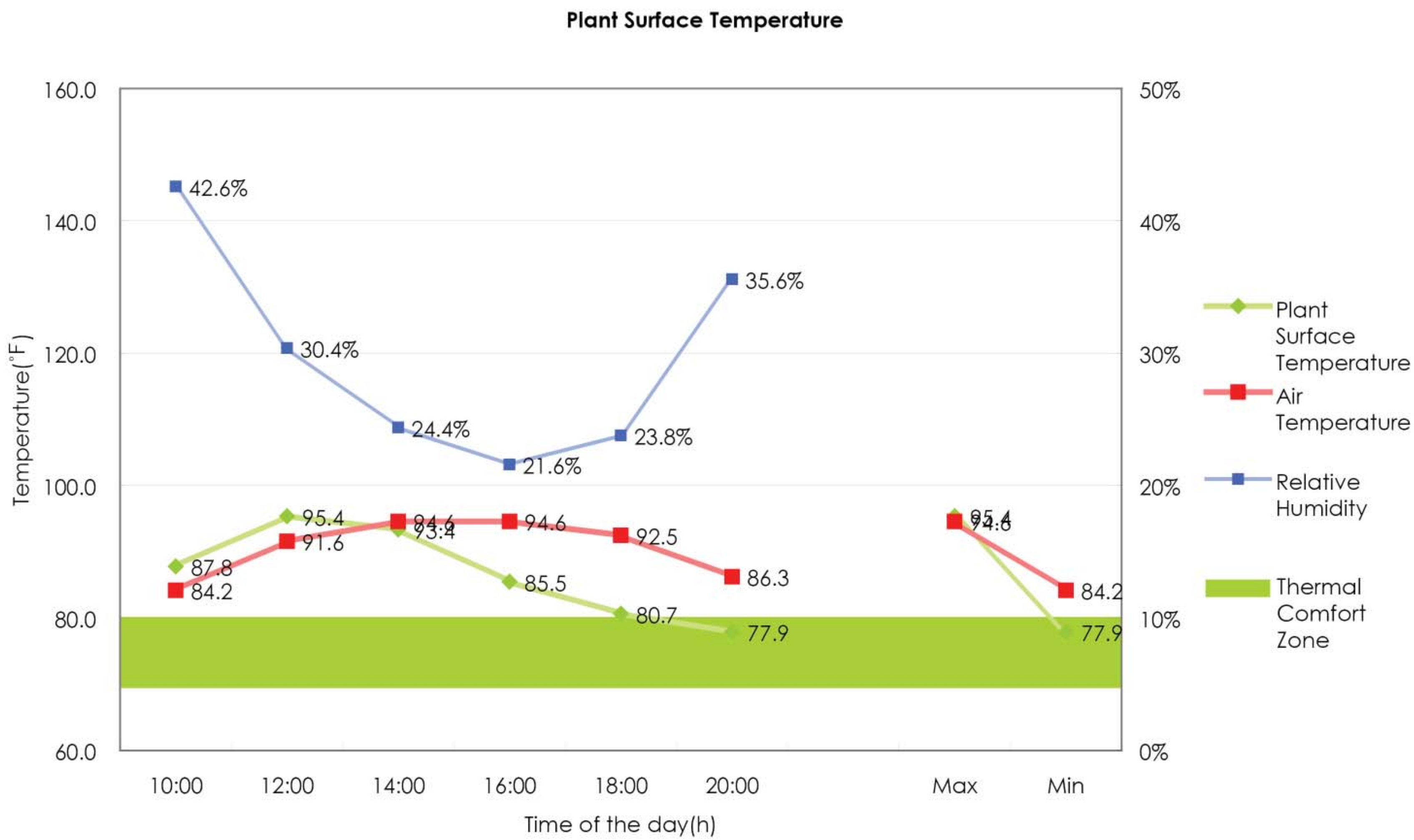



Brick Wall Surface and Ambient Temperature
160.0
140.0
120.0
100.0
80.0
60.0
Temperature(˚F)
50%
40%
30%
20%
10%
0%
10:00
12:00
14:00
16:00
18:00
20:00
Max
Min
Time of the day(h)
42.6%
30.4%
35.6%
23.8%
119.6
112.1
114.4
102.5
104.0
101.0
99.1
94.6
91.6
89.5
84.2
86.3
107.1
Brick Wall Surface Temperature
Brick Wall Surface Temperature in Shade
Brick Wall Ambient Temperature
Brick Wall Ambient Temperature in Shade
Air Temperature
Relative Humidity
Thermal Comfort Zone

