Strategies to Address the Climatic Barriers to Walkable, Transit-Oriented Communities in Florida

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Florida’s explosive population growth in the 20th century can be attributed at least in part to its climate, with abundant sunshine and mild winters offering a preferable alternative to conditions found at more northern latitudes. But ironically, the built environment that accommodated this growth was conceived with climate as an afterthought. In his examination of Broward County in South Florida, architect Anthony Abbate describes how development decisions were driven by the automobile and affordable air conditioning, a pattern that was repeated throughout the state. These technologies have allowed life to occur with little regard to climate. But if communities in Florida wish to become less auto-dependent, climate must take on added importance. Activities such as walking and using public transportation inherently require interaction with the natural environment. In Florida, this could mean exposure to extreme heat, humidity, and rainfall – conditions that the state’s Transit Oriented Development guidelines recognize as a significant barrier to walking and transit use.

This paper seeks to identify policy and design solutions that can mitigate the challenges that climate poses to creating walkable, transit-oriented communities in Florida. It identifies the typical summertime weather conditions in Miami, which was selected to be the study area because it contains a wide variety of densities and transit options in addition to newly revised zoning and land use regulations. It then examines the body’s physiological response to these conditions and uses this information to determine how far an average adult male can walk while maintaining “thermal comfort.”

This distance, called the “comfort shed,” is offered as an alternative to the quarter-mile “ped shed” or “transit shed” typically identified in transit and TOD literature. Along with this new proposed walking distance, this paper proposes revised density standards required to support different forms of transit-oriented development in Florida. Finally, it offers an overview
of design solutions that can be used to further mitigate the impact of climate on pedestrians and transit users.

**Limitations of scope**

Before proceeding, it is important to identify the scope of this paper. First, the analysis in this paper is based off of conditions observed from one study area – Miami – but climate varies widely by region, city, or even by neighborhood or block. As such, while these results may be generalized to other Florida communities with similar summer climate conditions, the methodology used in the analysis was designed to be easily replicated. Additionally, this paper does not specifically address issues related to climate change. A trend toward more extreme weather conditions – particularly a rise in global temperatures – would likely lead to a variety of undesirable consequences for Florida, one of which would presumably be making outdoor activity more difficult. However, the analysis in this paper is based solely on past observed conditions.

This paper is also concerned primarily with the neighborhood and city scales. A wide body of literature is available discussing built-form responses to climate at the building and site scales, and though there is some overlap, those topics are not specifically addressed here. Finally, this paper is not presented as a one-size-fits-all solution or as the way Florida communities should be developed in a normative sense. Instead, it seeks to provide a mix of land use and design solutions that may be employed if a Florida community wishes to become more walkable or transit-oriented.
SECTION 2

Literature Review

This paper attempts to identify the appropriate policy and design solutions to address the climatic challenges of creating less auto-dependent communities in Florida. It begins with an examination of existing literature that seeks to answer three questions:

1. What does the literature say about the interface between climate and walking, biking, and transit use, particular in a tropical or subtropical context?
2. What does the literature say about the human body’s response to the climatic conditions found in tropical or subtropical areas?
3. What are the built-form responses to the climate conditions found in Florida?

What does the literature say about the interface between climate and walking, biking, and transit use, particular in a tropical or subtropical context?

A limited body of literature

Eliasson (2000) surveyed planners in southern Sweden to determine “if, why, and when” climate is considered in the planning process. The results of the survey indicate that a majority of planners saw climatic factors as being of only minor importance to their decision-making process. This sentiment is seen throughout the body of literature on walkability, active transportation, and transit use developed not just by the planning community but also by the urban design, architecture, transportation, and public health fields. While topics such as walkability are frequently discussed, the interface between these activities and climate is not a prominent theme.

[4]
Several recent literature reviews have discussed walkability and transit in detail, but have made little to no mention of climatic factors. Saelens, Sallis, and Frank (2003) synthesized planning, transportation, and public health literature covering the topic of “active transportation,” which includes walking and cycling. Climate is barely mentioned in the review, with the exception of a brief discussion on the seasonal fluctuation of rates of cycling to work or school. The authors further acknowledge that “more comprehensive investigation of nonbuilt environmental influences is clearly required” (p. 88). Kashef (2010) synthesized literature on neighborhood design and walkability from the planning, design, transportation, and environmental health fields. His comprehensive review, covering 92 sources, made no mention of climatic conditions. Ewing, Handy, Brownson, Clemente, and Winston (2006) examined “classic” urban design literature to develop a list of factors thought to influence the walkability of a community. The resulting list of 43 “perceptual qualities” did not address issues of climate or weather. In the public health realm, Besser and Dannenberg (2005) examined environmental predictors of achieving the recommended 30 minutes of daily physical activity by walking to and from public transit. But because the study was based entirely on National Household Travel Survey (NHTS) data, it included no information about climatic conditions.

**Rough measurements**

The Besser and Dannenberg study calls attention to one potential factor influencing the limitation of available literature may be the use of “coarse” measurements in previous studies. Ewing, et al. (2006) noted that previous attempts to measure how the built environment impacts travel behavior and physical activity have focused on “gross qualities” such as street connectivity and distance to parks. Typical measures for walkability and bikeability use “crude measures such as number of travel lanes and presence of marked crosswalks” (p. S223). McGinn, Evenson, Herring and Huston (2007) echo this sentiment. According to McGinn, et al., research on how environment interacts with outdoor physical activity (including walking) focuses primarily on factors such as access and sprawl. The authors note that weather and providing trees for shade “may also play an important role in an individual’s decision to be physically active,” (p. 588) but they did not elaborate further.
Research is geographically limited

Others have noted that studies on walkability and active transportation have been geographically limited. O’Hare (2006) writes, “Most of the literature and influential policy on urban walkability, and related concepts such as transit-oriented development, is produced in urban regions located in the temperate zones of the Western world” (p. 1). Most transportation and urban planning studies have been limited to small, excessively urban areas in more temperate climates, such as San Francisco, Seattle, and Portland, Oregon (Saelens, et al., 2003). O’Hare (2006) notes that the studies from such areas may be limited in their utility when applied to climates like that found in Florida: “The coastal subtropical city lacks the icy winds, snow, sleet, frost and other winter discomforts of the temperate city. The pleasant winter pedestrian conditions of the subtropical city are offset, however, by the summer challenges of heat, humidity and glare” (p. 4).

Walkability and climate

Despite its overall limitations, the literature does contain some discussion of how climate impacts walkability. Much of it comes from the public health field, which has placed a good deal of emphasis on the concept of “active transportation in recent years. Active transportation recognizes that physical activity is an inherent component of certain types of transit use, such as walking, including walking to public transit (O’Hare, 2006).

Buys and Miller (2010) conducted 24 qualitative interviews with residents of high-density dwellings in inner-city Brisbane, Australia, which has a subtropical climate. The interviews revealed a generalized perception that walking was made more difficult due to the climatic conditions of Brisbane, particularly in instances where long walks were required in hot weather. Combining walking with use of public transit also was seen as an uncomfortable proposition. One survey remarked that a “sweaty walk” to public transport stop on a humid and hot sub-tropical summer day was unbearable and “too energetic” (p. 6).
Merril, Shields, White, and Druce (2003) found that season and climate have a significant impact on the physical activity of adults in the United States. In particular, they noted that this effect was stronger in areas with climates similar to Florida’s. Counties that ranked in the bottom quartile in terms of the percentage of adults meeting physical activity recommendations were more likely to have the highest percentage of days with “moist, tropical” conditions. Work by Eves, et al. (2008) supports the notion that conditions found in subtropical summers can depress physical activity. The authors examined active transportation behavior in hot, humid Hong Kong by observing the number of individuals willing to climb stairs or walk at least half the length of a moving sidewalk system. They found that as humidity increased the willingness of individuals to climb stairs or walk decreased.

A study by McGinn, et al. (2007) produced a contradictory result. It found no agreement between perceived and objective measures of weather as a barrier to physical activity and active transportation. But the study measured walking and active transportation rates by asking survey participants how often they engaged in such activities in a typical week, whereas weather data was based on observations from a set 30-day period, calling its reliability into question. Additionally, individuals who did participate in active transportation were more likely to identify weather as a barrier.

The quarter-mile (or half-mile) walk

The notion that people are less likely to voluntarily engage in physical activity in hot, humid weather seems self-evident, but attempts to quantify the degree to which this is true do not seem to exist in the literature. O’Hare (2006) “gently” questions whether the traditional “400-meter walk” standard (or its quarter- or half-mile American analogues) is as useful in subtropical contexts as it is in temperate cities. His question appears to be the only example in the literature calling for revised walkability standards for subtropical cities. For instance, the most recent set of walkability guidelines published by the Florida Department of Transportation in 1995 advocates for a half-mile walking radius to transit stops.
Climate and transit

Literature discussing climate’s impact on public transportation is even rarer. There does not appear to be any literature that addresses the issue in an overt fashion. Buys and Miller (2010) touched on the issue in their survey of residents in the dense inner-core of Brisbane. They identified a general perception that in contrast to a “seamless” journey by car, “including walking in one’s trip, alongside using public transport, was onerous, especially in the subtropical Queensland climate” (p. 8). But while subtropical climates may be somewhat of a barrier to public transportation use, Newman and Kenworthy (2000) call the notion that such climates lead to automobile dependence a myth. The say the myth goes as follows: “Automobile dependence is inevitably induced by warm climates where people can enjoy low-density suburban lifestyles, whereas compact transit-oriented cities are mostly in cold climates” (p. 17). But Newman and Kenworthy found that no correlation exists between gasoline consumption and average annual temperature, and that many dense, transit-oriented cities such as Barcelona are in places with hot climates. They state:

“The use of transit seems also to be related to more than just climate. All our data show that it depends on how fast transit is relative to cars, how frequently it comes and how easy it is to get to ... If low-density planning and high car use are encouraged in a city, it is probably for deeper reasons than lifestyle induced by climate” (p. 18).

Some measure of climate responsiveness can be seen in transportation literature relating to elements such as bus stop shelters. Ash, Hosser-Cox, Olinger, Ovre, and Szapa (2009) examined the barriers to use of public buses in Minneapolis. The three primary factors they identified were delays, lack of comfort, and uncertainty regarding routes and stops. They did, however, note that the area’s harsh winters could make long waits painful, and they called for additional heated bus shelters. But while Ash, et al. and others recognize shelters and other structural solutions as potential solutions, the literature appears silent on to what degree these measures can influence ridership or comfort.
Saelens, et al. (2003) also noted that transportation literature tends to focus only on travel choice from a categorical perspective. Thus, the duration of exposure or the intensity of exertion associated with walking, cycling, or accessing public transportation is unknown. Besser and Dannenberg (2005) agreed, stating that few studies have examined the amount of physical activity associated with the use of transit.

**Climate and cycling**

Literature addressing the interface between climate and cycling is better developed, particularly with respect to the impact of rainfall on ridership numbers. The studies are certainly older; Nankervis (1990a) cited studies from Sweden and Denmark that were conducted as far back as the 1970s and 80s. Nankervis (1990b) also found that heavy rain and temperature were factors in deterring cycling in Melbourne, Australia, which has a temperate climate. But, he noted that results may vary by climate type, and that the impact was very small, due perhaps to the “strong commitment of the riders” (p. 92). Rose (2008) recently re-examined the issue in Melbourne and found that weather was less of a barrier for cyclists than walkers. A survey of Melbourne university students revealed that 20 percent of respondents who lived near campus listed weather as a barrier to walkability, whereas just 10 percent listed weather as a barrier to cycling.

Nosal (2010) examined bike ridership in Montreal, measuring traffic and weather conditions (temperature precipitation, wind speed and humidity) at five collector points. The results indicated that ridership increased until the temperature reached 28 degrees Celsius, while humidity tended to decreased ridership. Moderate-to-heavy rainfall was found to decrease ridership and have a lagging effect throughout the day. Precipitation in the previous three hours decreased ridership in the current hour by as much as 36 percent, while precipitation in the morning decreased total daily ridership by 13 to 15 percent.
What does the literature say about human physiological responses and “thermal comfort” in subtropical/tropical climatic conditions?

Utilizing a form of transportation other than a private automobile almost certainly entails at least some outdoor physical activity. But due to factors such as very high heat and humidity, outdoor physical activity has different implications in Florida than it does in other more temperate parts of the United States. More detailed information about the Florida climate is available later in this paper, but in general the heat, humidity, intense sunshine, and frequent heavy rains can make outdoor activity difficult on many occasions. For instance, Sheffield-Moore, et al. (1997), found that physical activity in humid conditions leads to increased ratings of perceived exertion and discomfort relative to the same activity at the same temperature with lower humidity. Eves, et al. (2008) called referred to this as increased “punishment” and stated that high humidity is a barrier to removing heat from the human body. The Sheffield-Moore study was conducted indoors did not examine the impact of the sun, but Brown and Banister (1985) found that solar radiation significantly increased heart rate and cardiovascular strain.

Thermal comfort – definitions and approaches

The interaction between environmental conditions and the human body (and mind) is most commonly examined through the prism of “thermal comfort.” The concept of thermal comfort has been around for decades. According to Höppe (2002), it does not have a single definition but instead is defined through three approaches: Psychological, thermophysiological, and human heat balance.

Psychological approaches: In its 55P Standard, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) describes thermal comfort as “that condition of mind that expresses satisfaction with the thermal environment” (p. 7). This definition is perhaps the most common given for thermal comfort. Höppe (2002) notes that this
definition is inherently subjective and may vary widely among individuals, but that psychological aspects nevertheless play an important role in determining comfort.

**Thermophysiological approaches:** Thermophysiological approaches are dominated by mean skin temperature and deal with the minimum rate at which nervous signals travel from thermal receptors in the skin to the hypothalamus (Mayer, 1993; Höppe, 2002).

**Human heat balance approaches:** In human heat balance approaches to thermal comfort, comfort is achieved when heat flows two and from the body are balanced and skin temperatures and sweat rates are within an acceptable range. Both of these factors are dependent on the metabolism of the body, which is dictated by an individual’s activity level. As with thermophysiological approaches, human heat balance models are also heavily influenced by mean skin temperature (Höppe, 2002).

Djongyang, Tchinda and Njomo (2010) add to this list with a fourth category: Adaptive approaches developed from field studies intended to analyze the real acceptability of thermal environment, which “strongly depends on the context, the behavior of the occupants, and their expectations” (p. 2630). This line of research is seemingly promising with respect to climate situations on the margins, but due to logistical research limitations, this paper focuses only on what Djongyang, Tchinda and Njomo call the “rational heat-based” approach.

