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Recent developments in evaluation methods and characteristics of comfort environment in underground subway

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In recent years, due to the rapid progress of urbanization, the subway system with the advantages of large transport capacity, punctuality, efficiency, convenience and safety has become one of the main transportation modes in metropolitan areas. With the increase in passenger flow, the comfort of subway passengers has attracted extensive attention from the academic community. In this paper, we begin by analyzing the characteristics of the subway environment and sort out six environmental elements that affect passengers' comfort, including thermal environment, vibration, noise, lighting, air quality, and air pressure. In addition, the measurement scheme, calculation model, and evaluation method of each element are outlined based on relevant norms and literature. Through reviewing the studies in the past 2 decades, it is found that the in-depth research is still in demand for a comprehensive comfort evaluation model with multi-element coupling. A deep understanding of the subway passengers' comfort is the basis for the design, development, and operation regulation of the subway environmental control system. Measures to improve comfort, especially the exploitation of energy-saving air conditioning systems, will provide strong support for the sustainable and sound growth of the rail transit industry.

KEYWORDS
subway, passenger comfort, thermal environment, air quality, vibration

Introduction

Recently, along with the global economic development and urbanization construction, urban population and buildings have increased dramatically, resulting in increased pressure on urban traffic. In addition, problems such as traffic congestion and environmental pollution have gradually emerged. Therefore, in order to alleviate the contradiction of land use, expand land resources and improve the population capacity of the city, practitioners turn their attention to the development of underground space, thus the subway came into being (Nezhnikova, 2016; Yu et al., 2020). As a novel transportation mode, compared with traditional transportation modes, the subway has the advantages of large passenger volume, high speed, punctuality, and small occupation of urban land area. With the rapid popularization of subways in metropolitan areas, the ridership is increasing steadily. People's requirements for taking the subway are no longer only safety and convenience. The comfortable environment has also become a major factor motivating passengers to choose subway travel (Mohammadi et al., 2020).

As a classification of the underground space, the guarantee of the comfort of subway environment is not the same as that of the aboveground buildings. Because the internal space form, environmental elements, and internal personnel activities in underground spaces are significantly different from those in conventional buildings, personnel requirements for environmental comfort vary greatly (Li et al., 2017). In general, the physical environment elements closely related to human comfort mainly include the vibration level, noise intensity, thermal and humid environment, air pressure variation, and air quality conditions. Moreover, there may be mutual synergistic or antagonistic effects among them, which jointly affect the physiological response and subjective evaluation of the human body to the artificial environment. Currently, a considerable amount of research has been devoted to analyzing the subway environment and evaluating passengers' comfort. This paper aims to make a systematic review of the relevant studies in the past 2 decades and critically point out the future research direction, expecting that the follow-up targeted work can facilitate the sustainable and sound growth of the rail transit industry.

The remaining sections of this paper are structured as follows: *Characteristics of the subway environment* Section illustrates the characteristics of subway environment by comparing the aboveground buildings. *Elements affecting passengers' comfort* Section outlines the environmental elements affecting passengers' comfort and lists the research work in the last 2 decades. *Evaluation of environmental elements* Section elaborates on the evaluation approaches of the six key elements respectively based on relevant standards or literature. *Limitations and future directions* Section proposes the limitations of the existing research and the priorities for future work. The major conclusions of this review are presented in *Conclusion* Section.

Characteristics of the subway environment

In order to maintain a comfortable subway environment, it is necessary to have an accurate and comprehensive grasp of the characteristics of subway environment. Undoubtedly, the design and evaluation criteria of aboveground buildings cannot be automatically applied to the interior environment of the subway because of their different characteristics.