Concrete Pavement Surface and Ambient Temperature

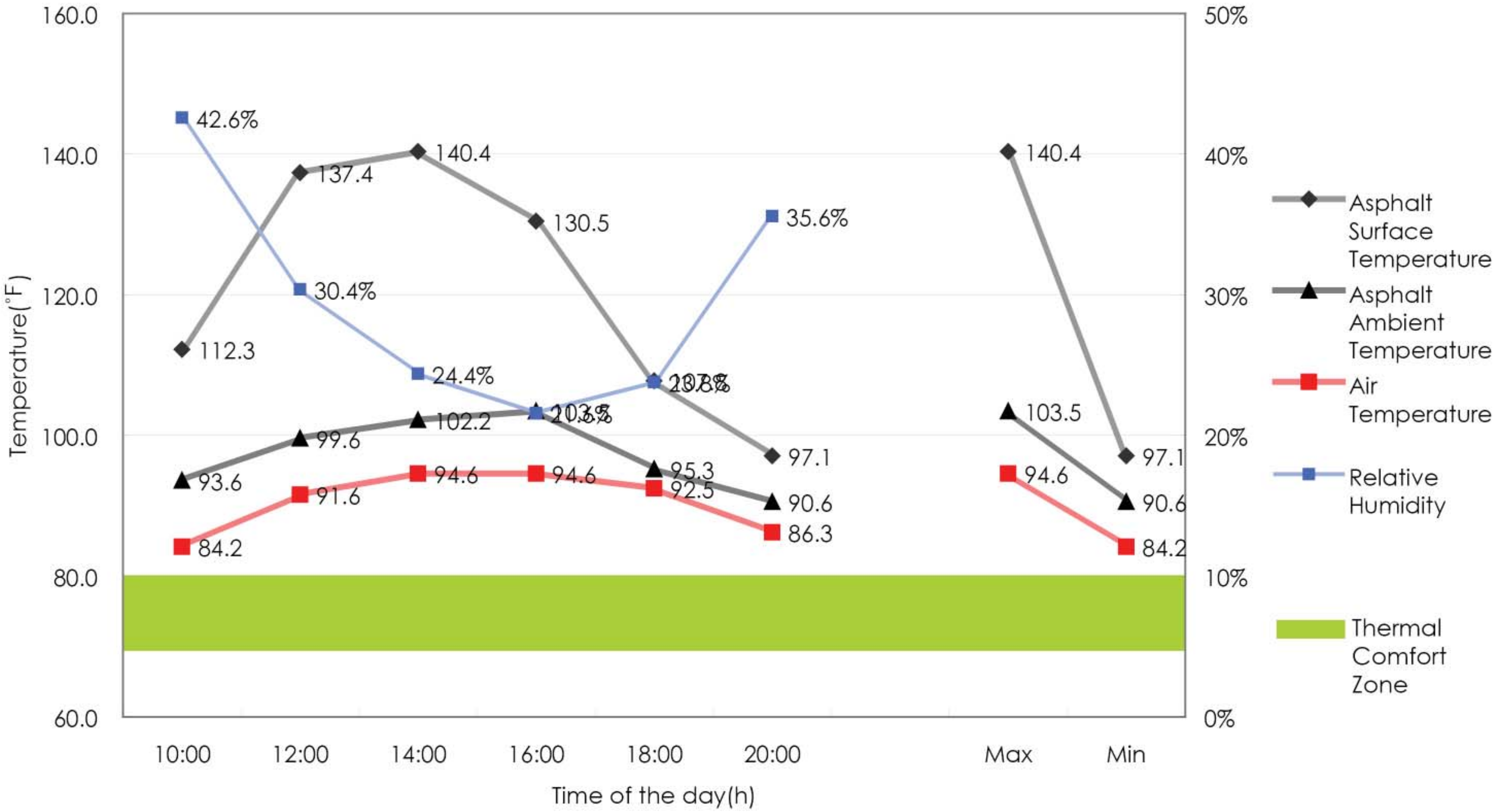


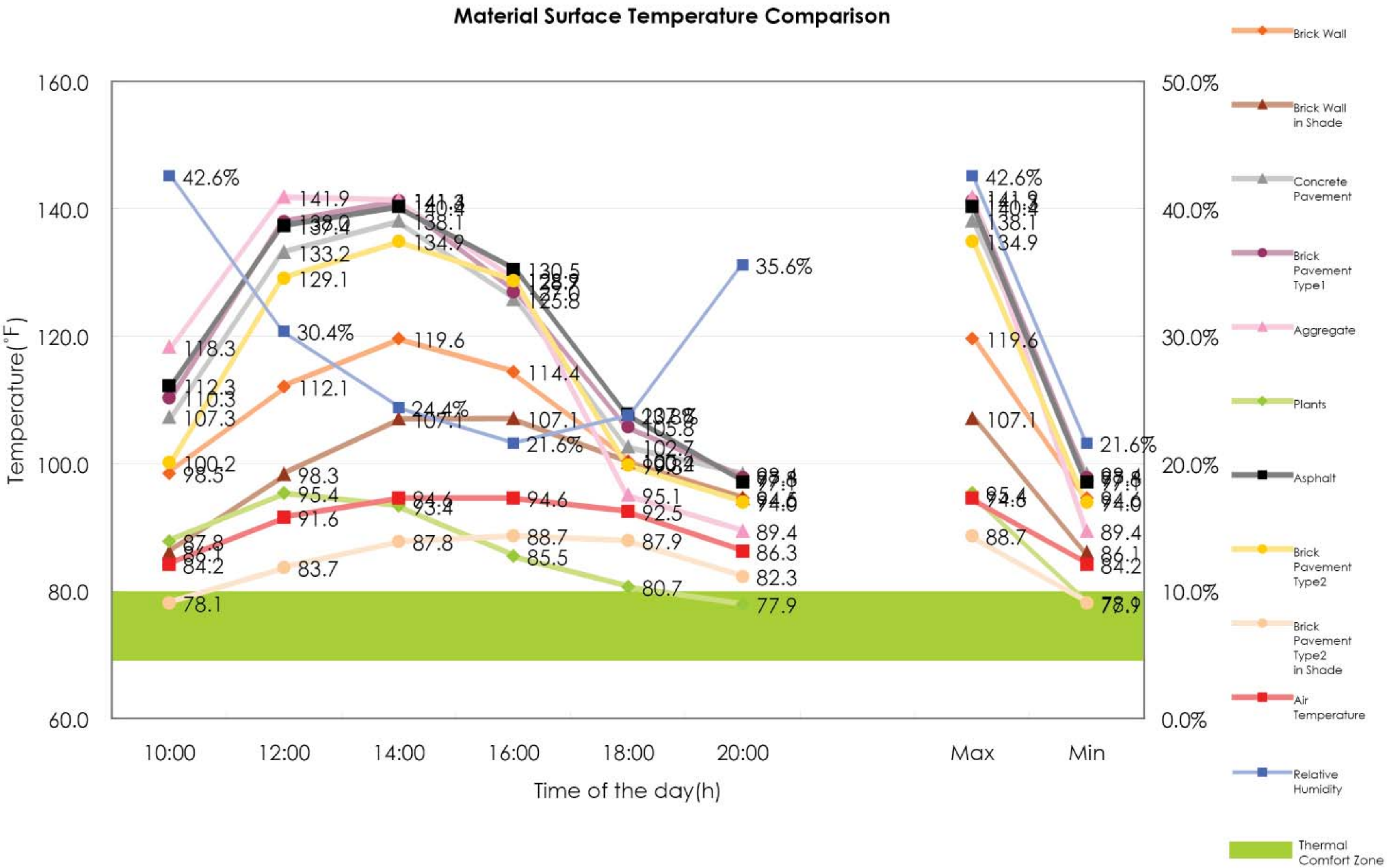

Brick Pavement Type1 Surface and Ambient Temperature
160.0
140.0
120.0
100.0
80.0
60.0
Temperature(°F)
50%
40%
30%
20%
10%
0%
10:00
12:00
14:00
16:00
18:00
20:00
Max
Min
Time of the day(h)
42.6%
30.4%
24.4%
23.8%
35.6%
110.3
138.0
141.3
127.0
105.8
97.8
96.6
102.5
104.0
89.5
98.0
101.0
99.1
84.2
91.6
94.6
86.3
Brick Pavement Type1 Surface Temperature
Brick Pavement Type1 Ambient Temperature
Brick Pavement Type1 Ambient Temperature in Shade
Air Temperature
Relative Humidity
Thermal Comfort Zone