**The six basic human environmental parameters**

Human thermal comfort is generally dictated by six primary factors:

- Air temperature
- Radiant temperature
- Air speed
- Humidity
- Metabolic rate
- Clothing insulation
These six criteria were first identified by MacPherson in 1962 (Djongyang, Tchinda & Njomo, 2010) and have since been repeated by a variety of sources (ASHRAE Standard 55P, Höppe, 1999; Havenith, 2002; Skinner & de Dear, 2001; Spagnolo & de Dear, 2003). The first four factors are environmental while the latter two are behavioral. Air temperature, air speed and humidity are fairly self-explanatory climatic measures. A brief explanation of the less intuitive radiant temperature, metabolic rate, and clothing insulation factors follows.

**Radiant temperature:** Refers to the radiant heat impacting the body. In indoor environments, this is measured by calculating the temperature of the surrounding walls weighted by the proportion of an individual’s body surface facing each area. In outdoor environments, this relationship becomes more complex due to the direct, diffuse, and shortwave radiation from the sun (Spagnolo & de Dear, 2003). Radiant temperature is often referred to as the “mean radiant temperature,” which ASHRAE (p. 23) defines as “the temperature of a uniform, black enclosure that exchanges the same amount of thermal radiation with an occupant as the actual enclosure.” In outdoor environments, the “actual enclosure” portion can be replaced with “actual environment.”

**Metabolic rate:** Is defined as, “the reflection of the cellular life that results from the consumption of oxygen (O2) and rejection of carbon dioxide (CO2). In the steady state, the quantity of metabolic heat produced is deduced from the consumption of oxygen, calculated from the rate of ventilated air and the difference of concentration between the inspired and expired air” (Candas, 2000 as cited in Djongyang, Tchinda & Njomo, 2010). Metabolic rates are derived from established values given in the thermal comfort literature.

**Clothing insulation:** Refers to the total, effective, intrinsic, or resulting insulation provided to an individual by clothing. A full explanation of what these values mean or how they are calculated is beyond the scope of this paper, but clothing insulation can be derived from the ISO 9220 standard table available in ASHRAE 55P (Djongyang, Tchinda & Njomo, 2010).
An overview of prominent comfort indices and their components

This subsection contains a brief overview of some thermal comfort indices and components that are widely discussed in the literature. It is by no means a comprehensive list.

**Fanger’s PMV and PPD:** Fanger conducted controlled experiments to develop an equation that described thermal comfort as “the imbalance between the actual heat flow from the body in a given thermal environment and the heat flow required for optimum (i.e. neutral) comfort for a given activity” (Djongyang, Tchinda & Njomo, 2010, p. 2628). This equation became the basis for the “Predicted Mean Vote” scale, which ranks comfort on a seven-point scale. The PMV index was then incorporated into the “Predicted Percentage Dissatisfied” scale, which determines the percentage of people likely to feel a sensation outside the middle three rungs of the PMV scale – slightly cold, neutral, and slightly warm (Djongyang, Tchinda & Njomo, 2010).

**PET:** The Physiological Equivalent Temperature developed by Höppe (1999) is based on the Munich Energy balance Model for Individuals (MEMI). It is defined as “the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. This way PET enables a layperson to compare the integral effects of complex thermal conditions outside with his or her own experience indoors” (Höppe, 1999, p. 71). But because PET is a climate index designed to assess the thermal environment, it does not take into account clothing and activity level (Spagnolo & de Dear, 2003).

**UTCI:** Another recently developed climate index is the Universal Thermal Climate Index. Developed over the past decade by a cooperative of bioclimatologists with European Union funding, the UTCI is a standardized tool designed to assess outdoor thermal conditions across all conditions (Jendritzky, 2009). Though the index is backed by complex calculations, the model requires only the four main environmental variables – air temperature, radiant temperature, humidity, and wind velocity – to calculate.
The Gagge or Pierce Two-Node Model: The Gagge Two-Node Model (also sometimes referred to as the Pierce model after the laboratory in which it was conceived) divides the body into two concentric cylinders – an inner body core with a temperature of 37.1 degrees Celsius and an outer skin layer with a temperature of 33.1 degrees Celsius (Djongyang, Tchinda & Njomo, 2010).

SET: The Standard Effective Temperature index developed by Gagge, Nishi and Gonzalez (1972) is based on Gagge’s two-node model and defined as “the equivalent dry bulb temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for activity concerned, would have the same heat stress (skin temperature, Tsk) and thermo-regulatory strain (skin wettedness, w) as in the actual test environment” (Gagge, Fobelets & Berglund, 1986). Pickup & de Dear (1999) adapted the index for the outdoors under the moniker “OUT_SET.”

Skin wettedness as a measure of comfort

Though indexes such as PMV and SET take skin wettedness caused by sweat secretion into account, Fukazawa & Havenith (2009) and Djongyang, Tchinda & Njomo (2010) have noted that in warm environments, skin wettedness is strongly correlated with discomfort than factors such as skin temperature. Gagge developed the measurement of skin wettedness over the body (w) in 1937, and Winslow, Herrington, and Gagge (1939) suggested the measure contributed to thermal discomfort. Skin wettedness is now recognized as one of the most convenient indices to predict thermal comfort level for humans in warm conditions (Havenith, 2002; Fukuzawa & Havenith, 2009).
Indoor vs. outdoor thermal comfort

While indoor thermal comfort has been studied in depth for many decades due to the efforts of the air conditioning industry and ASHRAE (Skinner & de Dear, 2003), outdoor studies have been less common. Spagnolo and de Dear (2003) provide four reasons why:

1. People in developed countries where most research has been conducted to date spend a larger proportion of their life indoors than out.
2. In work environments, thermal comfort is assumed to be directly related to productivity, so it is deemed economically important for employers to define and provide employees’ preferred thermal conditions.
3. The outdoor thermal environment is considerably more difficult to engineer and control than the indoor counterpart.
4. Ownership of, and responsibility for, many outdoor spaces are not so clearly defined as indoor built environments (p. 721)

Outdoor studies

Outdoor studies that do exist have traditionally been predicated on the assumption that indoor models will work outside, but research has shown that this is not necessarily the case (Spagnolo & de Dear, 2003; Ahmed 2003). Spagnolo and de Dear (2003) identified the three areas on which outdoor thermal comfort research has tended to focus:

“1) Modifying the microclimates of semi-outdoor locations, or outdoor locations which have been modified in some way to moderate the full impact of the outdoor environment
2) Climate and tourism
3) The thermal comfort of pedestrians.” (p. 722)
Of those categories, the latter is particularly relevant to this study. According to Spagnolo and de Dear (2003), pedestrian activity in urban areas tends to be concentrated around buildings, which serve to shade pedestrians from direct solar radiation and deflect or channel wind flow. The authors also cite studies by Murakami, et al. (1999) and Nikolopoulos, Baker and Steemers (2001) as prominent examples of pedestrian thermal comfort studies. Murakami, et al. looked at the effects of vegetation and wind flow around buildings. They found that plant canopies can reduce ground temperature by 2 to 4 degrees Celsius and SET by up to 7.5 degrees Celsius. Conversely, negligible wind conditions can increase SET by 9 to 12 degrees Celsius. Nikolopoulos, Baker and Steemers assumed that people will choose places to sit based on comfort. They found that human responses to microclimate may be subconscious, and that modeling outdoor thermal comfort is more complex than modeling the physiological effects.

Other recent research has attempted to more thoroughly develop thermal comfort standards for outdoor areas. Cheng, et al. (2010), recognized an increase in research into outdoor thermal comfort has in the early part of the 21st century. One such recent study was conducted by Monteiro and Allucci (2008; 2009), who examined 22 predictive models to develop a thermal comfort index for subtropical environments, but their index, the Temperature of Equivalent Perception, does not factor in behavioral variables such as clothing and metabolic heat.

*Psychological factors play an important role*

As mentioned by Nikolopoulos, Baker and Steemers (2001) and Ahmed (2003), perception plays a key role in how people perceive weather and climate. Höppe (2002) notes that when outdoors, people may be comfortable in climatic conditions that would be considered unacceptably hot by indoor standards. This is consistent with the view that when engaging in certain outdoor activities such as going to the beach, people may voluntarily expose themselves to “objectively adverse conditions” (Spagnolo & de Dear, 2003).
Spagnolo and de Dear (2003) also state that, “psychological dimensions appear to play an important role in the perception of the thermal environment outdoors, including the range of effects, expectations, cognition and perceptual allisthesia” (p. 737). Allisthesia is a psychological mechanism that can help explain the differences in sensations in different seasons. The concept can best be explained as follows: “If we are feeling cold then anything that warms us will feel pleasant, even if the same stimulus will cause overheating in the long-term” (p. 737). Ahmed (2003) further noted that “a person’s comfort preference, keeping within a range, continually adjusts to ambient situation” (p. 109).

*Differences by gender*

Temperature perceptions may also differ by gender. Eves, et al. (2008) also noted that males are more susceptible to hot, humid climate conditions than females. Women have a larger surface area per unit of body mass, allowing for greater heat loss through “radiant mechanisms.” Women also tend to sweat less and start to sweat at higher skin and core temperatures than do men for comparable heat-exercise loads.

*Steady-state limitations of models*

Models such as PMV/PPD, PET and SET are based on steady-state heat models that assume that climate conditions will not change much and that individuals will remain in them for a long time. According to Höppe (2002), these steady-state models are not appropriate for most outdoor conditions, where people tend to remain outdoors for shorter amounts of time (less than 30 minutes) and where conditions are less stable. As an example, Höppe describes a situation in which an individual is walking through areas that are both shaded an unshaded. This is a frequent occurrence in real-world environments and is certainly relevant to this paper. Höppe argues that such situations require a non-steady state or “transient” comfort index, for which there was no accepted international standard as of 2002. However, Lin and Deng (2008) disagree with this assessment, stating that while the PMV and PPD models may only be used in
steady-state situations, the two-node model (and indices based on it) may be used to predict transient comfort.

**What are the built-form responses to the climate conditions found in Florida?**

Though designing cities as a response to local climatic conditions is a concept that has been around since antiquity, technological advances in the 20th century led to a built form in Florida that largely ignored the natural environment (Abbate, 2005). But in recent years there has been resurgence in interest in climate-responsive design. Much of this renewed emphasis has been focused on issues of energy use and environmental sustainability, through vehicles such as the U.S. Green Building Council’s “Leadership in Energy and Environmental Design (LEED)” program. Though there is some overlap between these responses and the issue at hand, this section generally does not include literature developed for building-scale projects. Instead, it focuses on built-form responses suitable for the climate conditions typically found in Florida. A thorough discussion of these conditions is included later in this paper, but for the purposes of this literature review, the climate conditions will be assumed to be a subtropical climate with hot, humid summers characterized by periods of heavy rainfall and intense sunlight.

**The built environment shaping climate**

The interaction between climate and the built environment is a two-way relationship -- climate impacts urban development which in turn creates a “microclimate” or a small area that has different climatic conditions than its surroundings. Bekele (2008) states that urban form heavily influences microclimates based on the following factors:

- An area’s basic climate conditions
- Street orientation and width
- Distribution of “mass,” or building density and bulk within a city
- Shading
- Solar heat
- Anthropogenic heat
- Vegetation

Cities also tend to become “urban heat islands” that are warmer than their surroundings. According to Woodlum (1964), this is due to a combination of urban-specific factors that cause cities to experience less evaporative cooling and, as a result, higher temperatures (as cited in Rainham & Smoyer-Tomic). Due to the urban heat island phenomenon, cities may experience temperatures that are 3 to 6 degrees Celsius higher than their surroundings while also experiencing more intense and frequent rainstorms (Rainham & Smoyer-Tomic).

**Built-form responses: Promoting ventilation through building and street orientation**

According to Bekele, Jones and Rajamani (2008) one of the two main objectives for designing a city in a hot and humid climate is to promote ventilation of streets. The authors conducted wind-tunnel tests to determine the optimal orientation and placement of buildings to promote air circulation and breezes in urban areas. From this research, they developed three key recommendations:

- Orient buildings at a 45 degree angle to prevailing winds: Orienting buildings parallel to prevailing winds puts most buildings not directly facing the incoming winds under “negative pressure,” creating a channeling effect that allows for less air circulation around buildings. A 45-degree orientation creates both positive and negative air pressures, allowing breezes to be carried around buildings and promoting circulation at all street levels.
- Avoid placing tall buildings between prevailing winds and the rest of the city: High-rise towers can block prevailing winds before they can move into the area.
When placed directly in the line of prevailing winds, tall buildings create air movement on their windward sides while causing decreased air movement on their leeward sides due to a “shielding effect.”

- Use relatively narrow streets when possible: To promote air circulation, street-to-canyon ratios should be 0.7 or less. This ratio tends to hold up in all areas except those dominated by high-rise buildings, which create different patterns.

Bekele, et al. and Goncalves and Duarte (2008) also recommend varying building heights to further promote circulation. Goncalves and Duarte write, “It was observed that for (the) subtropical climate of Sao Paulo, hybrid aspect of the urban fabric, including building spacing and heights, offered advantages with respect to air flow around buildings and the consequent dispersion of air pollution” (p. 8).

Closely tied to the orientation of buildings is the orientation of streets. Richards states, “The appropriate orientation of streets creates building sites that allow for better energy efficiency and good subtropical design of the various housing types and densities in the neighborhoods. Luxmoore, et al. (2004) states that street layouts should allow for favorable orientation of houses and enough room for vegetation on lots. Bekele, et al. again recommends locating buildings at 45 degrees to prevailing winds for the best airflow results.

**Built-form responses: Promoting shading through vegetation**

The second main objective for urban design in hot humid climates identified by Bekele, et al. (2008) is providing “maximum shade” where it is required. The primary technique advocated in available literature is using natural vegetation to provide shade (Luxmoore, Jayasinghe & Mahendran, 2004; Abbate, 2005; Goncalves & Duarte, 2008). Richards states that providing shade via streetscapes with substantial tree and vegetation cover will lower ambient air temperature. This effect can be dramatic. Makamuri, Ooka, Mochida, Yoshida and Kim (1999) found that plant canopies can reduce ground surface temperatures by 2 to 4 degrees Celsius, while Standard Effective Temperature (SET) can be lowered by up to 7.5 degrees
Celsius. Lin, Matzarakis and Hwang (2010) also found that the amount of shading in an area significantly affects outdoor thermal environments.

The 2006 Brisbane City Center Master Plan suggests maximizing the amount of natural shade in public spaces, streetscapes, and landscapes with the goal of filtering or blocking Ultraviolet Radiation (UVR). Providing shade with natural vegetation has a number of other benefits such as directing breezes (Abbate, 2005) and providing shade in the summer while allowing “dappled” light and direct sun exposure in the winter (Brisbane City Centre Master Plan, 2006; Goncalves & Duarte, 2008). Positioning of trees is important. Goncalves and Duarte conducted a “solar geometry analysis,” or a superposition of shadows on a scale model of a city to inform the location of trees. Luxmoore, et al. (2004) also points out that the provision of vegetation in cities is most commonly an exercise in “re-vegetation,” or replacing natural plant-life lost due to urban development.

