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Effect of Open-Window Gaps on the Thermal Environment inside Vehicles Exposed to Solar Radiation

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Abstract: To avoid a sharp rise in temperature in the cabin of parked vehicles exposed to solar radiation, experienced drivers leave some windows partly open when the vehicle is parked in the sunlight to achieve cooling through natural ventilation. However, the effectiveness of this measure to reduce the temperature under different weather conditions has not been verified. To this end, this study investigates the effect of open windows on the thermal environment of a vehicle under different environmental conditions. A field measurement, in which two identical vehicles with and without window gaps were used, was carried out in Daxing District, Beijing. The measurements were conducted for 15 days under different window gaps and ambient conditions. The results revealed that open windows resulted in a maximum temperature reduction of 6.7 °C in cabin air temperature under high temperature and high solar radiation, while only 0.6 °C can be reduced under low temperature and low solar radiation. The results also showed that when window gaps effectively reduce the air temperature, lower air temperature can be obtained with larger open-window areas.

Keywords: vehicle thermal environment; open-window gap; field measurement; comparison

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1. Introduction

1.1. Environment inside Vehicles Exposed to Solar Radiation

In the past five years, the number of vehicles in China has increased by more than 15 million every year. With this per capita vehicle ownership growth, vehicle-related problems have garnered increasing attention from relevant industries [1]; the thermal environment of vehicles is one of these problems. Vehicles have higher heat gains than buildings because of their metal structure and large glass areas. After hours of parking in an unshaded area, the air and inner surface temperatures of the vehicle rapidly rise, resulting in various problems.

The safety problem of vehicles caused by the extreme thermal environment is a crucial issue that must be addressed. Every year, infants and pets die from hyperthermia after being trapped in vehicles under sunlight and without ventilation [2–5]. Furthermore, high temperature is the third-highest factor causing traffic accidents [6]. The low performance of drivers under high-temperature conditions is a crucial factor affecting crashes [7]. The cabin temperature can reach 76 °C in summer with an outdoor temperature of 41 °C and surface solar radiation of 802 W/m^2 [8]. At extremely high ambient temperatures and upon sun exposure, the maximum cabin temperature can reach 90 °C [9]. When the vehicle cabin interior temperature reaches a maximum of 45 °C, some components in the vehicle may deteriorate and damage [10,11]. Driving safety may be reduced owing to the reduction of driver alertness and component reliability caused by high temperatures.

A vehicle cabin is a space where passengers may stay for a long time. Therefore, its thermal comfort is one of the dominant indicators of occupant satisfaction [12,13]. Because a large part of the cooling load is contributed to by the solar energy passing through the glazing [14], solar radiation has a significant influence on the thermal sensation and thermal comfort of the human body [10,12–16]. Bhavsar et al. [17] measured temperature variations in the cabin of a closed vehicle parked in the sun for 150 min; the results revealed that on hot summer days, the vehicle's cabin temperature rises to a minimum of 49 °C and a maximum of 60 °C when the ambient temperatures are 38.5 °C and 44 °C, respectively. This environment makes passengers uncomfortable and may cause suffocation until the vehicle is sufficiently ventilated or air-conditioned. Levinson et al. [18] measured the soak temperature of two vehicles with high and low solar reflection coefficients of the shell and found that solar radiation led to more load on the vehicles with a low solar reflection coefficient. The cabin air temperature difference between the two vehicles reached 5–6 °C, where the highest temperature difference of 11 °C appeared in the ceiling. Al-Kayiem et al. [19] conducted experimental and numerical studies on the temperature distribution on surfaces and the air cavity in the car cabin. They concluded that the dashboard functioned as a sink of solar radiation and a source of convection heat transfer to the adjacent air particles. Cabins of vehicles were considered contaminated by high concentrations of organic compounds [20,21], and changes in their thermal environment were observed to affect the concentration of harmful volatile organic compounds (VOCs). In particular, under high-temperature conditions in summer, the interior components of vehicles were observed to produce more harmful air pollutants and affect people's health [22]. The total VOC (TVOC) concentrations inside each vehicle under static and high-heat conditions were found to depend on the interior temperature and were four- to 20-fold higher than those in the driving state [23]. Yoshida and Matsunaga [24] showed that compounds identified in the indoor air of a new vehicle continue to persist for more than 3 years from the concentration measurement time after delivery. The TVOC concentrations in summer reportedly exceeded the indoor guideline value (300 Ag/m^3) during this period.

With an increasing number of vehicles, the greenhouse gas emissions caused by transportation are increasing [25–27]. To prevent this, the use of electric vehicles is being encouraged politically and economically [28,29]. Moreover, the improvement in the energy efficiency of the air-conditioning system of vehicles is a viable means of reducing these emissions. However, a heating, ventilation, and air-conditioning (HVAC) system decrease the mileage of electric vehicles by 30–40% [30,31]. Nevertheless, expanding the vehicle range while guaranteeing air-conditioning requirements is challenging. A large startup load requires the air-conditioning system to consume more fuel or electricity [19].

1.2. Radiation and Ventilation of Vehicles

Reduction of the temperature in the cabin during outdoor parking in summer can improve the safety and thermal comfort of passengers, avoid excessive concentration of pollutants in the vehicle, and reduce energy consumption by the air-conditioning system. Indeed, the reduction of radiant heat transfer is considered an effective means of decreasing the cabin temperature. The use of solar reflective coatings for opaque surfaces of vehicle shells and glazings coated with a spectrally selective layer can decrease the startup load of vehicles parked under the sun [18,32,33]. An experimental comparison of identical black and silver compact sedans indicated that increasing the solar reflectance of the shell of the vehicle by approximately 0.5 lowered the temperature by approximately 5–6 °C [18]. Soulios et al. [33] used the EnergyPlus simulation program to predict the thermal behavior of parked vehicles. The results showed that spectrally selective glazing can reduce the cabin air temperature of parked vehicles by 12.5 °C, and the reduction of the cabin air temperature of parked vehicles can reach 23.8 °C when combined with solar reflective opaque surfaces.

