Assessing Pedestrian Thermal Comfort within the Buenos Aires Climatic Context

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ABSTRACT

With over 50% of the world’s 6 billion people presently living in metropolitan areas and an estimated 70% projected by the year 2050 (UN-Habitat, 2010) urban environments have become the mean scenery for human activity. These environments are strongly subjected to the effects of buildings which shift wind patterns and limit solar radiation exposure. This research is a study on how these changes may directly affect the Buenos Aires city inhabitants. The methodology consists of three subsequent steps.

Firstly, three daily two hour time frames have been identified for the morning, midday and afternoon period. These represent three daily cycles for when pedestrian activity is at its highest. In addition, the climate was analyzed and the months were grouped into three climatic periods, cool, mild and warm. Both these studies have been crossed creating a nine time frame schedule which mixes climate and outdoor activity.

Secondly, iterations were carried out within each time frame in order to analyze the combined effects of air speeds and solar radiation levels upon the Physiological Equivalent Temperature (P.E.T) proposed by Hope (1998).

Lastly, the resulting P.E.T. has been weighed against De Dear’s adaptive thermal comfort equation proposed for indoor scenarios (De Dear, 1997). The amount of hours in which the resultant P.E.T. was within the established 90% acceptability for the different combinations were noted creating a trend for each of the nine time frames, represented by the comfort graphs.

These graphs show which combinations of air speed and solar radiation are going to be preferable over others for sedentary activities during the times when people tend to be outdoors. It was concluded that during the months with the cooler temperatures and lower solar angles, solar availability becomes less important thermally than wind protection, and vice versa.

INTRODUCTION

This investigation sets the bar for assessing open urban spaces in order to provide tools which work towards more thermally responsive metropolitan environments. Drawing people outdoors and prolonging their stays contributes to a more lively city offering greater interaction between its citizens, and encourages lower levels of energy consumption. For this case study, the city of Buenos Aires was chosen as a setting, as it presents a climate without extremes which could be exploited for sedentary activities throughout the year.

Initially, the climate data will be analyzed and broken down into three groups composing the annual cycle. Additionally, three key time frames are selected for their characteristic peak outdoor

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activity breaking down the daily cycle. As a result of this section, 9 time frames (3 for each of the 3 periods) are tagged as representative and identified as a schedule for outdoor occupancy.

Subsequently, the physiological equivalent temperature (PET) comfort model proposed by Hope (1998) is assessed and compared to Fanger’s (1970) predicted mean vote (PMV) model. Both these models are then related to each other and to comfort. Moreover, to account for user adaptation, an adaptive thermal comfort model proposed by De Dear (1997) is also balanced with the previous two models and comfort. PMV and PET simulations were carried out for a hypothetical individual. Using the results of these simulations, equations are estimated for predicting the effects upon PET of changing one’s clothing or metabolic rates. These equations are then carried for calculating the PET in a sedentary state with the Clo values corresponding to each of the climatic periods. Iterations are then carried out to understand the combined effects of solar and wind exposure upon PET for each of the established time frames. The results of these are then plotted into 9 comfort graphs corresponding to the nine time frames, showing the most desirable combinations of sun and wind exposure for each.

Finally, the effect of altering one’s exposure to sun while maintaining the same air speed during one time frame is related to the °K difference on PET. These results are then again plotted into one graph for each period assessing the extent of the adaptive opportunities individuals may have in outdoor scenarios.

The main contribution of this paper is to show for the nine time frames, which are the most favourable combinations of solar radiation and wind speed for sedentary activities to develop in the Buenos Aires climatic context. This methodology may well be translated and applied for different climates.

CLIMATE ANALYSES FOR OUTDOOR SEDENTARY ACTIVITIES

The weather data for the city of Buenos Aires (34°36’S; 58°22’W) here presented in Table 1. It is the data extracted of an average in the form of a typical meteorological year for the period between 1995 and 2005. In the table one may see how the abrupt changes of mean daily air temperature (column 2: Tm) was used to break down the annual cycle into a warm, mild and cool period. The former period does not present exceedingly high air temperatures at an average mean of 23°C. Nevertheless, the high levels of solar radiation along with absolute humidity recordings close to the limit recommended for comfort of 12 g/kg (Szokolay, 2008), could contribute to discomfort. During the mild period the mean temperature takes a step down going to mean daily values in between 15 to 20°C. However, there is still a high availability of solar radiation which in this scenario could be exploited. Finally, the cool period presents mean daily air temperatures in the range of 10 to 15°C which could potentially limit the development of outdoor sedentary activities.

