buildings

MDPI

Article

Investigation of Bus Shelters and Their Thermal Environment in Hot–Humid Areas—A Case Study in Guangzhou

Yan Pan [1,2], Shan Li [2,3,*] and Xiaoxiang Tang [1,2,*]

1 School of Architecture, South China University of Technology, Guangzhou 510641, China; 202210180979@mail.scut.edu.cn
2 State Key Lab of Subtropical Building and Urban Science, South China University of Technology, Guangzhou 510641, China
3 School of Architecture and Civil Engineering, Fuzhou Institute of Technology, Fuzhou 350506, China
* Correspondence: ls13024@gmiot.com (S.L.); ssxxtang@scut.edu.cn (X.T.)

Abstract: The acceleration of urbanization intensifies the urban heat island, outdoor activities (especially the road travel) are seriously affected by the overheating environment, and the comfort and safety of the bus shelter as an accessory facility of road travel are crucial to the passenger's experience. This study investigated the basic information (e.g., distribution, orientation) of 373 bus shelters in Guangzhou and extracted the typical style by classifying the characteristics of these bus shelters. Additionally, we also measured the thermal environment of some bus shelters in summer and investigated the cooling behavior of passengers in such an environment. The results show that the typical style of bus shelters in the core area of Guangzhou is north–south orientation, with only one station board at the end of the bus, two backboards, two roofs (opaque green), and the underlying surface is made of red permeable brick. The air temperature and relative humidity under different bus shelters, tree shading areas, and open space in summer are 34–37 °C and 49–56%, respectively. For the bus shelters with heavy traffic loads, the air temperature is basically above 35.5 °C, and the thermal environment is not comfortable. During the hot summer, when there is no bus shelter or trees to shade the sun, the waiting people adjust their position with the sun's height, azimuth angles, and direct solar radiation intensity to reduce the received radiation as much as possible, which brings great inconvenience to them. When only bus shelters provide shade, people tend to gather in the shaded space, and cooling measures such as umbrellas, hats, and small fans are still needed to alleviate thermal discomfort. However, the aforementioned various spontaneous cooling behaviors still cannot effectively alleviate overheating, and it is very important to increase auxiliary cooling facilities in bus shelters.

Keywords: bus shelter; typical geometric model; thermal environment; cooling behavior; field investigation

check for updates

Citation: Pan, Y.; Li, S.; Tang, X. Investigation of Bus Shelters and Their Thermal Environment in Hot–Humid Areas—A Case Study in Guangzhou. *Buildings* **2024**, *14*, 2377. https://doi.org/10.3390/buildings14082377

Academic Editor: Cinzia Buratti

Received: 5 July 2024
Revised: 29 July 2024
Accepted: 30 July 2024
Published: 1 August 2024

1. Introduction

A rapid global urbanization process has occurred in the past twenty years [1], the economic aggregate has continuously reached a new level, and people's living standards have continued to improve. At the same time, population growth, industrial structure changes, land-use expansion, and consumption pattern changes brought about by urbanization [2,3] have led to a series of environmental problems, especially the urban heat island, which has a significant negative impact on the health of urban residents. For example, a high-temperature event lasted for 30 days in 2022, covering more than 5 million square kilometers of China, affecting more than 900 million people, and the highest temperature in many places such as Shanghai, Shenzhen, exceeded 40 °C [4]. In cities across the U.S. from Phoenix to New York, people suffered from heat exhaustion, heat stroke, heat cramps, and more. In Texas, more than 300 people died from heat in 2023—the highest number since the state started tracking the deaths in 1989 [5]. India has also been experiencing frequent heat waves recently; in 2024, the country suffered the longest heat wave on record, with temperatures hovering between 45 and 50 °C in many cities. As a result, more than 200 people have died from the heat wave so far this summer [6], and nearly 25,000 suspected cases of heat stroke have been reported nationwide in May alone.

Urbanization also increases the need for people to travel [7], among which road travel is a common way, and the comfort and safety of the bus shelter as an accessory facility of road travel are crucial to the passenger's experience [8]. Especially in the summer, due to the influence of the heat island effect, the thermal environment of the bus shelter may become very poor [9]. Therefore, it is particularly important to take measures to alleviate the thermal environment to improve residents' willingness to choose road travel, thus reducing transportation's carbon emissions. Previous studies mainly focus on radiation regulation, air temperature reduction, and air flow strengthening; these three factors are closely related to thermal comfort, to improve the thermal environment of bus shelters.

As for radiation regulation measures, the objective is to regulate two types of radiation: solar and long-wave radiation. To block solar radiation, one way is to add sunshades to the roof and sides of the shelter [10], while another way is planting trees around the bus shelter [11]. Lanza K et al. [12] found that planting trees around bus shelters was more effective in reducing passenger flow loss caused by thermal discomfort than changing the parameters of bus shelters themselves. To diminish long-wave radiation, materials with high solar reflectivity or daytime radiative cooling ability are chosen to build the shelter and reduce the surface temperature of the bus shelter, thereby reducing the long-wave radiation heat transfer intensity between the bus shelter's surfaces and human body. Montero-Gutierrez et al. [10] installed radiant cooling modules on bus stations' surfaces to improve the thermal comfort of passengers in hot–dry climates, and their results showed a reduction in discomfort feelings of 40–50% when the modules reached the set point temperature.

With regard to air temperature reduction, planting trees around the bus shelter can effectively reduce the air temperature and provide a cool environment, and its mechanism is mainly the transpiration of plants and shading of solar radiation [13]. Another effective method is to install a water spray cooling system, which is activated during the hot period to reduce the ambient temperature using the effect of water evaporation [14]. For instance, Ulpiani et al. [15] evaluated the cooling effect of an urban cooling shelter fitted with a misting system, and they found that the air temperature reduction between the misted zone and the reference point reached 3.5 °C. In addition, some active measures such as an evaporative cooling air supply unit [9] and ground source heat pump [16] are also effective. Velasco et al. [9] evaluated the cooling effectiveness of a three-step adiabatic cooling system equipped by a bus stop named Airbitat Oasis Smart Bus Stop.

Additionally, enhancing the air flow is also one of the ways to improve the thermal comfort of the bus shelter. Ideally, it is necessary to consider a high sky view factor (SVF) to ensure strengthening the air flow between bus shelter and surrounding environment during the design stage [17]. However, numerous practical considerations render the natural ventilation environment of the bus shelter generally unsatisfactory [18]. Therefore, some mechanical ventilation measures have been utilized, such as fans and fresh air units. It is reported that there are many applications of fans at bus stations to improve the thermal comfort of passengers in Singapore [19].

However, a limitation of the aforementioned research is that the subjects are not typical enough, resulting in insufficient universality of the conclusions. For example, Gao et al. [20] used stainless-steel tubes and waterproof cloth instead of billboards to simulate a real station platform and studied the effect of the spray system on the thermal environment. Therefore, it is imperative to investigate a large number of bus shelters, and establish their typical models by analyzing their characteristics, which is one of the novelties of this study. In addition, the thermal environment of some representative bus shelters in summer should be evaluated, and the cooling behaviors of waiting people in such environments will be investigated, which is another novel aspect of the present study. The workflow of this study is shown in Figure 1. This will lay a foundation for the thermal environment improvement of bus shelters and point out the future optimization direction of a bus shelter's thermal environment.

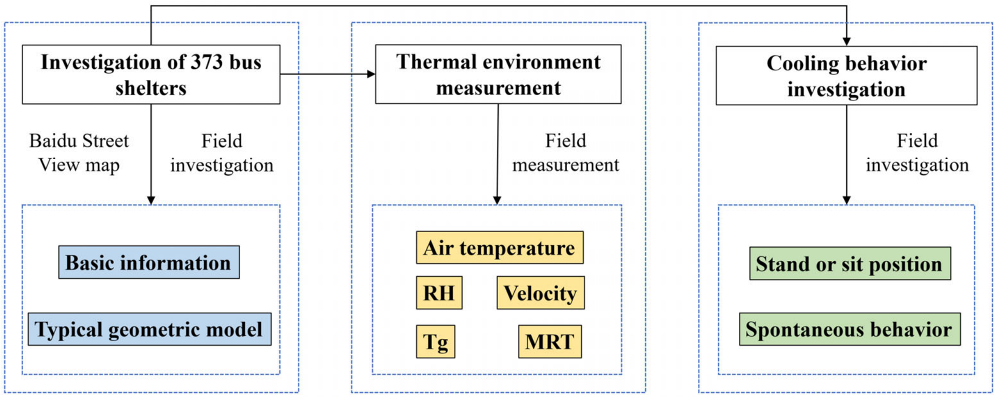

Figure 1. Workflow of investigation of bus shelters, their thermal environment, and cooling behaviors.