In addition, many approaches to improve the thermal comfort of the cabin by changing the ventilation mode have been introduced [34,35]. A Renault Zoe electric vehicle was used for experiments with a ventilation system directly powered by photovoltaic (PV) and DC motor fans. Kolhe et al. [36,37] found that after powering the ventilation fans using solar

PV energy, in some cases, the car cabin temperature dropped near to that of the ambient temperature. Sudhir et al. [38] studied a vehicle parked in Muscat exposed to sunlight for a considerably long time. The vehicle was installed with an indigenously designed and developed cabin ventilation system powered by solar PV energy. They found that when the ventilation system was turned on, the temperature inside the car was approximately 10 °C lower than when the ventilation system was turned off. Jaiswal et al. [39] designed a new ventilation system to regulate the temperature inside a parked car by employing an exhaust fan, a blower, temperature sensors, and electronic control circuitry, under the constraint that the ignition system was off. Experiments were performed on a prototype cabin designed and fabricated based on a simulation performed using SOLIDWORKS. It was proven that when the ambient temperature was 39 °C, the temperature inside the vehicle dropped by 20 °C after the intelligent ventilation system was powered on.

Natural ventilation is more common and easier than mechanical ventilation. McLaren et al. [40] conducted an observational study and continuously measured the temperature rise for 60 min in a dark sedan on 16 different clear sunny days with ambient temperatures ranging from 22.2–35.6 °C. It was observed that a window opening of 38.1 mm decreased neither the rate of temperature increases in the vehicle (closed: 3.4 °C per 5 min; opened: 3.1 °C per 5 min) nor the final maximum internal temperature. King et al. [41] examined the changes in the internal temperature of various-sized automobiles during summer in Brisbane. Temperatures approaching ambient were only achieved when ventilation was provided by windows that were open for at least 200 mm (half). A lesser gap (50 mm) resulted in interior temperatures exceeding 50 °C, which is extremely hot for children. Infants left in such an environment quickly lose fluid from sweating and could dehydrate by 8% in 4 h. These studies investigated health issues and explored the effect of open windows on the reduction of the threat from high temperatures to infants and pets. There is a focus on the upper limit of cabin air temperature after opening windows, rather than the difference in the thermal environment of the cabin with or without open windows under the same conditions, so the effect of open windows on the cabin thermal environment has not been quantified.

1.3. Study Aims

Many experienced drivers typically leave a part of the windows open when parking outdoors in summer to avoid a sharp increase in the internal temperature of the vehicle. However, the effectiveness of open windows and the appropriate gap size under different weather conditions need to be studied. Previous studies on the effect of open-window gaps on the thermal environment of vehicle cabins were conducted by comparing and analyzing measurement results using a single vehicle [40]. Indeed, this method ignores the change in outdoor environmental conditions during the measurement. Each test usually needs more than 1 h, and the waiting time for the vehicle to recover the ambient temperature between the two measurements is extremely long, resulting in inaccurate and inconsistent solar radiation and ambient temperature measurements. Thus, the use of two different vehicles can improve the reliability of measurements. However, two different vehicles with different shell colors and shapes experience inconsistent radiation heat exchange, thereby limiting the measurement efficiency [18].

To overcome these limitations, in this study, two identical vehicles were used for measurement, and the cabin temperature of vehicles with and without small window gaps was measured at the same time under different weather conditions. This study is novel in that a comparative measurement study was carried out on two identical vehicles, and the air temperature of the cabin with different open-window gaps was measured in September and October in Daxing District, Beijing, China; the measurement results were used to quantify the effect of the area of open-window gaps on the thermal environment of the cabin under different environmental conditions. Furthermore, the VOC concentration was measured and analyzed to supplement the discussion on the effect of high temperatures and ventilation on the cabin environment. In Section 2, detailed information on the measured vehicle, measurement site, and data acquisition equipment is provided. Some representative measurement days are selected, and their details are also given in this study. In the next section, the temperature changes under different weather conditions are described, and only some representative periods are selected for analysis. Finally, the effect of open windows on the cabin thermal environment under different ambient conditions is discussed. The best practice of leaving window gaps during outdoor parking under different environmental conditions is suggested. The temperature drop owing to open windows and the influence of ventilation on the VOC concentration are also examined.

2. Methods

2.1. Heat Transfer Process of a Vehicle Cabin

As shown in Figure 1, the thermal environment in the vehicle cabin with open windows is affected by many ambient factors when parking, including solar radiation, ambient radiation, ambient temperature, air infiltration, and ventilation. The radiation heat transfer in a vehicle is relatively complex. Both long- and short-wave radiations can act on the external surface of the vehicle to raise the temperature of the exterior surfaces. In addition, a certain amount of solar radiation can directly enter the cabin through the window glass, raising the temperature of the interior surface of the vehicle. The transmission rate of longwave radiations, such as ground and sky radiations, is low; thus, radiation heat transfer is primarily affected by shortwave radiations. In general, the radiation heat exchange is affected by the angle of direct solar incidence and surface solar radiation [42]. The convective heat transfer between the vehicle and outdoor ambient air is primarily affected by the temperature difference between the ambient and exterior surfaces of the vehicle. The temperature of the exterior surface of the vehicle shell increases owing to the effect of radiation and convection, and the temperature of the inner surface rises because of the heat conduction, affecting the cabin air temperature. Because of different wind and thermal pressures on both sides of the cabin windows, using small window gaps leads to heat exchange through natural ventilation, which is affected by the ambient wind speed and temperature difference inside and outside the vehicle.

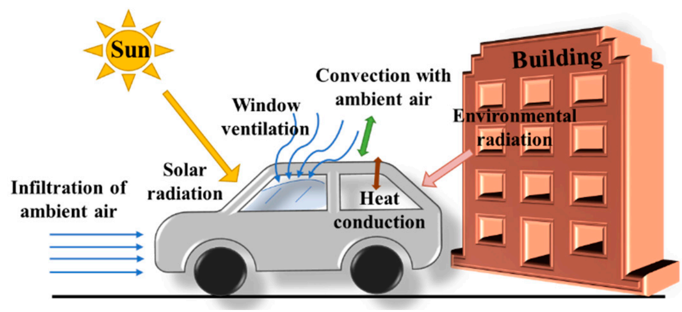


Figure 1. Factors affecting the vehicle cabin thermal environment.

The heat exchange process between the parked vehicle and the surrounding environment reveals that the cabin thermal environment is primarily affected by solar radiation, ambient temperature, and surrounding wind speed. These factors must be measured for a relatively long period, that is, several hours, to study the variations in the thermal environment in the cabin after opening the windows during outdoor parking.

