Research on Thermal Comfort of the Expressway Service Area in Qinling Mountains

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Abstract In order to understand the current indoor thermal environment of the expressway service area in Qinling Mountains, field measurements were conducted by using the Relative Warmth Index (RWI) and questionnaires were dished out, whereby their thermal environments were evaluated comprehensively. It turns out that the thermal neutral temperature of expressway service area in Qinling Mountains of China is 25.02°C(SET*). The thermal acceptable range of 22.39-28.36 °C(SET*) and the thermal comfortable range of 24.60-27.60 °C(SET*) are derived from 80% of the acceptable and comfortable criteria.

1. Introduction
At present, research on transportation architectures both at home and abroad focuses on terminals of metro, train and long-distance bus, whereas little research has been conducted on the thermal and humid environment and human thermal comfort in expressway service area. Zhu Peigen of PLA University of Science and Technology used a combination of questionnaire survey and field test to evaluate the thermal comfort environment of a subway station in Nanjing, and concluded that it is more accurate to use a combination of a questionnaire survey and relative thermal index RWI to evaluate the thermal comfort of subway passengers [1]. Zhijiang Kuang of Shanghai Maritime University conducted research and actual measurements using the Ningbo Tianyi Square subway station as an example and analyzed using the Relative Warmth Index (RWI) and the Heat Deficit Rate (HDR), which proved that the dynamic thermal environment analysis method is feasible for evaluating the thermal environment of subway stations [2]. Yuan Guangpu of the Hebei University of Technology studied the winter thermal comfort of a highway service area and proved that the use of dynamic evaluation index RWI combined with questionnaire survey can accurately evaluate the winter expressway service area thermal environment by using a combination of the questionnaire survey and field to test [3]. The expressway service area is an important place for the majority of drivers and passengers to rest, eat, shop, repair, refuel and stay during the road trip [4]. The research results also provide a reference for the optimal regulation of indoor temperature in expressway service area of the Qinling Mountains.

2. Materials and Methods
The survey was conducted in the expressway service area of Qinling Mountains. In the summer and autumn, 31 service area buildings were tested and investigated continuously for indoor human thermal comfort. During this test, the buildings were in good operating condition.

A combination of subjective and objective methods was used. A subjective questionnaire survey on the thermal comfort of people in the service area was conducted while recording the objective environmental parameters at the time. The measurement points were located in the service area lobby,
supermarket, and dining room. The research period was from July 28, 2020, to August 16, 2020, and research was conducted between 07:30 and 19:00 every day, with each service area tested for at least 48 hours.

The questionnaire includes:
(1) Subjects' background: This includes the subject's gender, age, status (driver, tourist, or worker), length of stay in the service area, and city of long-term residence;
(2) Subjects' dressing: The subjects' dressing combinations were recorded, and the thermal resistance of the clothing was calculated accordingly;
(3) Subjects' activity intensity, used to calculate their metabolic rate;
(4) Subjective evaluation of subjects with thermal sensation, thermal acceptability, thermal comfort, and humidity conditions. According to ASHRAE 55-2017 standards, the scales and corresponding point value for thermal sensation, thermal acceptability, thermal comfort, and humid sensation voting are shown in Table 1.

| Thermal Sensation | Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot |
|-------------------|------|------|---------------|---------|---------------|------|-----|
| Scale             | -3   | -2   | -1            | 0       | +1            | +2   | +3  |

| Thermal sensations | Comfortable | Slightly uncomfortable | Uncomfortable | Very uncomfortable |
|--------------------|-------------|------------------------|---------------|-------------------|
| Scale              | 1           | 2                      | 3             | 4                 |

| Thermal Acceptability | Fully acceptable | Just acceptable | Just unacceptable | Fully Unacceptable |
|-----------------------|------------------|-----------------|-------------------|--------------------|
| Scale                 | 1                | 0.1             | -0.1             | -1                 |

| humid sensation | Very humid | A bit humid | Neutral | A little dry | Dry | Very dry |
|-----------------|------------|-------------|---------|--------------|-----|----------|
| Scale           | -3         | -2          | -1      | 0            | +1  | +2       | +3      |

The environmental parameters include indoor air temperature, black-bulb temperature, relative humidity, and the wind speed, as well as outdoor temperature and outdoor humidity [5]. The instruments and parameters used for the tests are shown in Table 2.