**Built-form responses: Promoting shading and shelter through built structures**

In addition to vegetation, the built environment can itself be a source of shading. Richards, for instance, states that parks and public spaces should have mature shade trees and man-made shade structures. Buildings are the most obvious man-made source of shade, but they are just one solution. Available literature advocates various structures such as arcades, awnings, breezeways, canopies, overhangs, and verandas that can provide shading benefits in addition to offering pedestrians shelter from the frequently heavy rains that are typical to Florida. Much of this literature comes from Australia, where the urban form has embraced such methods for centuries (Brisbin & Raxworthy, 2008; O’Hare, 2006). O’Hare notes that traditional Australian main street was lined with awnings to provide sun shading, while Brisbin and Raxworthy discuss the “veranda” in detail. Verandas are generally partially-enclosed spaces that have a roof and are supported on one side by a building and on the other by columns. These areas form the boundary between interior and exterior space. Verandas are particularly popular in Queensland, Australia and they are “conceptually and environmentally appropriate
to sub-tropical cities” (p. 8). Brisbane, located in Queensland, calls for arcade cover along all pedestrian routes in its City Centre Master Plan:

“Adequate shelter from sun and rain is critical. People should be able to move comfortably around the city centre in all but the most severe weather conditions. Additional shelter can be provided, although the extensive network of arcades already offers good protection. Arcades further reinforce the city’s permeability and create breaks and links between blocks” (p. 61).

O’Hare (2006) proposes that cities place sidewalk awnings at 100- to 200-meter intervals along walking routes to provide pedestrians with cover from passing rain. For Broward County, Abbate (2005) proposes a continuous network of deep overhangs and canopies surrounding buildings.

**Built-form responses: Designing compact, walkable communities**

A large amount of planning and urban design literature exists in support of creating compact walkable communities with a mixture of uses, and these concepts are central pillars of the New Urbanism movement (Congress for the New Urbanism, 1996). The literature applying these concepts to the subtropical context is less well-developed. Richards offers thorough recommendations in the “Subtropical Neighbourhood Design” manual prepared for the Centre for Subtropical Design in Australia. The manual suggests:

- Smaller street blocks with dimensions of 70 to 120 meters deep and 150 to 220 meters long to allow for walkability and increased connectivity
- Neighborhoods built around centers that are no more than a five-minute or 400-meter walk from residences
- An interconnected network of streets and sidewalks
- Neighborhoods that provide a high-density mixture of housing types
• Neighborhoods defined by local and regional landscape elements (such as rivers and coastlines), that aggregate to form cities and towns

Many of these suggestions are similar to those found throughout planning literature. However, density takes on a different and perhaps more important role in the subtropical context. Richards states that buildings should be “broken down in mass and scale” and configured as collections of buildings that allow for ventilation. Higher-density dwellings also take on added significance because they use up less land on a site, allowing for greater use of vegetation (Richards).

In addition to block layout and densities, catering to the needs of pedestrians may also help create a more walkable built environment. O’Hare (2006) recommends providing free drinking water along walking routes to promote health and comfort for pedestrians and timing traffic signals at intersections to be more attentive to cut down pedestrian wait times in harsh weather conditions. He also recommends minimizing the use of “high-glare” pavement that can be harsh to look at in sunny conditions and dark pavement that stores and radiates heat. He suggests mid-tone pavement provides the best results in the subtropics (O’Hare, 2006).

Synthesis of literature

The topics discussed in this paper do not seem to be well-addressed in literature. Most studies and literature reviews that focus on walking for transportation or public transit use do not address climate or do so only in passing. Research on walkability and active transportation has typically been conducted in temperate climate zones in the Western world, and these studies have frequently relied on coarse measurements to determine how the built environment impacts travel behavior. Studies that have directly addressed the impact of climate on walking have found that climate and seasonality have a significant impact, especially in instances of high heat and humidity. Literature linking transit use and climate seems to be even less well-developed. Research for this paper turned up no instances where the impact of heat and humidity on transit ridership was studied.
Similarly, literature addressing outdoor thermal comfort is somewhat limited, but there has been an uptick in interest in the topic in the past decade. Measures of thermal comfort are divided into three general categories – psychological, thermophysiological, and human heat balance approaches. Models that are based on the human heat balance equations are perhaps most well-suited to deal with the topic at hand because they are dependent on the body’s metabolism, which will necessarily be higher when an individual is walking than when sitting or standing. In addition to metabolism, five other main “biometeorological” factors dictate human heat balance. Four are climate variables – air temperature, mean radiant temperature, relative humidity and air velocity – while the fifth, clothing characteristics, is behavioral.

Unfortunately for the purposes of this paper, most thermal comfort models and their supporting literature were developed for steady-state indoor situations where an individual remains in a constant climate-controlled environment for a long period of time. But these conditions do not adequately represent the experience of a pedestrian or transit user, who is likely to encounter a range of microclimates in a much shorter period – minutes as opposed to hours – than someone working or sleeping indoors. Outdoor studies of thermal comfort have shown that psychological factors such as expectations play a key role in actually determining comfort, and the research for this paper found no universally accepted model to objectively evaluate outdoor thermal comfort in transient conditions.

In contrast to the limited bodies of literature related to outdoor thermal comfort and the interaction between climate and transit, there is an abundance of literature addressing the impact of the built and natural forms on outdoor environmental conditions. In hot, humid climates, buildings and vegetation can be used to provide shade that substantially reduces both ambient and radiant temperatures in addition to providing potential shelter from rainfall. The height, bulk and orientation of built structures can also be manipulated to optimize airflow around buildings, a factor which can be crucial to maintaining comfort in the most extreme summer conditions in Florida. Finally, density and connectivity also play an important role in allowing individuals to maintain comfort outdoors because they can reduce the total distance one needs to walk to access a transit stop or a destination.
In summary, the impact of climate on the comfort of pedestrian and transit users has not been extensively studied. However, thermal comfort literature identifies six key biometeorological variables that can be used to determine how far an individual might be able to walk in an outdoor setting before experiencing discomfort. Four of these variables have to do with environmental conditions, and design literature has shown how three of these – air temperature, mean radiant temperature, and wind speed – can be modified to make outdoor environments in hot, humid climates more favorable for human activity. Additionally, literature has identified increasing density and connectivity as a means to promote the kind of walkable, transit-oriented environments that are at the center of this paper.
Florida’s climate is one of its greatest assets, but during the warmer months of the year, the weather can make outdoor activity difficult. For six months out of the year, temperatures are capable of topping 90 degrees Fahrenheit with relative humidity in excess of 50 percent. Those hot summer months coincide with the rainy season in which thunderstorms deliver the majority of the state’s annual rainfall, which in most regions of the state exceeds 50 inches per year (Black, 1993). According to the Florida Department of Transportation and Department of Community Affairs, these climate extremes are often cited as an obstacle to encourage walking and transit use. The 2010 draft report “A Framework for TOD in Florida,” puts the problem succinctly:

“In Florida, TODs not only need to consider the land use and urban design elements of density, intensity and mix of uses, but given the extreme climate conditions of heat and thunderstorms, the quality of the walking environment is another major design element to creating successful TODs. While the average distances for walking in moderate climates maybe 5-10 minutes, in Florida this time could be cut in half in weather extremes.” (p. 2)

It is therefore the goal of this paper to examine just how much climate conditions impact the distance an individual can walk and to identify policy and design solutions to mitigate these challenges to the extent possible. To develop these recommendations, we must take the following broadly defined steps:

1. Identify a study area
2. Assess the climate averages for air temperature, humidity, and wind speed in the study area, focusing in particular on the hours when most trips are made
3. Estimate averages for mean radiant temperature at the desired hours
4. Select a criteria that – to the extent possible – objectively evaluates human physiological responses and thermal comfort in the identified weather conditions

5. Apply the findings about physiological responses and thermal comfort findings to real-world situations in order to formulate policy goals

This paper is subject to time and research constraints that limit its scope to one city and preclude the possibility of collecting data or conducting surveys in the field. To make the findings herein more broadly applicable, however, the methodology in this paper is presented as a method to assess the impact of climatic conditions on pedestrians and transit users by using only publicly available data and software.

Summary of methodology

Below is an outline of the methodology described in this section. Each step is explained in detail below or in Appendix A where noted:

- Identified the study area (Miami) and the time of year when outdoor activity is most difficult due to climatic conditions (July)
- Determined the four climate-based biometeorology inputs:
  - Used NCDC data to determine July averages for air temperature, relative humidity, and wind speed for three times of day – 8 a.m., 1 p.m., and 5 p.m.
  - Used ENVI-met software to estimate mean radiant temperature values for two sample urban environments
- Applied vegetation and architectural treatment scenarios to the two sample environments in ENVI-met and recorded changes in estimated MRT values
- Determined the average MRT values for the “sidewalk” areas of each treatment environment at each time of day and with each treatment scenario
• Used values established in literature to determine the two behavioral biometeorology inputs:
  o Estimated a clothing value (clo) for appropriate summer “business casual” for a male
  o Estimated a metabolic rate for an individual walking at a speed of 1.34 m/s\(^{-1}\), or 80.4 meters per minute
• Identified the “test subject,” in this case the average American male, and determined the body surface area of the subject
• (Appendix A) Used Richard de Dear’s Human Heat Balance calculator do calculate minute-by-minute values for skin temperature (\(T_{sk}\)) and evaporative heat loss through regulatory sweating (\(q_{sw}\)) for each combination of urban environment, treatment, and time of day
  o Inputs were the six biometeorology variables and the subject body surface area to calculate
• (Appendix A) Used the partitional calorimetry spreadsheet developed by Atkins and Thompson to determine the maximal evaporative capacity of the environment (\(q_{emax}\)) for each combination of urban environment, treatment, and time of day
  o The radiative heat transfer coefficient (\(h_r\)) and the partial water vapor pressure of ambient air (\(P_a\) in mmHg) were calculated using the Visual Basic interface in the EnvironData tab of the spreadsheet
  o The saturated water vapor pressure of the skin surface (\(P_s\)) was determined using skin temperature (\(T_{sk}\)) values provided by de Dear’s calculator
  o All other calculations were made using equations 3-12
• (Appendix A) Calculated skin wettedness (w) of the test subject in each environment, treatment, and time combination using equation 1 and the \(q_{sw}\) and \(q_{emax}\) values derived through the above methods
  o Values were calculated for each minute of a 30-minute period
• These values were then compared to the 0.33 comfort requirement threshold and the 0.5 thermal constraint threshold

Determining a study area

For the purposes of this analysis, it was necessary to select a single study area on which to focus. I selected the City of Miami for three primary reasons: It is one of the densest places in Florida and contains a wide mix of population densities within one jurisdiction, it has Florida’s most diverse and extensive transit system, and it recently adopted a new form-based land use code, Miami 21, that contains a range of zoning options and design regulations that are potentially related to this topic. Each of these selection criteria is briefly discussed below, followed by a brief overview of the climate in Miami.

Miami population and density characteristics

The City of Miami is the second largest city in Florida by population, with a population of 362,470 as of the 2000 U.S. Census and an estimated 2006 population of 404,048. Incorporated in 1896, the city is comprised of 35.67 square miles of land area and 19.59 square miles of water (U.S. Census Bureau, 2009; City of Miami, 2011). It is located just west of the Atlantic Ocean and North of Biscayne Bay in Southeast Florida. According to 2000 Census figures, it has a population density of 10,160.9 persons and 4,159.7 housing units per square mile, or 15.87 persons and 6.5 housing units per acre. Miami is one of the densest communities in the South Florida, the densest region in the state. It is one of just 10 U.S. Census Designated Places in Florida with a population density in excess of 10,000 persons per acre. All of these places lie in are located in South Florida – eight in Miami-Dade County, home to the city of Miami, and two in Broward County immediately to the north.
Population densities vary widely within the city itself, however. According to GIS analysis of 2000 Census data, 32 of the city’s 312 Census Block Groups have densities in excess of 35 persons per acre. These dense areas are located throughout the city in neighborhoods such as Allapattah Brickell, Flagami, Liberty City, Little Havana, and Omni. However, of Block Groups with at least 100 residents, 72 have densities lower than 10 persons per acre, and 29 average fewer than five persons per acre. These neighborhoods are mostly concentrated along the city’s waterfront in places such as Coconut Grove and the Upper East Side.
Miami’s Transit System

The City of Miami is serviced by Miami-Dade Transit, a department of the Miami-Dade County government. Founded in 1960 and originally known as the Metropolitan Transit Authority, MDT is the 14th largest public transit system in the United States and the largest system in Florida (Miami-Dade County, 2010a; Miami-Dade County, 2010b). The system consists of three principle “main-line” components:

- Metrobus, a bus system servicing most areas of the county
- Metrorail, a 22.6-mile electrically powered, elevated heavy rail system with 22 stations between Medley, Fla. in the north and Kendall, Fla. in the south
- Metromover, a 4.4-mile elevated people mover with nine stops that connects the central business districts of the City of Miami –Downtown, Brickell, and Omni

Together Metrobus, Metrorail and Metromover record more than 326,000 boardings on a typical weekday (Miami-Dade-County, 2010a). Service characteristics, including operating hours, headways, and peak vehicle requirements are given in Table 3.1.
Table 3.1: MDT Service Characteristics by Transit Mode, 2009

<table>
<thead>
<tr>
<th>System Characteristics</th>
<th>Metrobus</th>
<th>Metrorail</th>
<th>Metromover</th>
<th>STS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Hours</td>
<td>24 hours</td>
<td>5:00am - 12:00am</td>
<td>5:00am - 12:20am</td>
<td>24 hours</td>
</tr>
<tr>
<td>Number of Routes</td>
<td>83 ³</td>
<td>1</td>
<td>3</td>
<td>Demand Response</td>
</tr>
<tr>
<td>No. of Stations/ Stops</td>
<td>8,943</td>
<td>22</td>
<td>20</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Headways</td>
<td>7 ¼ - 60 minutes</td>
<td>7 ¼ minutes</td>
<td>1 ½ - 3 minutes</td>
<td>(Pick up +/- 30 minutes of scheduled time)</td>
</tr>
<tr>
<td>Midday Headways</td>
<td>12 - 60 minutes</td>
<td>15 minutes</td>
<td>1 ½ - 3 minutes</td>
<td></td>
</tr>
<tr>
<td>Weekend Headways</td>
<td>12 - 60 minutes</td>
<td>30 minutes</td>
<td>1 ½ - 3 minutes</td>
<td></td>
</tr>
<tr>
<td>Routes Miles</td>
<td>2,615 round trip miles</td>
<td>22.4 miles</td>
<td>4.4 miles</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak Vehicle Requirements</td>
<td>680</td>
<td>84</td>
<td>21</td>
<td>276</td>
</tr>
<tr>
<td>Total Fleet Size</td>
<td>818</td>
<td>136</td>
<td>29</td>
<td>355 (176 sedans, 70 vans, 109 lift equipped vans)</td>
</tr>
<tr>
<td>(Section 15 Report)</td>
<td>(741 full-size/ 75 minibus)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual Revenue Miles</td>
<td>29,189,472</td>
<td>8,743,641</td>
<td>1,126,255</td>
<td>13,084,419</td>
</tr>
<tr>
<td>Annual Boardings</td>
<td>75,808,000</td>
<td>18,244,476</td>
<td>8,100,144</td>
<td>1,491,924</td>
</tr>
<tr>
<td>Park-Ride Spaces</td>
<td>2,671</td>
<td>9,655</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Annual Operating Expenses</td>
<td>$334,727,320</td>
<td>$78,399,299</td>
<td>$23,265,217</td>
<td>$44,522,040</td>
</tr>
<tr>
<td>Annual Operating Revenues</td>
<td>$78,370,756</td>
<td>$15,646,396</td>
<td>$0</td>
<td>$6,958,586</td>
</tr>
<tr>
<td>Annual Revenues (Other)</td>
<td>$8,052,752</td>
<td>$0</td>
<td>$0</td>
<td>N/A</td>
</tr>
<tr>
<td>Base Fare</td>
<td>$2.00</td>
<td>$2.00</td>
<td>Free</td>
<td>$3.00</td>
</tr>
</tbody>
</table>

*Source: National Transit Database, Miami-Dade Transit, April 2010*

**Miami’s Code**

On May 20, 2010, Miami became the first major city in the United States to put a “form-based code” into effect (Miami21.org; American Planning Association, 2011). Form-based codes, “address the relationship between building facades and the public realm, the form and mass of buildings in relation to one another, transitions between different types and sizes of buildings, and the scale and types of streets and blocks” (American Planning Association, 2011). The code, developed primarily by the Miami-based consulting firm Duany Plater-Zyberk & Company (DPZs), is heavily influenced by tenets of New Urbanism and Smart Growth (Miami21.org).