2.2. Measurement Object and Site

This study was conducted in Daxing District, Beijing, China (39°73′ N, 116°33′ E). Measurements were carried out during the transition period from summer to autumn in Beijing. Compared with summer, the solar radiation and air temperature in this period are reduced; however, the surface solar radiation is still intense on some days. Two white medium-sized sport utility vehicles of the same model were chosen for measurements, as shown in Figure 2a. The selected vehicles were new with the same production date, mileage, and interior trim, with no sundries inside the vehicle and no sunshade film on the windows; thus, the internal environment of the vehicles was as consistent as possible. The vehicles were parked on an open field, and both faced South. Although the site was empty and vehicles were not excellently shaded, shielding factors existed owing to the influence and limitations of the site. The vehicles were located in the same position and orientation during all measurement days. The vehicle on the west and east sides are, respectively, marked as A and B in Figure 2b, which also illustrates the measurement site.

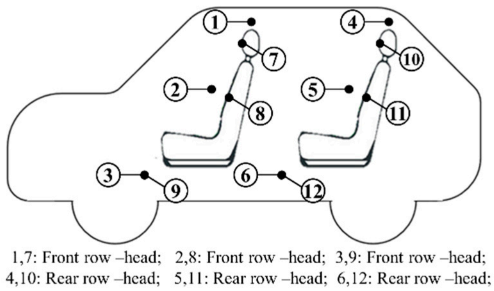
(**a**) (**b**)

Figure 2. Measurement object and site: (**a**) two identical vehicles; (**b**) vehicles' orientation and surrounding buildings in the site during the measurements.

2.3. Data Acquisition and Measurement Equipment

The outdoor air temperature entering the cabin can directly affect the thermal environment of the cabin; thus, a small environmental weather station was established to measure the ambient wind speed and air temperature. The ambient wind speed outside the vehicles was measured using Gill Wind Sonic. The anemometer was placed at the vehicle's front and fixed at a height of 2.2 m with a support to prevent the effect of personnel walking on the wind speed. The unit vector method [43] was used to calculate the average wind direction in the measurement period, as expressed in Equation (1). The arithmetic mean of wind speed was used to represent the average wind speed. The sensor used to collect the ambient temperature was a TR-71wb recorder placed at the support. The surface solar radiation data were from Wheat A, and the time step was 1 h. A forward looking infrared (FLIR) photographed the exterior surface temperature to guarantee an identical initial state for the vehicles.

Additionally, the air temperature must be measured to describe the cabin's thermal environment. As the cabin space was small, the direct sunlight area was not fixed, and the environment in the cabin was uneven. Therefore, the points representing the height of the head, chest, and feet of the front and rear passengers were considered as the measuring points. A total of six air temperature measuring points were set to represent the air temperature distribution in the vehicle. The thermal sensation of the head and chest is warmer than the overall thermal sensation [44], indicating that the air temperature at the height of the head and chest greatly affects the thermal sensation of the human body. Therefore, their average value was regarded as the air characteristic temperature in the cabin, as expressed in Equation (2). The inner surface temperature is directly affected by solar radiation, which is different from the air temperature. Therefore, six surface temperature measuring points were set near the air temperature measuring points. The air temperature in the cabin was measured by a TR-71wb recorder, and thermocouples measured all surface temperatures. Air temperature measuring points 1–6 and surface temperature measuring points 7–12 are shown in Figure 3a. All temperature sensors were placed in a paper shell wrapped with aluminum foil to prevent the influence of radiation on the temperature, as shown in Figure 3b. The measurement time interval of all equipment was set to 1 min.



(**a**)

(**b**)

Figure 3. Measuring points in the cabin: (**a**) air and surface temperature measuring points; (**b**) raw picture of the air temperature measuring point.

Table 1 lists the measurement data and accuracies of all devices. DNPH and Tenax-TA sorbent tubes were used to collect VOC in the vehicle cabin, and all sampling tubes were quantified using high-performance liquid chromatography or gas chromatography-mass spectrometry to obtain the VOC concentration data.

$$\overline{\theta} = \text{Arctan}\left(\frac{\frac{1}{n}\sum_{i=1}^{n}\sin\theta_i}{\frac{1}{n}\sum_{i=1}^{n}\cos\theta_i}\right) \quad (1)$$

where $\overline{\theta}$ is the average wind direction angle, n is the number of samples, and θ is the instantaneous wind direction angle.

$$Tc = \frac{T_{f-head} + T_{f-chest} + T_{r-head} + T_{r-chest}}{4} \quad (2)$$

where T_c is the average air temperature in the cabin, and $T_{f\text{-}head}$, $T_{f\text{-}chest}$, $T_{r\text{-}head}$, and $T_{r\text{-}chest}$ are the air temperatures at the head and chest heights in the front and rear, respectively.

Table 1. Measurement uncertainties.

Name	Instrument Type	Measurement Content	Measurement Range	Accuracy	Resolution
Anemometer	Gill Wind Sonic 	wind speed	Speed: 0–60 m/s; Direction: 0–359°	±2% ±3°	0.01 m/s; 1°
Temperature data recorder	TR-71wb 	Air temperature	−40–110 °C	±0.3 °C	0.1 °C

Table 1. *Cont.*

Name	Instrument Type	Measurement Content	Measurement Range	Accuracy	Resolution
Thermocouple	WRNK-191 	Interior surface temperature	−100–200 °C	±0.4%	0.1 °C
Thermal imager	FLIR E85 	Shell surface temperature	−20–120 °C; 0–650 °C; 300–1200 °C	±2 °C	384 × 288

2.4. Experimental Procedure and Measurement Cases

Before the measurement, the vehicles were parked at the test site simultaneously. First, the surface temperature of the two vehicles was photographed using FLIR to confirm their identical initial state. Subsequently, the window opening area was controlled by a fixed-length rubber block and Vernier caliper. The operation of the vehicles should be consistent as much as possible to obtain the same initial conditions.

Ten control measurements were performed under different weather and open-window conditions to analyze the effectiveness of open windows. Five groups of comparative measurements were carried out to compare the effects of different open-window areas and the number of open windows on the thermal environment of the vehicles. Details of seven representative measurement days are shown in Table 2.

Table 2. Description of the measurement cases.