For the subway environment, the characteristics are explained as follows. 1) Subway belongs to underground space, which is less affected by solar radiation, and the surrounding rock and soil have strong heat storage capacity (Kajtar et al., 2015; Li et al., 2017). Hence, the air temperature fluctuation in the subway environment is small and usually behaves as cool in summer and warm in winter. However, the air humidity in underground space is generally higher than that in buildings above ground, especially in summer. The humid environment not only seriously degrades people's comfort, but also endangers human health. 2) High levels of noise and vibration can result in discomfort to the human body. Since the subway environment is relatively closed, severe noise pollution and long reverberation time become a trigger for neurasthenia syndrome (Dong et al., 2021). 3) Due to the lack of natural lighting in the subway environment, people are unable to connect to the external environment through windows as in the aboveground buildings, which easily leads to the loss of sense of time and direction. People in this environment for a long time are also prone to depression and loneliness (Martinez-Nicolas et al., 2014). 4) The air pollution problem in the subway environment is also quite tricky. Due to the difficulty of direct access to sunlight and natural outdoor breeze, fresh air is often in short supply. As a result, various pollutants are not easy to be diluted, and bacteria and molds tend to breed. The overall air quality is thus an essential concern. (Xu and Hao, 2017). 5) High-speed trains passing through tunnels and stations produce a piston effect, namely, the air in the tunnel is driven by the train and flows at high speed in the direction of the train, thereby generating positive pressure at the front of the train and negative pressure at the rear. The resulting drastic air pressure changes will also have a significant impact on passengers' comfort (Xue et al., 2014).

Elements affecting passengers' comfort

Like aboveground buildings (Leccese et al., 2021), the subway space is also an artificial environment, which is an overall environmental state formed by physical elements such as thermal environment, light level, noise, air quality, mechanical vibration, and atmospheric pressure. These elements are inherently closely related to the comfort of subway passengers. Furthermore, each element can be subdivided in detail: the thermal environment can be represented by air temperature, relative humidity, air velocity near the human body, temperature of the envelope structure' inner surface and other objects (Ampofo et al., 2004); the light environment can be

TABLE 1 Previous work on the comfort of subway passengers in recent years.

Research	Scenarios		Environmental elements					
	Subway station	Subway cabin	Thermal environment	Vibration	Noise	Lighting	Air quality	Air pressure
Ampofo et al. (2004)	√	√	√	—	—	—	—	—
Abbaspour et al. (2008)								
Katavoutas et al. (2016)								
Pan et al. (2020)								
Passi et al. (2022)								
Burnett and Pang, (2004)	√	—	—	—	—	√	—	—
Casals et al. (2016)								
Lai et al. (2020)								
Zhou et al. (2022a)								
Gershon et al. (2006)	√	√	—	—	√	—	—	—
Iachini et al. (2012)								
Ghotbi et al. (2012)	√	—	—	—	√	—	—	—
Vogiatzis, (2012)	√	—	—	√	√	—	—	—
Zou et al. (2015)								
Vogiatzis et al. (2018)								
Sun et al. (2014)	—	√	—	—	√	—	—	√
Han et al. (2016)	√	—	√	—	√	√	√	—
Liu et al. (2017)	√	—	√	—	—	—	—	—
Assimakopoulos and Katavoutas, (2017)								
Li et al. (2021)								
Yang et al. (2022)								
Niu et al. (2017)	√	√	—	—	—	—	—	√
Amador-Jimenez et al. (2017)	—	√	√	√	√	√	√	—
Pan et al. (2019)	√	—	—	—	—	—	√	—
Izadi et al. (2019)	√	—	—	—	—	—	—	√
Li et al. (2020)	√	—	√	—	—	—	√	—
Wu et al. (2020)								
Yu et al. (2021)								
Lin et al. (2022)								
Mohammadi et al. (2020)	—	√	√	√	√	√	√	—
Xu et al. (2020)	—	√	—	—	—	√	—	—
Xu et al. (2022)								
Xiong et al. (2020)	—	√	—	—	—	—	—	√
Li et al. (2022)								
Ren et al. (2022)	√	√	—	—	—	—	√	—
Zhou et al. (2022b)	—	√	√	√	√	—	—	—

characterized by luminous flux, illuminance, color temperature, etc. (Kruisselbrink et al., 2018); the sound environment can be reflected by sound power, sound intensity, sound pressure, etc. (Teodorović and Janić, 2017); the air quality is implicated in the concentration levels of particulate matter (PM), total volatile organic compounds (TVOC), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_x), sulfur oxide (SO_x), ozone (O_3), bacteria, fungi, etc. (Passi et al., 2021); the mechanical vibration can be characterized by vibration frequency, vibration intensity, etc. (Barone et al., 2016); the air pressure can be quantified by background pressure, pressure change rate, pressure transient intensity, etc. (Schwanitz et al., 2013). In recent years, a considerable amount of work has been dedicated to studying the impact of these six elements on the comfort of subway passengers, with some researchers only examining the association between a single element and comfort, and others exploring the coupling effects of several elements on comfort. Table 1 lists the representative relevant studies in the last 2 decades.

