Measuring the Effectiveness of San Francisco's Planning Standard for Pedestrian Wind Comfort

Hyungkyoo Kim
Department of Urban Design and Planning, Hongik University, Seoul, South Korea
gusailsang@gmail.com

Elizabeth Macdonald
Department of City and Regional Planning and Department of Landscape Architecture and Environmental Planning, University of California, Berkeley, California, USA
emacdon@berkeley.edu

Corresponding Author
Hyungkyoo Kim
Address: Department of Urban Design and Planning, Hongik University, 94 Wausan-ro, Mapo-gu, Seoul, 04066, South Korea
Phone number: +82-10-9912-9413
Email: gusailsang@gmail.com

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Abstract

In 1985, San Francisco adopted a wind comfort standard in its Downtown Area Plan in response to increasing concerns about the city’s downtown public open spaces becoming excessively windy. After 30 years of implementation, this study revisits the standard and examines its effectiveness in promoting pedestrian comfort. 701 valid samples were collected from 6 months of field study, which combined surveying pedestrians and on-site collection of microclimate data. Statistical analysis and an assessment using the physiological equivalent temperature (PET) show that 11 mph (4.92 m/s), the comfort criterion in places for walking, performs as an effective determinant of outdoor comfort in San Francisco. This study sheds light on climate-resilience of cities as they have become key urban challenges today.

Keywords

Wind, Outdoor thermal comfort, Urban planning, Field study, Physiological equivalent temperature, San Francisco

1. Introduction

In 1985, San Francisco became one of the first cities in North America to adopt a Downtown Area Plan, which was supplemented by City Planning Codes, on ground-level wind currents to mitigate adverse effects of wind. This approach was in response to increasing public concerns over the deteriorating environmental quality of the city's public open spaces. It was perceived that many of those spaces located in the downtown area became uncomfortable places to walk or stay due to excessive ground-level winds and shade induced by the surrounding high-rise buildings (Vettel 1985). These were side effects of the 'Manhattanization' of San Francisco in the 1960s and 1970s, during which arrays of high-rise buildings that dominate San Francisco's urban skyline today were constructed (Vettel 1985; Keating & Krumholz 1991; Hartman 2002).

Since then, the plan has mandated that new developments in five parts of the city, including most parts of the downtown area as well as four additional areas, as illustrated in Figure 1, all associated with high density or development potential and substantial pedestrian activities, be designed or adopt measures to mitigate ground-level wind current in surrounding public streets and open spaces. To ensure acceptable comfort, the plan required that the equivalent wind speed (EWS) in areas where people are seated and where people are walking should not exceed 7 mph (3.13 m/s) and 11 mph (4.92 m/s), respectively, for no more than 10 percent of the time year round, between 7 am and 6 pm. An additional measure, 26 mph (11.62 m/s) for no more than 1 hour per year, was adopted to secure pedestrian safety (City and County of San Francisco 1985).[i]

This approach has been in effect for 30 years in San Francisco as a planning measure to promote comfort in the city's outdoor spaces and has influenced the design of many new buildings in its downtown. It has also inspired planners in Toronto, Canada, in developing a similar solution to mitigate the adverse effects of wind (Bosselmann et al. 1990, 1995), and other North American cities like New York City, Boston, and Chicago have adopted similar approaches (American Society of Civil Engineers 2004).

Recent literature witnesses substantial interest in the impact of microclimate or weather conditions on the perceived outdoor comfort of pedestrians in cities. (de Montigny et al. 2012; Saneinejad et al. 2012; Böcker et al. 2013; O'Neil et al. 2013; Pantavou et al. 2013; Clarke et al. 2014; Liu et al. 2014). A growing number of studies pay specific attention to the role of wind on people's walking behavior and present mixed findings(Aultman-Hall 2009; Tucker & Gilliland 2007; Chan & Ryan 2009; Zheng S et al. 2013; Stathopoulos & Blocken 2016; Zheng C et al. 2016).

Directly related to San Francisco's wind comfort standard, Arens et al. (1989) introduced the development of the standard and research it was built on. Several studies discussed the significance of San Francisco's approach in urban planning and design practice but without any empirical analysis (Loukaitou-Sideris & Banerjee 1993; Bosselmann 1998; Marcus & Francis 1998; Brown & DeKay 2001; Gehl 2010; Donn 2011; Gehl & Svarre 2013). Bosselmann et al. (1988) investigated outdoor thermal comfort in San Francisco using field survey and simultaneous collection of microclimate data, and Arens and Bosselmann (1989) estimated thermal comfort under different surrounding development conditions. Zacharias et al. (2004) studied the relationship between microclimatic conditions and people's behavior in San Francisco's several downtown public open spaces. But none of these studies attempted empirical examination of whether San Francisco's thirty-year effort in promoting wind comfort in its public open spaces has been successful. More recently, Kim and Macdonald (forthcoming) examined changes in San Francisco's urban form and the resulting wind environment after adoption of the wind planning approach in 1985, and Kim and Macdonald (2016) explored to what extent wind discourages sustainable transportation mode choice in San Francisco. These two studies present findings related San Francisco's attempt to promote wind comfort but lack examination of the wind comfort standard itself and suggest further investigation.