Date	Vehicle Number	Number of Open Windows	Total Open-Window Area (m^2)
9 September	A	Four	0.070
	B	/	/
13 September	A	Four	0.070
	B	/	/
17 September	A	Four	0.056
	B	/	/
22 September	A	Four	0.070
	B	Two	0.035
23 September	A	Four	0.070
	B	Four	0.056
12 October	A	Four	0.056
	B	Two	0.028
14 October	A	Four	0.056
	B	/	/

3. Results

3.1. Typical Day Analysis

A typical day in the unstable period from 8 September to 20 October was selected to investigate the temperature reduction by the window gaps and the influence of window gap size on the cabin thermal environment. The temperature measurement results were recorded from 7:00 to 16:30 on 17 September and the distribution of the air temperature difference between the two vehicles is shown in Figure 4. At 12:06, four windows of vehicle A were opened, with a total open area of 0.014 m^2. Table 3 presents the ambient condition information for this day during the measurement period. The average wind direction on this day was 252°, the normal angle with the window was 72°, and the average wind speed was 0.78 m/s, which is less than the lower soft wind level in the wind grade of 1.5 m/s [45]. According to Figure 4, the solar radiation rises and then falls throughout the day, remaining at a high level from 11:00 to 15:00 and reaching a maximum at 12:00. The ambient temperature rises slowly, reaches a maximum of 32.4 °C at 12:55, and then decreases slowly. The cabin temperature begins to rapidly rise at 7:30, which is faster than that of the ambient temperature. The difference between the ambient and cabin temperatures gradually increased and reached a maximum value of 30.3 °C at 13:19. The wind and thermal pressures on both sides of the window gap ventilated vehicle A and promoted heat diffusion. Therefore, the temperature of vehicle A slightly decreased after opening the window and reached a heat balance at 13:00; further, the temperature remained relatively stable, fluctuating at 55.3 °C. The air temperature of vehicle B continually rose owing to the continuous accumulation of heat and reached a maximum at 13:22. The air temperature of vehicle A began to significantly decrease at 14:31, 10 min earlier than that of vehicle B, because of a decrease in the outdoor temperature and solar radiation. The obtained results are reasonable because natural convection is more sensitive to changes in the outdoor air temperature. Under the measured ambient conditions on 17 September, the air temperature of vehicle A after opening windows decreased by 3 °C within 15 min, with a maximum temperature drop of 6.7 °C at 14:52 and an average drop of 4.7 °C during the measurement time, proving the effectiveness of open windows in reducing the temperature of a vehicle cabin.

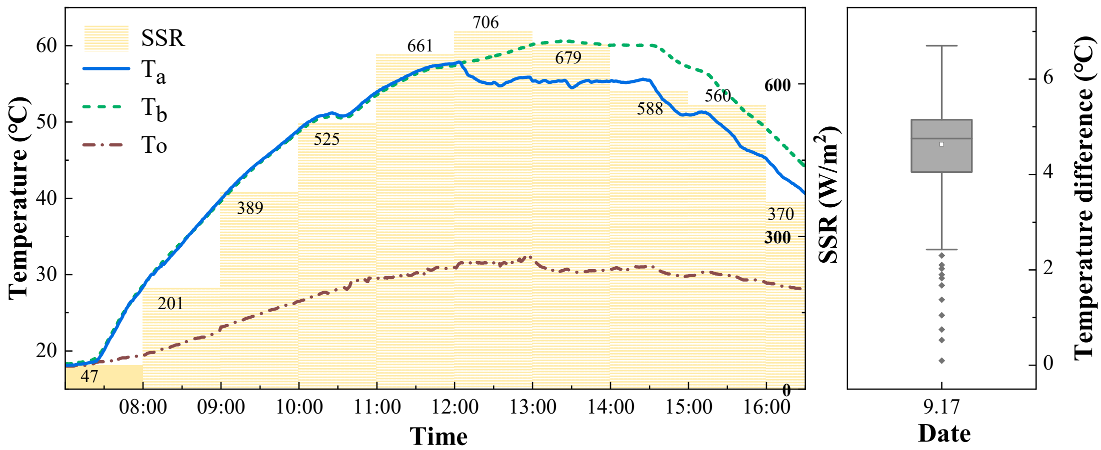


Figure 4. Air temperature variations and temperature differences of two vehicles on 17 September.

Table 3. Ambient conditions on 17 September.

Date	17 September
Average outdoor air temperature (°C)	27.3
Maximum outdoor air temperature (°C)	32.4
Average wind speed (m/s)	0.78
Average wind direction (°)	252

3.2. Effect of Ambient Temperature and Solar Surface Radiation

Figure 5 illustrates the variation curve and temperature difference of the cabin air temperature of the two vehicles from 13:40 to 16:00 on 9 September, 13 September, and

14 October. During these days, the windows of vehicle A were open with the same area size. Table 4 lists the ambient conditions for these days. The outdoor air temperature on 9 and 13 September was similar, and the average temperature difference was only 0.7°. The wind direction and normal angle with the window on these days were 52° and 50°, respectively. Surface solar radiation (SSR) was higher on 13 September, which raised the cabin air temperature of vehicle B with closed windows. Under measured ambient conditions on 13 September, the maximum temperature drop caused by open windows and average temperature drop were 2.6 and 2.1 °C, respectively. On 9 September, with a high outdoor air temperature and relatively low SSR and average wind speed, the maximum temperature drop caused by open windows and average temperature drop were only 1.8 and 1.4 °C, respectively. However, on 14 October, the results were different from the other two days. Open-window gaps to reduce the cabin air temperature are not effective under low SSR and ambient temperature conditions.