The code, which completely replaced Miami’s previous zoning and land-use regulations, is generally thought to be more pedestrian friendly in a city that up until this point has been
built primarily around the car (Viglucci and Rabin, 2009). It places most of the city into one of four general zones on a transect that gradually reduces densities and intensity of uses from the urban core to rural and natural landscapes (Figure 3.2). Article 3 of the nine-article code outlines provisions that are general to all zones while Article 5 addresses provisions that are specific to zones. Articles 8 outlines standards for sidewalks and public thoroughfares, while Article 9 prescribes landscape requirements, including the provision of street trees. In addition to its unique status as a form-based code, Miami21 is somewhat unique in that it contains provisions designed to lower the Urban Heat Island effect, including requirements that certain buildings have roofs that are light-colored, high albedo or planted surfaces.

**Figure 3.2: The Miami 21 Transect**

![The Miami 21 Transect](source: City of Miami)

**Climatic conditions in Miami**

While most of Florida lies within the far southern reaches of the “humid subtropical zone” of the Northern Hemisphere, South Florida and Miami fall within what is known as a “tropical savanna region” that shares its climate with most of the Caribbean islands. The humid subtropical zone is characterized by long, hot and humid summers with relatively mild, wet winters (National Climatic Data Center). In South Florida, summer is again characterized by hot, humid conditions with frequent showers and thunderstorms, but winters tend to be dry (National Weather Service, 2009).
During the summer months in Miami, which generally runs from mid-April to mid-October, daily maximum temperatures average in the upper-80s (Fahrenheit) while average minimums fall within the mid-70s. Dew-point temperatures are in the low- to mid-70s on average, indicating a relatively high level of moisture. Convection in the form of showers and thunderstorms occurs on an almost daily basis, generally occurring as late-night and morning showers in coastal areas and afternoon thunderstorms over interior areas (National Weather Service, 2009). These conditions – high heat and humidity with frequent rain events – act as a barrier to walking and transportation use (FDOT & DCA, 2010).

**Developing the climate variables**

This portion of the paper describes how the environmental inputs that determine human thermal comfort were gathered or estimated. This process can be briefly summarized as:

- Gathering hourly climate data for air temperature, humidity, and wind speed for the month of July recorded over 20 years at a weather station in Miami
- Filtering the data to determine average readings for three times during the day – 8 a.m., 1 p.m. and 5 p.m.
- Converting the data into appropriate units for thermal comfort metrics
- Estimating mean radiant temperature values using the ENVI-met software program

The process that went in to each of these steps is now described in greater detail below. First, however, a brief refresher on why these variables are important is provided.

*The “biometeorological” variables and their impact on comfort*

As outlined in Section 2, four environmental variables have an impact on the heat exchange between a human subject and his or her environment. They are air temperature,
mean radiant temperature, relative humidity, and wind speed. A detailed scientific explanation of how these “biometeorological” variables impact thermal comfort is beyond the scope of this paper, but much of the process can be understood intuitively. Perhaps the easiest to understand is air temperature, which is how we typically conceptualize “hot” or “cold” days. The body gains heat as it comes into contact with hot air and loses heat as it comes into contact with cold air (Canadian Centre for Occupational Health and Safety, 2008). This process is known as convection. In hot environments, a breeze will often feel pleasant. One of the reasons for this is that increasing air velocity can help the body lose heat through convection. It also helps the body lose heat through evaporation of sweat from the skin. However, if humidity is high as is often the case in Florida, sweat does not evaporate as efficiently, causing further discomfort.

The fourth biometeorological variable, mean radiant temperature, has a complicated scientific definition, but it is relatively easy to understand. MRT is a synthetic measure of the biometeorological influences of long- and short-wave radiation fluxes. In technical terms, it is defined as “the uniform temperature of a hypothetical spherical surface surrounding the subject (emissivity $\varepsilon=1$) that would result in the same net radiation energy exchange with the subject as the actual, complex radiative environment” (Matzarakis, Rutz & Mayer, 2006). In plain terms, this is the concept that it feels much warmer in direct sunlight than it does in the shade. The body absorbs both long- and short-wave radiation from a variety of sources. Short-wave radiation generally comes from the sun or from solar radiation that reflects off of surfaces, while long-wave (or infrared) radiation is emitted by our surroundings – buildings, walls, and the ground. MRT is essentially the temperature that the surface of a hypothetical object would need to have in order to exchange the same amount of radiation as a human body would with its surroundings. An illustration of the heat exchange process is given in Figure 3.1:
Gathering hourly air temperature, humidity, and wind velocity data

Three of the biometeorological variables – air temperature, relative humidity, and wind speed – are widely available through a variety of online resources, but these sites generally provide only monthly averages for data. To most accurately assess the impact of climate conditions on walking and transit use, we need to examine diurnal climate data, or the average conditions at each hour of the day.

At least one online resource (http://www.microclimates.org/diurnal/) provides diurnal data for select U.S. cities, but such data can also be obtained from the National Climatic Data Center (NCDC), a division of the United States Department of Congress, the National Oceanographic and Atmospheric Administration (NOAA), and the National Environmental [36]
For the purposes of this study, I selected 20 years of hourly climate data collected at the Miami International Airport collected between 1991 and 2010. There are numerous weather stations in the Miami area, but I selected this one because its location – 25°47'N / 80°19'W – is close to some of Miami’s most densely populated areas. It is also located approximately nine miles inland, meaning it is more likely to record higher temperatures and lower wind speeds than stations closer to the Atlantic Ocean. As such, I assumed that it would provide more conservative thermal comfort estimates. Using Microsoft Excel and Access, I aggregated the NCDC data – first by month and then by hour. The end result was a table of mean observation values for each hour of each month.

Filtering the climate data to the desired times of day

To provide an accurate assessment of climates impact on walking and transit use, it makes the most sense to examine conditions at the hours people typically travel during the months in which weather conditions are the most extreme. According to household travel survey data compiled in the Southeast Florida Regional Travel Characteristics Study (also known as Travel 2000), 76.3 percent of all trips in Miami-Dade County begin between 7 a.m. and 5:59 p.m., with the busiest hours being 7 a.m. (12.5 percent), 8 a.m. (11.1 percent) and 5 p.m. (8.6 percent).

For this study, I selected three observation hours: 8 a.m., 5 p.m., and a midday hour of 1 p.m. These values reflect typical times for morning and evening commutes, and a time close to solar noon in the summer months, which occurs at 12:27 p.m. on July first, according to an online calculator made available by NOAA (http://www.srrb.noaa.gov/highlights/sunrise/sunrise.html).
According to the World Meteorological Organization, July and August are the hottest months of the year in Miami, with each month having a mean daily maximum temperature of 31.7 degrees Celsius (89.1 degrees Fahrenheit). My examination of the NCDC climate data revealed almost no differences in the hourly climate averages for July and August. For the purposes of this study, I selected the July values, which are given in Table 3.2.

Table 3.2 - Climate averages for July in Miami

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature C</th>
<th>% Relative Humidity</th>
<th>Wind speed in meters/second</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 a.m.</td>
<td>26.64</td>
<td>82.39</td>
<td>1.84</td>
</tr>
<tr>
<td>1 p.m.</td>
<td>28.69</td>
<td>74.64</td>
<td>2.92</td>
</tr>
<tr>
<td>5 p.m.</td>
<td>31.01</td>
<td>28.37</td>
<td>4.51</td>
</tr>
</tbody>
</table>

Converting the filtered data to the appropriate units

Most thermal comfort calculations require that climate data be in specific units – generally degrees Celsius for air and mean radiant temperature, percent relative humidity, and meters per second for air speed. NCDC data provides air temperature in Fahrenheit, wind speed in miles per hour, and uses dew point in degrees Fahrenheit to measure humidity. Air temperature and wind speed are easily converted using widely known formulas:

- Fahrenheit to Celsius: °C=(5/9) x (°F-32)
- Wind m/s = 0.44704 x Wind mph

Converting dew point to relative humidity is significantly more complicated. (A full explanation is beyond the scope of this paper but may be found in the following document from NOAA: [http://www.wrh.noaa.gov/slc/projects/wxcalc/formulas/wetBulbTdFromRh.pdf](http://www.wrh.noaa.gov/slc/projects/wxcalc/formulas/wetBulbTdFromRh.pdf).) Fortunately, an easy-to-use Excel formula is given in a weather conversions spreadsheet from the Golden Gate Weather Services consulting firm ([http://ggweather.com/wx_calc.htm](http://ggweather.com/wx_calc.htm)): 
\[ 6.108 \times \exp(17.27 \times \frac{((D \times -32) \times \frac{5}{9} + 273.16 - 273.16)}{((D \times -32) \times \frac{5}{9} + 273.16 - 35.86)} / \left( 6.108 \times \exp(17.27 \times \frac{(T \times -32) \times \frac{5}{9} + 273.16 - 273.16)}{((T \times -32) \times \frac{5}{9} + 273.16 - 35.86)} \right) \times 100 \]

Where \( D \) = dew point in degrees Fahrenheit and \( T \) = air temperature in degrees Fahrenheit.

**Developing the mean radiant temperature variable**

Mean radiant temperature (MRT) is perhaps the most important meteorological parameter affecting human heat balance during sunny weather conditions (Bryan, 2001; Matzarakis, Rutz & Mayer, 2006). But unlike the first three environmental variables, MRT is not easily obtained from an online resource.

It is possible to record MRT measurements in the field, but the process is complex, time-consuming, and requires expensive equipment (Matzarakis, Rutz & Mayer, 2006). Additionally, outdoor MRT values vary widely based on the time of year and the sun’s position in the sky, so if one wishes to study conditions in the summer, observations must be made during that time period.

Fortunately, it is possible to calculate outdoor MRT values using one of at least two software programs that are available for free to the public. RayMan 1.2, developed by Andreas Matzarakis at the University of Freiberg in Germany, is a simple program that calculates MRT values based on inputs such as latitude and longitude, date, time of day, topography, and obstacles such as buildings and trees. ENVI-met 3.1, developed by Michael Bruse of the University of Mainz in Germany, is a three-dimensional microclimate model based on the laws of fluid and thermal dynamics. It simulates the interactions between the different components of the urban environment, namely soils, surfaces, buildings, plants, and air. It is more complicated to use than RayMan, but it is capable of processing a wider range of inputs (e.g. soil type and temperature) and producing more comprehensive outputs (e.g. the heat and...
vapor exchanges occurring between the ambient air and ground or wall surfaces). While this paper’s analysis requires only MRT estimates, I selected ENVI-met to provide these because the program’s comprehensiveness, which would be useful for anyone wishing to conduct a more thorough, in-depth analysis of an urban environment.

Using ENVI-met

A full explanation of ENVI-met and its capabilities is available online (http://envi-met.com/). However, the program needs two user-generated files to run a simulation. The first is a configuration file that stores information about where the site is located in the world, the timing and length of the simulation, and climatic variables such as air temperature and wind speed. The second file contains information about the physical properties of the site to be tested. This includes the dimensions of the built environment (buildings, etc.), information on plant and soil types, and surface materials such as pavement or asphalt. These parameters are defined using an interface inside the ENVI-met program in which the user programs information (including x-, y- and z-coordinates) into a grid of cells. The dimensions of these cells can range from 0.5 meters to 10 meters, depending on the desired resolution, and models may be as large as 130 x 130 cells in the horizontal dimension (Rosheidat & Bryan, 2010). The model has also been configured with “nesting grids” placed around the study area so that the hypothetical boundaries of the environment do not influence the results (Rosheidat, Hoffman & Bryan, 2008).
Applying ENVI-met to the Miami context

To calculate MRT values using ENVI-met, I first created configuration files designed to simulate the climatic conditions at three times of day – 8 a.m., 1 p.m., and 5 p.m. – on July 1. While ENVI-met is capable of running simulations over a 24-hour period, I designed these simulations to capture only one-minute “snapshots” to cut down on the time needed to run the simulations, which depending on the size of the model and the speed of an individual computer can take several hours or more. These smaller simulations took approximately 20 minutes each to run.

Next, I built two sample environments in the program’s area input editor. Each model is centered at a latitude of 25.47 and a longitude of -80.13. I wish to stress that these two environments are not modeled after any actual place for two reasons. First, obtaining actual data – architectural dimensions, plant sizes and types, soil compositions, etc. – from a real place in Miami would have been beyond the time and research constraints of this paper. Second, even if I had been able to obtain that information, MRT values vary widely within urban environments (Matzarakis, Rutz & Mayer, 2006), meaning that any additional precision gained through simulating an exact environment would be lost when transferred to other areas.