Evaluation of environmental elements

Thermal environment

Thermal environment is generally the most important factor in an artificial environment. Maintaining an almost constant body temperature is a basic physiological requirement of the human body. The thermal environment acts on the heat transfer process between the human body and the outside, thus directly affecting the thermal balance of the human body. As shown in Eq. 1, when the body heat storage (S) is greater than zero, in other words, heat production is greater than heat dissipation, the body temperature rises. As a result, the human body will have a warm feeling, and *vice versa*.

$$M - W - C - R - E - S = 0 \quad (1)$$

where M represents the metabolism rate and can be obtained based on the size of the body's activity, W/m^2; W means the human mechanical work, W/m^2; C denotes the amount of heat that a person transferred into the surrounding environment by convection, W/m^2; R represents the amount of heat that a person transferred into the surrounding environment by radiation, W/m^2; E means the heat lost by evaporation of sweat and the water vapor exhaled by the body, W/m^2; and S represents the heat storage, W/m^2.

Among the large number of thermal comfort indicators proposed in the literature (Rocca, 2017), the most widely used indicators are the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). PMV proposed by Professor Fanger represents the hot and cold sensation of the vast majority of people in the same environment (Fanger, 1970). PMV adopts the seven-point scale (ASHRAE-55, 2013), namely from +3 (hot) to 0 (neutral) and then to -3 (cold). PMV is defined as:

$$\begin{aligned} PMV = \left(0.303e^{-0.036M} + 0.028\right)\Big\{ & (M - W) \\ & - 3.05 \times 10^{-3} \times \left[5733 - 6.99(M - W) - p_a\right] \\ & - 0.42 \times \left[(M - W) - 58.15\right] \\ & - 1.7 \times 10^{-5} M\left(5867 - p_a\right) - 0.0014M(34 - t_a) \\ & - 3.96 \times 10^{-8} f_{cl} \times \left[(t_{cl} + 273)^4 - \left(\overline{t_r} + 273\right)^4\right] \\ & - f_{cl} h_c (t_{cl} - t_a)\Big\} \end{aligned} \quad (2)$$

where f_{cl} denotes the ratio of a person's surface area while clothed to the surface area while naked; t_a means the air temperature, °C; $\overline{t_r}$ represents the mean radiant temperature, °C; p_a means the partial vapor pressure, Pa; h_c is the convective heat transfer coefficient, W/(m^2•°C); t_{cl} is the surface temperature of clothing, °C.

PPD provides the relationship between PPD and PMV through the method of probability analysis. It is adopted to predict the percentage of dissatisfied people under the current PMV value. ISO7730 standard uses PMV-PPD index to evaluate and describe the thermal environment (ISO, 2005). The standard's recommended value for the PMV index is between -0.5 and +0.5, representing no more than 10% of the population allowed to feel unsatisfied. The quantitative relationship between PMV and PPD is as follows:

$$PPD = 100 - 95\,exp\left[-\left(0.03353PMV^4 + 0.2179PMV^2\right)\right] \quad (3)$$