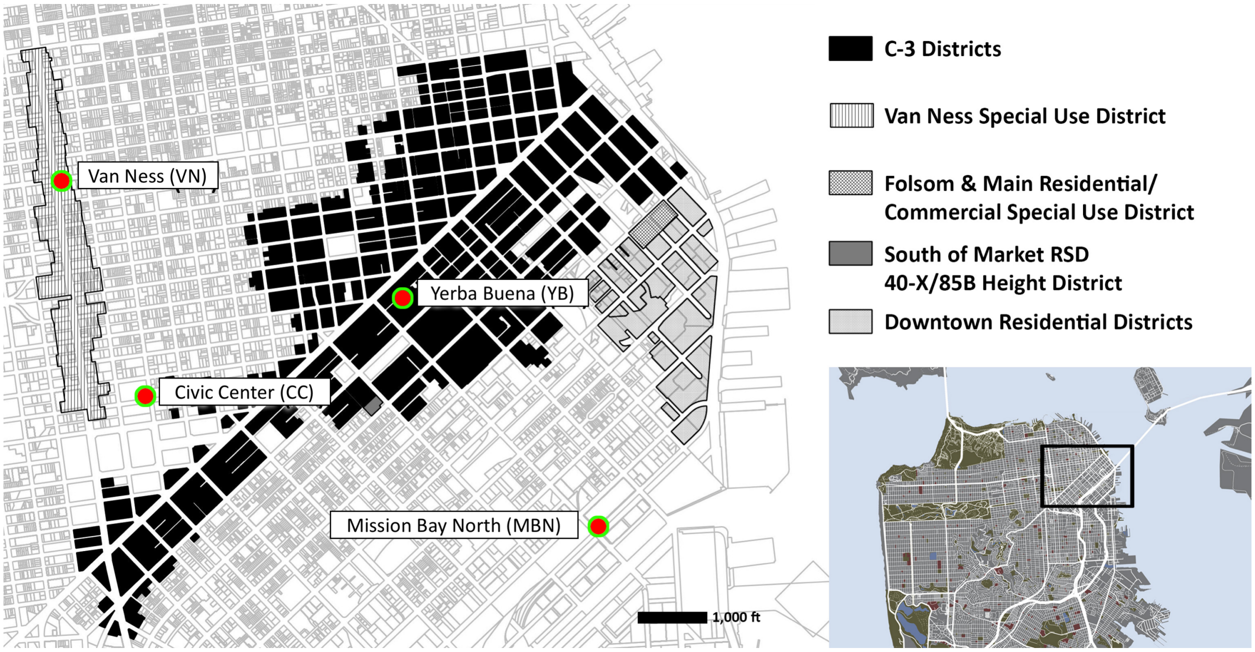

Figure 1. The five areas subject to San Francisco's wind planning and the four selected locations for field study.

In light of the issues raised so far, this study revisits San Francisco's wind comfort standard adopted in the Downtown Area Plan and City Planning Codes in 1985 and examines whether it performs as an effective determinant of outdoor comfort in the city after thirty years of implementation.

2. San Francisco’s Wind Comfort Standard

Planners of San Francisco adopted the two comfort criteria, 3.13 m/s in areas for sitting and 4.92 m/s for walking, and a safety criterion, 11.62 m/s, based on findings from a series of studies that examined the relationship between the mechanical effect of wind on people’s acceptable range of comfort and safety (Davenport 1972; Penwarden 1973; Penwarden & Wise 1975; Hunt et al. 1976; Jackson 1978; Lawson 1978; Melbourne 1978; Arens 1981). The maximum permissible duration per year, 10 percent, where wind speeds can exceed the allowable limits was decided based on findings of Penwarden (1973). The selection of time interval of interest, between 7 am and 6 pm, came from Arens et al. (1989) to represent a period when the city’s population is most exposed to the wind.

The concept of EWS, instead of mean wind speed, was used in determining the wind comfort and safety levels in San Francisco. It reflects the speed and flow of wind that are rarely constant in outdoor urban environments and is defined as a mean wind speed adjusted to incorporate the effects of gustiness of wind on pedestrians (Arens et al. 1989). The gustiness metric is turbulence intensity which is the root-mean-square of wind speeds measured over a period of time, divided by the mean speed. The EWS and turbulence intensity are expressed as Formulae 1 and 2, respectively.

$$U_{eqv} = \acute{U} \times (1 + 3I) \tag{1}$$

$$I = \frac{1}{\acute{U}} \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(U_i - \acute{U}\right)^2} \tag{2}$$

where U_{eqv} = EWS; $\acute{U}$ = mean wind speed; I = turbulence intensity; and U_i = wind speed measured at i.