Instead, these environments were designed to be rough approximations of two typical urban morphologies. The first environment is intended to mimic a “suburban” area of single-family homes surrounded by grass yards. The second is modeled after a “mid-rise” district consisting of five-story buildings with a canyon ratio (height to width) of approximately 1:2. Both areas were designed to be fully compliant with Miami’s adopted zoning standards, or as fully compliant as possible given differences in units of measurement and precision constraints within the software itself. The suburban area (Figure 3.3) is designed to be legal under the conditions outlined in the T3 Sub-Urban Zone, and the mid-rise environment (Figure 3.4) is compliant with the T5 Urban Center Zone. The T3 zone represents a purely residential neighborhood while the T5 zone could be residential, commercial, or a mix thereof.
Figure 3.3 – T3 Sub-Urban Center Zone ENVI-met model

Figure 3.4 – T5 Urban Center Zone ENVI-met model
Each model was built in a simulated area consisting of 60 cells on the x-axis, 70 cells on the y-axis, and 30 cells on the z-axis. Each cell represents two meters, for a total area in meters of 120 x 140 x 60. The T3 zone consists of eight single-family homes, each 12 meters wide, 18 meters deep, and six meters tall (simulating pitched roofs is not possible in ENVI-met). The T5 zone consists of four five-story buildings. Each is 44 meters wide, 24 meters deep and 18 meters tall. In all instances, lot sizes, floor-area ratios, and setbacks are compliant with the regulations in the respective zones.

Both environments contain one north-south street that is 18 meters wide by 120 meters long, and one east-west street that is 18 meters wide by 84 meters long. In the T3 zone, sidewalks are two meters wide and are separated from the street by a two-meter grass strip. In the T5 area, sidewalks are four meters wide and are separated from the street by a two-meter “street furniture zone” consisting of red brick pavers. All streets and sidewalks are defined as concrete pavement in this simulation. In those areas not covered by pavement or buildings, I set the default soil type to “loamy soil.” I created the T3 and T5 models to initially have no vegetation other than the grass yards in the suburban area.

With the two initial models completed, I then ran simulations for each model at 8 a.m., 1 p.m., and 5 p.m. to gather three sets of “baseline” MRT data for both the T3 and T5 environments, for a total of six data sets. I then applied “treatments” to each environment. In the T3 zone, I simulated two networks of street trees that formed a continuous canopy over the sidewalk areas. One canopy consisted of “light” trees with heights of 15 meters, and the other was comprised of “very dense” trees 15 meters in height with distinct crowns.

These tree models were taken directly from the default “PLANTS” database included with the ENVI-met software. The words “light” and “very dense” are obviously subjective terms, but their impact can be measured objectively through a measure known as “Sky View Factor” or SVF. SVF is defined as “the ratio of radiation received by a planar surface to the radiation emitted by the entire hemispheric environment” (Watson & Johnson, 1987, as cited in Gal, et al., 2007). SVF is a dimensionless measure between zero and one (Oke, 1988). With only houses
providing shade, the default mean SVF value along the sidewalks in the T3 zone is 0.91. With the light tree treatment, the SVF drops to 0.56, and with very dense trees it falls further to 0.25.

In the T5 zone, I first applied a continuous canopy of “light” street trees in the same fashion as the first T3 treatment. For the second treatment, I created a network of “archways” or covered walkways placed over the sidewalk. These areas measure six meters deep by six meters high and cover the entire width of the sidewalk (Figure X.X). The buildings extend above these covered walkways, meaning that from a height of six meters to the top of the building, the width of the building increases to 47 meters and the depth to 27 meters. Under Miami code, archways are permitted in the T5 zone via a Special Area Plan. Further discussion of the specifics related to this architectural feature is included in the Recommendations section of this paper.

I ran simulations at the three specified times for all four treatment techniques, bringing the total number of MRT datasets collected to 18, one for each combination of environment, time, and treatment. The ENVI-met model output provided MRT values for each cell in the simulation, but for the purposes of this study, we are only interested in the values from the areas in which people would be walking, namely, sidewalk areas. Using Microsoft Access, I ran a query to identify those readings from inside the “Treatment Area,” an example of which is depicted in Figure 3.5.
I then averaged the values collected from each of these treatment areas to provide an MRT value for each environment and treatment area combination at each of the three points during the day. The resulting MRT values are available in the Results section of this paper.

**Objectively evaluating the body’s thermal comfort response**

To this point in the methodology section, we have identified a study area – Miami – and determined three hourly July climate averages for the variables that impact thermal comfort – air temperature, mean radiant temperature, humidity, and wind velocity. This portion of the methodology section deals with selecting a model that can use these variables to assess the thermal comfort of an individual walking in Miami summer conditions.
Selecting a best-fit model – skin wettedness

Of all the available indices and measures, skin wettedness \((w)\) appears to be the most appropriate measurement for several reasons:

1. It is strongly correlated with discomfort in warm environments, more so than other physiological measures such as skin temperature (Fukazawa & Havenith, 2009; Djongyang, Tchinda & Njomo, 2010);

2. Skin wettedness is a dimensionless measure for which a bright-line threshold of “discomfort” has been established in the literature (Gagge, 1937), and this threshold is dynamic depending on activity level (Havenith, Holmer & Parsons, 2002);

3. It makes intuitive sense for evaluating discomfort over relatively short periods of time in hot, humid climates.

That last point is clearly the author’s opinion, but it is based on the following reasoning. Many outdoor thermal indices have been developed to evaluate thermal stress, not thermal comfort (Spagnolo & de Dear, 2003). But while walking outside on an unshaded street on a muggy Miami morning for 15 minutes might leave an individual drenched in sweat, he or she would likely not be at risk of an excessively elevated core temperature (Höppe, 2002) or of any heat-related illness. However, if we assume this walk was taking place as part of a morning commute at the start of a work day, being drenched in sweat at its conclusion would be a highly undesirable outcome.

Skin wettedness equation

Djongyang, Tchinda & Njomo (2010) describe skin wettedness \((w)\) as follows:
“The skin wettedness is a rationally derived physiological index defined as the ratio of the actual sweating rate to the maximum rate of sweating that would occur if the skin was completely wet, and skin temperature was incorporated into such a model to indicate the sensation of “comfort and discomfort” caused by perspiration. Skin wettedness is important in determining evaporative heat loss. It ranges from about 0.06 caused by the evaporative heat loss due to moisture diffusion through the skin alone (i.e. with no regulatory sweating) for normal conditions, to 1 when theoretically a skin surface is totally wet with perspiration, a condition that occurs rarely in practice.” (p. 2634)

According to Fukuzawa & Havenith (2009), skin wettedness is defined as:

\[
w = \left( \frac{q_{sw}}{q_{emax}} \right) + 0.06
\]  

Where \( q_{sw} \) is the evaporated heat flux from the clothed body caused by regulatory sweating (W m\(^{-2}\)), \( q_{emax} \) is the maximal evaporative heat flux from the body with the actual clothing and skin temperatures for a totally wet skin (W m\(^{-2}\)), and 0.06 is the minimal skin wettedness by skin diffusion (dimensionless).

**Comfort threshold**

The index is a dimensionless with a maximum value of 1. According to Gagge, et al. (1969), thermal comfort is realized when \( w \) is less than 0.3. This limit is said to be the “thermal comfort limit of the whole body” (Fukuzawa & Havenith, 2009). Havenith, Holmer and Parsons (2002) offer a slightly modified comfort threshold that is dependent on activity level:

\[
\text{comfort requirement: } w < 0.0012M + 0.15
\]
Where \( M \) is equal to the metabolic rate in \( \text{W m}^{-2} \). For the purposes of this paper, this work-specific comfort requirement is used in lieu of the fixed standard of 0.3. According to Djongyang, Tchinda & Njomo (2010) for skin wettedness values between 0.3 and 0.5 thermal discomfort progressively increases. When skin wettedness exceeds 50 percent, an individual is then said to be in a condition of “thermal constraint.”

Calculating skin wettedness

The equation to calculate skin wettedness is simple, but determining its two main inputs, \( q_{sw} \) and \( q_{emax} \), involves calculations of a significantly more complicated nature. The methods used to calculate these variables are detailed thoroughly in Appendix A – Calculating skin wettedness. The remainder of the methodology section describes three additional variables needed to calculate skin wettedness that have not been described in the methodology section to this point. These sections also appear in Appendix A.

Selecting the final model inputs

Using the tools described in Appendix A to calculate \( w \) via \( q_{sw} \) and \( q_{emax} \) requires three additional variables for which values have not yet been identified. They are:

- subject surface area \( (\text{m}^2) \)
- clothing units (clo)
- metabolic rate \( (\text{W m}^{-2}) \)

For this study, our test subject will be the average American male as defined by the 2008 National Health Statistics Report from the U.S. Department of Health and Human Services. Females are not addressed in this study because they possess a greater body surface area and are therefore able to evaporate heat more easily through radiant mechanisms. Therefore, it is assumed our subject is a male in order to provide more conservative estimates. The 50\(^{th}\) percentile American male is 176.3 centimeters tall and weighs 88.3 kilograms. These bodies
may be converted into surface area (m\(^2\)) using the formula given by Atkins and Thompson (2000):

\[
\text{surface area (m}^2\text{)} = 0.00718 \times \text{weight}^{0.425} \times \text{height}^{0.725}
\]

The surface area of the average American male is 2.05 m\(^2\).

Clothing units may be calculated using de Dear’s model or numerous other published resources. For the purposes of this study, a value of 0.49 is used for all simulations. This is an approximation of appropriate “business casual” clothing for the summer season. The ensemble includes: men’s briefs (0.04), a t-shirt (0.08), calf-length socks (0.03), thin straight trousers (0.15), and a short-sleeve dress shirt (0.19). The total clo value is thus 0.49.

Metabolic rate may also be estimated using de Dear’s calculator among many other sources. For the purposes of this study, I used a metabolic rate (W m\(^{-2}\)) of 150, equivalent to a walking speed of 1.34 m/s\(^{-1}\), an approximation of the average human walking speed.

*Combining q\(_{sw}\) and q\(_{emax}\) to calculate wettedness*

With q\(_{sw}\) and q\(_{emax}\) determined through the process described in Appendix A, it was then possible to calculate skin wettedness (w) for each minute in a half-hour period using equation 1. These values were then compared against the dynamic “comfort requirement” threshold established by Havenith, Holmer and Parsons (2002) and the “thermal constraint” threshold of 0.5 identified by Djongyang, Tchinda & Njomo (2010). Assuming a metabolic rate of 150, equation 2 dictates that the comfort requirement is 0.33.
Section 4

Results and Discussion

This section contains the results of the analysis described in the methodology section. All simulations assumed a male subject with a body surface area of 2.05 m\(^2\), wearing clothing with a clo value of 0.49, and walking at a metabolic rate of 150 W m\(^{-2}\). The air temperature, mean radiant temperature, relative humidity, and wind speed combinations used for each environment, treatment, and time combination are shown in Tables 4.1 and 4.2.

Table 4.1 – Climate data for the T3 Environment

<table>
<thead>
<tr>
<th>Climate variables</th>
<th>MRT values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temp. °C</td>
<td>RH %</td>
</tr>
<tr>
<td>8 a.m.</td>
<td>26.64</td>
</tr>
<tr>
<td>1 p.m.</td>
<td>28.69</td>
</tr>
<tr>
<td>5 p.m.</td>
<td>31.01</td>
</tr>
</tbody>
</table>

Table 4.2 – Climate data for the T5 Environment

<table>
<thead>
<tr>
<th>Climate variables</th>
<th>MRT values for T5 environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temp. °C</td>
<td>RH %</td>
</tr>
<tr>
<td>8 a.m.</td>
<td>26.64</td>
</tr>
<tr>
<td>1 p.m.</td>
<td>28.69</td>
</tr>
<tr>
<td>5 p.m.</td>
<td>31.01</td>
</tr>
</tbody>
</table>

A full minute-by-minute accounting of each analysis is available in Appendix A – Skin Wettedness Calculations. It includes transient values for the subject’s skin temperature (Tsk) and evaporative heat loss from the skin due to regulatory sweating (qsw), the saturated water vapor pressure at the skin surface (Ps) in mmHG and kPa, the maximal evaporative capacity of

[50]
the environment (qemax), and the overall skin wettedness (w). Variables such as heat transfer coefficients, clothing values, and sky view factor are listed at the top of each table.

The remaining tables in this section summarize the full results of Appendix A. Each table details the results for the three treatment options in one environment at one time of day, e.g. T3 at 8 a.m. Four pieces of information are included for each treatment. The first two columns contain the number of minutes in each simulation where skin wettedness (w) is less than 0.33 and 0.50, respectively. The third column contains the skin wettedness values five minutes into the simulation. The fourth column details how far an individual could walk and maintain a skin wettedness of less than 0.33. This number reflects a walking speed of 1.34 meters per second or 80.4 meters per minute. Distances are rounded off to the whole minute and are offered as a conservative estimate. For instance, if w exceeded 0.33 sometime between the 5 and 6 minute mark, the five-minute value (402 meters) is used.

Tables 4.3 to 4.5 contain the results for the T3 “suburban” environment, while 4.6 to 4.8 contain results for the T5 “midrise” environment:

| Table 4.3 - T3 8 a.m. walking distance threshold values (where w = skin wettedness) |
|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
|                                    | Minutes where w < 0.33 | Minutes where w < 0.50 | Approximate walking distance in "comfort" | w value at 5 minutes |
| No treatment                       | 2                      | 8                      | 160.8 | 0.421 |
| Light trees                        | 3                      | 10                     | 241.2 | 0.396 |
| Dense trees                        | 3                      | 13                     | 241.2 | 0.370 |

| Table 4.4 - T3 1 p.m. walking distance threshold values (where w = skin wettedness) |
|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
|                                    | Minutes where w < 0.33 | Minutes where w < 0.50 | Approximate walking distance in "comfort" | w value at 5 minutes |
| No treatment                       | 3                      | 10                     | 241.2 | 0.372 |
| Light trees                        | 4                      | 15                     | 341.6 | 0.344 |
| Dense trees                        | 5                      | > 30                   | 402.0 | 0.313 |

| Table 4.5 - T3 5 p.m. walking distance threshold values (where w = skin wettedness) |
|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
As expected, these results show that the summer climate conditions in Florida make outdoor activity difficult. In the suburban environment with no trees, the average American adult male would experience uncomfortable skin wettedness in fewer than three minutes if walking normally outside at 8 a.m. Even with robust shade treatments such as dense tree canopies or archways, the maximum “comfortable” walking time in any environment was seven minutes, corresponding to a distance of 562.8 meters.
However, these results clearly demonstrate that shade treatments can have a meaningful impact on walking distance. In all circumstances, natural or artificial shade treatments led to reductions in skin wettedness values after five minutes of walking. In all but one scenario, this led to at least some increase in the amount of time before a W of 0.33 or higher was reached. The increases themselves are small—generally just one or two minutes—but because the numbers from the “no treatment” scenarios are themselves so small, even these marginal time improvements have a big impact. For instance, in the T3 and T5 environments, the introduction of dense trees and archways, respectively, increased the walking time from three to five minutes. This in turn expanded the walking distance from just 241.2 meters to 402 meters.