In addition, there is often a transition interval where people stay briefly in buildings, which may connect two spaces with different thermal environment parameters. When a person passes through or stays in the area for a short time and his/her activity state changes, the thermal sensation in this space will differ from that when he/she stays in the same space for a long time. Therefore, it is necessary to put forward the thermal comfort index for this kind of transition space to guide the determination of air conditioning design parameters. Thus, the U.S. Department of Transportation proposed the Relative Warmth Index (RWI) and Heat Deficit Rate (HDR) to decide the design parameters of the subway stations' platform, hall, and carriage, respectively for warm and cold environments (United States Department of Transportation, 1976). RWI and HDR can be calculated as follows (Yang et al., 2022):

$$RWI = \frac{\left(M\left(I_{cw} + I_a\right) + 6.42\left(t_a - 35\right) + R_0 I_a\right)}{\left(\left(65.2 \times \left(5858.44 - p\right)\right)/1000\right)}\left(p > 2269Pa\right) \quad (4)$$

$$RWI = \frac{\left(M\left(I_{cw} + I_a\right) + 6.42\left(t_a - 35\right) + R_0 I_a\right)}{234}\left(p \le 2269Pa\right) \quad (5)$$

$$HDR = \frac{D}{\Delta\tau} = 28.89 - M - \frac{\left(6.42\left(t_a - 30.56\right) + R_0 I_a\right)}{\left(I_{cw} + I_a\right)} \quad (6)$$

where I_{cw} denotes the insulation of clothing based on wet cloth assumption, clo; I_a denotes the insulation effect of air boundary layer, clo; R_0 represents the average incident radiant heat from sources other than walls at room temperature, W/m^2; p is the vapor pressure at dry bulb temperatures, Pa; $\Delta\tau$ means the exposure time, s; D means the thermal debt, J/m^2.

$$M = M_1 - \frac{T}{360}\left(M_1 - M_2\right)\left(T < 360\,\text{s}\right) \quad (7)$$

$$M = M_2\left(T \ge 360\,\text{s}\right) \quad (8)$$

$$I_{cw} = I_{cw1} - \frac{T}{360}\left(I_{cw1} - I_{cw2}\right)\left(T < 360\,\text{s}\right) \quad (9)$$

$$I_{cw} = I_{cw2}\,(T \geq 360\,\mathrm{s}) \tag{10}$$

where M_1 and M_2 are the initial and terminal metabolic rate, respectively, W/m^2; I_{cw1} and I_{cw2} are the initial and terminal insulation of clothing based on wet cloth assumption, respectively, clo; T is the time required to go from the previous environment to the next, s.

$$I_a = 0.3923 v_a^{-0.4294} \tag{11}$$

where v_a is the inducing speed of human body movement, m/s.

The parameters in the calculation formula of the above evaluation indexes are usually obtained through field tests and questionnaires, in other words, a combination of objective and subjective means (Abbaspour et al., 2008; Pan et al., 2020). On the one hand, the field measurement is carried out by selecting representative locations in the subway environment, so as to arrange corresponding sensors to monitor and record thermal environmental parameters. It is worth emphasizing that the layout density and height of measuring points in a certain space need to be carefully determined (Katavoutas et al., 2016). On the other hand, thermal comfort is a subjective feeling of passengers. Even in the same thermal environment, passengers will make different judgments. A large number of questionnaires are needed to derive statistical rules. The content of the questionnaire generally includes some basic information, such as the age, gender, activity status and clothing of passengers. In addition, thermal sensation vote (*TSV*), humidity sensation vote (*HSV*), draft sensation vote (*DSV*), and thermal comfort vote (*TCV*) should also be collected and analyzed (Yang et al., 2022).

Vibration

Subway vibration will not only make passengers stand unstable, but also easy to make passengers feel tired. Moreover, it may even cause resonance in the internal organs of the human body, endangering the physical and mental health of passengers. The types of train vibration can be divided into transverse vibration, longitudinal vibration, vertical vibration and yaw vibration, longitudinal pendulum vibration, torsional pendulum vibration around each axis. Among them, vertical vibration, transverse vibration and yaw vibration have great influence on passengers' comfort. The main effect of vibration on the human body is the frequency of vibration. The range of vibration frequencies that humans can perceive is 1–1,000 Hz. Generally, ground vibration in the frequency range of 1–80 Hz is considered as perceptible whole-body vibration, to which the human body is particularly sensitive and in which the resonant frequencies of the organs are concentrated.

