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Boundary-Resolved Thermal Sufficiency of Occupied Zones in a Hot-Desert Freeway Deck Park

Wei Yu*

School of English Language and culture, Xi'an Fanyi University, Xi'an, Shaanxi, 710105, China

* Correspondence: 1876765@163.com

Abstract

Hot-desert deck parks need thermal evidence of whether occupied spaces reach comfort-relevant end states, not whether the design reduces some calculated heat load. In this paper, a novel Residual Thermal Sufficiency Analysis (RTSA) is formulated based on COMFA, an approach used to quantify distances between final temperatures and comfort intervals for adults and children. The application of RTSA is demonstrated for a 31,700 m² freeway deck park in downtown El Paso, Texas, considering the documented local climate, ENVI-met simulation validation, COMFA sensation limits, changes in site-scale microclimatology, and four occupied-place level COMFA transitions. RTSA helps answer questions about which spaces reach thermal sufficiency after the design, which do not and remain either warm or cool, and what physical control measures need to be applied to close the rest of the distance. The response to intervention at the site scale was relatively modest, involving a 0.67 °C drop in air temperature and a 0.30% increase in relative humidity, while substantial reductions were achieved for solar radiation (−25.2%) and wind speed (−17.2%). At the place scale, however, a different ranking emerged. Water plaza had the greatest reduction in COMFA value (from 247 to 69 W m^{−2}), yet it retained significant adult and child heat residual (19 and 29 W m^{−2} according to Brown and Gillespie thresholds). Amphitheater and pedestrian street had similar performance, falling from 147 and 149 to 46 and 42 W m^{−2}, achieving adult sufficiency under the Brown and Gillespie limits, respectively. Pedestrian street had just 2 W m^{−2} exceeding the child upper limit. Winter green patch was adjusted from −101 to −55 W m^{−2}. The findings highlight the necessity of focusing thermal design decisions on residual distance, occupant category, season, and activity zones. RTSA can show designers in which spaces further canopy, misting, surface cooling, or permeable shelter from wind needs to be considered.

Keywords: outdoor thermal comfort; COMFA; hot-desert park; deck park; heat safety; child thermal comfort; shade; ENVI-met; residual sufficiency; El Paso

1. Introduction

Urban outdoor heat stress arises from the complex interplay of climate, form, material, wind, and occupant activity. Urban canopy layer characteristics include street geometry, sky view, thermal storage, and surface moisture, whereas perceived heat relies on the body's energy balance rather than air temperature alone [2, 9, 27]. The distinction is critical to hot and dry cities where direct radiation, ground surface heating, dryness, and wide temperature difference can cause severe heat exposure in daytime and sometimes cool-side stress following sunset. A public

place, accordingly, needs different thermal interventions at different times of the day.

Such considerations apply even more intensely to a freeway deck park where the surface plane is artificial, structurally defined, and paved. Limited soil depth, rooting volume, structural capacity, visual appearance, and maintenance access preclude many thermal strategies. Thermal assessment has to be strategic in this case as a particular canopy element, water spraying system, cool surface area, or wind break should be positioned where it affects human thermal experience within the actual occupied zone. Research of hot-arid streets and courtyards confirms a strong impact of geometry, orientation, shading, and surface manipulation on pedestrians' thermal perception especially with intense solar access [1, 3, 12]. Analogous findings from thermal comfort science show that radiation shading and cooling tend to influence comfort more significantly than minor temperature variations [5, 11, 18, 24, 25].

Heat-mitigation studies also point out the uninterchangeability between the green, blue, and grey approaches. Trees, turf, cool pavements, reflectors, water features, and ventilation systems are characterized by differential coverage, operation costs, and seasonal applicability [4, 16, 19, 22, 26, 30]. Planting may create shadow but can affect airflow as well; mist can be beneficial in dry environment but is effective only locally and requires operation; a solid surface can shield against winter wind but excessive shading can be undesirable in summertime. A comprehensive thermal assessment has thus to associate the actual design element with a specific thermal performance measured as energy budget change.

1.1. From magnitude of cooling to sufficiency in design

Outdoor thermal comfort indices including PET, UTCI, and COMFA were formulated due to the multi-path energy exchange inherent to human thermal sensation [5, 6, 11, 13, 14, 31]. In particular, COMFA is helpful for design as the term definitions refer to implementable thermal measures. Shade blocks short-wave radiation, misting and water evaporation facilitate heat loss through dry air, cooling surface helps with infrared energy exchange, and vegetation and porous screens mitigate convection. The COMFA index tailored to children illustrates an example where the same thermal condition does not imply the same degree of sufficiency for child occupants [7].

The problem here is that pre- and post-intervention COMFA values are often regarded as reduction amounts. An improvement of 178 W m^{-2} can still result in non-neutral heat exposure whereas a minor reduction can push the place below the neutral boundary. A winter COMFA value must be evaluated in reverse because an increase towards the neutral point means better shelter from the wind. The fundamental question, therefore, is not which place changed the most. What matters more is whether there is any place that achieves neutral or better conditions, which place is still out of the neutral window, and how a corresponding design measure could bring it closer to neutral.