The lowest walking time values are found at 8 a.m., where the no-treatment values are just two and three minutes for the T3 and T5 zones, respectively, and increased shading of any kind adds just a one-minute improvement. At first glance, this seems somewhat counter-intuitive because we often think of “the heat of the day” in terms of temperature, and the highest ambient air temperatures definitely occur later in the afternoon. But while 8 a.m. has the lowest ambient air temperature of the three tested times, it also has the highest relative humidity, the lowest wind speed, and the highest average mean radiant temperature (Tables 4.1 and 4.2). Having a higher average mean radiant temperature at 8 a.m. than at 1 p.m. when the radiation fluxes from the sun are more intense may also seem curious, but this is explained by the way in which MRT is calculated, where the radiative fluxes are weighted relative to the proportion of an individual’s body facing the source of the radiation. In practical terms, this means that when the sun is directly overhead, it hits a smaller area (the top of an individual’s head and shoulders) than when it is lower in the sky.

But the sun’s lower position in the sky also means that it casts longer shadows, meaning that shade is likely to vary greatly depending on which areas are examined. An analysis of MRT values by side of street revealed that the South and West sides of the street had significantly higher MRTs than their North and East counterparts (Table 4.11).
When side of street was taken into account, MRT values on the shady side of the street were lower than those on the sunny side by amounts ranging from 7.7 degrees Celsius to more than 36 degrees Celsius. Additionally, the MRT average for the North and East sides of the street was at least 13 degrees Celsius cooler than the average value for all sides of the street. Assuming that these shadier walking areas are available and that an individual chooses to take them, I calculated skin wettedness values using these new MRT inputs. The results are shown in Tables 4.12 and 4.13.

<table>
<thead>
<tr>
<th>Table 4.11 - MRT values for 8 a.m. by side of street (where w = skin wettedness)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>New MRT values for T3 environment</strong></td>
</tr>
<tr>
<td><strong>New MRT values for T5 environment</strong></td>
</tr>
<tr>
<td>No treatment</td>
</tr>
<tr>
<td>All sides of street</td>
</tr>
<tr>
<td>South and West sides</td>
</tr>
<tr>
<td>North and East sides</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.12 - T3 8 a.m. walking distance threshold values for North and East sides of street (where w = skin wettedness)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minutes where w &lt; 0.33</strong></td>
</tr>
<tr>
<td>No treatment</td>
</tr>
<tr>
<td>Light trees</td>
</tr>
<tr>
<td>Dense trees</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.13 - T5 8 a.m. walking distance threshold values for North and East sides of street (where w = skin wettedness)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minutes where w &lt; 0.33</strong></td>
</tr>
<tr>
<td>No treatment</td>
</tr>
<tr>
<td>Light trees</td>
</tr>
<tr>
<td>Archways</td>
</tr>
</tbody>
</table>
While the lower mean radiant temperature at 8 a.m. provided some comfort improvement over the initial calculations, discomfort was still reached before the five-minute mark in all scenarios. Even in the treated T5 environments with MRT values lower than 25 degrees Celsius, discomfort was reached between the four- and five-minute marks. Thus, even with the best-case scenario shading treatment applied, the maximum comfortable walking distance at 8 a.m. is 321.6 meters.

The relatively uncomfortable conditions at 8 a.m. are consistent with the concepts that high humidity (Eves, et al., 2008) and negligible wind conditions (Murakami, et al., 1999) decrease the body’s ability to evaporate heat. This can be further visualized by examining the inputs that went into the preceding skin wettedness calculations (Table 4.15).

Humidity is related to the partial water vapor pressure of ambient air \( (P_a) \), which uses relative humidity and dry bulb temperature as its two inputs. This number is then plugged in to the equation for \( q_{emax} \).

\[
q_{emax} \left( W \cdot m^{-2} \right) = f_{pcl} \times h_e \times (P_s - P_a)
\]  

(4)

A higher relative humidity will make the \( P_a \) value larger, which will accordingly make \( q_{emax} \) smaller. Wind speed, referred to here as \( v_a \), impacts the convective heat transfer coefficient:

\[
h_c \left( W \cdot m^{-2} \cdot K^{-1} \right) = 8.3 \times (v_a^{0.6})
\]  

(8)

A lower wind speed will lead to a lower convective heat transfer coefficient, which in turn will lead to a lower evaporative heat transfer coefficient:

\[
h_e \left( W \cdot m^{-2} \cdot K^{-1} \right) = h_c \times 16.5
\]  

(9)
Finally, a lower evaporative heat transfer coefficient, plugged into the equation for \( q_{\text{emax}} \), will lead to a smaller maximal wettedness value. The values for \( P_a \) and \( h_c \) and their impact on \( q_{\text{emax}} \) is shown in Table 4.15.

**Table 4.15 - \( P_a \) and \( h_c \) values for T3 and T5 environments**

<table>
<thead>
<tr>
<th>Time</th>
<th>RH %</th>
<th>( P_a ) (kPa)</th>
<th>Wind m/s</th>
<th>( h_c )</th>
<th>T3 ( q_{\text{emax}} ), no treatment at 5 mins.</th>
<th>T5 ( q_{\text{emax}} ), no treatment at 5 mins.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 a.m.</td>
<td>82.39</td>
<td>3.41</td>
<td>1.84</td>
<td>11.97</td>
<td>142.64</td>
<td>138.95</td>
</tr>
<tr>
<td>1 p.m.</td>
<td>74.64</td>
<td>3.29</td>
<td>2.92</td>
<td>15.79</td>
<td>162.28</td>
<td>161.55</td>
</tr>
<tr>
<td>5 p.m.</td>
<td>63.09</td>
<td>3.02</td>
<td>4.51</td>
<td>20.49</td>
<td>195.74</td>
<td>184.66</td>
</tr>
</tbody>
</table>

Overall, these results show that in some instances, it is possible to make a “quarter-mile/400-meter/five-minute walk” in comfort. However, this statement comes with the qualifiers of “just barely” and “only when sufficient shade is provided.” Additionally, when humidity is too high or wind speed too low, the five-minute walk becomes a much more uncomfortable proposition.

**Walking and waiting**

The preceding scenarios were designed to simulate an individual performing one outdoor activity – walking. But on many trips, an individual performs multiple activities that correlate with widely differing metabolic rates. For instance, when taking public transportation, individuals are likely to walk to a transit stop and then either sit or stand waiting for a bus or train. In such a scenario, an individual’s metabolic rate would drop from 150 (W m\(^{-2}\)) to 70 for standing or 60 for sitting. Unfortunately, the steady-state thermal comfort models that are widely available at this time are poorly suited to deal with such situations.
One possible approach to deal with these differences in metabolic rate is to use a time-weighted average as proposed in ASHRAE’s Standard 55P (where “met” is a different way of expressing metabolic rate):

“A time-weighted average metabolic rate may be used for individuals with activities that vary over a period of one hour or less. For example, a person that typically spends 30 minutes out of each hour "lifting/packing," 15 minutes "filing, standing," and 15 minutes "walking about" has an average metabolic rate of 0.50x2.1+0.25x1.4+0.25x1.7=1.8 met. Such averaging should not be applied when the period of variation is greater than one hour. For example, a person that is engaged in "lifting/packing" for one hour and then "filing, standing" the next hour should be treated as having two distinct metabolic rates.” (p.34)

Applying the ASHRAE time-weighting method to our analysis, we might suppose that an individual has a metabolic rate of 150 (W m\(^{-2}\)) while walking and a rate of 70 while standing relaxed. If we assume that an individual walks for five minutes and then stands for five minutes, the metabolic rate would be:

\[
0.50 \times 150 + 0.50 \times 70 = 110 \text{ (W m}^{-2}\text{)}
\]

If we plug this metabolic rate into the T3 model with very dense trees at 8 a.m. using the MRT values from the North and East sides of the street only, we see the following results:

| Table 4.16 - T3 8 a.m. walking distance threshold values for North and East sides of street using time-weighted metabolic rate (where w = skin wettedness) |
|---|---|---|
| Minutes where \( w < 0.33 \) | w value at 5 minutes |
| Dense trees | 9 | 0.2759 |

[57]
As shown in Table 4.16, applying the time-weighted approach gives the impression that an individual would maintain a comfortable skin wettedness level for more than nine minutes while walking and standing in densely shaded areas of the T3 environment at 8 a.m. At first glance, this would seem to indicate that a five-minute walk and a five-minute wait are mostly acceptable. However, the w value at five minutes using the weighted average is 0.2759, well within the range of comfort. This is well below the value estimated for the same environment at a metabolic rate of 150 (W m\(^{-2}\)). In that simulation (Table 4.12) the w value at five minutes was 0.357, and discomfort was reached at some time between the four- and five-minute marks, both of which were well below the time-weighted estimates. As such, weighting metabolic rates may lead us to falsely conclude that an individual will maintain comfort.

Whether using a steady-state model with a fixed or weighted metabolic rate, we are not able to say with any great precision how far an individual may be able to walk to a transit stop and how long he or she may be able to wait there while still maintaining a comfortable skin wettedness. If we instead focus on the thermal environment of the place at which an individual will be waiting, we can at least assess how comfortable the environment is in general. Table 4.17 contains skin wettedness values for an individual waiting in the T3 environment at 8 a.m. at two different MRT levels. The first MRT level (53.29) is derived from Table 4.1 and corresponds to the average MRT for the entire sidewalk environment with no treatment applied. The second MRT level (30.445) corresponds to the average MRT for the North and East sides of the streets with the “very dense” tree treatment applied. I selected these values to provide an approximation of waiting at a shaded and unshaded bus stop.

<table>
<thead>
<tr>
<th>Minutes where w &lt; 0.33</th>
<th>w value at 5 minutes</th>
<th>w value at 10 minutes</th>
<th>w value at 30 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRT 53.29</td>
<td>9</td>
<td>0.245</td>
<td>0.333</td>
</tr>
<tr>
<td>MRT 30.445</td>
<td>&gt; 30</td>
<td>0.153</td>
<td>0.186</td>
</tr>
</tbody>
</table>
As the results indicate, MRT once again has a major influence of comfort. They also show that an individual can stand in an optimally shaded environment for more than 30 minutes without experiencing thermal discomfort.

Because 70.9 percent of individuals using transit in Miami-Dade County wait an average of 10 minutes or less for a bus or train (Southeast Florida Travel 2000), it is assumed for the purposes of this study that an individual waiting at a shaded transit stop following a “comfortable” walk will continue to maintain thermal comfort until boarding the transit vehicle.
In 2010, the Florida Department of Transportation and the Florida Department of Community Affairs released a joint draft report titled “A Framework for TOD in Florida.” As a Florida-specific framework for creating communities that maximize walking trips and transportation, the report identifies the key considerations and questions to be addressed when implementing TOD in the state. One of these is the extreme climate of Florida and its impact on walking and transit use:

“In Florida, TODs not only need to consider the land use and urban design elements of density, intensity and mix of uses, but given the extreme climate conditions of heat and thunderstorms, the quality of the walking environment is another major design element to creating successful TODs. While the average distances for walking in moderate climates maybe 5-10 minutes, in Florida this time could be cut in half in weather extremes. To mitigate these unique climate issues, TODs in Florida should include a range of measures to enhance the walking environment and/or shorten the walking trip lengths. This could include creating shaded walking conditions, shelters, maintaining natural breezeways and further concentrating uses within the first quarter-mile radius of the station to reduce walk times to major destinations.” (p. 2)

This statement can be distilled down to the following: The climate conditions in Florida make walking and transit use difficult, but these challenges can be overcome through shortening walking distance and implementing design solutions. The results detailed in the previous section of this paper echo this sentiment exactly.
This paper numerically demonstrates that the acceptable walking distances in July in Miami are very short without shading, but that walk times gradually improve with the introduction of natural or artificial shade. With an appropriate amount of shade, it is possible on many occasions to comfortably make the “five-minute walk” of a quarter mile or 400 meters. But even with shading, if relative humidity is too high or wind speeds are too low, the body will not be able to evaporate heat fast enough and excessive sweatiness and discomfort will occur.

These findings lend themselves to two general categories of policy prescriptions:

- Density recommendations derived from “comfortable” walking distances
- Design recommendations intended to facilitate the best possible walking environments with respect to climatic conditions

This section details specific recommendations that fit into each category.

**Density recommendations**

Estimates of how far individuals are willing to walk for transportation or to access transit have traditionally been set at either a quarter-mile or half-mile (FDOT & DCA, 2010). These distances have then been used to identify appropriate housing and employment densities to support communities oriented around walking and transit. FDOT and DCA recommend that the highest densities of uses should be located within a quarter mile radius known as the transit core, with densities gradually decreasing out into the half-mile radius, known as the transit neighborhood.
The “comfort shed” three-minute walk

This paper proposes a new walking guideline for Miami – the three minute walk. This “comfort shed” of 240 meters or just shy of 800 feet (787.4 feet), is a distance at which the average individual will almost always maintain thermal comfort, even in the stifling humidity and still air of the morning commute hours. The maximum walking time at 8 a.m. on the average July day was four minutes, and that is assuming the entire walk was made through an environment with optimal shade provided by dense trees. The three-minute walk therefor provides a slightly more conservative estimate of a walking distance that will not lead to excessive sweating. The “transit core” should be redefined as a 240 meter area around the transit or neighborhood center.

Revised density guidelines

“A Framework for TOD in Florida” provides density guidelines for various combinations of neighborhood and transit types. Densities to support commuter or light rail, and bus rapid transit (BRT) or bus service are given for regional, community and neighborhood centers. A summary of these densities appears in table 5.1.
### Table 5.1 - Florida TOD density guidelines

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional Center</td>
<td>Commuter/light rail &gt; 70</td>
<td>&gt;55,000</td>
<td>&gt;180,000</td>
</tr>
<tr>
<td></td>
<td>BRT/Bus</td>
<td>45 - 70</td>
<td>50,000 - 80,000</td>
</tr>
<tr>
<td>Community Center</td>
<td>Commuter/light rail 30 - 40</td>
<td>25,000 - 30,000</td>
<td>45,000 - 55,000</td>
</tr>
<tr>
<td></td>
<td>BRT/Bus</td>
<td>25 - 40</td>
<td>10,000 - 15,000</td>
</tr>
<tr>
<td>Neighborhood Center</td>
<td>Commuter/light rail 15 - 25</td>
<td>15,000 - 20,000</td>
<td>10,000 - 20,000</td>
</tr>
<tr>
<td></td>
<td>BRT/Bus</td>
<td>5 - 15</td>
<td>1,000 - 2,000</td>
</tr>
</tbody>
</table>

*Source: A TOD Framework for Florida*

In Table 5.1, the minimum net housing density refers to dwelling units per acre and is based on total FAR and the desired mix of uses in the type of center. Dwelling unit square footage is assumed to be 1,200 square feet per unit in regional centers, 1,500 square feet in community centers, and 1,800 square feet in neighborhood centers (FDOT & DCA, 2010). Gross population and employment density refer to the number of persons or jobs per square mile.