| Instrument name and model | Measurement range | Measurement accuracy |
|--------------------------|-------------------|----------------------|
| FLUKE 971 Temperature and Humidity Meter | Temperature: -20°C to +60°C | Relative humidity: 5% to 95% |
| KIMOHQ210 black ball thermometer | 0°C to 150°C | ± 0.2°C RH |
| FLUKE923 Anemometer | 0.2 to 20 m/s | 5% + 3 words (reading) |

3. Results

3.1 Subjects
A total of 897 thermal comfort questionnaires were collected for this survey campaign, and the number of subjects surveyed was 465 in summer and 432 in autumn. The proportion of men and women was 57.3% and 43.7%. The age distribution was 52.5% of 20-29 years old, 33.3% for 30-39 years old, and 14.2% for other age groups. Northerners accounted for 91.2% and southerners to 8.8%. 88.6% of the
subjects stayed for less than 30 min.

3.2 Environmental parameters
The outdoor air temperature varied from 25.00 to 37.90 °C, and the outdoor relative humidity varied from 46.40% to 89.00% during the summer; the indoor air temperature varied from 22.00 to 36.30 °C, and the indoor relative humidity varied from 42.40% to 87.98%; the indoor wind speed varied from 0 to 0.40 m/s, the average wind speed is 0.24 m/s, which shows that the indoor wind speed is low. The outdoor air temperature varied from 15.70 to 28.50 °C and the outdoor air relative humidity varied from 56.00% to 80.50% in autumn; the indoor air temperature varied from 16.80 to 27.20 °C and the indoor air humidity varied from 60.20% to 79.91%; the indoor wind speed varied from 0 to 0.20 m/s.

3.3 Test data processing
The drivers and passengers entering the service area do not stay long and are highly mobile, and the thermal and humid environment is influenced by a variety of factors, so it is more appropriate to study according to the non-stationary environment [3][6], so the Relative Warmth Index (RWI) is used to evaluate the thermal comfort of personnel in the highway service area. The correspondence between the Relative Warmth Index (RWI) and ASHRAE thermal sensation scales is shown in Table 3.

| Thermal Sensation | ASHRAE Thermal Sensation Scales | Relative Warmth Index (RWI) |
|-------------------|--------------------------------|-----------------------------|
| Warm              | +2                             | 0.25                        |
| Slightly warm     | +1                             | 0.15                        |
| Neutral           | 0                              | 0.08                        |
| Slightly cool     | -1                             | 0                           |

Fig. 1 shows the descriptive statistics of the Relative Warmth Index (RWI) values calculated in the two seasons. According to the "acceptable thermal environment" recognized in the ASHRAE standard, more than 80% of people would be satisfied with TSV between -1 and +1, so the values between -1 and +1 are considered as thermal comfort, and the corresponding RWI values between 0 and 0.15 are considered as thermal comfort. The values of 50% of the RWI in summer ranged from 0.03 to 0.24; the values of 50% of the RWI in autumn ranged from 0.03 to 0.16. Compared with Table 4, it can be seen that the thermal environment in expressway service area of Qinling Mountains is hot in summer and more comfortable overall in autumn.

In building the thermal comfort model, the neutral temperature is characterized by the standard effective temperature (SET*). The standard effective temperature (SET*) combines human activity, clothing thermal resistance, the indoor air temperature, relative humidity, wind speed, and average
radiation temperature into one temperature parameter, which is calculated using Rayman. The human activity condition, clothing thermal resistance, the indoor air temperature, relative humidity, and wind speed are derived from questionnaires and test surveys; the mean radiation temperature is derived from the Belding empirical formula [7]:

$$T_r = T_g + 2.44V^{0.5} (T_g - T_a)$$

$T_r$ is the average radiation temperature, °C; $T_g$ is the count of the black globe temperature, °C; $V$ is the wind speed, m/s; $T_a$ is the count of the air temperature, °C. The calculation results of the average indoor radiation temperature $T_r$ in the service area and the standard effective temperature ($SET^*$) are shown in Table 4. The difference between the average radiation temperature and the standard effective temperature ($SET^*$) in summer is small, and the difference between the average radiation temperature and the standard effective temperature ($SET^*$) in autumn is large, so it is known that the correlation between the average radiation temperature and the standard effective temperature ($SET^*$) in summer is higher.

|                  | Minimum value | Maximum value | Average value | Standard deviation |
|------------------|---------------|---------------|---------------|--------------------|
| **Summer**       |               |               |               |                    |
| Average radiation temperature/°C | 21.25    | 36.00      | 32.58        | 8.36               |
| Standard effective temperature/°C | 20.90    | 37.20      | 32.10        | 8.70               |
| **Autumn**       |               |               |               |                    |
| Average radiation temperature/°C | 17.30    | 23.70      | 19.58        | 3.32               |
| Standard effective temperature/°C | 20.70    | 21.20      | 21.11        | 0.29               |