<table>
<thead>
<tr>
<th>Month</th>
<th>Tm °</th>
<th>Tmin °</th>
<th>Tmax °</th>
<th>AH g/kg</th>
<th>RH %</th>
<th>GGHorn kWh/m²</th>
<th>GDhorn kWh/m²</th>
<th>Wind m/s</th>
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<tr>
<td>Jan</td>
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<td>16.3</td>
<td>32.8</td>
<td>13</td>
<td>67</td>
<td>7.1</td>
<td>4.3</td>
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<td>14.9</td>
<td>31.8</td>
<td>12</td>
<td>70</td>
<td>6.5</td>
<td>4.1</td>
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<td>72</td>
<td>5.2</td>
<td>3.2</td>
<td>3.3</td>
</tr>
<tr>
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<td>17.6</td>
<td>9.4</td>
<td>27.1</td>
<td>10</td>
<td>76</td>
<td>3.8</td>
<td>2.3</td>
<td>2.9</td>
</tr>
<tr>
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<td>14.8</td>
<td>7.0</td>
<td>24.5</td>
<td>8</td>
<td>78</td>
<td>2.8</td>
<td>1.7</td>
<td>2.7</td>
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<tr>
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<td>4.0</td>
<td>21.0</td>
<td>7</td>
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<td>1.0</td>
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<tr>
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<tr>
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<td>22.3</td>
<td>7</td>
<td>70</td>
<td>4.3</td>
<td>2.4</td>
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</tr>
<tr>
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<td>4.4</td>
<td>3.9</td>
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<tr>
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<td>11</td>
<td>64</td>
<td>7.0</td>
<td>3.7</td>
<td>3.8</td>
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</tbody>
</table>

Source: meteotest, 2006
TIME FRAMES

Outdoor spaces are extremely sensible to quick changes as time passes, therefore, it is important to isolate periods of time of higher relevance creating an outdoor “schedule”. This schedule is meant to address the time frames when outdoor activity is at its peak. These peaks tend to happen when people move from one building to the other usually matching rush hour times in the morning and the afternoon. Additionally, there is a drastic peak of pedestrian activity at midday when people go out for lunch. Therefore, three daily time frames have been established as of key relevance for people to be lured or to remain outdoors:

Crisscrossing these three time periods with the three previously established climatic periods gives way to the nine “time frames” (TF) which serve as a setting for this investigation.

PEDESTRIAN THERMAL COMFORT

The Rayman© research tool (Matzarakis & Rutz, 2006) was used for the comfort simulations, which require the inputs shown in Table 2 and estimates both, PET and PMV. The inputs required for the simulations are grouped into external and personal parameters. The former group varying with the context presented and the later depending on the different individuals. In this case the hypothetical individual here presented.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Parameter</th>
<th>Simulation Data</th>
</tr>
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<tbody>
<tr>
<td>External</td>
<td>Julian Date</td>
<td>Time frame</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>Time Period</td>
</tr>
<tr>
<td></td>
<td>Air Temperature</td>
<td>Time Frame</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity</td>
<td>Time Frame</td>
</tr>
<tr>
<td></td>
<td>Wind Velocity</td>
<td>Iterations</td>
</tr>
<tr>
<td></td>
<td>Cloud Cover</td>
<td>Time Frame</td>
</tr>
<tr>
<td></td>
<td>GGhor</td>
<td>Iterations</td>
</tr>
<tr>
<td>Personal</td>
<td>Gender</td>
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</tr>
<tr>
<td></td>
<td>Weight</td>
<td>75 Kg.</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>1.75 m.</td>
</tr>
<tr>
<td></td>
<td>Age</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Activity</td>
<td>Sedentary 100 W</td>
</tr>
<tr>
<td></td>
<td>Clothing</td>
<td>Climatic Period</td>
</tr>
</tbody>
</table>

For the simulations, mean air temperature and relative humidity was taken from each of the established nine time frames. However, for the solar radiation and wind velocity parameters, iterations were run. Solar radiation was simulated with increments of 100 W/m², and the upper limit was established by the maximum average found in the given period. Similarly, air speed iterations were run with increments of 0.5 m/s, and the upper limit for all time frames is set at 5 m/s which is the established maximum acceptable air speed for outdoor sedentary activities (Nikolopoulou, 2002).