3. Methods

A field study that consisted of pedestrian survey and on-site recording of microclimate conditions was the main mode of data collection in this research. The survey focused on people's perception of wind and comfort. The microclimate data, collected using a meteorological station and solar power meter, included wind speed, temperature, solar radiation, and relative humidity.

Among the three criteria, we were able to measure only the effectiveness of 4.92 m/s, the comfort criterion in areas for walking. Because the participants of the field study were all pedestrians who were walking by and were standing up while being questioned, it was practically impossible for us to study the effectiveness of 3.13 m/s, the comfort criterion in areas for sitting. 11.62 m/s, the safety criterion, was not studied either because of its very low probability of occurrence and of concerns on safety while carrying out research.

3.1. Selection of Study Areas

We selected four locations in San Francisco for the field study after carrying out close observations of pedestrians and their behavior in a number of public open spaces in San Francisco. As indicated in Figure 1, they are (1) Yerba Buena Lane in the Financial District, (2) southeast corner of Van Ness Avenue and California Street intersection along the Van Ness Avenue Corridor, (3) northeast corner of Golden Gate Avenue and Larkin Street intersection in the Civic Center neighborhood, and (4) north corner of 4th and King Streets intersection in Mission Bay North. For convenience, we refer to the four locations as YB, VN, CC, and MBN respectively, in the rest part of this study. Common conditions of the four locations include medium to high development density so that ground-level wind currents are frequently accelerated by tall buildings, high level of ambient wind speed so that a wide range of wind speed can be covered, and high volume of pedestrian traffic so that a large sample size can be acquired.

Located in the Financial District, the central business district of San Francisco, YB is a 170-meter-long car-free open space surrounded by high-rise buildings that exceed 40 stories. It accommodates a wide range of pedestrian activities, including walking, sitting, eating, standing, and lingering, and provides connections to major streets, open spaces, and retail shops in the area. VN is a vibrant street corner along the Van Ness Avenue Corridor, a major thoroughfare that runs north-south between the South of Market and Marina District neighborhoods. At VN, pedestrians engage in diverse activities, such as going to a bank or coffee shop, using ATM machines, and waiting for cable car or pedestrian signal to cross the streets. Located at the southeast corner of an open space sandwiched between several high-rise buildings, CC is also a place where a large volume of pedestrian traffic exists mostly by office workers and tourists. MBN is a focal point for pedestrian activity in the Mission Bay North neighborhood where many people are lingering, shopping, having coffee, and waiting for pedestrian signal to cross the streets. Originally an active industrial waterfront, today MBN stands close to the Caltrain Station and AT&T Park and accommodates many high-rise condominiums and mixed-use buildings.

3.2. Survey Design

The field study focused on examining the effectiveness of 4.92 m/s, the comfort criterion in the area for walking, in determining outdoor comfort in San Francisco. We identified relevant independent and dependent variables from the ANSI/ASHRAE Standard 55-2010 Thermal Environmental Conditions for Human Occupancy (American Society of Heating, Refrigerating, and Air-Conditioning Engineers 2010). We also reviewed a body of high-impact studies that investigated factors affecting people's comfort in public open spaces for key additional variables (Nikolopoulou et al. 2001; Spagnolo & de Dear 2003; Thorsson et al. 2004, 2007; Eliasson et al. 2007; Nikolopoulou & Lykoudis 2007; Lin, 2009; Lenzholzer & van der Wulp 2010; Chen & Ng 2012; Cheng et al. 2012; Villadiego et al. 2014). The independent variables include those on individual characteristics of survey participants (gender, metabolic rate, clothing insulation, and time spent outside in the last 1 hour), location, and microclimatic conditions (EWS, temperature, solar radiation, and relative humidity). The dependent variables were three measures that successfully quantify perceived outdoor comfort, which are thermal sensation (-3: *cold*; -2: *cool*; -1: *slightly cool*; 0: *neutral*; 1: *slightly warm*; 2: *warm*; 3: *hot*), wind sensation (-2: *no wind*; -1: *slight wind*; 0: *moderate wind*; 1: *strong wind*; 2: *very strong wind*), and wind preference (-1: *I want more wind*; 0: *neutral*; 1: *I want less wind*).

Among these variables, time spent outside in the last 1 hour and the three dependent variables were directly asked of the participants. Metabolic rate was collected by asking the participants to list their engaged activities in the last 1 hour and for how long (e.g., working at desk for 40 minutes, having lunch for 10 minutes, and walking for 10 minutes). Each activity was converted to a time-weighted 'met' value, using the ANSI/ASHRAE Standard 55-2010. The insulation performance of each garment was converted to a 'clo' value by following the same standard. Gender, clothing insulation, and location were not directly asked but recorded by surveyor based on observation. All variables on microclimatic conditions were collected with a meteorological station and a solar power meter.