This paper uses the concept of residual sufficiency analysis for thermal assessment of a desert freeway deck park. The research questions are: Which occupied zones become neutral under final COMFA evaluations according to adult and child comfort limits, and what remains to be done with residual heat or cold side? The significance of the approach is that it treats final COMFA values separately with respect to whether they exceed or fall below the neutral boundary while preserving adult and child limits as two distinct decision criteria. Moreover, the analysis assigns each residual to a zone-appropriate design measure.

The paper is structured in a journal style. The next section explains the location and thermal data, occupied zones, visualization formats, and COMFA boundaries. Section 3 defines the equations and categories used in residual sufficiency analysis. Section 4 presents the thermal responses and transitions of COMFA in different zones. The discussion part follows by interpreting the findings for hot-desert urban design, sensitive exposure to young people, seasonal wind management, and design reviews. Section 6 responds to the research question.

2. Materials and Thermal Record

2.1. Site and occupied zones

This research examines a freeway deck park in downtown El Paso, Texas at coordinates 31.761942 and -106.491952 at elevation approximately 1140 m above sea level. El Paso has a desert mixed climate under the Köppen-Geiger

classification [28]. According to the thermal record, the city sees summers with temperatures around 35–40 °C, precipitation about 220 mm annually, around 302 sunny days, and plentiful daylight hours. These conditions call for shortwave management, cooling surface, dry air evaporation, and wind regulation design strategy.

Occupied zones in this project include a water plaza, amphitheater, pedestrian walkway, and winter green patch with wall. The water plaza is a static leisure and game place where shade and water spray operate nearby users. The amphitheater is a seat where exposure duration is a significant consideration. The pedestrian passage is a dynamic place where shading and surface material continuity prevail over local thermal shelter. The winter patch of vegetation and wind barrier wall creates a cool-side shielding place where reduced wind-related heat loss is desirable.



(a) Water plaza



(b) Amphitheater



(c) Pedestrian street



(d) Winter green patch

Figure 1. Occupied deck-park zones.

This spatial separation in Fig. 1 is critical since the four locations do not share the same thermal purpose. Child-sensitive and long-term activities are found in the water plaza area, while the amphitheater focuses on seating thermal exposures. Meanwhile, the pedestrian walkway manages access within the park, and the winter green provides an alternative seasonal issue, moving the focus from cooling to sheltering. If the park was viewed merely as one homogenized surface, the above information would be obscured by the residual design effort required in each location.

2.2. Measurement and model record

The values are derived from the El Paso deck park data record in Li et al. [20]. The pedestrian level measurements were made on 26 September 2021 using a MaxiMET GMX501 weather station. Comparison between the observed conditions and those predicted by ENVI-met resulted in the following correlations: air temperature $R^2 = 0.8245$, $RMSE = 0.49$ and relative humidity $R^2 = 0.7451$, $RMSE = 1.08$. The hot-day design record consists of three measurements taken on 10 June 2020 at 12:00, 15:00, and 19:00.

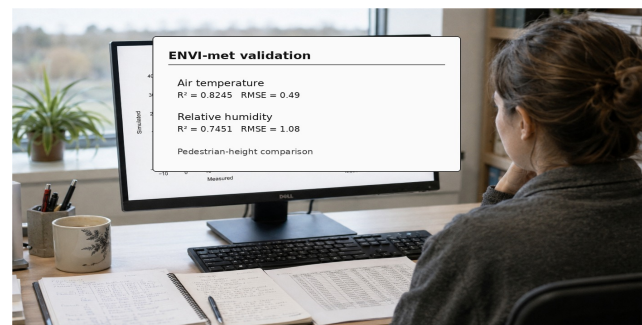
Table 1. Site and model record.

Record item	Value	Interpretation for RTSA
Deck and climate	31,700 m ² deck area; 1140 m elevation; 35–40 °C summer temperatures; 220 mm annual rainfall; 302 sunny days	High radiation and low moisture make shade geometry, surface heat, dry-air evaporation, and wind control primary design variables.
Model validation	Air temperature $R^2 = 0.8245$, RMSE = 0.49; relative humidity $R^2 = 0.7451$, RMSE = 1.08	Pedestrian-height outputs have sufficient comparative reliability for zone-level interpretation.
Hot-day record	10 June 2020 at 12:00, 15:00, and 19:00	Midday, peak-afternoon, and evening conditions are kept separate.
Site-scale response	Air temperature -0.67 °C; relative humidity $+0.30\%$; wind speed -17.2% ; solar radiation -25.2%	Radiation and wind changed more strongly than bulk air temperature.
Focused wind response	22.8–30.2% reduction in selected locations	Wind moderation is spatially concentrated and should be tied to occupied use.