The personal inputs were fixed for the values of a hypothetical individual while performing a sedentary activity. The only variable in this case is therefore the Clo input, as it is assumed that the same person would dress differently on relation to the climatic periods. Thus, this variation follows the yearly cycle, but not the daily one.

ESTABLISHING A RELATIONSHIP BETWEEN PET AND PMV WITH THERMAL COMFORT

As PMV was developed in a comfort chamber it is usually a tool made for assessing indoor comfort (Fanger, 1970), while The PET model was developed for translating outdoor combinations into a thermal equivalent. Moreover, the former model could be related to comfort through the percentage of
people dissatisfied (P.P.D.) while PET only gives a thermally equivalent temperature, which leaves the question of how comfortable one is unanswered. However, this model has been previously related to comfort (Matzarakis & Mayer, 1996) by estimating a fixed level of thermal stress corresponding to each thermal sensation. Although it is a significant contribution, this relationship does not consider personal adaptation to the annual climatic variations as it is the same sensation regardless of the climatic period. In order to account for user climatic adaptation, a link between PET and a model of adaptive comfort needed to be established. The model chosen for this task was the one presented by De Dear et al. (1997) originally intended for indoor settings and here presented in equation (1). The fact that PET is the thermal equivalent to an indoor setting is what allows for an effective comparison between these two models.

\[ T_n = 17.8 + 0.31 T_m \]  

(1)

\( T_n \): Comfort temperature  
\( T_m \): Monthly mean temperature

Subsequently, to plot the adaptive comfort band for 90% acceptability, De Dear et al. (1997) suggest adding and subtracting 2.5°C to the \( T_n \). The results of the application of this model and its band to the presented climate of Buenos Aires is here plotted in Figure 1. The three climatic periods previously presented are overlaid, establishing the upper and lower limits of adaptive comfort for 90% acceptability for each period.

![Figure 1: Adaptive comfort equation and 90% acceptability band presented for the year.](image)

Finally, the association is made between all the models and the degree of thermal stress as can be seen in Figure 2. To the left of the figure, the association presented by Matzarakis & Mayer (1996) is shown while to the right, the association is made with the model of adaptive comfort using the limits for each period found in Figure 1.

The initial link by Matzerakis and Mayer between comfort and PET resemble the ranges for the calculated bands of the cool period. However, the warmer the period the farther they stray. Therefore, this suggests that according to the adaptive model, people would prefer warmer temperatures during the warmer periods. At this point it needs to be recalled that adaptive model used supposes a limited array of adaptive opportunities commonly found in the interior of an office building. By contrast, in a successful outdoor scenario, the opportunities are plenty such as moving to sunny areas, or exposing oneself to faster air movements. This agrees with the argument that successful outdoor spaces are not those which meet one “optimal” comfort situation at a given time, but rather, offers several (Katschner, Steemers, & Yannas, 2000). Ultimately, this widens considerably the hypothetical comfort band.
RELATIONSHIP BETWEEN PET AND PMV

As the Rayman© tool allows the calculation of PET and PMV simultaneously for the same inputs, both results could be related to each other. However, when calculating PET values, the Rayman© tool keeps a fixed value for clothing and metabolic rate of 0.9 Clo and 80 Watts respectively and is not sensible to changes on these parameters. Nevertheless, this is not the case for the PMV simulations which are sensible to changes in all parameters. Therefore, a way to convert PET into PMV had to be addressed to understand the effects of changes in clothing and metabolic rates. For this task, simulations were carried out using the external data for all the days of the mild period during the morning time frame (8:00 & 9:00), for the case of the hypothetical person presented in Table 2 using the fixed values for Clo and metabolic rates (0.9 Clo and 80 W). The resulting PET values where linked to their PMV counterparts. This relationship is here shown in Figure 3.

Once this relationship had been established, the equation that enables the conversion of PMV results into PET was extracted (2).

\[
\text{PET} = 5.93 \times (\text{PMV}) + 21.3
\]
Through this equation the corresponding changes upon PET for different metabolic rates and/or Clo values became distinguishable. However, to understand the incidental change of one of the parameters, the other one has to be isolated. To accomplish this, runs are made calculating both PMV and PET while maintaining one of the two fixed and the other as a variable. Starting with the incidence upon PET for changes in Clo, a simulation is made for all the hours of the morning time frame during the warm period. For this simulation, the data for the hypothetical person was used with an 80W activity rate (fixed value) and a 0.5 Clo (corresponding to the warm period). The PMV output estimates the 0.4 Clo difference, but the PET does not. Therefore, by converting the PMV into PET' and weighing against the resulting PET, it will be possible to determine the effect of a 0.4 Clo change upon PET. Dividing this difference by 4 allowed to determine the effect of a change in 0.1 Clo for each of the different hours. A similar methodology was followed to determine the effect of a 20W increase or decrease of activity rate upon thermal comfort through PET. Both results are here plotted in Figure 4.