3.3. Collection of Microclimate Data

The meteorological station consisted of four parts, which are Kestrel 4500NV Weather Tracker, rotating vane mount, tripod, and signboard. Wind speed, temperature, and relative humidity were measured and recorded by the Weather Tracker that has an accuracy level of +/- 3% for wind speed, +/- 0.5 °C for temperature, and +/- 3% for relatively humidity. It was placed on the vane mount, which rotated with the wind. The Weather Tracker and the vane mount were securely fixed on the tripod at a height of 1.5 meters above the ground level. The signboard was set up to attract pedestrians to participate, but not providing any information about the survey topic to minimize bias. In addition, Ambient Weather SP-216 Solar Power Meter was used to collect solar radiation data. It has an accuracy level of +/- 10 W/m^2 or +/- 5%. When measuring solar radiation, it was hand-held vertically above the ground surface at a height of 1.5 meters, away from any obstacles.

3.4. Field Study Procedure

We carried out the field study at the four selected study locations, YB, VN, CC, and MBN, on weekdays from noon to 5 pm to catch both lunch and commuting pedestrian traffic, and for 6 months from July, the windiest and second hottest month in San Francisco, to December, the least windy and coldest month so as to encompass a wide range of meteorological conditions. On days after early November when the daylight saving time was no longer in effect, the field study ended at 4 pm, because the solar radiation neared zero around that time. We did not conduct any field study on wet days.

The meteorological station was set up so as not to interfere with any pedestrian traffic or commercial activities in the vicinity. The surveyor stood 2 meters away from the station. Microclimate data was set up to be automatically logged at every 10 seconds. Participants were asked to stand 3 meters away from the station and not in the direction where wind was blowing from in order not to block any wind. The surveyors recorded each participant's gender, clothing status, and time when the survey began and ended on a separate sheet. Each participant spent 3 minutes on average to complete the survey. The EWS was calculated based on the wind speed data continuously collected during this 3-minute period. This recording restarted whenever there was a new participant. Readings of temperature, relative humidity, and solar radiation collected at the beginning of each survey were recorded as they remained constant during the 3-minute period.

We collected 701 valid samples out of 709 from a total of 26 field studies. The number of invalid samples was significantly reduced by keeping the survey compact and simple. Also, the surveyor stood closely to the participants to review the survey as they filled it out to provide prompt assistance.

3.5. Data Analysis

After coupling survey results with microclimate data, this study follows several studies on a similar topic that combine two analytical approaches in verifying significant differences in the perceived outdoor comfort (Liu et al. 2016; Middel et al. forthcoming) between when the EWS is below the criterion and when above or equal to the criterion: statistical analysis and a thermal comfort index. This is intended to complement each approach and reinforce the findings.

A body of studies used statistical analyses to estimate the impacts of microclimate and individual physiological parameters on perceived outdoor thermal comfort (Pearlmutter et al. 2014; Tung et al. 2014; Creemers et al. 2015; Kim & Macdonald 2016). While some of them considered the dependent variables to have interval properties, meaning that the distances between each vote are equal for convenience of analysis, we argue that it may make more sense to regard them as ordinal since the distances are likely to be unequal. We adopted piece-wise ordinal logistic regression models so as not only to incorporate the nature of the dependent variables but also to distinctively measure the impacts under the two different wind conditions. All independent variables introduced earlier were included in the models to estimate thermal sensation, wind sensation, and wind preference. We also applied relevant statistical tests to verify the differences between the two wind conditions.

Second, we carried out an assessment of thermal comfort based on physiological equivalent temperature (PET), a thermal comfort index that is one of the most widely used for evaluating outdoor thermal comfort (Hwang et al. 2011; Chen & Ng 2012). PET is defined by Mayer and Höppe (1987) and Höppe (1999) as the air temperature, expressed in °C, in which the human energy balance under indoor conditions equals the energy balance, for the same skin temperature and rhythm of perspiration, as in the actual outdoor conditions. PET builds upon the Munich Energy Balance Model for Individuals and incorporates various microclimate variables, such as air temperature, relative humidity, wind speed, and global radiation, and thermos-physiological variables, such as clothing insulation and activity levels of an individual. Although PET was originally developed in Germany, research has readily demonstrated the effectiveness of its application to the American context (Hall et al. 2016; Taleghani et al. 2016; Crewe et al. forthcoming; Middel et al. forthcoming). In this study, we computed PET from the field study data using the RayMan software (Matzarakis et al. 2007, 2010).

4. Results

4.1. Descriptive Statistics

Among the 701 participants who provided valid samples, there were more men (58%) than women (42%). YB had the most participants (34%) and was followed by CC (26%), VN (23%), and MBN (17%). The metabolic rate of each individual ranged between 0.6 met and 4.5 met with a mean of 1.7 met; the clothing level between 0.30 clo and 1.64 clo with a mean of 0.86 clo; and the time spent outside in the last 1 hour between 0 and 60 minutes with a mean of 26 minutes. The numbers of participants from each of the four locations were relatively evenly distributed. The EWS ranged between 0.85 m/s and 13.05 m/s with a mean of 5.23 m/s. Among the 701 samples, 334 were below 4.92 m/s, the comfort standard at question, and 367 were above or equal to the criterion. Air temperatures were between 12.3 °C and 24.3 °C with a mean of 17.4 °C, solar radiation between 6 W/m^2 and 949 W/m^2 with a mean of 238 W/m^2, and relative humidity between 46.2% and 94.4% with a mean of 69.8%.