The record in Table 1 establishes why final sufficiency cannot be inferred from air-temperature change alone. A 0.67 °C decrease appears modest, but a 25.2% solar-radiation reduction and a 17.2% wind-speed reduction can have substantial effects on the body energy budget. The validation values also justify comparative interpretation while preserving caution about exact person-to-person sensation.



(a) Field record



(b) Model check



(c) 12:00



(d) 15:00



(e) 19:00

Figure 2. Measurement and modelling record.

The sequence in Fig. 2 connects the calculations to a measured and modelled thermal record. The field panel represents pedestrian-height observation, the model-check panel indicates validation against measured temperature and humidity, and the time panels separate thermal conditions that are likely to be governed by different combinations of radiation, surface heat, and wind.

2.3. Thermal controls and COMFA thresholds

Each occupied zone is linked to a physical control pathway. The water plaza combines mist with canopy shading; the documented components are 79 W m⁻² from mist-related convective and evaporative effects and 99 W m⁻²

from canopy radiation blocking. The amphitheater combines tree shade, grass surface, and a 22 W m^{-2} winter wind-blocking benefit. The pedestrian street uses roof shade, tree shade, and cooler ground exposure for a 107 W m^{-2} summer COMFA reduction. The winter green patch uses a vertical wall and tree-row alignment to increase COMFA from -101 to -55 W m^{-2} in winter.



Figure 3. Thermal control elements.

The visual controls in Fig. 3 correspond to the COMFA pathways used in the calculations. Shade changes shortwave exposure, mist supports evaporative relief in dry air, cooler paving reduces surface-related radiant loading, and permeable shelter moderates convective heat loss. This connection allows the final residuals to be translated into buildable design actions rather than left as comfort classifications.

Table 2. Zone-level thermal inputs.

Occupied zone	COMFA transition	Main control channel	Thermal interpretation
Water plaza	247 to 69 W m^{-2}	Mist and canopy shade	Strongest summer reduction, but strict adult and child limits require residual correction.
Amphitheater	147 to 46 W m^{-2} ; 22 W m^{-2} winter wind benefit	Tree canopy, grass surface, and wind filtering	Seated use can reach adult sufficiency while retaining a small child heat residual.
Pedestrian street	149 to 42 W m^{-2}	Roof shade, tree shade, and cooler ground	Continuous route shade nearly completes child sufficiency and reaches adult sufficiency.
Winter green patch	-101 to -55 W m^{-2}	Vertical wall and tree row	Cold-side deficit is reduced by protecting users from excessive wind exposure.

The values in Table 2 show that the largest COMFA change is not automatically the most complete thermal result. The water plaza changes the most, but it begins farthest above strict neutral limits. The pedestrian street changes less, yet ends closest to the child upper neutral boundary. The winter green patch is evaluated by upward movement toward neutral because it begins on the cool side.

Table 3. COMFA sensation limits.

Thermal sensation	Kenny et al.	Brown and Gillespie	Cheng and Brown, children
Cold	< -150	< -150	Not specified
Cool	-150 to -20	-150 to -50	-140 to -110
Neutral	-20 to 150	-50 to 50	-110 to 40
Warm	151 to 250	50 to 150	40 to 80
Hot	> 250	> 150	> 80

The thresholds in Table 3 explain why one final COMFA value can support different conclusions. A final value of 69 W m^{-2} is neutral under the broader Kenny et al. adult interval but remains warm under the Brown and Gillespie adult interval and under the child interval. The analysis therefore treats the selected comfort interval as a design boundary rather than as a descriptive label.

**Figure 4.** Thermal state references.

The reference provided in Fig. 4 makes the reasoning about the COMFA direction clear. Warm side locations should move downward into the neutral interval, while cool side locations should move upward. This visual explanation is used later when interpreting the green patch in winter. There, the beneficial COMFA change will be an increase.

3. Analytical Procedure

3.1. Residual distance from neutral conditions

For a given comfort interpretation s , the neutral interval is specified as $[L_s, U_s]$. For the occupied zone i , its initial COMFA level is E_i^0 and its final COMFA level is E_i^1 . The residual distance above the upper neutral boundary, defined as the heat side residual, is:

$$H_{i,s}(E) = \max(0, E - U_s) \quad (1)$$

while the residual distance below the lower neutral boundary, the cold side residual, is:

$$C_{i,s}(E) = \max(0, L_s - E) \quad (2)$$

and finally the total residual outside the neutral interval is:

$$R_{i,s}(E) = H_{i,s}(E) + C_{i,s}(E). \quad (3)$$

Zero residual implies a COMFA value within the selected neutral interval. Positive residual indicates the thermal distance that must still be removed. Residual sign determines the required design direction. For example, heat-side residual requires reduction in body energy budget, while cold-side residual requires an increase toward neutral conditions.