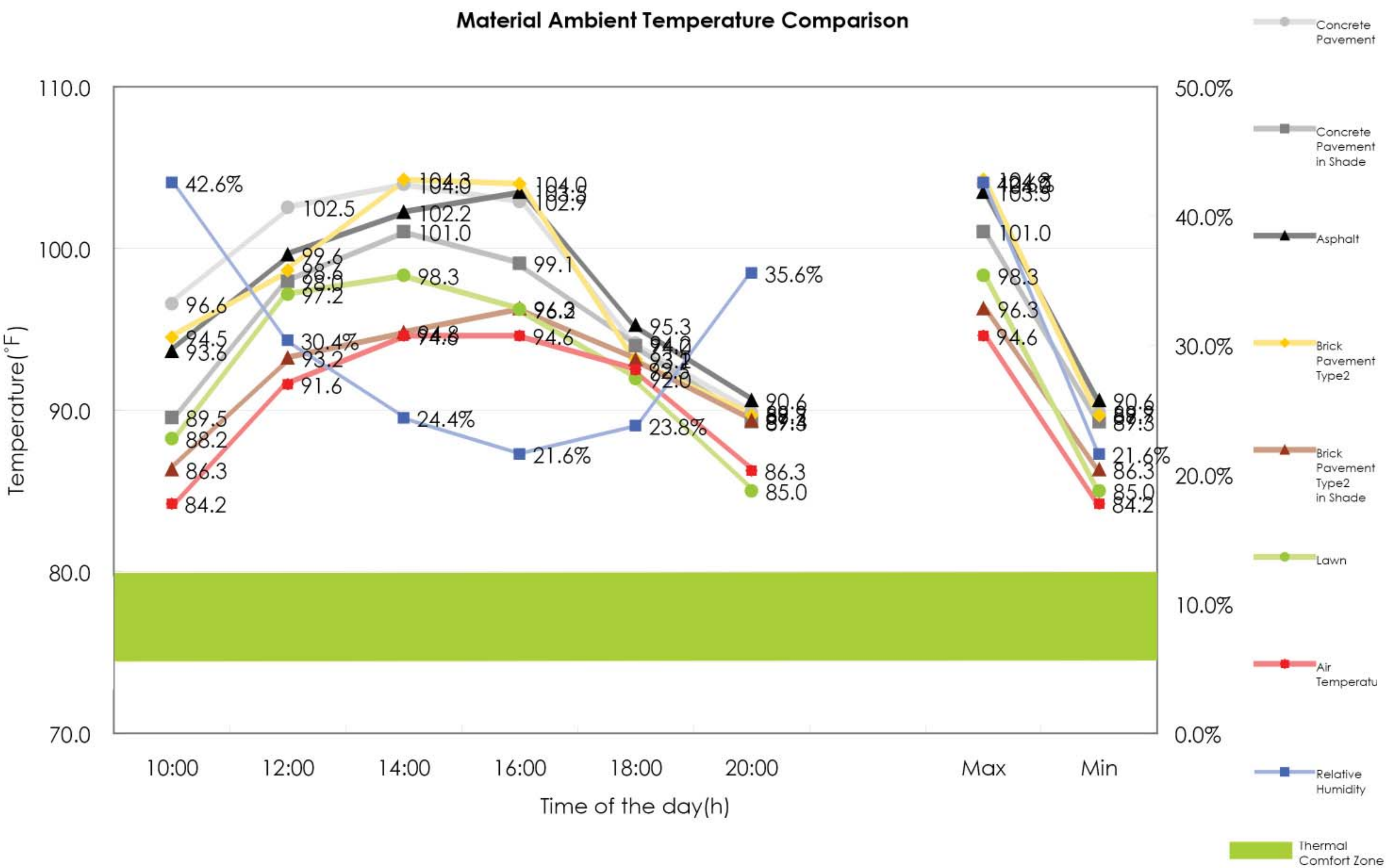


Plant Surface Temperature
160.0
140.0
120.0
100.0
80.0
60.0
Temperature(°F)
50%
40%
30%
20%
10%
0%
42.6%
30.4%
24.4%
21.6%
23.8%
35.6%
95.4
91.6
87.8
84.2
94.6
93.4
94.6
85.5
92.5
80.7
86.3
77.9
84.2
77.9
10:00
12:00
14:00
16:00
18:00
20:00
Max
Min
Time of the day(h)
Plant Surface Temperature
Air Temperature
Relative Humidity
Thermal Comfort Zone

Asphalt Surface and Ambient Temperature




Material Surface Temperature Comparison
Temperature(˚F)
Time of the day(h)
10:00
12:00
14:00
16:00
18:00
20:00
Max
Min
Brick Wall
Brick Wall in Shade
Concrete Pavement
Brick Pavement Type1
Aggregate
Plants
Asphalt
Brick Pavement Type2
Brick Pavement Type2 in Shade
Air Temperature
Relative Humidity
Thermal Comfort Zone


Material Ambient Temperature Comparison
Temperature(°F)
110.0
100.0
90.0
80.0
70.0
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
10:00
12:00
14:00
16:00
18:00
20:00
Max
Min
Time of the day(h)
42.6%
102.5
96.6
94.5
93.6
89.5
88.2
86.3
84.2
30.4%
93.2
91.6
97.2
102.2
101.0
98.3
24.4%
99.1
94.6
21.6%
95.3
23.8%
35.6%
90.6
86.3
85.0
101.0
98.3
96.3
94.6
90.6
21.6%
86.3
85.0
84.2
Concrete Pavement
Concrete Pavement in Shade
Asphalt
Brick Pavement Type2
Brick Pavement Type2 in Shade
Lawn
Air Temperatu
Relative Humidity
Thermal Comfort Zone