2. Methodology

2.1. Bus Shelters Investigation

2.1.1. Research Objects

In 2021, the average daily motorized trips in Guangzhou were 24.13 million, of which 12.54 million were made in the central urban area (Liwan, Yuexiu, Tianhe, and Haizhu districts as well as the southern part of Baiyun and Huangpu districts), and the use of public transportation accounted for 52% of the total motorized trips. As of 2021, the city had 15,612 public buses (electric) and 1347 public bus (electric) lines. The annual passenger volume reached 1.359 billion, with an average daily passenger volume of 3.72 million [21].

The research sites are mainly distributed near the core area; that is, in and around the Guangzhou Ring Highway, and a few sites are distributed in areas outside the central city. This is because of the restriction of the Baidu Street View map, as some sites are located in remote streets without the Street View map. In addition, the core area is the area with the largest number of daily bus passengers [21], which is the focus of this study.

The research objects were randomly sampled and distributed in and around the core area as evenly as possible. A total of 373 bus shelters were selected. The proportion of bus shelters distributed in Baiyun District, Tianhe District, Yuexui District, Nansha District, Liwan District, Haizhu District, Panyu District, Huadu District, Zengcheng District, and Huangpu District is 6%, 26%, 25%, 1%, 13%, 12%, 9%, 1%, and 1%, respectively, as shown in Figure 2. Among them, the gray line is the highway, the red line is the Guangzhou Ring Highway, and the black spot is the location of the bus shelter for research.

2.1.2. Investigation Method

In this study, the basic information of bus shelters in 11 districts of Guangzhou is collected by using the combination of the Baidu Street View map and field investigation. The contents include the following: Street View map date, bus shelter orientation, number of combined shelters, number of station boards, number of roofs, types of roofs, and underlying surfaces.

The date of the Street View map is the corresponding date of the shooting street view provided by the Baidu Map, which is the basic information. Bus shelters have 8 orientations: east, west, south, north, southeast, southwest, northeast, northwest, respectively. The combined bus shelter means that some bus shelters are also equipped with public telephone booths. Although they are independent of the bus shelter, their morphological characteristics are consistent with those of the bus shelter, as shown in Figure 3. Therefore, the number of roofs can not only be used to count the number of bus shelters, but also the number of phone booth roofs when counting the number of combined bus shelters.

The number of bus shelter roofs is set as 0, 1, 2, 3, and greater than 3, respectively, and the number of bus shelter backplanes is consistent with the number of roofs. Due to the large area of some bus shelters, it is convenient for passengers to obtain traffic information by setting up stop boards at both ends, so the number of stop boards is 1 (only one end has a stop board) or 2 (both ends have a stop board). Bus shelters have roof types of transparent, opaque green, and opaque gray, respectively, and the underlying surface materials include permeable brick, tile, and cement.

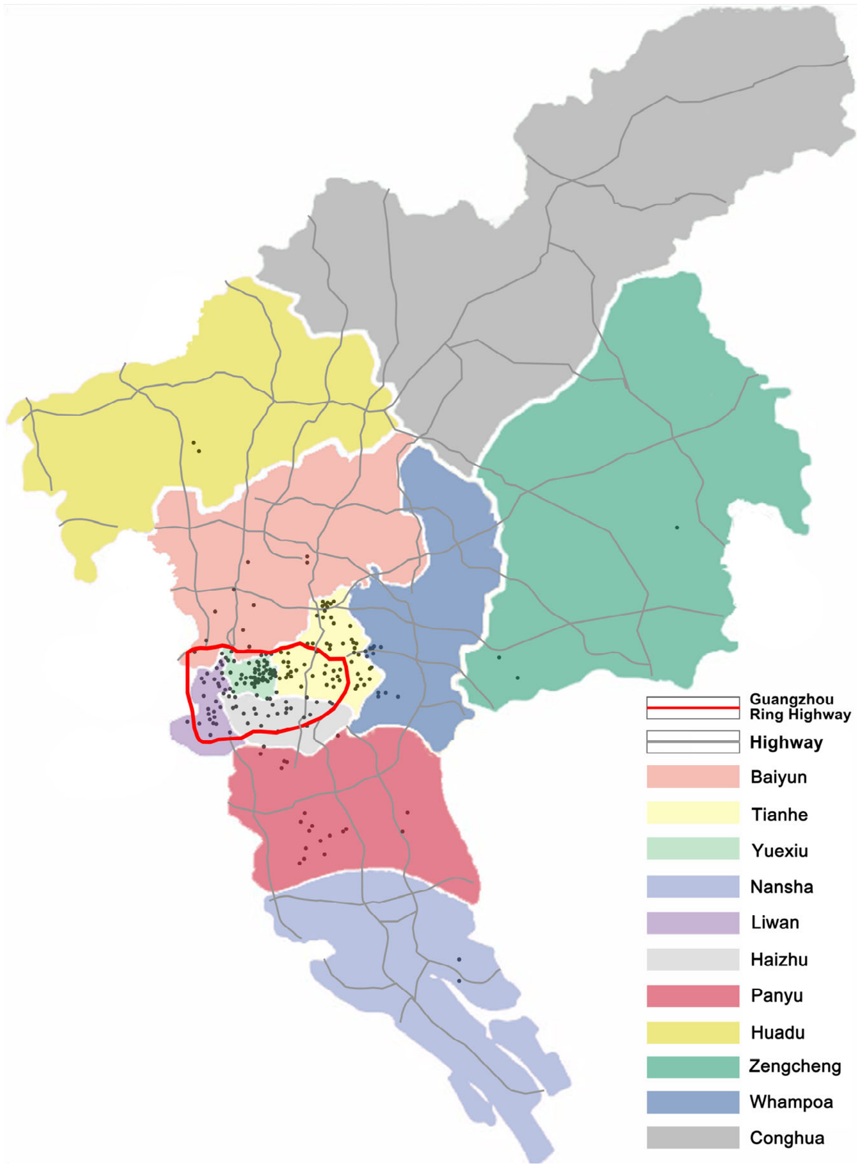

Figure 2. Distribution of survey objects (the area around the red line is the core area of Guangzhou).

Through correlation analysis, it can be found that there is no significant correlation between all factors (e.g., orientation, color, etc.). Consequently, the parameter with the largest proportion among all factors is selected, and the combination of all factors is summarized into a typical bus shelter model (see Section 3.2).

Figure 3. The combined bus shelters.

2.2. Thermal Environment Measurement of Bus Shelter

In order to find out the severity of the thermal environment in the bus waiting areas, different bus shelters were tested on 9 July 2022 in sunny weather, and the personnel cooling behaviors were investigated in Tianhe District and Yuexiu District from early July to early August. Considering the different thermal environments under different bus shelters, four representative types of bus shelters were selected according to the survey results of the bus shelter styles in Section 2.1, so as to understand the spontaneous cooling behavior of waiting personnel in the environment.

The basic information of the four types of bus shelters is shown in Table 1. In addition, two reference measured points are also listed, namely, the measured point under the tree and the measured point with no shading. The reason why we chose these points is as follows. Based on the results of ① and ③, the effect of the roof and backboard on the thermal environment can be highlighted, despite the difference in people and traffic flow. To demonstrate the influence of people and traffic flow, the measured points of ② and ④ are set up. Furthermore, the effects of the bus shelter shading and tree shading will be identified by comparing the results of ① and ⑤.

Table 1. The measured four bus shelters and two reference points.