3.2. Closure fraction and normalized residual

The residual closure fraction is determined according to:

$$Q_{i,s} = \frac{R_{i,s}(E_i^0) - R_{i,s}(E_i^1)}{R_{i,s}(E_i^0)}, \quad R_{i,s}(E_i^0) > 0 \quad (4)$$

while the normalized residual is:

$$N_{i,s} = \frac{R_{i,s}(E_i^1)}{U_s - L_s}. \quad (5)$$

While the two indicators have the same maximum values ($1 - Q_{i,s}$ and $N_{i,s}$), a high residual closure does not imply low residual. Similarly, the converse may also apply if a small COMFA reduction has been sufficient to reach the necessary neutral boundary.

3.3. Diagnostic categories

Each zone i is classified into one of four categories per comfort interpretation s . The *sufficient-retained* category has both initial and final COMFA values lying within the selected neutral interval. If the initial COMFA value of a zone lies outside the neutral interval, but its final value lies within, the category is *neutralized*. Zones with an initial COMFA value lying outside the neutral interval that moved closer but did not cross the neutral interval boundaries are called *narrowed-residual*. Finally, the *persistent-residual* category has both initial and final COMFA levels lying outside the neutral interval. These definitions refer to end-state sufficiency and not to preferences or other aesthetics.

The ability to classify a park as having multiple thermal outcomes at the same time is the reason to use the residual sufficiency metric as opposed to determining a single site-level heat reduction value.

4. Results

4.1. Dominant environmental response channels

Design intervention affected solar radiation and wind speed more effectively than bulk air temperature and relative humidity. Mean air temperature dropped by 0.67 °C and relative humidity increased by 0.30%. Solar radiation averaged 25.2% reduction and wind speed averaged 17.2% reduction, while concentrated wind speed reduction reached 22.8–30.2%.

The numbers show that the thermal benefit in this deck park is not primarily a drop in ambient air temperature. The change in radiation and wind fields creates the thermal effect. This observation is corroborated by numerous outdoor comfort studies, which demonstrate how mean radiant temperature, shading, exposure to surface temperature and wind can dominate thermal sensation under clear sky conditions [10, 18, 22, 24]. As seen in Fig. 3, physical control elements influence different components of body energy budget.

4.2. COMFA transitions by occupied zone

Four zones showed different COMFA reductions and transitions. The water plaza changed from 247 to 69 W m⁻², which corresponds to a 178 W m⁻² reduction. The amphitheater decreased COMFA from 147 to 46 W m⁻², or a 101 W m⁻² reduction. The pedestrian street experienced a 107 W m⁻² reduction, decreasing COMFA from 149 to 42 W m⁻². Finally, the winter green patch transitioned from -101 to -55 W m⁻², increasing COMFA by 46 W m⁻².