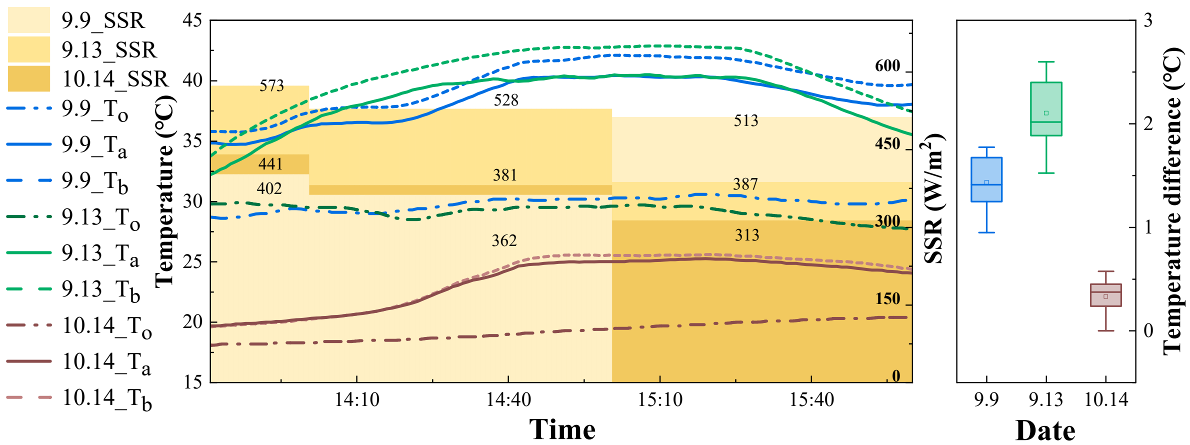


Figure 5. Air temperature variations in the cabin of two vehicles under different ambient conditions.

Table 4. Ambient conditions on 9 September, 13 September, and 14 October.

Data	9 September	13 September	14 October
Average outdoor air temperature (°C)	29.8	29.2	19.3
Maximum outdoor air temperature (°C)	30.6	29.9	20.4
Average wind speed (m/s)	0.33	0.46	0.88
Average wind direction	218°	140°	147°

3.3. Effect of Window Opening Conditions

Several sets of comparative measurements were conducted to examine the effect of different numbers of open windows and open-window areas on the thermal environment of the vehicles. Table 5 shows the ambient conditions, and Figure 6a illustrates the air temperature variations in the cabin of the two vehicles on 22 September. To observe the effect of the number of open windows on the thermal environment in the vehicles, four windows of vehicle A and two windows of vehicle B were opened, and the height of each window gap was approximately the same. In the rising phase of the ambient air temperature, the two vehicles maintained a temperature difference of 1.4 °C. From 15:00 to 15:30, both vehicles had a relatively stable temperature, and the temperature difference remained relatively constant. When the ambient temperature and SSR began to decrease, vehicle A began to cool down rapidly, approximately 13 min earlier than vehicle B; further, the temperature difference between the two vehicles began to increase, with a maximum temperature difference of 4.5 °C. During the measurement period, the average temperature difference between the two vehicles was 2.0 °C.

Table 5. Ambient conditions on 22 September and 23 September.

Data	22 September	23 September
Average outdoor air temperature (°C)	31.3	27.5
Maximum outdoor air temperature (°C)	32.9	28.1
Average wind speed (m/s)	1.02	0.89
Average wind direction	242°	252°

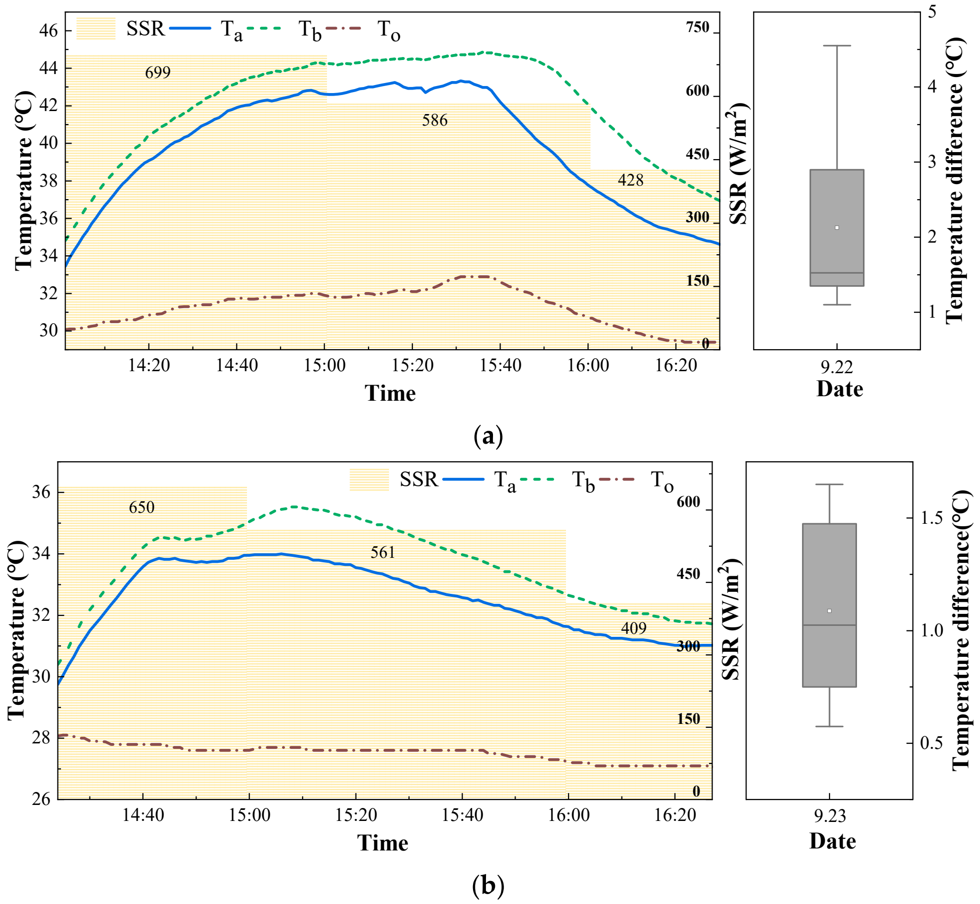


Figure 6. Variation of the air temperature of the vehicles on: (**a**) 22 September; (**b**) 23 September.

Figure 6b demonstrates the variation curves of the air temperature of the vehicles with four open windows and different open-window areas, measured on 23 September. When the air temperature of the cabins rises, the temperature difference between the two vehicles remains at 0.7 °C. However, the upper limit of the air temperature of vehicle A, which has a larger open-window area, is 1.8 °C lower than that of vehicle B. The same behavior was observed during the temperature drop phase. In addition, the temperature inside vehicle A began to drop earlier than that of vehicle B. Based on the measurement results, we can say that the cabin temperature decreases when more windows are open with larger open areas. This difference is more apparent when the cabin temperature drops.

