Thermal comfort and passive design strategy of bus shelters

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ABSTRACT: Bus shelters are semi-outdoor spaces with shelter provided in the form of a roof. The thermal comfort of bus shelters is as important as that of buses themselves in improving the quality of the experience of bus travel. This work conducted field experiments involving five bus shelters combined with numerical simulations using the RayMan model. The analytical results show that bus shelters that provide more shelter help reduce passenger exposure to direct solar radiation and provide comfortable spaces in which to shelter from the weather in Taiwan. Designers should also consider local sunlight patterns and simulate the sun duration for whole year in advance to create comfortable bus shelters.

Keywords: thermal comfort, passive design, bus shelters, RayMan

1. INTRODUCTION

Considerable research carried out thermal comfort in indoor environments, while outdoor and semi-outdoor environments have been relatively neglected. However, the importance of outdoor thermal comfort is growing due to an increased emphasis on recreation and leisure. It is important to develop comfortable outdoor and semi-outdoor environments using passive design strategies that consider climate and occupant behaviour.

Bus shelters can be considered a semi-outdoor space with shelter provided in the form of a roof. Bus shelters offer passengers a temporary environment to wait in and also represent the first stage of a bus journey. Consequently, the thermal comfort of bus shelters is as important as the internal environment of the bus for improving the quality of a bus journey. It is easy to improve the interior thermal environment of buses by air-conditioning but difficult to improve that of bus shelters except during the design phases. Therefore, it is very important to ensure the thermal comfort of bus shelters through passive design during the planning and design stages.

Thermal indices such as PMV [1], ET* [2], SET* [3] focus primarily on air temperature and humidity, and are combined with radiation fluxes, wind velocity, and occupant clothing and activity level for indoor thermal environments evaluation, particularly air-conditioned spaces. However, recently outdoor thermal indices have stressed the influence of outdoor solar radiation on outdoor thermal environments, such as PET [4, 5], OUT_SET* [6, 7].

Taiwan is located across a tropical and subtropical zone with hot and humid weather. The average daytime air temperature in summer reaches 34 ºC, with 80% relative humidity and 900 W/m² horizontal solar radiation. Traditionally, bus shelters in Taiwan have had poor comfort levels in summer owing to the lack of protection against solar radiation. Thus it is very important to design comfortable bus shelters that reduce solar radiation.

Previous research has used Computational Fluid Dynamics (CFD) to assess outdoor thermal environments in built-up areas, but these approaches are too complicated and cannot applied to other projects in the design process [8, 9]. RayMan, a model simulating outdoor thermal environments, was implemented by Matzarakis [10, 11] and accurately described outdoor thermal indices such as PET, PMV, and SET* for use in easy and complex environments [12]. Therefore, RayMan was calibrated using field experiment data and was applied here to simulate both the one day and long-term thermal environments and to forecast the thermal indices.

2. METHOD

2.1 Measurement and Instruments

This study examined several types of bus shelters using micro-meteorological instruments to analyze thermal comfort in semi-outdoor environments in subtropical Taiwan. To compare thermal comfort among bus shelters, measurements were conducted simultaneously at five points located within bus shelters and at one point outside the shelters. The field experiment approach was used to simultaneously record air temperature, globe temperature, surface temperature, relative humidity, wind velocity, and global radiation at each point. The instruments were fixed on a special tripod at different heights, and the instrumentation specifications met the standard of ASHRAE [13, 14].

2.2 Rayman Model and Thermal Indices

Mean radiant temperature (MRT) is the main factor for discussing human heat balance in outdoor environments, and is used to calculate thermal indices such as PET, SET* and PMV, which can help in describing thermal stress [4, 5]. Moreover, the RayMan model is a model for estimating MRT and other thermal indices in outdoor areas. The buildings, trees and obstacles around the modelled location can be imported based on fish eye photos or obstacle drawings to properly estimate the sun orbit and sun duration, and to produce continuous estimates of the MRT, surface temperature, and thermal indices [11].

2.3 Analysis Process

The measured MRT value provides the fundamental data, which is compared with the modelled MRT, and the most suitable weather parameter is identified for the RayMan model calibration for calibrating the RayMan model. This calibrated model can estimate the thermal environment for the experiment day and can also simulate the mean sun duration hours and sun duration ratio for the whole year. Finally, the thermal comfort of each bus shelter is evaluated using the thermal acceptable range, which was investigated in semi-outdoor environments in Taiwan. The analytical results can help in comparing thermal environment quality among different types of bus shelter.