Next, it is necessary to apply these density figures to a real-world context. One method to do this is to draw a circle with a 400-meter radius around each transit station and calculate the number of desired dwelling units, persons and jobs given the area of each circle. This quarter-mile “air buffer” (Figure 5.1) is used in the Miami-Dade County Transit Development Plan FY 2011-2020 (p. 2-3) and the Miami 21 TOD Diagram (Article IV, p. 26). But while this method allows for simple calculations, it is based on the assumption that individuals are able to walk to and from a transit stop in a straight line. In a real-world context of street networks and natural and artificial barriers, this is rarely the case.
Figure 5.1 – Miami 21 TOD map showing ¼ mile “pedestrian shed”

Source: City of Miami
It makes more sense to calculate distances from transit stops based on the street network surrounding them. As an example of why this is the case, consider an individual trying to access a transit stop that is located exactly 400 meters to the east by air distance. But to actually access the transit stop, the individual may have to walk 50 meters to the north to access a through east-west street that connects with the street on which the transit stop sits, and then walk 50 meters south to reach the stop itself. In this case, a 400-meter air distance actually translates to a 500-meter walk, and as we have seen, this may not be an insignificant difference when it comes to comfort in the most extreme summer weather conditions.

Calculating the area that is truly within a certain distance from a transit stop is possible using the “Network Analyst” tool in ESRI’s ArcGIS program. GIS data sets that contain the precise location of the City of Miami’s streets, 1,875 bus stops, 10 rail stations and 21 MetroMover stations are available online at the Miami-Dade County website GIS self-service page (http://miamidade.gov/wps/portal/Main/GIS#). Using this data, I calculated network buffers for the 400-meter and 240-meter walks around each transit stop. In instances where the buffers of two or more stops overlapped, they were merged and the actual land area under each buffer was counted only once. The results of this analysis are shown in Table 5.2:

<table>
<thead>
<tr>
<th></th>
<th>Number of stations/stops</th>
<th>Walkable acres at 400m</th>
<th>Walkable acres at 240 m</th>
<th>Walkable acres per station at 400m</th>
<th>Walkable acres per station at 240 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>MetroBus</td>
<td>1,875</td>
<td>19,274.35</td>
<td>14,098.34</td>
<td>10.28</td>
<td>7.52</td>
</tr>
<tr>
<td>MetroMover</td>
<td>21</td>
<td>801.4</td>
<td>420.65</td>
<td>38.16</td>
<td>20.03</td>
</tr>
<tr>
<td>MetroRail</td>
<td>10</td>
<td>565.65</td>
<td>209.38</td>
<td>56.56</td>
<td>20.93</td>
</tr>
</tbody>
</table>
Limitations of air buffers

As shown in Table 5.2, reducing the desired walking distance by 40 percent – from 400 meters to 240 meters – led to a 63 percent decrease in the walkable area around Metrorail stations. In contrast, bus stops saw just a 27 percent decrease in walkable area when the buffer was moved in from 400 to 240 meters. This discrepancy could be due to several factors. It is possible that areas around rail stations tend to have less connectivity than areas around bus stops. It is also possible that rail stations tend to be in the middle of blocks surrounded by parking lots. Since Network Analyst is intended primarily to calculate trip distances for automobiles, it may not be accounting for the fact that a pedestrian could “cut through” a parking lot or enter or exit a station on a foot path that does not directly follow a street.

As such, it appears that neither air buffers nor Network Analyst buffers provide an ideal measure of the walkable area around Miami transit stops, further detailed site analysis would be necessary to calculate exact walking distances.

But for the purposes of providing density guidelines for this study, it is presumed that the Network Analyst figures provide a more accurate measure of the true walkability around a given transit stop. Therefore, to determine revised density guidelines, I converted the figures in Table 5.1 into per-acre measures. The distances around Metrorail stations were used to calculate the minimum densities for the “Commuter/Light Rail” options while the Metrobus densities were used for the “BRT/Bus” calculations. In instances where the state TOD guidelines in Table 5.1 provided a range of densities, the mean of this range was used.
Table 5.3 - Density per acre with five-minute walk

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regional Center</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commuter/light rail</td>
<td>70.0</td>
<td>85.9</td>
<td>281.3</td>
</tr>
<tr>
<td>BRT/Bus</td>
<td>57.5</td>
<td>74.2</td>
<td>101.6</td>
</tr>
<tr>
<td><strong>Community Center</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commuter/light rail</td>
<td>35.0</td>
<td>43.0</td>
<td>78.1</td>
</tr>
<tr>
<td>BRT/Bus</td>
<td>32.5</td>
<td>39.1</td>
<td>19.5</td>
</tr>
<tr>
<td><strong>Neighborhood Center</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commuter/light rail</td>
<td>20.0</td>
<td>27.3</td>
<td>23.4</td>
</tr>
<tr>
<td>BRT/Bus</td>
<td>10.0</td>
<td>11.7</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Source: A TOD Framework for Florida

Table 5.4 contains the resulting density recommendations if the same gross number of housing units, persons and jobs established in table 5.3 were placed within 240 meters of a transit stop instead of 400 meters:

Table 5.4 – Density recommendations for a three-minute walk from transit using Network Analyst buffers

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regional Center</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commuter/light rail</td>
<td>189.1</td>
<td>232.1</td>
<td>760.0</td>
</tr>
<tr>
<td>BRT/Bus</td>
<td>78.6</td>
<td>101.4</td>
<td>138.9</td>
</tr>
<tr>
<td><strong>Community Center</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commuter/light rail</td>
<td>94.6</td>
<td>116.2</td>
<td>211.0</td>
</tr>
<tr>
<td>BRT/Bus</td>
<td>44.4</td>
<td>53.5</td>
<td>26.7</td>
</tr>
<tr>
<td><strong>Neighborhood Center</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commuter/light rail</td>
<td>54.0</td>
<td>73.8</td>
<td>63.2</td>
</tr>
<tr>
<td>BRT/Bus</td>
<td>13.7</td>
<td>16.0</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Interpreting the revised density recommendations

The densities given in Table 5.4 are quite high in comparison to almost everywhere in the United States, and they drastically exceed almost anything found in Florida. But it should be stressed again that they were derived using Miami’s present transportation system and
surrounding street network. Increasing connectivity (or more accurately assessing it using an on-site analysis) could lead to lower values, particularly around rail stations. But these density recommendations are offered here as a starting point if Miami were to apply the Florida TOD density recommendations to a 240-meter buffer around its present transit infrastructure.

To put these densities in context, it is best to focus on gross population density per acre because data metric is widely available and because it is perhaps more easy to conceptualize than net housing density or gross employment density. Tables 5.5 and 5.6 show the population densities for notable U.S. and Florida cities, respectively.

<table>
<thead>
<tr>
<th>National Rank</th>
<th>Place Name</th>
<th>Persons per acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Manhattan</td>
<td>104.59</td>
</tr>
<tr>
<td>2</td>
<td>Union City, NJ</td>
<td>82.78</td>
</tr>
<tr>
<td>3</td>
<td>Brooklyn, NY</td>
<td>54.56</td>
</tr>
<tr>
<td>5</td>
<td>New York, NY (all boroughs)</td>
<td>41.25</td>
</tr>
<tr>
<td>16</td>
<td>San Francisco, CA</td>
<td>25.99</td>
</tr>
<tr>
<td>28</td>
<td>Chicago, IL</td>
<td>19.92</td>
</tr>
<tr>
<td>32</td>
<td>Boston, MA</td>
<td>19.01</td>
</tr>
<tr>
<td>40</td>
<td>Philadelphia, PA</td>
<td>17.55</td>
</tr>
<tr>
<td>55</td>
<td>Miami city, FL</td>
<td><strong>15.88</strong></td>
</tr>
<tr>
<td>62</td>
<td>Washington, D.C.</td>
<td>14.56</td>
</tr>
<tr>
<td>115</td>
<td>Seattle, WA</td>
<td>10.50</td>
</tr>
<tr>
<td>269</td>
<td>Portland, OR</td>
<td>6.16</td>
</tr>
</tbody>
</table>

*Source: U.S. Census Bureau*
As shown in Tables 5.5 and 5.6, despite being among the densest places in the state of Florida, Miami is just the 55th densest area in the United States. Additionally, many of the density recommendations given in Table 5.4 are equivalent to the density found in Manhattan, America’s most dense area. The closest comparison city for each density recommendation is shown in Table 5.7.
Table 5.7 - Comparison Cities for Recommended Densities

<table>
<thead>
<tr>
<th>Regional Center</th>
<th>Commuter/light rail</th>
<th>Closest U.S. Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BRT/Bus</td>
<td>Manhattan</td>
</tr>
<tr>
<td>Community Center</td>
<td>Commuter/light rail</td>
<td>Manhattan</td>
</tr>
<tr>
<td></td>
<td>BRT/Bus</td>
<td>Brooklyn</td>
</tr>
<tr>
<td>Neighborhood Center</td>
<td>Commuter/light rail</td>
<td>Union City, NJ</td>
</tr>
<tr>
<td></td>
<td>BRT/Bus</td>
<td>Miami</td>
</tr>
</tbody>
</table>

Sources: U.S. Census Bureau, Hong Kong Special Administrative Region Government

While Miami itself has a city-wide density within the guidelines for bus transit at the neighborhood center level, all of the other density comparisons are found only in the New York metropolitan area. The density recommendations for commuter or light rail at the regional center level have no analog in the United States and are instead roughly equivalent to the Kwun Tong district in Hong Kong. Images illustrating the densities of Kwun Tong, Manhattan, Brooklyn and Union City are shown in Figures 5.2 to 5.5.

Figure 5.2 – Skyline of Kwun Tong neighborhood in Hong Kong

Source:Fotopedia.com

Figure 5.3 – Skyline of Manhattan
Figure 5.4 – Satellite photo of Brooklyn, NY

Figure 5.5 – Street-level view of 40th Street, Union City, NJ
It is important to keep in mind, however, that the density figures shown in Tables 5.5 and 5.6 are *city-wide* measurements. The actual densities of those areas are likely to vary between neighborhoods or even between blocks (Figure 5.6). Nevertheless, these figures provide a useful way to visualize the intensity of development that would be required along transit routes if all development is to occur within the Comfort Shed.
Miami’s code and its suitability for the revised guidelines

Based on the above guidelines, much of the City of Miami does not have an appropriate population density support to walkable, transit-oriented communities. Of the 310 Census block groups in the city with at least one inhabitant, 141 have a gross population density less than 16.0 persons per acre according to 2000 United States Census Data available in Miami-Dade GIS data. These 141 block groups take up more than 29,000 acres, which is more than 75 of the total land area in inhabited block groups. No block group had a population density in excess of 73.8 persons per acre, the minimum gross density required to support rail according to Table 5.4. Just eight block groups had gross population densities above 50 persons per acre.
These figures indicate that Miami will need to increase density in order to promote walking and transit use. Generally speaking, the recently adopted Miami 21 Code will allow this increase in density to occur in many areas of the city. Most of the city is now part of one of four general transects outlined in the form-based code: T3, T4, T5 or T6. Each transect has several sub-classifications that modify allowable uses, densities, and floor area ratios. However, a general overview of the allowable housing units per acre in each zone is provided in Table 5.8, and zones that allow dwelling units so as to satisfy transit requirements are marked with an “X.”

Table 5.8 - Housing units per acre and suitability for transit-supportive density in Miami 21 transect zones

<table>
<thead>
<tr>
<th>Regional Center</th>
<th>Community Center</th>
<th>Neighborhood Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable HU/acre</td>
<td>Rail</td>
<td>Bus</td>
</tr>
<tr>
<td>T3 - Restricted</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>T3 - Limited</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>T3 - Open</td>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>T4 - All</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>T5 - All</td>
<td>65</td>
<td>-</td>
</tr>
<tr>
<td>T6 - Restricted</td>
<td>150</td>
<td>X</td>
</tr>
<tr>
<td>T6 - Limited</td>
<td>150</td>
<td>X</td>
</tr>
<tr>
<td>T6 - Open</td>
<td>150 - 1000</td>
<td>X</td>
</tr>
</tbody>
</table>

Source: Miami 21 Code

Table 5.8 shows that all transect zones with the exception of T3-R and T3-L allow densities that support at least bus transit at the neighborhood center level, while zones T5 and above are capable of supporting rail. In areas where at least some transit accessibility is desired within the Comfort Shed, T3-R and T3-L zones should be increased to T3-O or higher.
Design recommendations

Six variables contribute to human heat balance and thermal comfort in outdoor environments. They fall into two categories: Environmental – air temperature, mean radiant temperature, relative humidity, and wind speed; and behavioral – clothing type and metabolic rate. Changes in any of these values can impact an individual’s skin wettedness and thermal comfort to varying degrees. In the warmer months of the year, higher wind speeds generally increase thermal comfort, while decreases in the other five variables lead to more comfortable conditions. But the degree to which these conditions can be intentionally modified varies.

Behavioral variables are seemingly easy to modify, but in practice this is not the case. Metabolic rate is directly associated with the activity level of an individual, and since this paper is focused solely on walking to access transit or another destination, it is not reasonable to adjust the metabolic rate. Individuals could choose to walk slower, but any savings in metabolic rate would likely be offset by a longer exposure time. Wearing lighter clothing that covers less of the total body surface area also is an option, but for individuals commuting to a job or other event where business attire is required, modifying clothing level is only possible if he or she has a place to change once at the destination.

Of the environmental variables, relative humidity is the most difficult to modify in a helpful way. Vegetation and water features may increase humidity (Black, 1993), but it is not feasible to lower relative humidity levels. Wind speed is also a variable over which control is somewhat limited. While certain steps can be taken to channel wind or to promote airflow – both very important considerations in the humidity of Florida – wind speed is still largely dependent on the weather conditions at any given moment.

That leaves air temperature and mean radiant temperature, both of which can be modified to a greater degree. While shading can lower ambient air temperatures (Richards), its greatest impact will be on the mean radiant temperature. In establishing the Comfort Shed walking distance, MRT was generally the only biometeorology variable altered, with all other
values remaining constant. The corresponding reductions in MRT alone led to meaningful improvements in walking distances. Based on these results, the following design recommendations are offered.