3.4. Temperature Differences at Different Locations

Figure 7a shows the temperature variation at the height of the head, chest, and feet of passengers on the driver's side in the front and rear rows of vehicle B from 8:00 to 17:00 on 12 October. Table 6 lists the ambient conditions on this day. The results revealed that the temperature difference in vehicle B is large. The temperature in the vehicle begins to increase as the value of SSR increases, and T_c reaches a maximum value of 47.3 °C at 14:19. The temperature at the height of the head and chest rapidly increases both in the front and rear rows. The temperature difference between the head and feet in the front row of the vehicle reaches a maximum value of 27.9 °C at 12:24. Simultaneously, the temperature difference between the chest and feet is 21.0 °C. The temperature difference between the front and rear rows inside the cabin is small. Under high-temperature exposure conditions, the temperature difference at the same height of the front and rear rows is predominantly small. However, a significant difference in the air temperature at the head height between the front and rear rows from 10:20 to 11:30 and from 15:00 to 16:00 exists. The rear row is exposed to the sun first and then shaded when the sun sets because the vehicle is not parallel to the building. At 14:20, a comparative measurement of the two vehicles was carried out; two windows of vehicle B were opened, which resulted in temperature fluctuations.

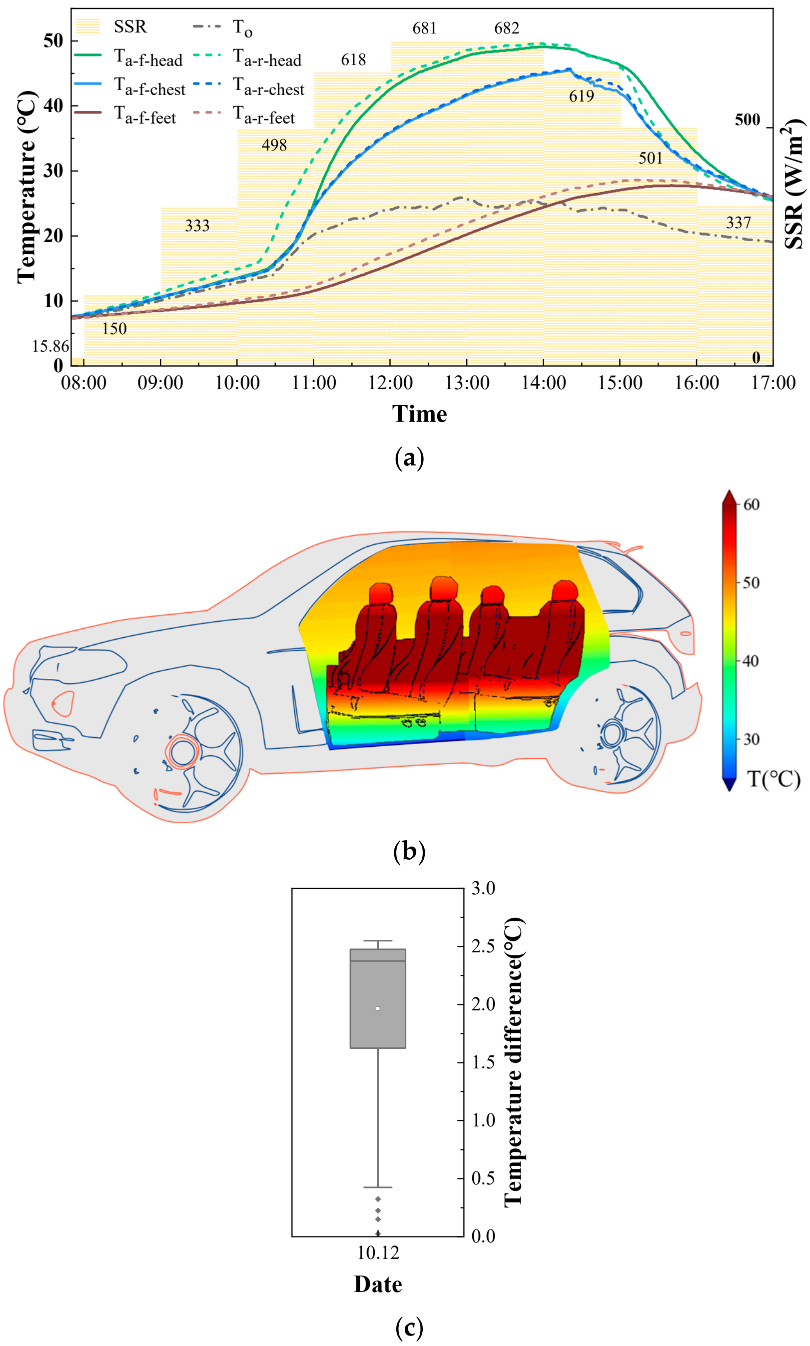


Figure 7. Cabin thermal environment on 12 October: (**a**) variation of the air temperature of vehicle B; (**b**) cabin air and the interior surface temperature distribution of vehicle B at 14:00 and (**c**) air temperature difference between the two vehicles.

Table 6. Ambient conditions on 12 October.

Data	12 October
Average outdoor air temperature (°C)	19.1
Maximum outdoor air temperature (°C)	25.9
Average wind speed (m/s)	0.60
Average wind direction	207°