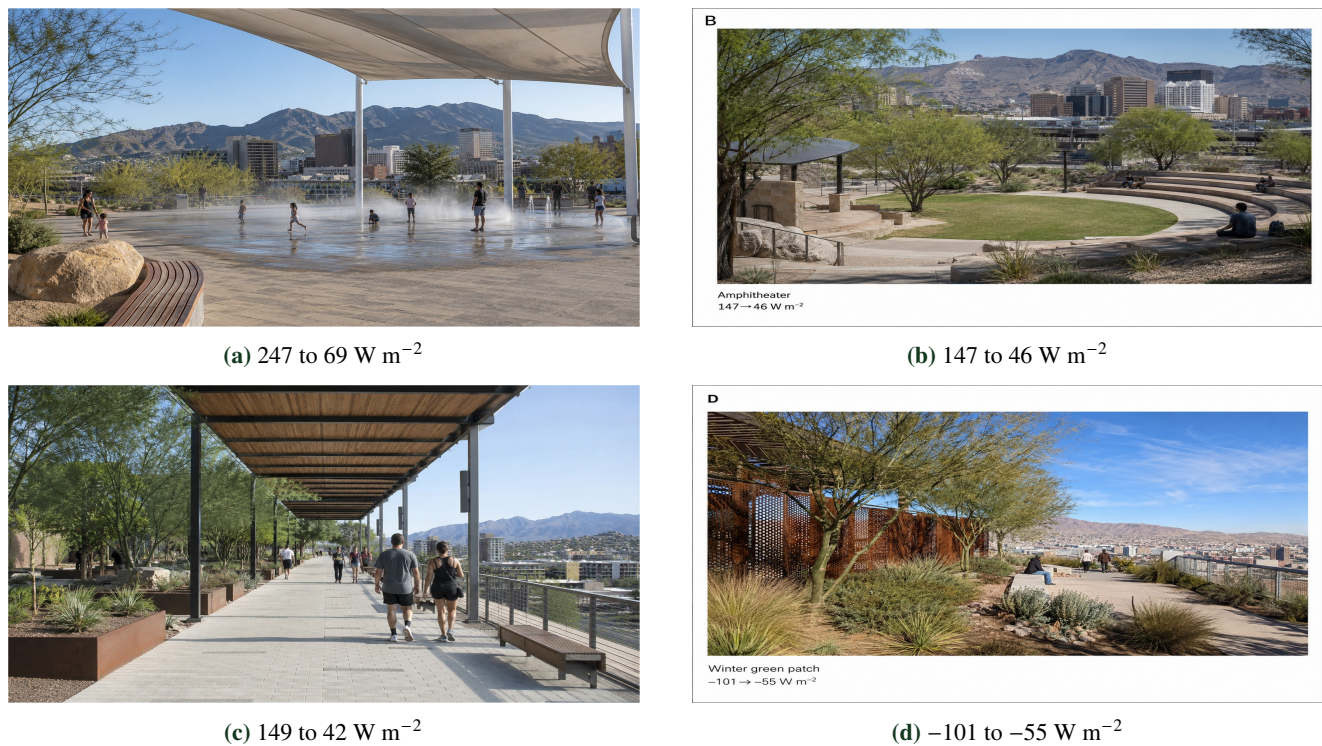


Figure 5. Zone-level COMFA transitions.

From the visual transition in Fig. 5, it can be observed that just because the largest numerical difference is obtained does not mean that the most sufficient final state is achieved. The water plaza will still exceed the adult and child upper neutral limits strictly. As for the amphitheater and pedestrian street, they will end up being within the strict adult limits due to the closeness of their original values to adult limits. Lastly, the winter green patch shows the reverse case whereby a positive COMFA difference can actually be helpful.

4.3. Adult and child sufficiency status

For sufficiency, the result depends on whether the neutral interval chosen is for adult or child. In case of the neutral interval according to Kenny et al. for adults, the water plaza is classified as sufficient after being warm before, while the other two places maintain sufficiency; only the winter green place will be classified as cool. For the Brown and Gillespie neutral interval, the two aforementioned areas qualify as being sufficient after remaining warm, but water plaza and the winter green patch stay warm and cool respectively.

Table 4. Thermal sufficiency status.

Occupied zone	Kenny et al.	Brown and Gillespie	Cheng and Brown, children
Water plaza	Warm to sufficient	Hot to warm residual	Hot to warm residual
Amphitheater	Sufficient retained	Warm to sufficient	Hot to warm residual
Pedestrian street	Sufficient retained	Warm to sufficient	Hot to warm residual, near sufficient
Winter green patch	Cool residual retained	Cool residual, near sufficient	Sufficient retained

The classifications in Table 4 show that user group changes the design conclusion. Adult sufficiency under Brown and Gillespie occurs at the amphitheater and pedestrian street, but the child interval still identifies warm-side exposure at both zones. The water plaza remains unresolved under both strict adult and child limits despite its large reduction. This finding prevents an adult-neutral result from being generalized to all users.



Figure 6. Final summer status.

These three panels for summer status (Fig. 6) make visible the adult/child discrepancy at the activity scale. The amphitheater and the pedestrian street are both sufficient for adults under the Brown and Gillespie criteria; however, the child interval remains more stringent. The pedestrian street is closer to meeting child criteria, while the water plaza remains the largest remaining warm-side residual even with the most substantial gross reduction.

4.4. Residual closure and design action

The residual closure value indicates what percentage of the gross violation has been mitigated. In the case of the water plaza, the Brown and Gillespie heat residual dropped from 197 W m^{-2} down to 19 W m^{-2} , resulting in 90.4% closure. When applying the child interval, the heat residual dropped from 207 W m^{-2} to 29 W m^{-2} , resulting in 86.0% closure. The amphitheater completely closes on the Brown and Gillespie criteria, leaving only a 6 W m^{-2} heat residual for the children. The pedestrian street achieves complete closure on the Brown and Gillespie criteria, leaving just 2 W m^{-2} for the child interval.

Table 5. Residual closure and design need.

Occupied zone	Interpretation	Initial residual	Final residual	Design reading
Water plaza	Kenny et al.	97 heat	0	Neutralized under broad adult limits.
Water plaza	Brown and Gillespie	197 heat	19 heat	Large closure but additional adult heat reduction remains.
Water plaza	Children	207 heat	29 heat	Largest final child residual; shade and mist reliability remain critical.
Amphitheater	Brown and Gillespie	97 heat	0	Adult sufficiency reached for seated use.
Amphitheater	Children	107 heat	6 heat	Small residual remains at seating and waiting edges.
Pedestrian street	Brown and Gillespie	99 heat	0	Adult route sufficiency reached.
Pedestrian street	Children	109 heat	2 heat	Near child sufficiency; continuity refinements are likely decisive.
Winter green patch	Kenny et al.	81 cold	35 cold	Partial cold-side correction under broad adult limits.
Winter green patch	Brown and Gillespie	51 cold	5 cold	Near adult cold-side sufficiency with calibrated shelter.