3.4 The standard effective temperature ($SET^*$) and the Relative Warmth Index (RWI)

To verify the correlation between $SET^*$ and RWI, a linear regression analysis of RWI and $SET^*$ was performed (Fig. 2), and there was a good linear relationship between RWI and $SET^*$ ($R^2 = 0.8796$). The thermal neutral temperature is characterized by $SET^*$, which corresponds to a predicted neutral temperature of 25.15 °C at RWI = 0.08. If the middle three divisions of the ASHRAE thermal sensation scale are considered acceptable, corresponding to an RWI of 0 to 0.15, the 80% predicted acceptable temperature range is 20.93 to 28.84 °C.

$$\text{RWI} = 0.01898 \times SET^* - 0.3974$$

$$R^2 = 0.8796$$

3.5 Thermal sensation votes (TSV) and the standard effective temperature ($SET^*$)

TSV was counted according to the 7-level thermal sensation scale of ASHRAE 55 (+3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold), and to verify the correlation between TSV and $SET^*$, a linear regression analysis of the mean thermal sensation vote (MTS) and $SET^*$ was performed (Fig. 3). A good linear relationship ($R^2 = 0.8552$) existed between TSV and $SET^*$. 

![Fig. 2 RWI and SET*](image-url)
MTS = 0.1935SET* - 4.8415 (R² = 0.8552) (2)

The neutral thermal temperature is characterized by SET*, which corresponds to the measured thermal neutral temperature of 25.02 °C when MTS=0. If ASHRAE thermal sensing scale -1~+1 is considered 80% acceptable and -0.5~0.5 is considered 90% acceptable, the temperature ranges of 90% and 80% acceptable are 22.43~27.60 °C and 19.85~30.18 °C.

3.6 Thermal comfort (TC) and thermal sensation votes (SET*)
To verify the relationship between TSV and TC, a linear regression was performed with summer and autumn data (Fig. 4).

TC = -0.2852TSV + 1.3070 (R² = 0.8526) (TSV ≤ 0) (3)
TC = 0.5530TSV + 1.4882 (R² = 0.9058) (TSV ≥ 0) (4)

When the thermal sensation shifts from neutral to hot or to cold, the thermal comfort vote value increases with it, and the discomfort increases. The comfort vote value corresponding to neutral thermal sensation ranges from 1.3 to 1.5, which is between comfort and slight discomfort. The sensitivity of subjects' comfort to changes in thermal sensation showed a significant asymmetry, being more sensitive to changes in thermal bias sensation and more prone to discomfort.

3.7 Thermal acceptability (TA) and thermal comfort (TC)
To verify the relationship between TA and TC, a linear regression analysis of TA and TC was performed (Fig. 5). There was a good linear relationship between TA and TC (R² = 0.815).

TA = -0.4742TC + 1.1872 (R² = 0.815) (5)

The comfort vote value corresponding to the acceptable and unacceptable cut-off point is 2.2, which
means that both comfortable and slightly uncomfortable categories of comfort votes can be considered acceptable.

Fig. 5 TA and TC

3.8 Discomfort percentage (PDc), dissatisfaction percentage (PDu)

From the relationship between thermal acceptability (TA) and thermal comfort (TC) and the relationship between humidity sensation (HS) and relative humidity (RH) in the previous paper, it is clear that the users of expressway service area in the Qinling Mountains have low requirements for thermal and humid environments, and the design goal is no longer to keep the environment near the thermal neutral temperature but to keep it within a wide thermal environment range. In the design of the indoor thermal environment of service area buildings, the information of the comfortable temperature range is more important than the thermal neutral temperature [10] and the comfortable temperature range is further analyzed by the discomfort percentage (PDc) and dissatisfaction percentage (PDu). The percentage of discomfort (PDc) was obtained by counting the respondents that were rated as "uncomfortable" by the thermal comfort (TC), and the relationship between the percentage of discomfort (PDc) and the standard effective temperature (SET*) was obtained by regression analysis (Fig. 12).

\[
P_{DC} = 0.520SET^{*2} - 27.191SET^{*} + 374.23 \quad (R^2 = 0.8599) \quad (6)
\]