Measured Points	①	②	③	④	⑤	⑥
Site	Changfu Road Station	Changxing Road Station	Tianhe Passenger Station	Tianyuan Road Station	Tree shading	No shading
Orientation	West	Southwest	North	South	NA	NA
Number of station boards	1	1	1	1	NA	NA
Number of backboards	0	2	3	2	NA	NA
Roof color and material	No roof	Green opaque	Green opaque	Green opaque	NA	NA
Underlying surface color and material	Permeable brick	Red permeable brick	Red permeable brick	Gray permeable brick	Red permeable brick	Gray cement
Tree shading	No	Yes	No	Yes	Yes	No
People and traffic flow	Few	Few	Many	Many	Few	Many

All the measured points are located in Tianhe District. The survey route and the distribution of measured points are shown in Figure 4. The bus shelters of Changfu Road Station, Changxing Road Station, Tianhe Passenger Station, and Tianyuan Road Station are the measured points of ①, ②, ③, and ④, respectively, while the measured points of

⑤ and ⑥ are the measured point under the tree and the measured point with no shading. Figure 5 shows the real images of the measured points.

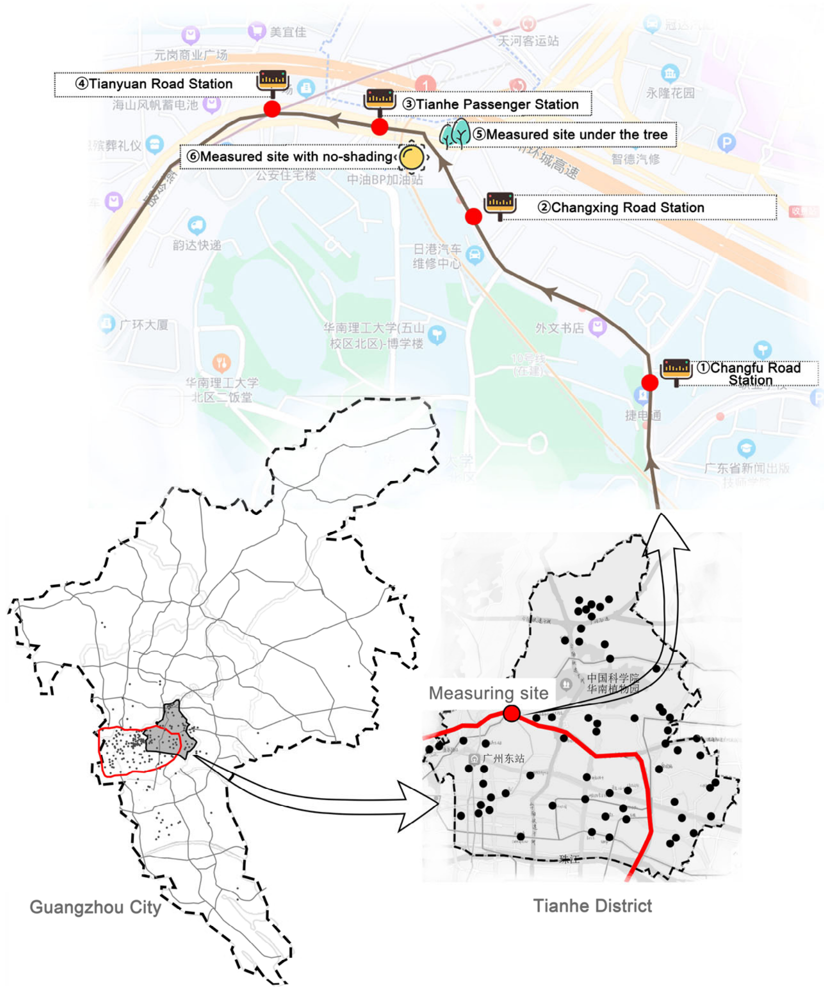

Figure 4. The distribution location and route of the measured bus shelters in Tianhe District, Guangzhou.

In this study, the black globe thermometer method was adopted; that is, the air temperature and relative humidity were measured by a temperature sensor (HOBO MX2302A, ONESET, Bourne, MA, USA), and the air velocity and black globe temperature (T_g) were measured by a thermal index meter (HD 32.3, Delta OHM, Senseca, Italy). In addition, the solar radiation intensity was collected by a pyranometer (K&Z CMP3, KIPP&ZONEN, Delft, The Netherlands) from a meteorological station.

Table 2 lists the instruments used in the test and their parameters. All instruments have been calibrated. The meteorological station is located on the roof of the State Key Lab of Subtropical Building and Urban Science of South China University of Technology, within 3 km of the measured site. Due to there being many people in the bus station, handheld instruments were used to measure the environmental parameters to avoid affecting normal pedestrian traffic, and the probe was 1.5 m high away from the ground. Every point was measured for a 30 min duration to cover its maximum 15 min response time, and the interval time was set at 15 s to capture the changes in environmental parameters.

Figure 5. The measured sites, bus shelter in (**a**) Changfu Road Station, (**b**) Changxing Road Station, (**c**) Tianhe Passenger Station, (**d**) Tianyuan Road Station, (**e**) measured site under the tree, (**f**) measured site with no shading.

Table 2. Specifications of measurement instruments.

Instrument	Range	Accuracy	Parameter	Interval
Temperature and humidity sensor (with radiation shield) (HOBO MX2302A)	−40–70 °C 0–100%	±0.2 °C ±2.5%	Air temperature Relative humidity	15 s
Thermal index meter (HD32.3)	10–100 °C 0–5 m/s	± 0.1 °C ±0.05 (0–1 m/s) ±0.15 (1–5 m/s)	Black globe temperature Wind speed	
Meteorological station (K&Z CMP3)	0–2000 W/m^2	±10 W/m^2	Solar radiation intensity	15 s

2.3. Measurement Data Analysis

Except for the above parameters measured directly, the mean radiant temperature (MRT) is one of the important parameters affecting human thermal comfort [22,23]. A higher MRT indicates a lower level of thermal comfort. According to a previous study, the test methods for the MRT mainly include the black globe thermometer method, double globe radiation thermometer method, and isothermal thermometer method [24]. As we mentioned before, we used the black globe thermometer method; then, the MRT can be calculated according to Equation (1) below:

$$\mathrm{MRT} = \left[\left(T_{\mathrm{g}} + 273\right)^4 + \frac{0.25 \times 10^8}{\varepsilon_{\mathrm{g}}} \left(\frac{|T_{\mathrm{g}} - T_{\mathrm{a}}|}{D}\right)^{\frac{1}{4}} \times (T_{\mathrm{g}} - T_{\mathrm{a}}) \right]^{\frac{1}{4}} - 273 \quad (1)$$

where D is the diameter of the black globe thermometer, which is 0.15 m; ε_{g} is the surface emissivity of the black globe, which is 0.95.

2.4. Investigation of Cooling Behavior of People in Waiting Area

Among the different waiting behaviors, some behaviors are closely related to the thermal environment. While measuring the thermal environment, the spontaneous behavior of the personnel caused by the harsh thermal environment is recorded, and then the necessity of the improvement of the thermal environment with cooling facilities is obtained.

In detail, we systematically observed and recorded the behaviors of individuals in every bus shelter by using a standardized table and taking photos, especially focused on behaviors that are indicative of thermal discomfort or attempts to cool down. These include the following: 1. seeking shade or moving to cooler areas; 2. fanning themselves with objects like papers or fans; 3. removing or adjusting clothing; 4. using portable cooling devices like handheld fans or mist sprays.

3. Results

3.1. Basic Information of Bus Shelters

3.1.1. Street View Date and Bus Shelter Orientation

Guangzhou is located near the Tropic of Cancer and experiences a high solar radiation intensity in summer. As a result, waiting people will adjust their position according to the sun's angle as well as the sunshade of the roof and backboard of the bus shelter. Therefore, a bus shelter with different orientations determines the distribution of people and the comfort of the waiting environment.

The date and orientation of the Street View maps of the 373 Guangzhou bus shelters investigated were analyzed, and the results are shown in Figure 6. Shading is essential for thermal comfort, and we will discuss its effect on the thermal environment of the waiting areas in Section 3.3, and people's behaviors in Section 3.4.

The Street View maps of bus shelters were mostly provided between October 2019 and March 2020 (Figure 6a). Earlier Street View maps may not accurately reflect the present situation of bus shelters; hence, they are not included in the scope of the information collection.