2.4 Subjects

This study sampled four different types of bus shelter sharing the same orientation (Case A, B, C, E); the other shelter, case D, is of the same type as case C but has the opposite orientation (Table 1). Additionally, an unsheltered outdoor location is also included in the experiment to provide a comparison. The instruments were set up on the ground in the centre of the bus shelter for cases A to E, while for case F the instrument was set up in a location with almost no shelter, as shown in Fig 1. The experiment locations were located close together to facilitate the comparison. The experiment was performed on July 27, 2005, which was a sunny day. The data was gathered at one-minute intervals from 8:00 to 17:30.

Table 1: Appearance and description of each bus shelter.

	Drawing	Description
A		West orientation Steel roof SVF=0.586
B		West orientation Wood roof SVF=0.404
C		West orientation Transparent plastic roof SVF=0.192
D		East orientation transparent plastic roof SVF=0.278
E		West orientation Composite steel roof SVF=0.212
F	Outdoor without sheltered	SVF=0.704
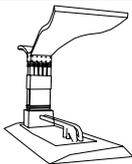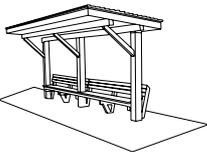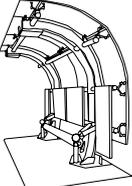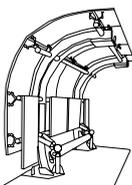
Figure 1: Photo of case E and instruments.

3. RESULTS

3.1 Field Experiment Data

Figure 2 shows that the various locations share similar variation in measured air temperature and the MRT of Fig. 3 reveals the significant differences among the various points. The MRT value was calculated by ISO 7730 [15], which is the function of air temperature, globe temperature, and wind velocity; therefore the differences in radiation among the various locations will affect the MRT value. Notably the air temperature and MRT of location D exceeded that of other locations before 14:00 and markedly reduced following that time. Since location D the only location with eastwards orientation, it has significantly higher air temperature than other locations, even the unsheltered location. The MRT of each location remains almost unchanged following 17:30 owing to the sunset effect.
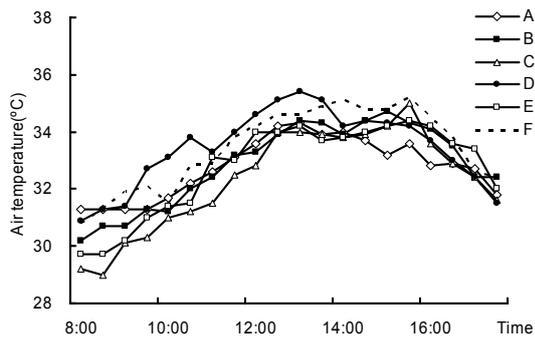
Figure 2: Measured air temperature for each bus shelter.
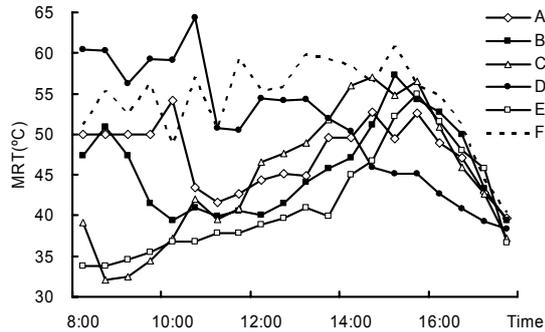
Figure 3: Measured MRT for each bus shelter.

3.2 Rayman Model Calibrations

Certain parameters in the RayMan model can be adjusted, such as bowen-ratio, albedo, linke turbidity, diffusion ratio and global radiation. To achieve a close fit between the modelled and measured values, the measured/modelled MRT is used to model calibration. Figure 4 illustrates the measured and modelled values of location A to F from 8:00 to 17:30. The figure reveals that the modelled value was slightly lower than the measured value in certain cases, but the peak temperature can be accurately predicted and the trend of the model variation was consistent with the measured value. The comparison demonstrates that the RayMan model performs well for predicting the MRT value and the parameters used for model calibration can provide an important basis for further analysis.
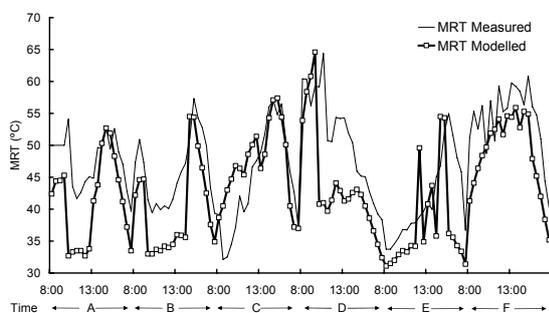
Figure 4: Measured and modelled MRT for each bus shelter.