4.2. Statistical Analysis

To examine the effectiveness of 4.92 m/s, the comfort criterion for walking areas, it was critical to verify whether there are any significant differences in people's comfort levels between a condition in which the EWS is less than 4.92 m/s and another in which the speed is 4.92 m/s or higher. First, we compared the frequency distributions of people's votes to the three comfort measures. Their differences were tested using Kruskal-Wallis one-way ANOVA. Second, we used a series of piece-wise ordinal logistic regression models to estimate the impacts of each driver of outdoor comfort. With a specific focus on the EWS, we compared its coefficients under the two wind conditions using the Chow Test analog to verify their differences.

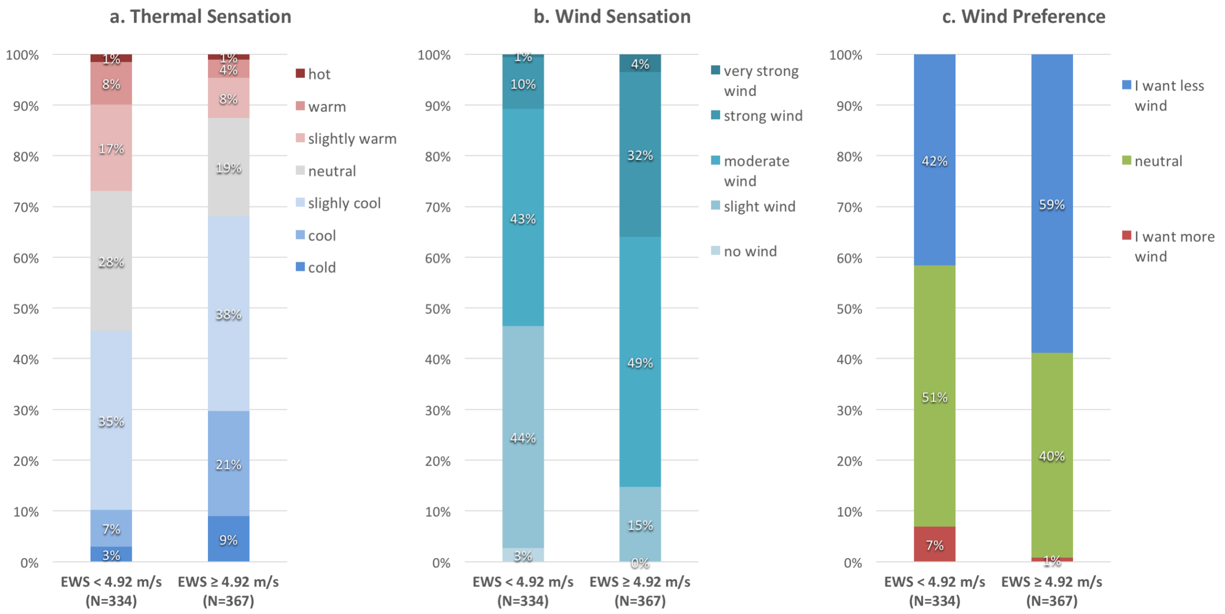

Figure 2. Frequency distribution (in percent) of (a) thermal sensation votes, (b) wind sensation votes, and (c) wind preference votes.

Figure 2 shows clear differences in the votes under the two wind conditions. Figure 2a depicts that when the EWS is below the criterion, 45% of the subjects voted for cold, cool, or slightly cool, and 26% for hot, warm, or slightly warm. When the EWS is above or equal to the criterion. 68% responded that they were feeling cold, cool, or slightly cool, and 13% hot, warm, or slightly warm. The χ^2-with-ties statistic generated by Kruskal-Wallis one-way ANOVA is

53.8 ($p < 0.001$), meaning that a significant difference exitst in thermal sensation votes between the two wind conditions.

Likewise, as shown in Figure 2b, which presents wind sensation votes, 47% voted for no or slight wind when the EWS is below the criterion, and 11% for strong or very strong wind. However, when the EWS is above or equal to 4.92 m/s, only 15% perceived no or slight wind while 36% strong or very strong wind. The χ^2-with-ties statistic is 108.2 ($p < 0.001$), meaning that the wind sensation votes under the two wind conditions significantly differ from each other.

Figure 2c shows that when the EWS is below the criterion, 7% preferred more wind, and 42% less wind. When the EWS is is above or equal to the criterion, only 1 preferred more wind, and 59% less wind. The χ^2-with-ties statistic is 26.0 ($p < 0.001$), suggesting that the wind preference votes under the two wind speed conditions are significantly different.