As displayed in Figure 6b,c, the orientation of bus shelters in Guangzhou is mainly south and north, accounting for 50% of all orientations, which is related to the street orientation planned in Guangzhou, while there are more east–west bus shelters in Baiyun District and Panyu District than other orientations.

The north- and south-oriented bus shelters' roof is unable to provide shade in the morning and afternoon due to the lack of nearby buildings and trees, but at midday, people are mostly in the shadow of the bus shelter. The backboard of the east- and west-oriented bus shelters provides shade in the afternoon and morning, respectively, while the roof provides shade at noon. Shading is essential for thermal comfort, and we will discuss its effect on the thermal environment of waiting areas in Section 3.3, and people's behaviors in Section 3.4.

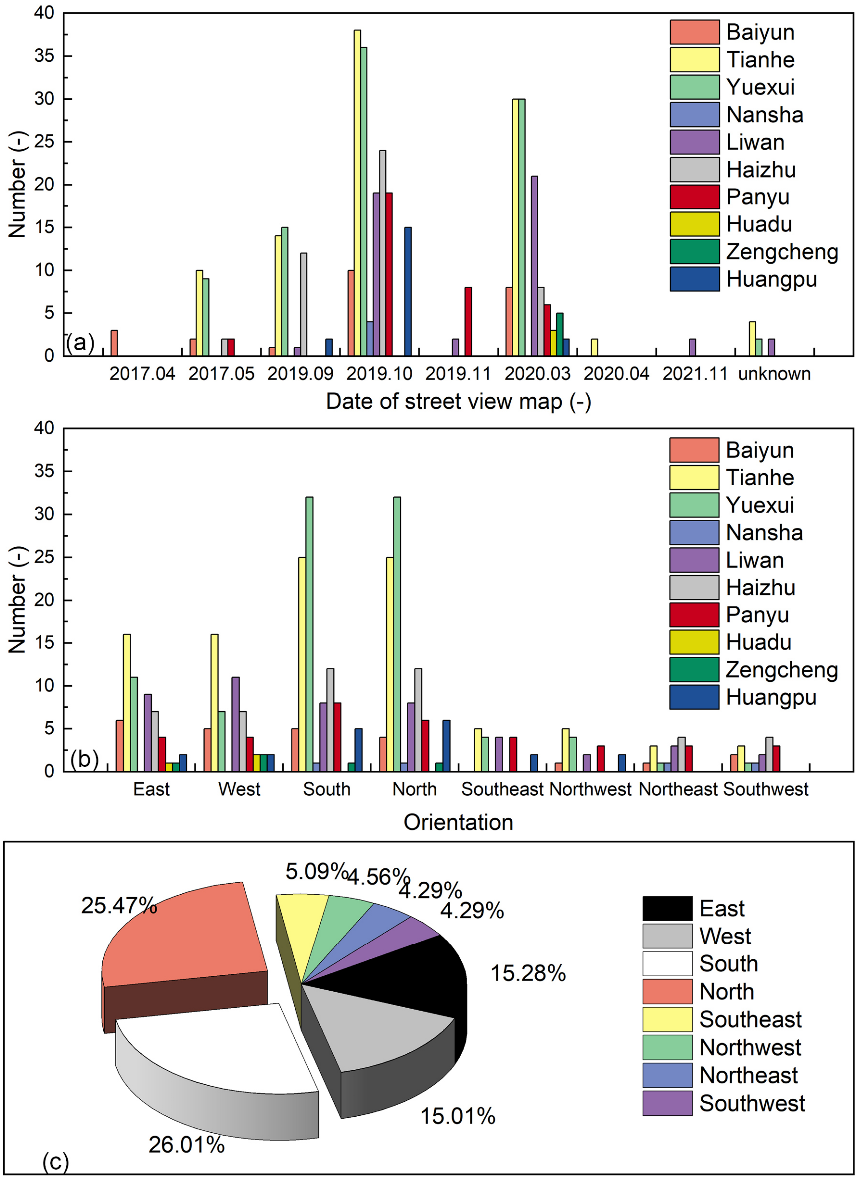

Figure 6. The statistics of shooting date and orientation of bus shelters, (**a**) shooting date of Street View map, (**b**) orientations of bus shelters in different districts, (**c**) proportion of bus shelter orientations of Guangzhou.

3.1.2. Combined Bus Shelter and Station Board

As illustrated in Figure 7, the combined bus shelters in Tianhe District, Yuexiu District, Liwan District, Haizhu District, and Huangpu District all account for more than 30%. The distance between the public phone booth and the bus shelter is relatively close, so the public phone booth should also be included when counting the number of boards. The bus shelters in the core area generally have boards at both ends of the platform to facilitate passengers to watch bus information, such as Yuexiu District, Liwan District, and Haizhu District, where bus shelters with boards at both ends account for 27%, 28%, and 33% of the number of shelters in the area, respectively. In suburban areas, however, combination shelters and bus shelters with bus boards at both ends are rather insignificant. With regard to the thermal environment, the bus boards can provide a shading effect, thereby enhancing the thermal comfort of people. However, in suburban areas, there is typically greater tree coverage than in urban areas [25], so it is acceptable for suburban areas to build bus shelters without boards.

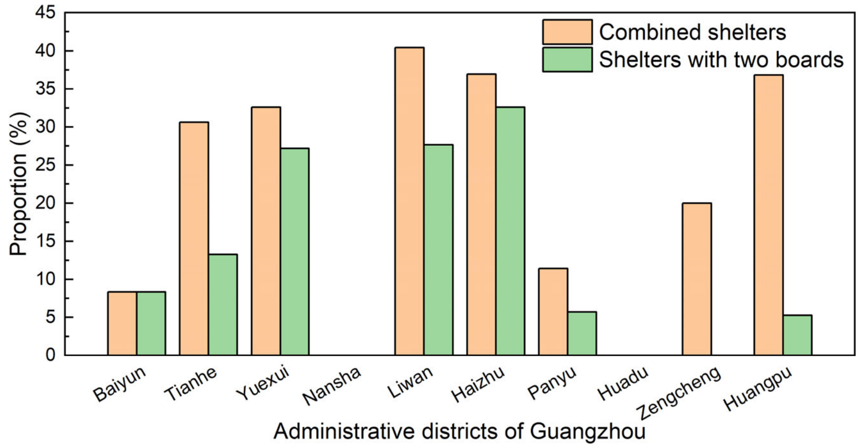

Figure 7. The proportion of combined bus shelters and bus shelters with two boards in different districts.

3.1.3. Number of Bus Shelter Roofs

The number of roofs of 373 bus shelters in Guangzhou were counted, and the number of public phone booths were ignored. The results are shown in Figure 8a,b. It can be found that different bus shelters with a different number of roofs in Liwan District almost have the same proportion. The reason is that Liwan District is an old city with a large number of arcade buildings, and the waiting area is below the arcade building [26]. As a result, extra roofs and backboards are not necessary to offer shade for the people waiting, as shown in Figure 8c. Therefore, Liwan District has a larger proportion of uncovered bus shelters than any other district.

In Tianhe and Haizhu districts, the proportion of bus shelters with three roofs is higher than that of the other number of roofs. In addition to the central city, the number of roofs in other districts is concentrated at one and two, because these areas have less population density and fewer waiting people, so there is less demand for bus shelter space. The bus shelters with two roofs make up the largest percentage (35%), which are followed by bus shelters with three and one roofs, accounting for 28% and 23%, respectively. This suggests that the bus shelters with two roofs in Guangzhou can meet the needs of most people waiting for buses.

Considering the public phone booths, the proportion of bus shelters with a different number of roofs is shown in Figure 9. As mentioned in Section 3.1.2, the combined bus shelters in Tianhe District, Yuexiu District, Liwan District, Haizhu District, and Huangpu District all account for more than 30%, so there is a significant difference between the number of bus shelters with more than three roofs in these districts and the number of public phone booths without consideration. Apart from the aforementioned center city, the number of roofs in other districts still concentrates at one and two, which means that there is still little demand for bus shelters in these areas. The highest proportion of all types is still the two-roof bus shelter, accounting for 34%, which is followed by three-roof shelters, accounting for 23%.