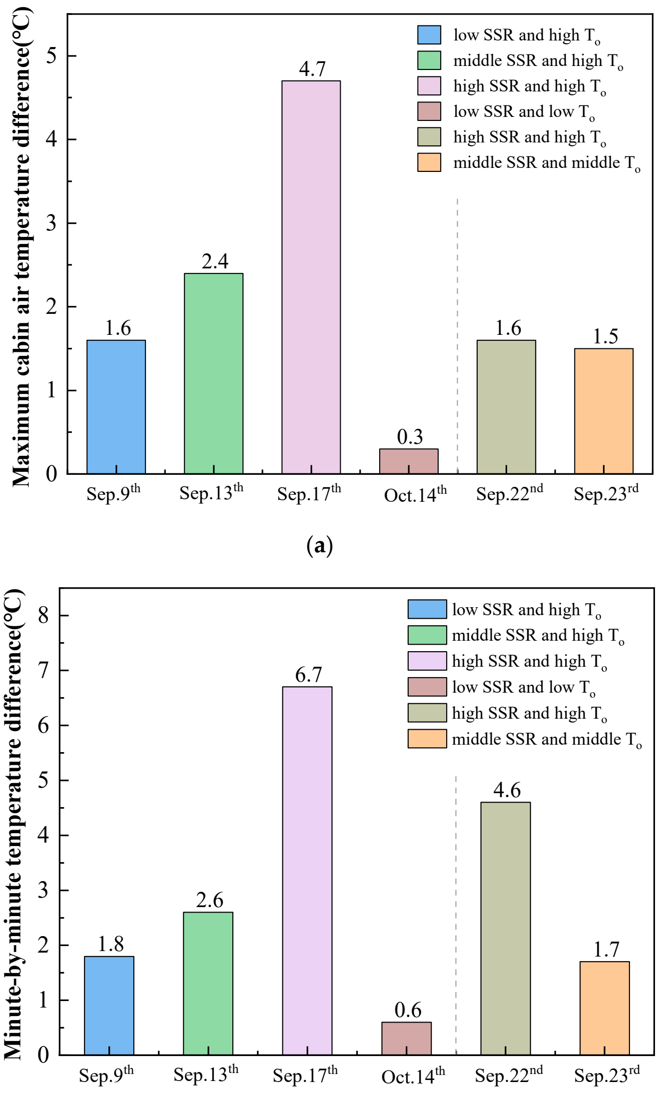
The temperature distribution of the seat surface is not the same as that of the air temperature. At 14:00, the cabin air temperature reaches a large value. The temperature at the chest and head heights of the front row and surface temperature near the cabin ground are 69.0, 50.5, and 29.0 °C, respectively. The air temperature at the head height in the cabin is higher than that at the chest height, whereas the air temperature at the feet height is the lowest. However, the cabin surface temperature is higher than the air temperature at the same height. Here, the surface temperature at the chest height is the highest, followed by the surface temperature of the head height, whereas the lowest is the surface temperature at the feet height. The temperature is assumed to be the same at the same height in each row, that is, the front and rear rows. According to the recorded values in six air and six surface temperature measuring points, the air and surface temperatures are linearly interpolated in the spatial height direction, with 200 interpolated values for each row, to obtain the temperature distribution of the cabin; the results are shown in Figure 7b. The upper and lower limits of the color bar are set to 60 and 25 °C, respectively. The highly nonuniform distribution of the cabin temperature can be intuitively understood. The nonuniform cabin environment causes different thermal sensations in the human body because the heat exchange characteristics and local thermal sensation between various parts of the human body and surroundings are different. Therefore, the level of comfort in this environment needs to be investigated. However, this study examined the effect of natural ventilation on the thermal environment in the vehicle when parked in the sunlight; thus, human thermal comfort will be investigated in future studies.

The temperature difference between vehicle A with four open windows and vehicle B with two open windows is shown in Figure 7c. The maximum temperature difference between the two vehicles reaches 2.6 °C at 14:55, proving that opening a larger area of windows is conducive to reducing the cabin temperature.

4. Discussion

4.1. Effect of Open-Window Gaps on the Cabin Air Temperature in Different Environmental Conditions

The measurements prove that the cracked open windows can reduce the upper-temperature limit in the cabin; however, the degree of this decline is affected by many factors. Both SSR and T_o are divided into high, medium, and low levels. The maximum air temperature in the cabin of the vehicles in six measurement days is compared, as shown in Figure 8a. The time when the air temperature of the two vehicles reaches its maximum value is not necessarily the same. In this study, the measured ambient wind speed is minimal. At this time, solar radiation is the most important key factor. In the three days with a high T_o, although the open-window area on 17 September was the smallest, the maximum temperature in the cabin was reduced by 4.7 °C owing to the high SSR on that day, which was higher than that on the other two days. When the SSR and T_o were low, the cracked window only reduced the maximum cabin temperature by 0.3 °C, which was not apparent. A comparison of the results for 22 September and 23 September reveals that opening more windows and larger areas is conducive to reducing the cabin's upper air temperature limit. Note, that the result is not the same as that reported in [36], in which the measurement was carried out for two days using one vehicle, and the parameters were recorded first with the windows closed. Subsequently, the doors were opened to return the vehicle's temperature to the ambient temperature. The measurements were continued for another hour with the windows cracked 1.5 in. This measurement method at different times of a single day may lead to different comparative measurement results with/without open windows. The limited measurement days may also lead to inaccurate results. This study avoided these situations by simultaneously conducting measurements on two vehicles over multiple days, thus obtaining accurate results. When vehicles are parked outdoors, they accumulate heat for a certain period. The cabin's temperature cannot always increase indefinitely, even with the greenhouse effect. The air temperature becomes stable when the amount of absorbed and the amount of heat emitted by the cabin balance. Compared to a vehicle with closed windows, a vehicle with cracked open windows emits more energy through thermal convection and ventilation, such that the heat balance is reached at a lower temperature. The minute-by-minute temperature difference between two vehicles is often greater than the difference between their maximum air temperature (Figure 8b), which occurs when the cabin temperature drops. Considering that the natural ventilation heat transfer through the window gap is more sensitive to changes in the ambient air temperature than the convective heat transfer between the vehicle surface and the environment, the cabin temperature of vehicles with cracked open windows decreases earlier than that of vehicles with closed windows.



(**a**)

(**b**)

Figure 8. Cabin air temperature difference between two vehicles under different ambient conditions: (**a**) difference of maximum temperature; (**b**) minute-by-minute maximum difference of temperature.

Because of the greenhouse effect, the stronger the solar radiation, the more heat is accumulated in the cabin, and the greater the difference between the ambient temperature and the air temperature inside the cabin. At this time, more heat is emitted through the window gaps because of the thermal pressure; thus, cracked open windows contribute to a larger decrease in the cabin temperature. The heat accumulation of the vehicle varies under different ambient conditions on the measurement day, as shown in Figure 9. The higher the value of SSR and T_o, the larger the temperature difference between the ambient air and the air in the cabin with closed windows; thus, the point deviation becomes more obvious. When the SSR and T_o are both low, the point deviation is almost not. Therefore, the higher the temperature and SSR, the better the cooling effect of open windows. The degree of point deviation indicates that it is beneficial to open windows under high T_o and SSR conditions. Under high T_o and low SSR conditions, windows may be left closed or open. However, it is unnecessary to open the windows when the SSR is low. Among all the measurement days, the ambient conditions on 17 September are most comparable to those of most summer days, and T_o and SSR are slightly lower than the maximum values in summer. Under the ambient conditions of this day, opening the window gaps can reduce the cabin temperature by 6.7 °C, which is considered to be representative of an effective cooling method. If the vehicle is exposed to more severe sun radiation, opening the window gaps can have a better temperature reduction effect.