In Fig 4, each location was assigned different parameters for model calibration owing to the differences in micro-climate among different locations.

To compare differences in thermal environment given the same weather conditions, this study attempts to apply the same group of parameters to all the model locations. Figure 5 indicates the result of MRT under the standard weather conditions. Location A exhibits higher MRT not only during 9:00-10:00 but following 13:00. Meanwhile, point E exhibits raised MRT only after 15:00.

The sky view factor (SVF) displayed in Table 1 indicates the proportion of the total sky area above the bus shelter that is covered, and thus indicates the extent of shelter provided by the roof. The SVF are exported by the model, and are determined by the imported fish eye photo (Fig. 6). Location A clearly has the highest SVF value (0.586) and demonstrates the worst sheltered performance, and thus causes the high MRT shown in Fig 5. Meanwhile, location E has a lower SVF value, of 0.212, and is considerably cooler than that of location A.
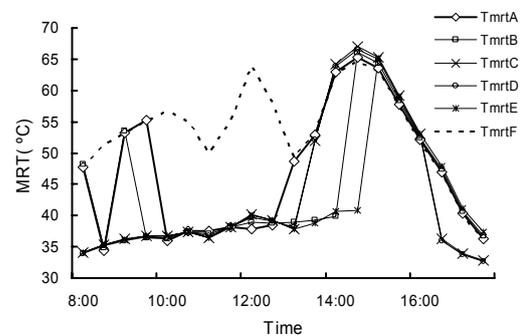
Figure 5: Modelled MRT under standardized climate parameters.
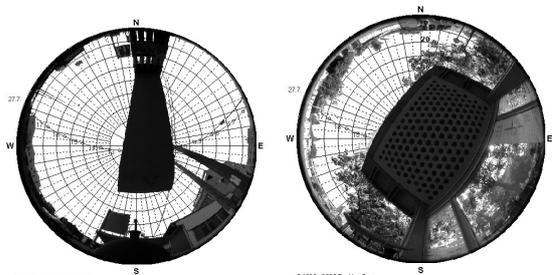
(1) Case A (SVF=0.586)   (2) Case E (SVF=0.212)

Figure 6: Fish eye photo with sun orbit of case A and E for 27 July 2005.

3.3 Correlation Analysis

Generally, the SVF values affect both the physical value and the thermal indices. The correlation between SVF and each index is significant, as illustrated in Fig 7. The figure indicates that the SVF indirectly affects the thermal indices and significantly influences semi-outdoor comfort.
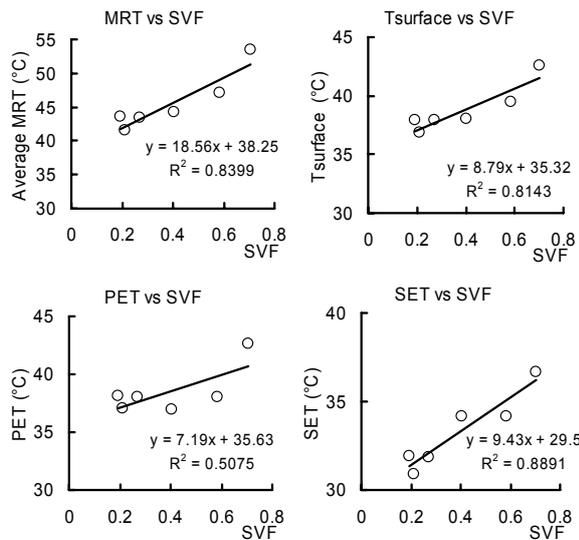
Figure 7: Correlation of SVF and Ts, MRT and thermal indices

3.4 Thermal Comfort of Bus Shelters

Lin performed thermal comfort field experiments in semi-outdoor areas of cultural and educational facilities in Taiwan, and found that the shelter ratio and ventilation performance significantly affect the subjective thermal sensation evaluation for occupants [16]. A further study investigating 5460 subjects in various semi-outdoor spaces in Taiwan also obtained the thermal acceptable range using the probit regression method [17]. Lin indicate that 90% of the occupants will feel comfortable while the SET* value is between 21.5°C -28.6°C, and 18.9°C -35.5°C SET* represent the 80% acceptability range. Figure 8 plotted the results together with the modelled MRT in locations A, E and F. Figure 8 shows that before 11:00 location E was comfortable under the strict 90% acceptability range, while location A was outside the comfortable range for the whole day. If the 80% acceptability range was applied for assessment, location A was uncomfortable for more than 3 hours, while location E was only uncomfortable for 1.5 hours. It is remarkable that people feel more comfortable at location E, which is more sheltered, than at location A, which is less sheltered, demonstrating that bus stops providing minimal shelter are not suitable for the local climate of Taiwan.
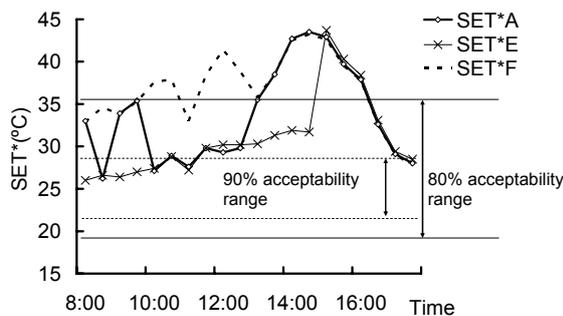
Figure 8: Variation of SET* of case A and E combined with thermal acceptability range in Taiwan.