3.1.4. Types of Bus Shelter Roof and Underlying Surface

The materials, colors, and other parameters related to the thermal environment of 373 bus shelters in Guangzhou are displayed in Figures 10–12. The roof types of the bus shelters are mainly opaque green, opaque gray, and translucent, as shown in Figure 10, with the majority of the shapes being flat with a few arcs, waves, etc. Among all the roof types, opaque green has the largest proportion (81%), opaque gray comes in second with 9% (see Figure 12a), and the majority of them are found in Panyu District. The rationale behind this choice of material is twofold. Firstly, opaque green materials typically exhibit a higher solar reflectance than their opaque gray counterparts [27,28]. Secondly, the color of opaque green materials is akin to that of trees, thereby ensuring a uniform color across the surface.

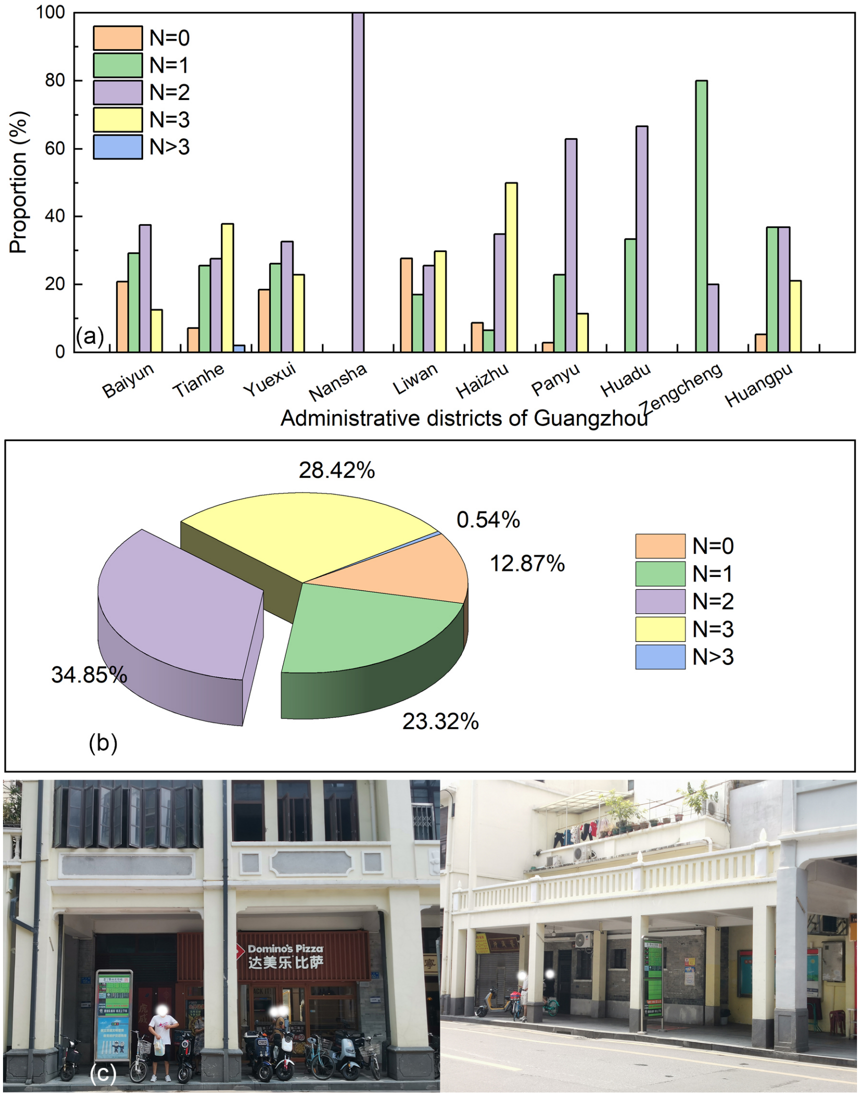

Figure 8. (**a**) Proportion of bus shelters with different number of roofs (excluding public telephone booths) in different districts, (**b**) proportion of bus shelters with different number of roofs (excluding public telephone booths) in Guangzhou, (**c**) Enning Road bus station in Liwan District.

As for the underlying surfaces, their materials and colors are gray permeable brick, red permeable brick, impervious brick, and cement, as shown in Figure 11. The highest proportion of the underlying surface type in the waiting area is red permeable brick, accounting for 52%, followed by gray permeable brick, accounting for 45% (see Figure 12b). Permeable brick has the ability to collect rainwater in rainy weather and improve urban flood resilience [29]. In addition, it can improve the outdoor thermal environment in hot weather by evaporating the absorbed rainwater [30]. Since the bus shelter is often set up on the sidewalk, it is consistent with the underlying surface type of the sidewalk. Some of the waiting areas are near remote roads or villages that are merely made of cement with no planning or maintenance.

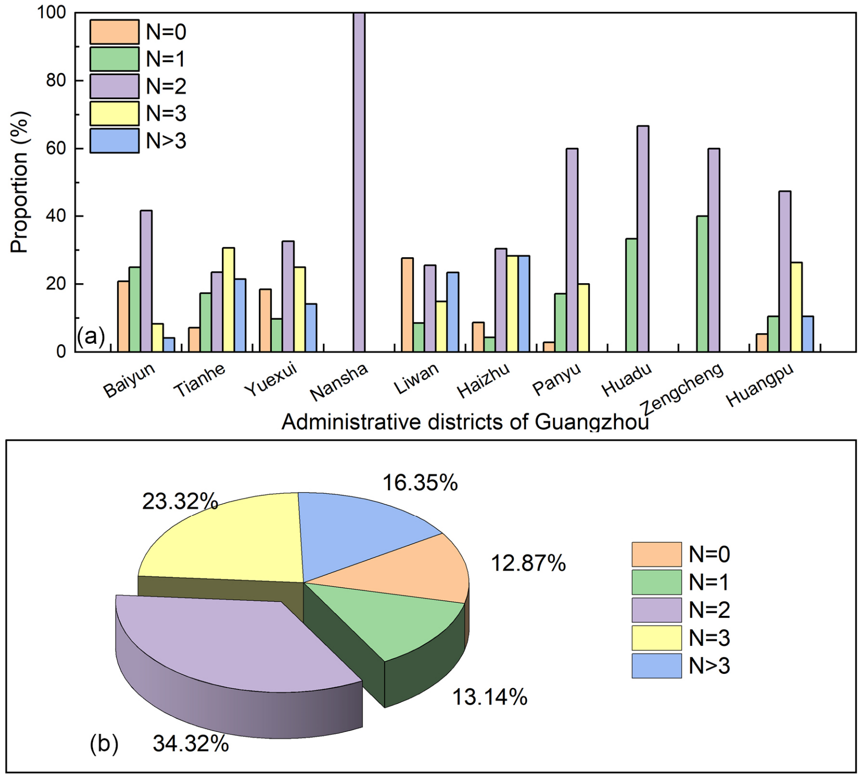

Figure 9. (**a**) Proportion of bus shelters with different number of roofs (including public telephone booths) in different districts, (**b**) proportion of bus shelters with different number of roofs (including public telephone booths) in Guangzhou.

Figure 10. The common types of roofs for the investigated bus shelters, (**a**) opaque green roof, (**b**) translucent roof, and (**c**) opaque gray roof.

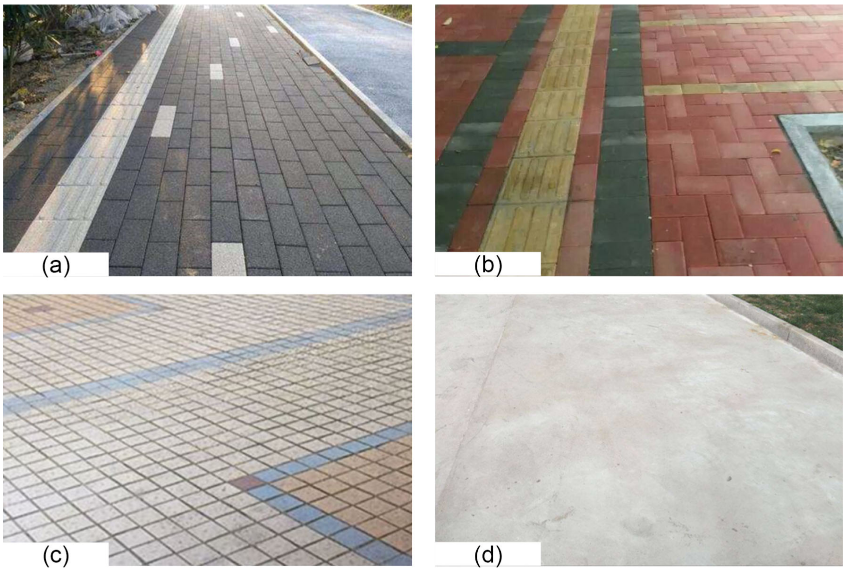

Figure 11. The different types of underlay surfaces of investigated bus shelters, (**a**) gray permeable brick, (**b**) red permeable brick, (**c**) impervious brick, and (**d**) cement.