Vibration comfort is an indicator of how good or bad passengers feel when riding the subway caused by vibration. Currently, the evaluation of vibration comfort is primarily from two perspectives: operating stability and riding comfort. According to GB/T 5599–1985, operating stability (W_0) is determined by vibration frequency and vibration acceleration, and its expression is:

$$W_0 = 3.57 \sqrt[10]{\frac{A^3}{f} F(f)} \tag{12}$$

where A denotes the vibration acceleration, m/s^2; f means the vibration frequency, 1/s; $F(f)$ denotes the frequency correction coefficient, 1/s.

In accordance with the above standard, when W_0 is less than 2.5, the stability level is I (excellent); when W_0 spans 2.5–2.75, the stability level is II (good); when W_0 spans 2.75–3.0, the stability level will be III (qualified).

Additionally, riding comfort is a measure of the average comfort of passengers and staffs on the subway. The evaluation procedure is based on the measurement of the vibration acceleration on the train floor. It can be obtained by calculating the acceleration in different directions at the position of the human body in line with the UIC 513–1994 standard (Mohammadi et al., 2020). It is worth highlighting that both two standards also elaborate on the measurement methods for the parameters in each indicator, guiding the placement of acceleration sensors and the sampling duration.

Noise

Noise, in the definition of physics, is the sound of a sounding object doing irregular vibrations; in the definition of physiology, it is the discordant sound that interferes with people's normal study, work and rest. In a noisy environment, it is easy to make people bored and agitated. Prolonged and high-decibel noise can also cause damage to the auditory system (Basner et al., 2014). The subway itself will produce some noise when operating, coupled with the noise of numerous passengers, thus the disturbing sound affects the comfort of subway passengers to a great extent.

The effect of noise on human body is not only related to the noise value, but also related to the exposure time (Rocca et al., 2022). To this end, the concept of "equivalent continuous A-weighted sound pressure level (L_{eq})" is defined, with the following expression (Ordoñez and Hammershøi, 2014):

$$L_{eq} = 10 \times lg\left(\frac{1}{T_0}\int_0^{T_0} \frac{p^2(t)}{p_0^2}\,dt\right) \tag{13}$$

where T_0 denotes the duration of time signal; $p(t)$ denotes the instantaneous sound pressure; p_0 denotes the reference effective sound pressure (20 μPa).

As a reference for noise thresholds, the U.S. Environmental Protection Agency (EPA) and the World Health Organization

(WHO) suggested a maximum daily L_{eq} of 70 dBA over 24 h and a limit of 75 dBA over 8 h with the same energy (Mohammadi et al., 2020). Furthermore, for shorter exposure durations, the health threshold can be set to 80 dBA for 3 h and 90 dBA for 30 min (Neitzel et al., 2009). In addition, the maximum permissible limits for train noise can also be identified from the Chinese standard GB 14892-2006.

Lighting

The influence of subway lighting environment on passengers is reflected on both physiological and psychological levels. The subway lighting system mainly relies on artificial light sources. Poor lighting environment will have a physiological impact on passenger comfort, primarily caused by inappropriate illumination, low illumination uniformity, glare, and maladaptive light-dark transitions. In addition, the psychological influence mainly includes color temperature, light color and atmosphere sense, light source height and relaxation degree, space shadow and tension sense.

To examine the visual comfort of passengers in the subway environment, it is necessary to combine objective field tests with subjective questionnaires (Bian and Luo, 2017). The objective approach is proposed to use relevant equipment to measure indicators that can characterize the light environment. A convincing test protocol can be adopted in accordance with the standards (e.g., Method for Determination of Illumination in Public Places GB/T 18204.21-2000). The physical quantities to be recorded cover illuminance, irradiation uniformity, color temperature of light source, glare, color rendering, etc. (Carlucci et al., 2015; Leccese et al., 2020; Shafavi et al., 2020). In turn, the design limits of the indicators specified by the relevant standards (e.g., General Technical Specification for Metro Vehicles GB/T 7928-2003, Railway Applications - Electrical Lighting for Rolling Stock in Public Transport System EN 13272-1:2019) can be used to compare with the measured data (Xu et al., 2022). The subjective approach aims to obtain passengers' visual responses to the subway environment through questionnaire surveys. In addition to collecting basic data and behaviors of passengers, designers also need to ask passengers to rate their visual comfort through non-professional language and ask for information such as their preferences (Allan et al., 2019).