The residual values in Table 5 give a more precise design reading than the raw COMFA transitions. The water plaza is not weak; it is the strongest cooling zone but begins with the largest heat-side excess. The pedestrian street is the clearest near-completion case because only 2 W m^{-2} remains under the child interval. The winter green patch is a shelter problem rather than a cooling problem, so its remaining need should be addressed through wind permeability and solar access rather than additional mist or shade.



Figure 7. Residual design actions.

The action views in Fig. 7 translate the final residuals into different design priorities. The water plaza needs denser shade and dependable mist near occupied edges. The amphitheater needs shaded seating and waiting protection. The pedestrian street needs uninterrupted route shade because its child residual is nearly closed. The winter green patch requires permeable shelter, not stronger cooling, because its remaining problem is cold-side exposure.

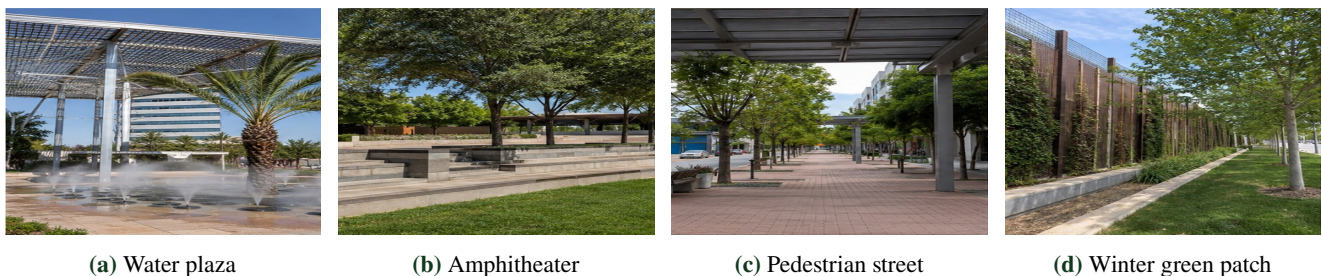


Figure 8. Residual correction set.

The last residual set in Fig. 8 represents the graphically synthesized results. Each of its four panels shows the non-uniformity of the residual design task. Much of the additional work should go into improving the water plaza under the child-sensitive regime; targeted shading of the amphitheater needs to be done on edges where seats are located; the pedestrian street is almost complete for children; and wind shelter is required for the winter green patch, but not additional cooling devices for hot summers.

5. Discussion

5.1. Final sufficiency vs. gross COMFA reduction

First, the results indicate the difference between gross COMFA reduction and final thermal sufficiency. The gross reduction is 178 W m^{-2} for the water plaza, thus making it the largest intervention by absolute value and the best solution for a summer heat wave. RTSA interprets this differently: the initial value of $178 + (-79) \text{ W m}^{-2} = 99 \text{ W}$

m^{-2} is still greater than the Brown and Gillespie adult threshold value by 19 W m^{-2} and higher than the child upper limit by 29 W m^{-2} . Meanwhile, the amphitheater and pedestrian street interventions have a COMFA reduction of 101 and 107 W m^{-2} , respectively, but both reach sufficiency under the adult Brown and Gillespie neutral interval because the gross initial values are closer to the adult limit.

This distinction is critical to design review and planning in hot-deserts. An architectural project might achieve substantial thermal benefits and still leave a popular location with a high density of usage outside of the neutral range for adults and/or children. Alternatively, moderate changes might bring the location inside the relevant neutral interval and therefore be highly valuable. The key evidence in such situations is the final residual distance, not simply the gross reduction in energy.

5.2. Thermal pathways and radiation

Second, the findings demonstrate why temperature is not sufficient as the primary indicator. Even though the $0.67 \text{ }^\circ\text{C}$ average decrease may seem insignificant, the corresponding change in the radiation and wind is much more relevant to the energy balance described in COMFA. This is supported by previous research, which has shown that the mean radiant temperature and shade are crucial factors contributing to outdoor thermal comfort on warm days [10, 18, 24]. This is also consistent with studies demonstrating that local cooling and shading effects often outweigh the importance of uniform site-scale air temperature decrease in green and blue infrastructure design [4, 17, 19, 22, 26].

Hence, it should be recognized that the reduction in site-scale air temperature in the El Paso deck-park case does not mean that the cooling effect is marginal or negligible. Rather, there is a specific change in the pathway to the thermal sensation, involving the radiation and wind. RTSA evaluates this change based on the locations where people spend time on the deck: sit down, walk through the site, wait for transportation, and use other facilities. The site-scale analysis is less relevant to this case because of practical constraints: it is unrealistic to cool the whole site uniformly.

5.3. Adult versus child thresholds and design implications

Third, the results show that adult and child thresholds significantly affect the conclusion about sufficiency. All three summer zones remain warm under child-neutral interpretation, despite being within Brown and Gillespie adult neutral intervals. Specifically, the residual energy of heat side is reduced by 29 W m^{-2} in the water plaza, 6 W m^{-2} in the amphitheater, and 2 W m^{-2} in the pedestrian street. These numbers clearly indicate that a general recommendation cannot be formulated, and further design efforts should be made towards reducing the heat residual in a certain order of priority: the water plaza first, followed by the amphitheater seating edge and shade continuity on the pedestrian street.