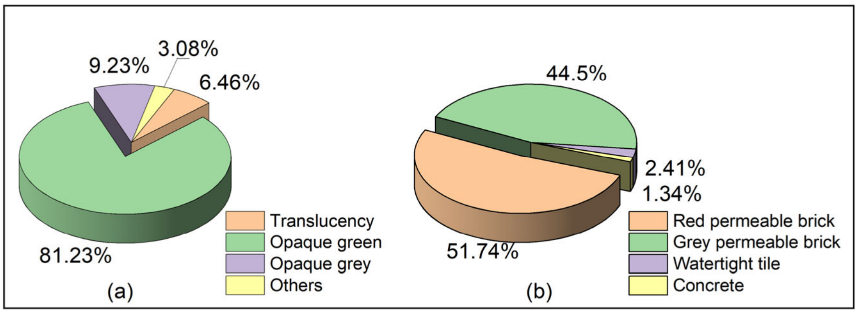

Figure 12. The proportion of (**a**) roofs and (**b**) underlying surfaces for the investigated bus shelters in Guangzhou.

3.2. Typical Style of Bus Shelter

Based on the analysis of Guangzhou's bus shelter characteristics, it can be concluded that the typical style of bus shelters is north–south orientation, with only one station board at the end of the bus, two backboards, two roofs (opaque green), and the underlying surface is made of red permeable brick. Representative stations that fit this description include Xikeng Station, Tuhua village Station, Light Industrial Secondary School Station (Figure 13), etc.

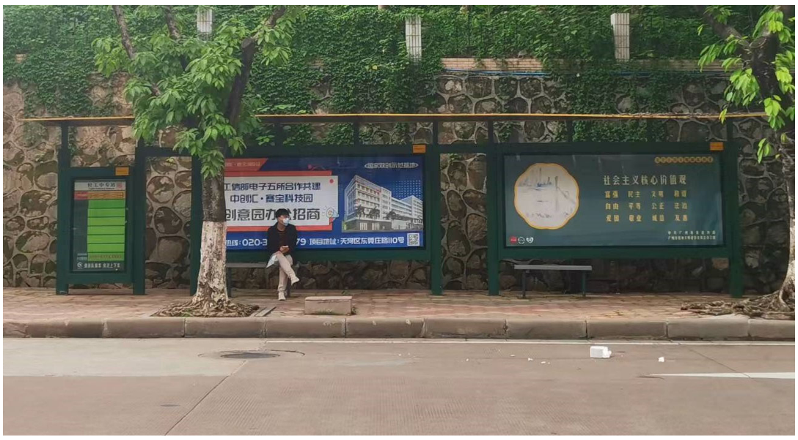

Figure 13. A typical bus shelter in Guangzhou (Light Industrial Secondary School Station).

3.3. Thermal Environment of Bus Shelter

The measured air temperature and relative humidity (RH) under different bus shelters, tree shading area, and open space are shown in Figure 14a. During the measurement period, the air temperature was 34−37 °C, and the average temperature of each measured point is ranked from high to low as follows. The temperatures for ⑥, ③, ④, ①, ⑤, and ② were 36.5 °C, 35.6 °C, 35.5 °C, 34.9 °C, 34.8 °C, and 34.1 °C, respectively. The variation trend of the RH is basically opposite to that of the air temperature, and the RH distribution of each measured point is between 49% and 56%. For the bus shelters with heavy traffic loads of people and vehicles, e.g., Tianhe Passenger Station (③) and Tianyuan Road Station (④), the air temperature is basically above 35.5 °C, and the thermal environment under the bus shelter is not comfortable, so it is very important to improve the thermal environment of the waiting area.

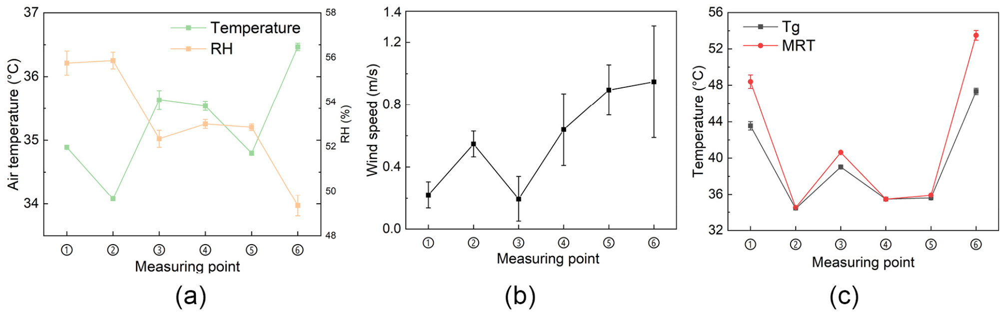

Figure 14. (**a**) Air temperature and relative humidity (RH), (**b**) wind speed, and (**c**) black globe temperature (T_g) and mean radiant temperature (MRT) at each measured point.

The wind speed of all measured points during the measurement period was between 0.2 and 1.0 m/s, and the wind speed of each measured point is ranked from high to low as follows. The wind speeds for ⑥, ⑤, ④, ②, ①, and ③ were 0.95 m/s, 0.90 m/s, 0.64 m/s, 0.55 m/s, 0.22 m/s, and 0.20 m/s, respectively (see Figure 14b). It can be seen that the existence of bus shelters will decrease the wind speed, thus reducing the thermal comfort levels in the outdoor environment, according to some previous studies [31].

According to the data of the weather station, the average solar radiation intensity during the measurement period was 765.7 W/m^2. As shown in Figure 14c, the black globe temperatures (T_g) of ②, ④, and ⑤ are closely comparable, which are 34.5 °C, 35.5 °C, and 35.6 °C, respectively. Because of the shade of trees above the three stations, the waiting area receives almost the same amount of solar radiation. For the measured point ③ without tree shading but with bus shelter shading, the T_g reaches 39.0 °C, and the MRT is about 6.1 °C higher than that of the measured point with tree shading, indicating that tree shading has a more notable effect on reducing the T_g than bus shelter shading. This finding further confirms the conclusion of Lanza K et al. [12], with planting trees around bus shelters more effective in reducing passenger flow loss caused by thermal discomfort than changing the parameters of bus shelters themselves. For the measured points ① and ⑥ without trees or bus shelters to shade the sun, the T_g is higher than 40 °C, and the MRT is near or higher than 50 °C, resulting in a terrible waiting environment. Especially for the measured point ⑥, the corresponding MRT is 53.5 °C, which is much higher than that of the other points, due to its higher air temperature and T_g.

3.4. Cooling Behavior of People under Bus Shelter

Since there is no bus shelter and trees to shade the sun, the air temperature and black globe temperature are high, so the waiting people adjust their positions according to the sun's altitude angle, azimuth angle, and direct solar radiation intensity, as shown in Figure 15. When there is no cloud cover and the direct solar radiation intensity is high, the waiting people move to the shadow of the station to relieve their thermal discomfort; when the sun's altitude angle is high, they will even crouch to ensure that the whole body is in the shadow of the station (Figure 15a). If there is no direct solar radiation, the waiting people will move from the rear of the station to the position near the road to observe whether the vehicle will arrive. Therefore, this waiting area without shade brings great inconvenience to the passengers.

Figure 15. The cooling behaviors of waiting people in the bus stations with only station boards, (**a**) crouching in the shadow of board, (**b**) carrying umbrella.