![Figure 4: °K incidence of adding or subtracting 0.1 Clo (left) or 20W (right)](image-url)

Upon observation of these figures, it becomes evident that the cooler the setting, the higher the effects of clothing and metabolic rate. Additionally, due to the similarity between both curves, it may be stated that adding a light pullover (0.20 Clo) is thermally similar to changing one’s activity rate from light to medium work intensity (120W and 160W respectively) (Szokolay, 2008), and the increment in PET will be more effective in cooler periods. Both equations are here presented.

\[
\text{Incidence of } \pm 0.1 \text{ Clo} = -0.0856 \times \text{PET} + 2.9 \tag{3}
\]

\[
\text{Incidence of } \pm 20 \text{ W} = -0.092 \times \text{PET} + 3.6 \tag{4}
\]

It needs to be stated at this point that both these formulas become less reliable when approaching extremes. This is due to the fact that it is based on a PMV conversion into PET, and it was already found by Nicol & Humphreys (2002) that the former model may not be reliable for temperatures below 10°C or above 30°C. Nevertheless, for the purposes of this study it does not present major problems as the focus is placed within the comfort areas which should be well off the extremes.

**APPLICATION OF THE FORMULAS – THE COMFORT GRAPHS**

As it becomes possible to convert the effects of both Clo and Metabolic rates, PET simulations for the presented hypothetical person are carried out for each of the presented nine periods. For the warm, mild and cool periods, different Clo values of 0.5, 0.9 and 1.2 were assigned respectively matching Argentinian’s cultural trends and responses to climate. The data from all the hours of each of the nine periods was used. Iterations were run for wind speeds from 0.5 to 5 m/s which is the established upper limit for comfort for sedentary activities outdoors (Nikolopoulos, 2002). Similarly, iterations
were run for solar radiation starting at 100W up to different limits established by the values found within each climatic period, with intervals of 100W (for the case of the cool period, 50W intervals were used).

Figure 5: Comfort graphs for each of the nine time frames. Each gradient represents a different percentage of hours in which the simulated PET for the hypothetical individual is within the 90% comfort band calculated for the different combinations of air speed and solar exposure.

All results for each hour were then weighed against the adaptive comfort limits calculated for each climatic period shown in Figure 2. This assessment was carried out to determine the percentage of hours
in which the different combinations of solar radiation and air speed result in PET values which fall within a 90% acceptability. This was done so, in order to produce graphs which would have a double entry, solar radiation and air speed, and therefore, understanding the comfort limits offered by a space. The resulting comfort graphs are here shown for all nine time periods in Figure 5.

The graph corresponding to the morning time frame of the warm period (upper right) will be used as an example. Supposing a scenario which presents a global solar radiation of 400W and 3 m/s, it may be distinguished that 10-20% of all of these hours, the hypothetical person will be with a PET value within the 90% acceptability band. This does not mean that these combinations would be uncomfortable 80-90% of the time, but it does mean that overall, a place which offers more wind protection will be more desirable at this moment. Additionally, it can be seen that the cool period presents the widest ranges of comfort. This could be misleading however, as this is mainly due to the effect of higher clothing which has a stronger effect under colder conditions rather than a reliance on the external conditions. Finally, the more slanted the lines are, the higher the effect of solar radiation in the given period and vice versa. Therefore, it may be concluded that thermally speaking, clothing takes precedence over the effects of solar radiation and air velocities during the cool period, yet wind protection is more highly desirable.

CONCLUSION

With the use of the comfort graphs presented one may predict through simulation which outdoor spaces would tend to be more comfortable than others for sedentary activities, within the Buenos Aires climatic context. It is clear that there is no such thing as an optimal combination for any period. Therefore, it is argued that the approach to achieving outdoor comfort should not focus on providing one ideal sensation, but rather offer several within close walking distances. The correct approach would therefore consist of providing a number of varieties with the appropriate combinations at the times when the outdoors has the highest potential to attract people, allowing the users of these spaces to find their own comfort.

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REFERENCES