The reason is the sensitivity of the water plaza area to prolonged and intensive activity among children and adults together, while the amphitheater seating area is associated with long-term staying in the same spot during performances, games, and conversations. Hence, both heat residuals need additional reduction for safety reasons. For instance, additional shade and mist in the water plaza would be helpful.

5.4. Heat side versus cold side in seasonal settings

Finally, the results demonstrate that the winter green patch is also a relevant location requiring additional design attention. The COMFA change of the zone leads to a positive effect (-101 to -55 W m^{-2}) because the initial value lies below the lower adult limit. The Brown and Gillespie adult residual changes from 51 W m^{-2} to 5 W m^{-2} , reaching 90.2% closure of the violation. This indicates the importance of a different seasonal strategy that involves thermal protection against cold winds and convective losses.

It should be noted that the seasonality affects the interpretation of vertical elements' function: a solid fence can create excessive shelter during a hot summer day and prevent proper ventilation. Instead, wind-calibrated walls

and tree rows can reduce the impact of the winds in winter and preserve some ventilation in summer. The design requirement is therefore precise calibration of wind protection.

In particular, the winter green patch must be well-protected against cold-side air movement, but not excessively isolated. This way, the nearby routes to the thermally comfortable areas will retain the advantage of ventilation.

5.5. Design implication and recommendations for future projects

RTSA can become an effective tool of thermal design review since it is based on available quantities: initial and final COMFA and neutral interval. In addition to the conventional thermal design evidence, the proposed method provides more accurate information about the nature of residual violation and the type of action needed next: shade, mist, surface cooling, heat or wind shelter, etc.

Specifically, for the deck park projects, the method can be useful due to budget limitations: large trees may not fit structural constraints, mist systems require operation, cool surface materials produce glare and are difficult to maintain, and wind screens may block ventilation. In such cases, thermal evaluation helps designers focus their attention on those areas that require more shade and sheltering: water plaza, amphitheater edges, and pedestrian streets.

The most urgent task is therefore the water plaza, which requires additional shading and mist system installation because of the highest child-sensitivity risk. In addition, the amphitheater edges need targeted shading, and continuous shade along the pedestrian streets should be completed. Finally, the wind shelter around the winter green patch should be installed to filter the cold winds.

6. Conclusions

This paper has identified which occupied zones of a hot-desert freeway deck park meet the thermal sufficiency criteria following design interventions, which zones remain outside the adult and child neutral intervals, and what design actions are necessary. As has been discussed previously, the answer to the question depends heavily on adult and child thresholds. Only the amphitheater and pedestrian streets reach adult sufficiency, but the water plaza and winter green patch zones are still thermally uncomfortable even after cooling interventions.

Under the child-neutral interval criteria, the situation looks slightly differently: the residual values for all summer zones remain significant. Still, they differ significantly by magnitude: the water plaza requires residual correction of 29 W m^{-2} , the amphitheater -6 W m^{-2} , and the pedestrian street has only 2 W m^{-2} left to be reduced. On the contrary, the winter green patch improves due to increased COMFA from -101 to -55 W m^{-2} , resulting in 90.2% closure of the Brown and Gillespie adult cold-side residual.

The major conclusion of the paper is the significance of residual sufficiency as the key design evidence. Under gross COMFA reduction criteria, the water plaza would be the best solution. However, the final value suggests that it remains a problematic case due to excessive residual heat energy. The pedestrian street is close to completion of residual design in terms of children safety, whereas the amphitheater requires additional protection for seated and waiting individuals.

Thus, the design action for the current example includes concentrated installation of dense shade and reliable mist at the water plaza; targeted design measures for the amphitheater edges; uninterrupted shade continuity on the pedestrian streets; and wind-permeable shelter around the winter green patch.

References

- [1] Ali-Toudert, F., & Mayer, H. (2006). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and Environment*, 41(2), 94-108.