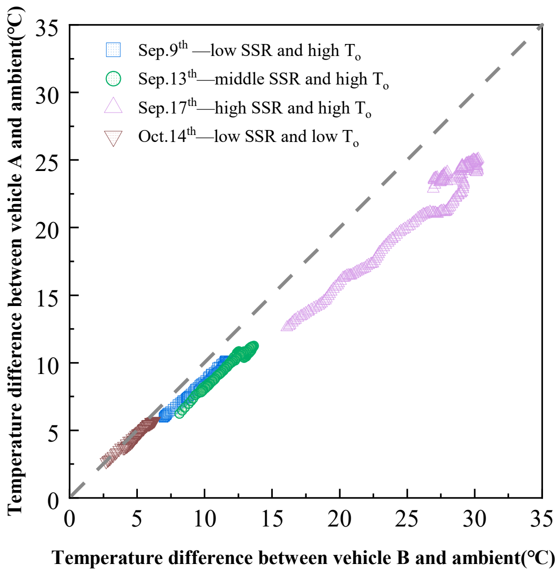


Figure 9. Temperature reduction effect of open-window gaps under different ambient conditions.

4.2. *Effect of Open-Window Gaps on VOCs in the Cabin*

The VOCs in the cabin were also measured in this study. Before conducting the measurement, the two vehicles were parked at the test site to guarantee the same initial conditions. Before opening the windows on the test day and before the end of the measurement, the VOCs were collected using a DNPH sorbent tube (for aldehydes and ketones) and a Tenax-TA sorbent tube (for nonaldehydes and nonketones) as the initial and experimental values, respectively. The reduction rate was used to indicate the degree of VOC reduction in the cabin after opening the windows, as expressed in Equation (3).

Figure 10 shows the R-value of benzene, toluene, formaldehyde, and acetaldehyde, which are the four main pollutants in the two vehicles, on 17 September. The results reveal that benzene, toluene, and acetaldehyde decreased by more than 50%, and formaldehyde decreased by a lower amount. The influence of temperature on the emission of pollutants in the cabin has been proved in a previous study [46]. The concentration of pollutants emitted by the interior surface is often lower at lower surface temperatures. Opening the window gaps caused a significant temperature drop in the cabin, which was conducive to reducing the concentration of pollutants released from the interior surface. The influence of ventilation on VOCs in the cabin depends on the ambient air quality of the vehicle [22]. In this study, there were fewer sources of pollutants as the site was relatively open with no travel lanes. Therefore, ventilation was also conducive to the overflow of pollutants in the cabin. Consequently, it can be proven that the temperature drop caused by the open windows and local ventilation can reduce the concentration of VOCs in the cabin.

$$R = 100\% * \frac{(C_{0\_b} - C_{1\_b}) - (C_{0\_a} - C_{1\_a})}{\frac{1}{2}(C_{0\_a} + C_{0\_b})} \tag{3}$$

where C_{0_a} is the initial VOC concentration in cabin A, C_{1_a} is the VOC concentration in cabin A before the end of the measurement, C_{0_b} is the initial VOC concentration in cabin B, and C_{0_b} is the VOC concentration in cabin B before the end of the measurement.

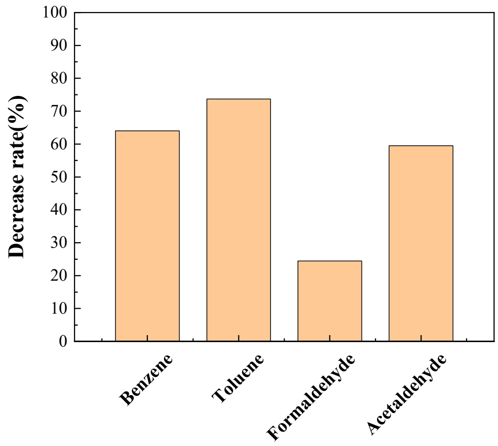


Figure 10. Decrease rate of the VOC concentration after the windows were opened.

5. Conclusions

To analyze and quantify the influence of the open-window gaps on the thermal environment of vehicles under different weather conditions, a field measurement study was conducted. Cabin air temperature and interior surface temperature were measured in two identical vehicles with or without open windows under different weather conditions. The main conclusions are as follows:

- For high temperature and high SSR, the natural ventilation method of opening the window gaps can effectively reduce the temperature in the cabin, with a maximum temperature drop of 6.7 °C. Therefore, it is recommended to open the window gaps.
- For high temperatures without high SSR, it is acceptable to both open or close the windows. However, it is unnecessary to open the window when both ambient temperature and SSR are low. In this case, the window gap can only bring a temperature drop of 0.6 °C, which is insignificant.
- With the increased area of open windows, the cooling effect improves. It is beneficial to increase the number and area of open windows to ensure safety.
- In addition, the VOC concentration of the vehicle with open-window gaps is lower than that of the vehicle with closed windows owing to the temperature drop and ventilation.

This study quantified the effect of open-window gaps on the cabin thermal environment under different weather conditions and lays a foundation for subsequent studies. Owing to the limitations of the measurement conditions, the effect of different inlet air volumes on the cabin's thermal environment was not analyzed. Future work will consider various measurement conditions and strengthened ventilation by adding external equipment to further reduce the temperature in the cabin under high temperatures and solar radiation conditions.

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Nomenclature

T_o	outdoor ambient temperature (°C)
T_a	air temperature of vehicle A (°C)
T_b	air temperature of vehicle B (°C)
T_f	temperature at front row of vehicle (°C)
T_r	temperature at rear row of vehicle (°C)
T_{head}	temperature at the head height (°C)
T_{chest}	temperature at the chest height (°C)
T_{feet}	temperature at the feet height (°C)
T_c	average temperature of air in cabin (°C)
SSR	surface solar radiation (W/m^2)
θ	wind direction (°)
$\overline{\theta}$	average wind direction (°)
n	amount of measured data
C_0	initial concentration of VOC (μg/m^3)
C_1	final concentration of VOC (μg/m^3)
R	VOC concentration reduction rate (%)
Subscript a	vehicle A
Subscript b	vehicle B

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