In addition to waiting close to the shadow area, the waiting people also shade and cool down by using an umbrella. As displayed in Figure 15b, when the solar radiation intensity is weakened, people also put the umbrella on the side of the body and move quickly along the umbrella handle to speed up the air flow and enhance the convective heat transfer on the human body's surface to reduce the surface temperature.

When there are no trees to shade the sun, the people under the bus shelter stand or sit in the shaded space formed by the bus shelter's roof and backboard, as shown in Figure 16a. Due to the high black globe temperature, people generally reduce the solar radiation and long-wave radiation received by the body by wearing hats and holding umbrellas (Figure 16b). Some people even quickly fan their clothes to accelerate the evaporation of sweat (Figure 16), which not only helps to reduce the discomfort of the attached wet clothes, but also to cool the body's surface via evaporation.

Figure 16. The cooling behaviors in the bus shelters without trees around, (**a**) standing or sitting in the shaded space, (**b**) wearing hats, (**c**) fanning clothes.

When trees are planted around the bus shelter, people are randomly distributed under the trees and under the bus shelter's roof, as shown in Figure 17. At this time, most people do not use umbrellas, but others still wear hats. This type of station is a better station design plan because it can arrange the waiting people in the positions of their choice and provide them with comfort and convenience.

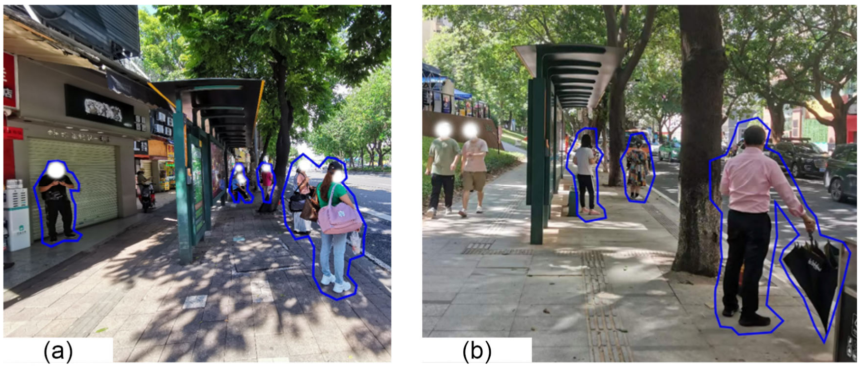

Figure 17. The cooling behaviors in the bus shelters with trees, (**a**) Tianhe Passenger Station, (**b**) Jianshe Road Station.

4. Discussion

One of the barriers to improving the thermal environment is the absence of a typical model for bus shelters, as we mentioned in the Section 1. Regardless of the research methodology we employ (simulation or experiments), we prefer to use the typical model to make the results more representative when comparing the impact of different measures on the thermal environment, especially for building performance simulation [32]. Therefore, the establishment of a typical model of bus shelters provides convenience for future research on improving the thermal environment.

The measurement results indicate that the thermal environment under bus shelters is synthetically affected by many factors, including the orientation, backboard, roof, underlying surface, etc. For example, the results of ① and ⑤ demonstrate that the tree shading exhibits a better effect on improving the thermal environment than the bus shelter shading, as the MRTs of ① and ⑤ are 48.4 °C and 35.9 °C, respectively. The underlying rationale, however, is that all the aforementioned factors exert an influence on the environmental parameters (e.g., solar radiation, air temperature), which affect thermal comfort. As a result, the thermal environment measurement results also point out the optimization directions. The first one is to reduce the solar radiation intensity received by waiting people, as the solar radiation represents the primary factor affecting their thermal comfort [33], and our findings corroborate this assertion (Section 3.3). It is recommended that the sizes of the bus shelter's roofs and boards should be increased to increase the shading area. Alternatively, the bus shelter's roofs and boards can be replaced with adjustable devices to better accommodate the changes in the sun's altitude and azimuth angles. In addition to the solar radiation regulation, reducing the air temperature of waiting areas is another direction to improve the thermal environment. The utilization of water spray represents a promising technique for this purpose, which cools the surface and air temperature mainly through water evaporation and has been widely used in urban outdoor environments [34,35] and building envelopes [36,37]. Furthermore, due to the existence of bus shelters reducing the wind speed of waiting areas (see Figure 14b), thus deteriorating the thermal comfort, it is necessary to increase the local wind speed via some active measures, such as a ceiling fan or pedestal fan.

This study still has several limitations, the most significant being the lack of a clearly established relationship between the thermal environment and cooling behaviors. Although this study provides valuable observations and measurements, it falls short in quantitatively linking specific thermal conditions to corresponding cooling responses. This gap makes it challenging to draw definitive conclusions about how different aspects of the thermal environment directly influence people's cooling behaviors. Additionally, without a robust analysis of this relationship, this study cannot fully inform the development of targeted interventions or improvements in thermal comfort strategies.

Therefore, the following study could focus on analyzing the data to identify patterns and correlations between the thermal environment and the observed cooling behaviors.

Meanwhile, it is necessary to determine which thermal conditions most frequently lead to spontaneous cooling behaviors, and assess the effectiveness of different cooling strategies from the aspects of technology and economy.

5. Conclusions

This study investigated the basic information (such as distribution, orientation, etc.) of 373 bus shelters in Guangzhou, and extracted the typical style by classifying the characteristics of these bus shelters. In addition, we also measured the thermal environment of some representative bus shelters in summer and investigated the cooling behavior of waiting people in such environment. Several conclusions can be addressed as follows:

(1) The typical style of bus shelters in the core area of Guangzhou is north–south orientation, with only one station board at the end of the bus, two backboards, two roofs (opaque green), and the underlying surface is made of red permeable brick.
(2) The air temperature and relative humidity under different bus shelters, tree shading area, and open space in summer are 34–37 °C and 49–56%, respectively. For the bus shelters with heavy traffic loads of people and vehicles, the air temperature is basically above 35.5 °C, and the thermal environment under the bus shelter is not comfortable, so it is very important to improve the thermal environment of the waiting area.
(3) During the hot summer, when there is no bus shelter or trees to shade the sun, the waiting people adjust their position with the sun's height angle, azimuth angle, and direct solar radiation intensity to reduce the received radiation as much as possible, which brings great inconvenience to the passengers.
(4) When only bus shelters provide shade, people tend to gather in the shaded space, and cooling measures such as umbrellas, hats, and small fans are still needed to alleviate thermal discomfort. However, the aforementioned various spontaneous cooling behaviors still cannot effectively alleviate overheating, and it is very important to increase auxiliary cooling facilities in bus shelters.

This study lays a foundation for the thermal environment improvement of bus shelters, and researchers can use this typical model to conduct experiments or simulations to make the results more representative. In addition, this study pointed out the future optimization direction of a bus shelter's thermal environment via the field measurement and investigation of cooling behaviors.

Author Contributions: Conceptualization, Y.P. and X.T.; methodology, Y.P. and X.T.; investigation, S.L.; writing—original draft preparation, Y.P. and S.L.; writing—review and editing, Y.P. and S.L.; visualization, Y.P. and S.L.; supervision, X.T.; funding acquisition, X.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant No. 51978272).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ma, W.; Jiang, G.; Li, W.; Zhou, T. How do population decline, urban sprawl and industrial transformation impact land use change in rural residential areas? A comparative regional analysis at the peri-urban interface. *J. Clean. Prod.* **2018**, *205*, 76–85. [CrossRef]
2. Singh, P.; Kikon, N.; Verma, P. Impact of land use change and urbanization on urban heat island in Lucknow city, Central India. A remote sensing based estimate. *Sustain. Cities Soc.* **2017**, *32*, 100–114. [CrossRef]
3. Zhang, H.; Qi, Z.-F.; Ye, X.-Y.; Cai, Y.-B.; Ma, W.-C.; Chen, M.-N. Analysis of land use/land cover change, population shift, and their effects on spatiotemporal patterns of urban heat islands in metropolitan Shanghai, China. *Appl. Geogr.* **2013**, *44*, 121–133. [CrossRef]
4. Shuqiao, L. Many Regions of China Experience Extreme Heat, with Temperature Records Broken. Available online: https://www.cma.gov.cn/en2014/news/News/202207/t20220718_4985934.html (accessed on 18 July 2022).