Our next step was to use a series of ordinal logistic regression models and compared the regression coefficients of EWS under the two wind speed conditions to verify the differences. The comparison was made with Chow Test analog. It is variation of regular Chow Test, a tool more frequently used for linear regression models. The Chow Test analog is suitable for testing whether the coefficients in two logistic regression models on different data sets are equal to each other (DeMaris 2004).

Table 1 presents estimation results from the piece-wise ordinal logistic regression models. In all cases, the EWS turns out to be a statistically significant factor at least at the 0.05 level, meaning that it is impactful in estimating thermal sensation, wind sensation, and wind preference when it is below 4.92 m/s and when above or equal to the criterion.

Table 1. Piece-wise ordinal regression models predicting thermal sensation, wind sensation, and wind preference.

Variable	**Thermal sensation**		**Wind sensation**		**Wind preference**	
	EWS<4.92	**EWS≥4.92**	**EWS<4.92**	**EWS≥4.92**	**EWS<4.92**	**EWS≥4.92**
Individual						
Gender (female=1) ^{a}	-0.5363*	-0.5282**	0.3683	0.1739	0.5858*	0.4222
Metabolic rate (met)	0.2476	0.3970	0.0514	-0.1342	-0.6368**	-0.2778
Clothing insulation (clo)	0.0354	0.3930	-0.7671	0.0782	0.4918	0.1134
Time spent outside in the last 1 hour (minutes)	0.0168**	0.0065	-0.0122	0.0061	-0.0033	-0.0076
Location						
Location YB (YB=1) ^{a}	-0.4117	-0.4337	-0.1286	-0.6091	0.0212	0.2806
Location VN (VN=1) ^{a}	1.1569*	0.4123	-0.5865	0.3745	-1.7320***	-0.0088
Location CC (CC=1) ^{a}	0.7345*	0.6525	-1.1690***	-0.7765	-1.5113***	-0.4785
Microclimatic condition						
EWS (m/s)	-0.2415*	-0.2029**	0.9825***	0.3561***	0.4538***	0.2646**
Temperature (°C)	0.3547***	0.5893***	-0.2067**	-0.2674**	-0.1369	-0.3353***
Solar radiation (W/m^2)	0.0009	0.0014*	0.0011*	-0.0004	0.0014**	-0.0001
Relative humidity (%)	-0.0250	0.0264	0.0112	-0.0450*	0.0394**	-0.0405*
Summary statistics						
N	334	367	334	367	334	367
Log likelihood	-468.770	-506.616	-317.188	-366.156	-262.957	-239.947
Likelihood ratio χ^2	124.21	158.33	90.76	85.44	69.17	46.75
p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
McFadden's pseudo R^2	0.117	0.135	0.125	0.105	0.116	0.089

Notes: a. dummy variable
$* p < 0.05$, $** p < 0.01$, $*** p < 0.001$

For thermal sensation, the coefficient of the EWS is -0.2415, when it is below the criterion, and -0.2029, when above or equal to the criterion. In other words, when the EWS is below the criterion, for a 1 m/s increase in the EWS the odds of the combined higher categories of thermal sensation (towards warm or hot) would be 0.7854 (= $e^{-0.2415}$) times lower than the combined lower categories (towards cool or cold), given the other variables are kept constant. When the EWS is above or equal to the criterion, a 1 m/s increase in the EWS would result in 0.8164 (= $e^{-0.2029}$) times lower odds of the combined higher categories of thermal sensation than the combined lower categories. The summary statistics of the three models suggest that they are statistically significant. The χ^2statistic from the Chow Test analogue is 14.5325 (df = 11), indicating that difference between the two coefficients is not statistically significant at the 0.05 level.

Similarly, in estimating wind sensation, the models suggest that for a 1 m/s increase in the EWS, when below the criterion, the odds of the combined higher categories (towards strong or very strong wind) of wind sensation would be 2.6711 (= $e^{0.9825}$) times higher than the combined lower categories (towards no or slight wind). When the EWS is above or equal to the criterion, for a 1 m/s increase in the EWS the odds would be 1.4278 (= $e^{0.1592}$) times higher. The summary statistics show significance of the three models. The χ^2 statistic from the Chow Test analogue is 39.4605 ($df = 11$), meaning that the two coefficients are significantly different from each other ($p < 0.001$).

In estimating wind preference, the models present that for a 1 m/s increase in the EWS, when below the criterion, the odds of the combined higher categories (towards 'I want less wind') would be 1.5462 (= $e^{0.4358}$) times higher than the combined lower categories (towards 'I want more wind'). When the EWS is above or equal to the criterion, for a 1 m/s increase in the EWS the odds would be 1.3029 (= $e^{0.2646}$) times higher. The summary statistics is 28.1332 ($df = 11$), meaning that the two coefficients are significantly different from each other ($p < 0.01$).

In sum, it seems clear that a 1 m/s increase in the EWS, when it is below 4.92 m/s, is more likely to make a larger impact on making pedestrians feel cooler or colder, perceive the wind to be stronger, and prefer less wind than when the EWS be above or equal to the criterion. Although the difference in the case of thermal sensation is not statistically significant, we are able to make an interpretation that pedestrians are more sensitive to wind when the EWS is below the criterion but become less susceptible once the EWS passes the threshold, 4.92 m/s.