Minimum discomfort percentage (PDc) corresponds to the standard effective temperature (SET*) of 25.38 °C. When the standard effective temperature is greater than 24.60 °C and less than 27.60 °C, the discomfort percentage (PDc) is lower than 20%, thus meeting 80% of the standard effective temperature range of thermal comfort is 24.60 ~27.60 °C (Table 6). The percentage of unsatisfactory percentage (PDu) can be obtained by counting the percentage of thermal acceptable (TA) votes less than 0. The regression analysis of the unsatisfactory percentage (PDu) and the standard effective temperature (SET*) (Fig. 6) were performed and the relationship equation was obtained as follows.

\[
P_{DU} = 0.8791SET^{*2} - 44.627SET^{*} + 578.53 \quad (R^2 = 0.9235) \quad (7)
\]

Minimum dissatisfaction percentage (PDu) corresponds to the standard effective temperature (SET*) of 25.38 °C. In the standard effective temperature greater than 22.39 °C, small greater than 28.36 °C, unsatisfactory percentage (PDu) is less than 20%. Thus, the standard effective temperature (SET*) range that satisfies 80% of thermal satisfaction is 22.39to 28.36°C (Table 5). As shown in Table 6, the lower limit of acceptable temperature is 2.21 °C which is lower than the lower limit of comfortable temperature. The upper limit of acceptable temperature is 0.76 °C which is higher than the upper limit of comfortable temperature. The range of acceptable temperature is larger than the range of comfortable temperature, and the range of acceptable temperature is 2.97 °C wider than the range of comfortable temperature.

The service area building has its special characteristics, with large mobility of people and open space, if the design is mainly based on the thermal comfort temperature range, it is bound to waste more energy; if all the design is based on the thermal acceptable temperature range, the thermal environment will be uncomfortable. Considering the thermal comfort and energy saving of the expressway service area, we should combine the thermal comfort temperature range with the thermal acceptable temperature range of the expressway service area. It is recommended designing the expressway service area with zoning, that is, the expressway service area is divided into low thermal environment requirement area and high
thermal environment requirement area. The low thermal environment requirement area mainly includes the service area lobby and other open space; the high thermal environment requirement area includes the service area lounge, non-open dining space, etc. The low thermal environment requirement area is designed with an "acceptable temperature range", and the high heat environment requirement area is designed with a "comfortable temperature range".

4. Conclusions

1. Through researching expressway service area in Qinling Mountains, it can be seen that the average air temperature is 30.88°C, the relative humidity is 60.37% in summer. The relative humidity is 67.12% in autumn. Wind speed with the seasonal changes is not obvious, the average wind speed is 0.06 m/s.

2. The regression analysis of thermal sensation and standard effective temperature shows that there is a definite linear relationship between thermal sensation and standard effective temperature in expressway service area in the Qinling Mountains of China. Characterized by the standard effective temperature (SET*), the neutral temperature is 25.02°C. The thermal acceptable range of 22.39-28.36°C(SET*) and the thermal comfortable range of 24.60-27.60 °C(SET*) are derived from 80% of the acceptable and comfortable criteria. It is suggested that when designing the thermal environment of the expressway service area in the Qinling Mountains, the "acceptable zone" standard should be used for the low requirement area and the "comfort zone" standard should be used for the higher comfort demand area.

3. The analysis of the correlation between the Relative Warmth Index (RWI) and thermal sensation vote (TSV) shows that the Relative Warmth Index (RWI) model can be used to predict the human thermal response of expressway service area in the Qinling Mountains, and has better applicability for summer studies.
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References
[1] Zhu, Pei-Gen, Wang, Chun-Wang, Tong, Xiao-Na. Study on dynamic thermal comfort evaluation of subway station passengers_Zhu Peigen[J]. HVAC, 2016, 46(2): 40, 101-104.
[2] Kuang Zhijiang. Thermal comfort evaluation of loop control system of Ningbo rail transit line 1 [J]. Refrigeration, 2016, (03): 49-54
[3] YUAN Guangpu, KONG Xiangfei, JIANG Lichao. Study on winter thermal comfort of a highway service area_Yuan Guangpu[J]. Building Science,2018, 34(8): 57-61, 70.
[4] Liu Jia. Research on the theory and technology of regional highway service area operation and management[D]. Chang'an University,2014.
[5] Ning Haoran. Research on human thermal comfort and thermal adaptation of heating building environment in severe cold regions[D]. Harbin Institute of Technology, 2017.
[6] Kapil Sinha, E. Rajasekar. Thermal comfort evaluation of an underground metro station in New Delhi using agent-based modeling[J]. Building and Environment,2020,177.
[7] Yang Liu. Building climatology [M]. Beijing: China Construction Industry Press,2010: 59.