5. Gaffney, T. What We Know about Extreme Heat's Health Impacts after the Hottest Summer on Record. Available online: https://www.statnews.com/2024/05/14/hottest-summer-2000-years-nature-study-climate-change-effects-health/ (accessed on 14 May 2024).
6. Mishra, S. India's Deadly Heat Kills over 200 People, Including Dozens of Poll Workers as Elections Wrap Up. Available online: https://www.independent.co.uk/climate-change/news/india-heatwaves-deaths-election-2024-b2555692.html (accessed on 3 June 2024).
7. Badland, H.M.; Duncan, M.J.; Mummery, W.K. Travel perceptions, behaviors, and environment by degree of urbanization. *Prev. Med.* **2008**, *47*, 265–269. [CrossRef]
8. Akabal, F.M.; Masirin, M.I.H.M.; Akasah, Z.A.; Rohani, M.M. Review on selection and suitability of rail transit station design pertaining to public safety. *Proc. IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *226*, 012033. [CrossRef]
9. Velasco, E.; Segovia, E. Effectiveness of equipping bus stop shelters with cooling and filtering systems in a city with tropical climate. *Smart Sustain. Built Environ.* 2023. *ahead-of-print*. [CrossRef]
10. Montero-Gutierrez, P.; Ramos, J.S.; Delgado, M.G.; Cerezo-Narvaez, A.; Amores, T.P.; Dominguez, S.A. Natural cooling solution for thermally conditioning bus stops as urban climate shelters in hot areas: Experimental proof of concept. *Energy Convers. Manag.* **2023**, *296*, 117627. [CrossRef]
11. Electricwala, F.; Kumar, R. Impact of Green Shading on Urban Bus Stop Structure. In Proceedings of the 2016 Second International Conference on Computational Intelligence & Communication Technology (CICT), Ghaziabad, India, 12–13 February 2016; pp. 615–622.
12. Lanza, K.; Durand, C.P. Heat-Moderating Effects of Bus Stop Shelters and Tree Shade on Public Transport Ridership. *Int. J. Environ. Res. Public Health* **2021**, *18*, 463. [CrossRef] [PubMed]
13. Lin, B.-S.; Cho, Y.-H.; Hsieh, C.-I. Study of the thermal environment of sidewalks within varied urban road structures. *Urban For. Urban Green.* **2021**, *62*, 127137. [CrossRef]
14. Farnham, C.; Nakao, M.; Nishioka, M.; Nabeshima, M.; Mizuno, T. Study of mist-cooling for semi-enclosed spaces in Osaka, Japan. *Procedia Environ. Sci.* **2011**, *4*, 228–238. [CrossRef]
15. Ulpiani, G.; Zinzi, M. Experimental assessment of the heat mitigation potential of an urban cooling shelter: Combining water misting with solar shading, wind shield, and smart control. *Energ Build.* **2023**, *299*, 113623. [CrossRef]
16. Alikhanova, A.; Kakimzhan, A.; Mukhanov, A.; Rojas-Solórzano, L. Design of a bus shelter based on green energy technologies for extreme weather conditions in Nur-Sultan, Kazakhstan. *Sustain. Energy Technol. Assess.* **2019**, *36*, 100544. [CrossRef]
17. Lin, T.P.; Matzarakis, A.; Huang, J.-J. Thermal comfort and passive design strategy of bus shelters. In Proceedings of the The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6–8 September 2006.
18. Wen, Y.; Leng, J.; Shen, X.; Han, G.; Sun, L.; Yu, F. Environmental and health effects of ventilation in subway stations: A literature review. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1084. [CrossRef] [PubMed]
19. Lim, A. Fans at Bus Stops to Cool You Down? Cool! Available online: https://www.sgcarmart.com/articles/news/lta-tests-use-of-electric-fans-at-five-bus-stops-in-singapore-17083 (accessed on 29 July 2024).
20. Gao, Y.; Meng, L.; Li, C.; Ge, L.; Meng, X. An experimental study of thermal comfort zone extension in the semi-open spray space. *Dev. Built Environ.* **2023**, *15*, 100217. [CrossRef]
21. *Annual Report on Transportation Development of Guangzhou in 2021*; Guangzhou Bureau of Planning and Natural Resources: Guangzhou, China, 2022.
22. Krüger, E.; Minella, F.; Matzarakis, A. Comparison of different methods of estimating the mean radiant temperature in outdoor thermal comfort studies. *Int. J. Biometeorol.* **2014**, *58*, 1727–1737. [CrossRef] [PubMed]
23. Liu, K.; You, W.; Chen, X.; Liu, W. Study on the influence of globe thermometer method on the accuracy of calculating outdoor mean radiant temperature and thermal comfort. *Atmosphere* **2022**, *13*, 809. [CrossRef]
24. Banfi, A.; Tatti, A.; Ferrando, M.; Fustinoni, D.; Zanghirella, F.; Causone, F. An experimental technique based on globe thermometers for the measurement of mean radiant temperature in urban settings. *Build. Environ.* **2022**, *222*, 109373. [CrossRef]
25. Nitoslawski, S.A.; Duinker, P.N.; Bush, P.G. A review of drivers of tree diversity in suburban areas: Research needs for North American cities. *Environ. Rev.* **2016**, *24*, 471–483. [CrossRef]
26. Fu, H.; Wang, P.; Zhou, J.; Zhang, S.; Li, Y. Investigating Influence of Visual Elements of Arcade Buildings and Streetscapes on Place Identity Using Eye-Tracking and Semantic Differential Methods. *Buildings* **2023**, *13*, 1580. [CrossRef]
27. Allmendinger, T. The solar-reflective characterization of solid opaque materials. *Int. J. Sci. Technol. Educ. Res.* **2016**, *7*, 1–17.
28. Levinson, R.; Berdahl, P.; Akbari, H. Solar spectral optical properties of pigments—Part II: Survey of common colorants. *Sol. Energy Mater. Sol. Cells* **2005**, *89*, 351–389. [CrossRef]
29. Luo, P.; Liu, L.; Wang, S.; Ren, B.; He, B.; Nover, D. Influence assessment of new Inner Tube Porous Brick with absorbent concrete on urban floods control. *Case Stud. Constr. Mater.* **2022**, *17*, e01236. [CrossRef]
30. Kubilay, A.; Derome, D.; Carmeliet, J. Impact of evaporative cooling due to wetting of urban materials on local thermal comfort in a street canyon. *Sustain. Cities Soc.* **2019**, *49*, 101574. [CrossRef]
31. Wong, N.H.; Chong, A.Z.M. Performance evaluation of misting fans in hot and humid climate. *Build. Environ.* **2010**, *45*, 2666–2678. [CrossRef]
32. Magni, M.; Ochs, F.; de Vries, S.; Maccarini, A.; Sigg, F. Hourly simulation results of building energy simulation tools using a reference office building as a case study. *Data Brief* **2021**, *38*, 107370. [CrossRef]

33. Hodder, S.G.; Parsons, K. The effects of solar radiation on thermal comfort. *Int. J. Biometeorol.* **2007**, *51*, 233–250. [CrossRef]
34. Di Giuseppe, E.; Ulpiani, G.; Cancellieri, C.; Di Perna, C.; D'Orazio, M.; Zinzi, M. Numerical modelling and experimental validation of the microclimatic impacts of water mist cooling in urban areas. *Energy Build.* **2021**, *231*, 110638. [CrossRef]
35. Ulpiani, G. Water mist spray for outdoor cooling: A systematic review of technologies, methods and impacts. *Appl. Energy* **2019**, *254*, 113647. [CrossRef]
36. Narumi, D.; Shigematsu, K.; Shimoda, Y. Effect of evaporative cooling techniques by spraying mist waster on energy saving in apartment house. In Proceedings of the PLEA 2009—Architecture Energy and the Occupant's Perspective: Proceedings of the 26th International Conference on Passive and Low Energy Architecture, Québec City, QC, Canada, 22–24 June 2009.
37. Alaidroos, A.; Krarti, M. Optimized controls for ventilated wall cavities with spray evaporative cooling systems. *Energy Build.* **2017**, *154*, 356–372. [CrossRef]