4.3. Assessment using PET

The RayMan calculation presents that when the EWS is below 4.92 m/s, the PET values range between 7.8 °C and 43.1 °C with the mean at 15.7 °C ($SD = 6.2$). When the EWS is above or equal to the criterion, the valued range between 5.2 °C and 35.6 °C with the mean at 12.4 °C ($SD = 4.5$). It can be interpreted that the PETs are generally lower when it is windier. A T-Test suggests that the two means are significantly different ($p < 0.001$).

The most widely used way of carrying out an assessment of thermal conditions using PET is calculating the neutral temperature and thermal acceptable range. Neutral temperature is the optimal temperature at which people perceive neither cool nor warm but feel comfortable (Fanger 1972). Accordingly, the neutral PET (nPET) is where the the mean thermal sensation vote (MTSV) equals zero. We calculated the MTSVs for every temperature interval with a bins width of 1 °C PET. Formulae 3 and 4 show the best fitted linear equations, and Figure 3 visualizes linear regression models. According to the regression lines, the nPET when the EWS is below 4.92 m/s (18.7 °C) is lower than that when the EWS is above or equal to the criterion (20.1 °C). This suggests that pedestrians in San Francisco accept lower temperatures when there is less wind but expect higher temperatures to be in a thermally neutral state in windier conditions.

$$\text{EWS} < 4.92\text{ m/s: } MTSV = 0.081 \cdot PET - 1.5186\ (R^2 = 0.74) \tag{3}$$

$$\text{EWS} \geq 4.92\text{ m/s: } MTSV = 0.1102 \cdot PET - 2.2173\ (R^2 = 0.75) \tag{4}$$

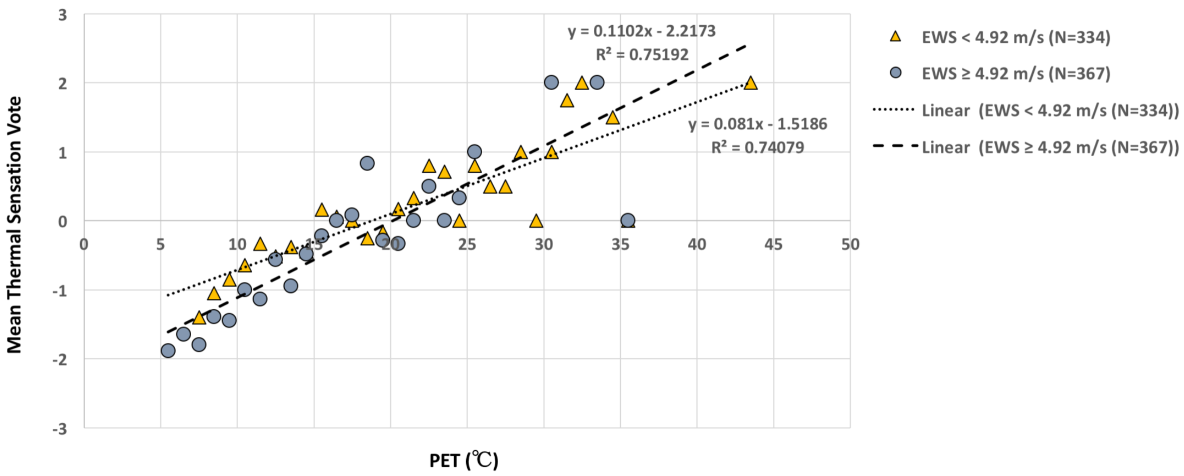

Figure 3. Linear relationship between PET binned at 1 °C and MTSV.

The second approach is to calculate the thermal acceptable range. It is based on the notion that an acceptable thermal condition is in which a substantial majority would agree that they feel thermally acceptable. The ANSI/ASHRAE Standard 55-2010 (American Society of Heating, Refrigerating, and Air-Conditioning Engineers 2010) specifies acceptable thermal environment as those conditions that 80 percent of the occupants would perceive thermally acceptable; i.e., 20 percent would find thermally unacceptable. The standard also presents that thermal sensation votes outside the three central categories (-1, 0, and 1) are considered unacceptable. Figure 4 shows the survey participant's percentage of thermal unacceptability rate for each 1 °C PET bin and the best fitted second-degree polynomial curves for the two wind conditions. When applying the 80 percent rule, which means that the thermal unacceptability rate equals 20 percent, our calculation shows that the lower boundaries are 10.9 °C, when the EWS is below the criterion, and 15.7 °C, when above or equal to the criterion. This indicates that in low wind level conditions, the majority of pedestrians would start feeling thermally unacceptable at a considerably lower temperature than in high wind level conditions. In other words, when there is strong wind, a higher temperature is required to keep people thermally acceptable.