*Street tree plan prescribing the amount of shade trees should provide*

In areas without tall buildings or with a low-density neighborhood character, street trees represent the best way to shade the walking environment. A plan or ordinance requiring street trees is therefore an essential component of walkability in extreme summer conditions. Many municipalities require trees to be planted along the right-of-way or on private property, but for the purposes of walkability in high heat and humidity, the mere presence of trees is not enough to ensure comfort. Trees must be placed close together and provide an appropriate level of shade in order to lower MRT to a sufficient level. Street tree plans should therefore favor species that limit Sky View Factor to the greatest extent possible while still allowing for airflow close to the ground. Examples of Florida streets with abundant shade are shown in figures 5.7 and 5.8. Figure 5.9 shows a side-by-side comparison from Miami 21 outlining the ideal and existing street tree and sidewalk conditions.
Figure 5.7 – Street-level view of Emathla Street, Coconut Grove, Miami

Source: Google

Figure 5.8 – Street-level view of 9th Avenue, St. Petersburg, FL

Source: Google
The Miami 21 Code contains an entire section devoted to landscaping. Article IX prescribes that street trees generally be placed at a maximum average spacing of 30 feet on center along all
roadways. These trees should mature to a height of at least 20 feet and must have a clear trunk of four feet, an overall height of 15 feet, and a minimum caliper of three inches at the time of planting. Trees must be placed within seven feet of the edge of the roadway and within seven feet of the sidewalk. Species must be typically grown in Miami-Dade County. Palm trees, which typically are used along right-of-ways in Florida, are allowed provided they have a minimum canopy of 15 feet at maturity and an average spacing of 25 feet on center. The Miami 21 Code should be further revised to dictate that trees limit SVF to a minimum standard. Establishing such a standard and determining which trees can accomplish this effectively is beyond the scope of this paper.

Requiring archways, galleries and breezeways in denser areas

In areas with more dense development where large, dense tree canopies are not feasible, sidewalks should be continuously covered by artificial means, in the form of an archway, overhang, gallery or other structure. The Miami 21 Code allows these features by Special Area Plan, but they should be required in all T-5 and t-6 neighborhoods. Examples of existing and proposed archways are shown in Figures 5.10 and 5.11.
Figure 5.10 – Miami 21 diagrams outlining guidelines for Galleries and Archways

Source: City of Miami

Figure 5.11 – Archways (at left) at City Place, West Palm Beach, FL

Source: Google
Figure 5.12 – Miami 21 Diagram showing proposed World Trade Center Miami streetscape with Archways

Source: City of Miami
Other design solutions

Other design considerations may impact the microclimate of an urban environment. These include things like implementing green or white roofs and modifying the albedo (or reflectivity) of ground or building surfaces. While these techniques may be able to make significant impacts on biometeorology variables in an environment, they were not studied or considered for the purposes of this paper.
SECTION 6
Conclusion

This paper has identified some of the challenges that climate poses to creating walkable and transit-oriented communities in Florida, and has provided policy and design solutions to address them. It proposed a methodology for estimating human thermal comfort through skin wettedness over time for individuals walking in a hot, humid outdoor environment. Based on these findings, it established a new “comfort shed” walking standard, a three-minute or 800-foot walk that the average individual should be able to complete in comfort even in the stifling humidity of a July morning in Miami. This comfort shed recommendation was then applied to Miami’s present transit system and street grid to establish revised density recommendations for transit oriented development. Finally, a few design techniques to lower the mean radiant temperature in pedestrian zones – and thus increase thermal comfort – were presented.

The issues discussed in this paper have thus far been underrepresented in both the literature and in practice. Further research is needed to develop a universally accepted method for evaluating pedestrian thermal comfort in a transient, outdoor environment. Additionally, because such a model is likely to involve numerous complex calculations, a software program that could estimate pedestrian comfort based on simple, easy to obtain environmental inputs would be most useful to individuals in the planning, design, architecture and engineering professions. These fields should also begin considering the thermal comfort of pedestrians in environments where climate can act as a significant barrier to outdoor activity. Much attention has been paid in recent years to making streets and sidewalks safer and more aesthetically pleasing, and this focus should now be broadened to also consider comfort.

As discussed at the opening of this paper, Florida has been primarily developed around the automobile, and technology and cheap, abundant energy have largely insulated its inhabitants from the extreme climate conditions of the summer months. But should these circumstances change – due perhaps to rising energy prices or increasing market demand for
“smart growth” communities – the day-to-day interaction between Floridians and climate will begin to take on added importance. As the analysis in this paper demonstrates, such a situation will lead to challenges, but none so significant that they cannot be overcome through innovative planning and design.
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APPENDIX A
Calculating skin wettedness

Calculating skin wettedness

The equation to calculate skin wettedness is simple, but determining its two main inputs, \( q_{sw} \) and \( q_{emax} \), involves calculations of a significantly more complicated nature. A full discussion of how to independently calculate these variables is beyond the scope of this paper. Fortunately, there are two publicly resources that can aid in calculating skin wettedness.

de Dear’s Human Heat Balance calculator for \( q_{sw} \)

The first tool is the Human Heat Balance calculator developed by Richard de Dear of the University of Sydney in Australia. The web-based calculator, which uses sourcecode originally developed by Huizenga (1995) for ASHRAE’s comfort tool, is available at http://web.arch.usyd.edu.au/~rdedear/. Using standard biometeorology inputs, de Dear’s tool calculates values for thermal comfort indices such as PMV/PPD and SET*, and also displays values for the two-node models main physiological outputs (UTCI, 2011). One of these values is “\( E_{sw} \),” which is the total evaporative heat loss from the skin and is equivalent to the \( q_{sw} \) described by Fukuzawa and Havenith (2009). Another value is the skin temperature, \( T_{sk} \), which is necessary to determine \( q_{emax} \). de Dear’s calculator may display \( q_{sw} \) and \( T_{sk} \) either as a final values at the end of a set period of time, or as transient values, where a value is given for each minute over a period of time. The latter is particularly useful for the purposes of this analysis. All \( q_{sw} \) and \( T_{sk} \) values given in this paper were calculated using this tool.
The second tool is “A Spreadsheet for Partitional Calorimetry” developed by Atkins and Thompson (2000), also of the University of Sydney in Australia. “Partitional calorimetry” is a term used to describe the calculation of “heat storage and heat lost or gained via dry and evaporative heat transfer pathways” (Atkins & Thompson, 2000). Calculating these heat exchanges is a “necessarily complex” affair that the Atkins and Thompson spreadsheet attempts to simplify.

The spreadsheet (available at [http://www.sportsci.org/jour/0003/ka.html](http://www.sportsci.org/jour/0003/ka.html)) automates its calculations using Visual Basic and requires a number of user-supplied inputs typically seen in exercise science fields. Some of these (such as subject height and weight) are easily estimated, but others require specific field measurements such as subject oxygen consumption and respiratory exchange ratio (RER). As such, it is not practical to use the automated calculation process to determine \( q_{emax} \). Instead, it is possible to manually calculate \( q_{emax} \) using the formulas in the spreadsheets “Calculations” page and explained in the accompanying article (Atkins & Thompson, 2000). The process is somewhat lengthy and involves a number of steps, but can be automated and replicated to a reasonable degree in a program such as Microsoft Excel. What follows is an explanation of how to calculate \( q_{emax} \) as outlined by Atkins and Thompson.

To begin, two variables may be calculated using automated Visible Basic elements on the “EnvironData” tab of the spreadsheet. They are the radiative heat transfer coefficient \( h_r \) \((\text{W.m}^{-2}.\text{K}^{-1})\) and the partial water vapor pressure of ambient air \( P_a \) in mmHg. The \( h_r \) calculator requires the user to specify the type of activity taking place (in this case, walking), that clothing temperature was not calculated, and to input the MRT in degrees Celsius. The \( P_a \) calculator requires the user to input the dry bulb temperature in degrees Celsius along with the relative humidity.

The \( P_a \) value may be converted from mmHg into kPa using the following equation (Atkins & Thompson, 2000):
\[ P_a (\text{kPa}) = P_a (\text{mmHg}) \times 0.1333 \quad (3) \]

Now we may begin to calculate the maximal evaporative capacity of the environment \( q_{\text{emax}} \) as defined by (McIntyre, 1980):

\[ q_{\text{emax}} \, (\text{W m}^{-2}) = f_{\text{pcl}} \times h_e \times (P_s - P_a) \quad (4) \]

Where \( f_{\text{pcl}} \) is the permeation efficiency factor of clothing, \( h_e \) is the evaporative heat transfer coefficient \((\text{W.m}^{-2}.\text{kPa}^{-1})\), \( P_s \) is the partial water vapor pressure at the skin surface \((\text{kPa})\), and \( P_a \) is the partial water vapor pressure of ambient air \((\text{kPa})\) (McIntyre, 1980).

**Permeation efficiency factor of clothing, \( f_{\text{pcl}} \) (Parsons, 1993)**

\[ f_{\text{pcl}} = \frac{1}{1 + (0.344 \times h_c \times I_{\text{cle}})} \quad (5) \]

Where \( h_c \) is the convective heat transfer coefficient \((\text{W.m}^{-2}.\text{K}^{-1})\) and \( I_{\text{cle}} \) is the effective clothing insulation \((\text{clo units})\) (Parsons, 1993).

**Effective clothing insulation, \( I_{\text{cle}} \) (McIntyre, 1980)**

\[ I_{\text{cle}} \, (\text{clo units}) = I_{\text{cl}} - \left[ \frac{(f_{\text{cl}} - 1)}{0.155 \times f_{\text{cl}} \times h} \right] \quad (6) \]

Where \( I_{\text{cl}} \) is the intrinsic clothing insulation \((\text{m}^2.\text{C.W}^{-1})\), \( f_{\text{cl}} \) is the clothing area factor \((\text{ND})\), and \( h \) = combined heat transfer coefficient \((\text{W.m}^{-2}.\text{K}^{-1})\) (McIntyre, 1980). The \( I_{\text{cl}} \) value is dependent on the type of clothing an individual is wearing and may be determined by standard clothing values available from a variety of sources, including tables in ASHRAE 55P.

[94]
Clothing area factor, $f_{cl}$ (Parsons, 1993)

$$f_{cl} = 1 + [0.31 \times (I_{cl} / 0.155)]$$ (7)

Where $I_{cl}$ is the intrinsic clothing insulation ($m^2{.^\circ}C.W^{-1}$) (Parsons, 1993). Again, the $I_{cl}$ value may be determined from values given in literature.

Convective heat transfer coefficient, $h_c$ (Kerslake, 1972)

$$h_c (W.m^{-2}.K^{-1}) = 8.3 \times (v_a^{0.6})$$ (8)

Where $v_a$ is air velocity in m/s$^{-1}$ (Kerslake, 1972).

Evaporative heat transfer coefficient, $h_e$ (Kerslake, 1972)

$$h_e (W.m^{-2}.K^{-1}) = h_c \times 16.5$$ (9)

Combined heat transfer coefficient, $h$ (Parsons, 1993)

$$h (W.m^{-2}.K^{-1}) = h_c + h_r$$ (10)

Where $h_c$ is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$) and $h_r$ is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$).

Saturated water vapor pressure at the skin surface, $P_s$ (Fanger, 1970)

$$P_s (mmHg) = 1.92 \times T_{sk} - 25.3$$ (11)

Where $T_{sk}$ is skin temperature in degrees Celsius (Fanger, 1970). This equation is valid for skin temperatures between 27 and 37 degrees (Atkins & Thompson, 2000). Transient values for skin temperature are provided by de Dear’s tool. $P_s$ (mmHg) may then be converted into $P_s$ (kPa) by (Atkins & Thompson, 2000):
\[ P_a (kPa) = P_s (mmHg) \times 0.1333 \quad (12) \]

Of the above values, some remain constant in any situation while others change depending on environmental or physiological variables:

- The clothing area factor, \( f_{cl} \) is tied directly to the clo value derived from available literature and does not change unless clo units are modified.
- \( P_a \) is dependent on the water vapor pressure of the ambient air and does not change unless values for air temperature or relative humidity are changed.
- All heat transfer coefficients are dependent on various combinations of environmental variables.
- The clothing variables \( f_{pcl} \) and \( l_{cle} \) are altered with changes in heat transfer coefficients or the clo value.
- \( P_s \) changes along with the skin temperature of the subject.

Because of the number of moving parts in this equation, it is necessary to calculate a \( q_{emax} \) value on a minute-by-minute basis in order to calculate skin wettedness at the same resolution. Because \( q_{emax} \) is dependent on the saturated water vapor pressure at the surface of the skin, this meant using skin temperature values (\( T_{sk} \)) provided by de Dear’s calculator.

**Selecting the final model inputs**

Using the above tools to calculate \( w \) via \( q_{sw} \) and \( q_{emax} \) requires three additional variables for which values have not yet been identified. They are:

- subject surface area (m\(^2\))
- clothing units (clo)
- metabolic rate (W m\(^{-2}\))
For this study, our test subject will be the average American male as defined by the 2008 National Health Statistics Report from the U.S. Department of Health and Human Services. Females are not addressed in this study because they possess a greater body surface area and are therefore able to evaporate heat more easily through radiant mechanisms. Therefore, it is assumed our subject is a male in order to provide more conservative estimates. The 50th percentile American male is 176.3 centimeters tall and weighs 88.3 kilograms. These bodies may be converted into surface area (m\(^2\)) using the formula given by Atkins and Thompson (2000):

\[
\text{surface area (m}^2\text{)} = 0.00718 \times \text{weight}^{0.425} \times \text{height}^{0.725}
\]

The surface area of the average American male is 2.05 m\(^2\).

Clothing units may be calculated using de Dear’s model or numerous other published resources. For the purposes of this study, a value of 0.49 is used for all simulations. This is an approximation of appropriate “business casual” clothing for the summer season. The ensemble includes: men’s briefs (0.04), a t-shirt (0.08), calf-length socks (0.03), thin straight trousers (0.15), and a short-sleeve dress shirt (0.19). The total clo value is thus 0.49.

Metabolic rate may also be estimated using de Dear’s calculator among many other sources. For the purposes of this study, I used a metabolic rate (W m\(^{-2}\)) of 150, equivalent to a walking speed of 1.34 m/s\(^{-1}\), an approximation of the average human walking speed.

Combining \(q_{sw}\) and \(q_{emax}\) to calculate wettedness

With \(q_{sw}\) determined by de Dear’s calculator and \(q_{emax}\) determined through the equations described by Atkins and Thompson and the \(T_{sk}\) values from de Dear, it was then possible to calculate skin wettedness (w) for each minute in a half-hour period using equation 1. These values were then compared against the dynamic “comfort requirement” threshold
established by Havenith, Holmer and Parsons (2002) and the “thermal constraint” threshold of 0.5 identified by Djongyang, Tchinda & Njomo (2010). Assuming a metabolic rate of 150, equation 2 dictates that the comfort requirement is 0.33.