- [2] Arnfield, A. J. (2003). Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology: a Journal of the Royal Meteorological Society*, 23(1), 1-26.
- [3] Bourbia, F., & Awbi, H. B. (2004). Building cluster and shading in urban canyon for hot dry climate: Part 2: Shading simulations. *Renewable Energy*, 29(2), 291-301.
- [4] Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, 97(3), 147-155.
- [5] Bröde, P., Fiala, D., Błażejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., ... & Havenith, G. (2012). Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology*, 56(3), 481-494.
- [6] Brown, R. D., & Gillespie, T. J. (1986). Estimating outdoor thermal comfort using a cylindrical radiation thermometer and an energy budget model. *International Journal of Biometeorology*, 30(1), 43-52.
- [7] Cheng, W., & Brown, R. D. (2020). An energy budget model for estimating the thermal comfort of children. *International Journal of Biometeorology*, 64(8), 1355-1366.
- [8] Chien, L. C., Guo, Y., & Zhang, K. (2016). Spatiotemporal analysis of heat and heat wave effects on elderly mortality in Texas, 2006–2011. *Science of the Total Environment*, 562, 845-851.
- [9] Erell, E., Pearlmutter, D., & Williamson, T. (2012). *Urban microclimate: designing the spaces between buildings*. Routledge.
- [10] Gál, T., Lindberg, F., & Unger, J. (2009). Computing continuous sky view factors using 3D urban raster and vector databases: comparison and application to urban climate. *Theoretical and Applied Climatology*, 95(1), 111-123.
- [11] Höppe, P. (1999). The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, 43(2), 71-75.
- [12] Johansson, E. (2006). Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco. *Building and Environment*, 41(10), 1326-1338.
- [13] Kenny, N. A., Warland, J. S., Brown, R. D., & Gillespie, T. G. (2009). Part A: Assessing the performance of the COMFA outdoor thermal comfort model on subjects performing physical activity. *International Journal of Biometeorology*, 53(5), 415-428.
- [14] Kenny, N. A., Warland, J. S., Brown, R. D., & Gillespie, T. G. (2009). Part B: Revisions to the COMFA outdoor thermal comfort model for application to subjects performing physical activity. *International Journal of Biometeorology*, 53(5), 429-441.
- [15] Kim, S. W., & Brown, R. D. (2021). Urban heat island (UHI) intensity and magnitude estimations: A systematic literature review. *Science of the Total Environment*, 779, 146389.
- [16] Krayenhoff, E. S., Broadbent, A. M., Zhao, L., Georgescu, M., Middel, A., Voogt, J. A., ... & Erell, E. (2021). Cooling hot cities: a systematic and critical review of the numerical modelling literature. *Environmental Research Letters*, 16(5), 053007.
- [17] Kumar, P., Corada, K., Debele, S. E., Emygdio, A. P. M., Abhijith, K. V., Hassan, H., ... & Jones, L. (2024). Air pollution abatement from Green-Blue-Grey infrastructure. *The Innovation Geoscience*, 2(4), 100100.
- [18] Lai, A., Maing, M., & Ng, E. (2017). Observational studies of mean radiant temperature across different outdoor spaces under shaded conditions in densely built environment. *Building and Environment*, 114, 397-409.

- [19] Lai, D., Liu, W., Gan, T., Liu, K., & Chen, Q. (2019). A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. *Science of the Total Environment*, 661, 337-353.
- [20] Li, X., Peng, J., Li, D., & Brown, R. D. (2023). A framework for evidence-based landscape architecture: cooling a hot urban climate through design. *Sustainability*, 15(3), 2301.
- [21] Li, X., Zhang, Y., Li, D., Xu, Y., & Brown, R. D. (2022). Ameliorating cold stress in a hot climate: Effect of Winter Storm Uri on residents of subsidized housing neighborhoods. *Building and Environment*, 209, 108646.
- [22] Liu, Z., Cheng, W., Jim, C. Y., Morakinyo, T. E., Shi, Y., & Ng, E. (2021). Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4. *Building and Environment*, 200, 107939.
- [23] Lenzholzer, S., Duchhart, I., & van den Brink, A. (2016). Research in landscape architecture and the special role of designing. In *Research in landscape architecture—methods and methodology*. Routledge Abingdon.
- [24] Middel, A., Selover, N., Hagen, B., & Chhetri, N. (2016). Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona. *International Journal of Biometeorology*, 60(12), 1849-1861.
- [25] Nikolopoulou, M., & Steemers, K. (2003). Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings*, 35(1), 95-101.
- [26] Norton, B. A., Coutts, A. M., Livesley, S. J., Harris, R. J., Hunter, A. M., & Williams, N. S. (2015). Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landscape and Urban Planning*, 134, 127-138.
- [27] Oke, T. R. (1988). Street design and urban canopy layer climate. *Energy and Buildings*, 11(1-3), 103-113.
- [28] Peel, M. C., McMahon, T. A., & Finlayson, B. L. (2004). Continental differences in the variability of annual runoff-update and reassessment. *Journal of Hydrology*, 295(1-4), 185-197.
- [29] Rizwan, A. M., & Dennis, L. Y. (2008). A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences*, 20(1), 120-128.
- [30] Santamouris, M. (2013). *Energy and climate in the urban built environment*. Routledge.
- [31] Vanos, J. K., Warland, J. S., Gillespie, T. J., & Kenny, N. A. (2012). Thermal comfort modelling of body temperature and psychological variations of a human exercising in an outdoor environment. *International Journal of Biometeorology*, 56(1), 21-32.
- [32] Wilson, S. M., Richard, R., Joseph, L., & Williams, E. (2010). Climate change, environmental justice, and vulnerability: an exploratory spatial analysis. *Environmental Justice*, 3(1), 13-19.