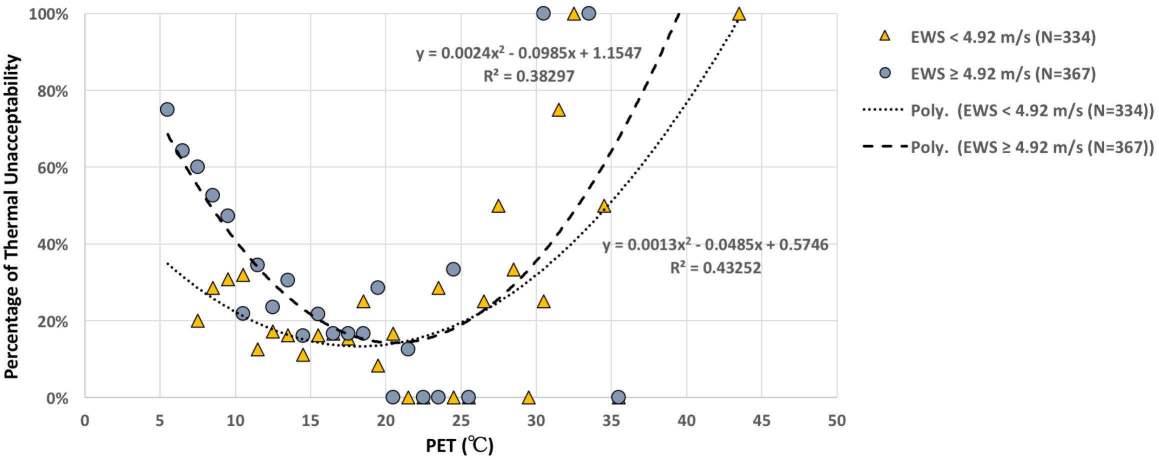

Figure 4. Second-degree polynomial relationship between PET binned at 1 °C and percentage of thermal unacceptability.

5. Conclusion

5.1. Summary of Findings

This study examined whether the wind comfort standard of San Francisco, stipulated in the city's Downtown Area Plan and City Planning Codes, performs as an effective determinant of outdoor comfort in the city. Specifically, it investigated the performance of 4.92 m/s, the wind speed criterion for comfort in places for walking. A 6 month-long field study at four locations in San Francisco and the follow-up analysis present the following findings.

First, our initial observation of the votes of thermal sensation, wind sensation, and wind preference identified clear differences in their distribution between when the EWS is below 4.92

m/s and when above or equal to the criterion. Second, a series of piece-wise ordinal logistic regression models and Chow Tests analog revealed the significance difference in the impact of wind speed on wind sensation and wind preference when other variables were kept constant, but less so in the case of thermal sensation. Third, using the PET, we were able to verify that the temperature at which people feel thermally neutral or acceptable has to be higher when the EWS is above or equal to 4.92 m/s than when it is below the criterion. Overall, we conclude from the findings that the criterion operates well as a determinant of outdoor comfort in San Francisco's public spaces.

5.2. Concluding Remarks

There are several shortcomings of this study. First, the effectiveness of the other comfort criterion in areas for sitting, 3.13 m/s, and the safety criterion, 11.62 m/s, has not been identified in this study. Future studies can take on this for further evaluation of San Francisco's wind comfort and safety standards. Second, a larger sample size collected from more than four locations in the city and over a longer period of time would have enhanced the accuracy and representativeness of study findings.

There are two issues that need discussion. The first is whether 4.92 m/s is the only ideal standard in areas for walking in San Francisco. Although the study findings suggest that in overall it performs as an effective determinant of outdoor comfort in the city, we are not able to verify whether other wind speeds, such as 4.47 m/s (10 mph) or 5.36 (12 mph), may outperform the existing criterion. A complete outdoor thermal comfort study in San Francisco in the future may provide an answer to this. The other is the generalizability or exportability of the study findings. It may be difficult to generalize them so as to apply to everywhere because of the peculiarity of San Francisco’s climate regime. However, it may make a strong case for the need to seek an understanding of the annual climate portrait of a city to establish standard that is appropriate and effective so as to enhance its climate-resilience.

Nevertheless, this research makes significant contributions to planning practice. It revisits a planning approach of San Francisco that has been implemented for 30 years and that has influenced the design of many new buildings and formation of the city’s downtown skyline. Using empirical evidence, it provides planners of San Francisco with an opportunity to analyze the effectiveness of a planning standard that was adopted with an inter-disciplinary background as a determinant of outdoor comfort that may shape future planning of the city. Planners in cities that experience seasons every year in which wind is combined with low temperatures like San Francisco, including Toronto, New York City, Boston, and Chicago as introduced earlier, may benefit from this study in establishing plans or policies, or evaluating existing ones if any, against the excessive wind impacts to secure comfort. Planners in cities located in hot climate regions may consider adopting a reverse approach by adopting planning measures to promote breeze in public open spaces.

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[i] In accordance with this journal's manuscript guidelines that mandate use of SI units, speeds originally in mph will be presented in m/s in the rest of the manuscript.