3.5 Whole Year Sun Duration Simulation

The main reason that SVF affects thermal comfort is that shelter provides protection against direct solar radiation, reducing the duration hours of exposure to the sun and reducing the radiation exposure of bus shelter occupants. Therefore, mean possible sun duration and sun duration ratio are also calculated using the model and listed in Table 2 and Fig 9. In principle, better sheltered (or low SVF) bus stops have shorter mean possible sun duration and sun duration ratio and could be located in the comfort zone.

Notably, during some months the sun duration ratio for location B, which had lower SVF, was higher than that of A, which had higher SVF. This difference exists because the SVF values of the two locations are close to one another and the orbit of the sun varies according to the month. This result indicates that SVF is only the initial [factor in determining the solar radiation and thermal comfort, and local sun orbit should be considered for creating well sheltered spaces for comfortable semi-outdoor environments.

Due to the role of bus shelters in reducing radiation being influenced by hot conditions in the summer; the radiation reduction effect in winter should be influenced by the different levels of solar radiation and wind velocity during winter. Meanwhile, cloud cover is only used in the model calibration and is not included in the long-term simulation. The real number of sun duration hours and sun duration ratio are affected by cloud cover and other micro-climate factors.

Table 2: Mean possible sun duration hours for each bus shelter.

	Mean sun duration[hour]					
	A	B	C	D	E	F
Jan	6.2	5.6	2.4	2.5	1.7	8.2
Feb	6.0	5.0	2.2	3.2	1.5	9.0
Mar	5.1	5.0	3.6	4.3	1.9	9.4
Apr	4.2	5.0	3.5	4.4	2.7	10.1
May	4.9	5.9	3.7	4.1	3.1	10.8
Jun	5.8	6.2	4.0	4.1	3.0	11.3
Jul	5.5	6.1	3.8	4.1	3.0	11.1
Aug	4.2	5.4	3.4	4.3	3.0	10.3
Sep	4.8	4.8	3.7	4.4	2.2	9.7
Oct	5.4	5.1	2.7	3.7	1.5	9.2
Nov	6.4	5.1	2.3	2.8	1.7	8.4
Dec	5.9	6.4	2.3	2.3	1.5	7.9
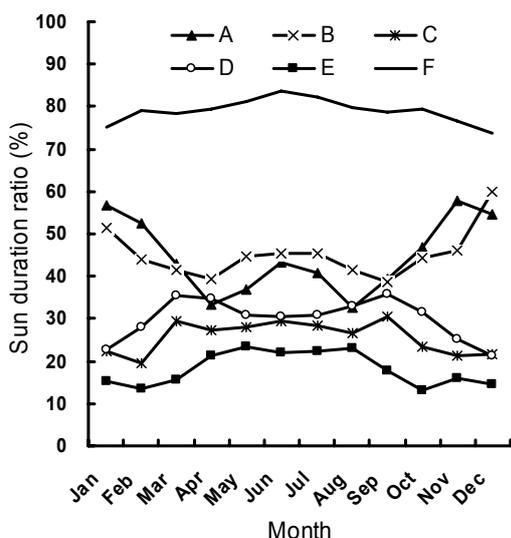
Figure 9: Variation of sun duration ratio of each bus shelter.

4. CONCLUSION

This investigation examines thermal comfort of bus shelters in Taiwan and performed field experiments together with numerical simulations. This study reaches the following conclusions:

1. The RayMan model was applied in this work and achieves a good fit between the simulation and measured data. The exported sun duration data are also useful for long-term simulation.

2. Bus shelters with lower SVF (or better sheltered) can help reduce direct solar radiation and provide comfort spaces for the local weather and the preferences of occupants in semi-outdoor environments in Taiwan.

3. To design bus shelters passively, spaces should have good shelter and lower SVF values, and designers should consider local patterns of sunlight and simulate these patterns over the entire year.

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