Air quality

Poor air quality not only brings people discomfort, but also seriously threatens human health. In such a relatively closed environment as subway space, air pollution deserves more and more attention. The poor air quality in the subway environment can be caused by the following reasons. Firstly, the subway station is a long and narrow underground space with good air tightness. Only a few station entrances and ventilation shafts are connected to the outside, and the internal air environment of the station is regulated only by the air conditioning system. Hence, too little fresh air and insufficient exhaust air will lead to an increase in the concentration of pollutants (Klepczyńska Nyström et al., 2010; Martins et al., 2015). Secondly, people will carry particulate matter and breathe out certain organic matters, such as inhalable particulate matter, carbon dioxide, volatile organic compounds, etc. Thirdly, formaldehyde and volatile organic compounds released by construction and decoration materials in the station also deteriorate indoor air quality (Passi et al., 2021). Fourthly, most of the subway stations are buried deep underground, lacking sunlight, and it is easy to breed bacteria, mold and other microorganisms.

The existing literature has comprehensively expounded the air pollutants' types, concentration levels, sources, influencing factors and impacts on human health in the subway environment (Cepeda et al., 2017; Xu and Hao, 2017; Luo et al., 2018; Chang et al., 2021). This section focuses on the evaluation scheme of subway air quality. The evaluation of subway air quality is subjective in nature because different people have different levels of perception of air conditions. Consequently, in addition to the data obtained from field measurement, it is also essential to acquire a certain number of passengers and staffs' satisfaction with subway air quality, environmental comfort, and air odor sense. Therefore, on the one hand, testing instruments should be reasonably set up in the subway environment according to relevant standards or norms (refer to Indoor Air Quality Standard GB/T 18883-2002) to monitor the concentration of air pollutants. Mathematical models can be used to synthesize the measured data and assess the subway air quality against the standard limits. For example, some Chinese standards set concentration limits for major pollutants (Ambient Air Quality Standard GB 3095–2012, Code for Design of Metro GB 50157-2013, Standard for Design of Ventilation Air Conditioning and Heating of Urban Rail Transit GB/T 51,357–2019, etc.) (Leng and Wen, 2021). On the other hand, the subjective evaluation of the subway air quality can be collected by questionnaire survey. This method directly takes into account the human factor and is a perfect complement to the objective field test method. Passengers' background information (gender, age, etc.), exposure to the subway environment (duration of each ride, number of rides per week, etc.), and subjective perceptions about air quality in different periods and locations should be included in the questionnaire setting. In short, a favorable air quality in the subway environment can be characterized as: no known pollutants in the air reach the concentration index limits determined by the recognized authority, and the vast majority of people (>80%) do not express dissatisfaction.

Air pressure

During the high speed of a subway train, the air inside the tunnel fluctuates violently, forming complex pressure waves (pressure transients). The sharp pressure fluctuations outside the train will be transmitted into the cabins through the gaps in the train body, air ducts and air conditioning system, causing pressure fluctuations inside the train. The pressure waves act on the eardrum, producing pressure difference between the inner and outer sides of the tympanic membrane, thereby resulting in symptoms such as tinnitus and earache (Raghunathan et al., 2002). In extreme cases, pressure fluctuations may rupture the eardrum. Therefore, the issue of subway passengers' comfort caused by aerodynamic characteristics is gaining attention.

The criteria used to ensure the eardrum comfort of the crews and passengers comprise the pressure change magnitude Δp, the pressure change rate (pressure gradient) dp/dt, and the pressure monotonic change value in a certain period $\Delta p/\Delta t$. Among them, $\Delta p/\Delta t$ overcomes the limitations of the former two. It provides the threshold of pressure fluctuation associated with comfort level from the physiological perspective. The standard UIC 799–11 states that the maximum pressure change within 3 s should not exceed 800 Pa (Liu et al., 2020). In addition, it is worth mentioning that the investigation of pressure fluctuation patterns can rely on both data acquisition from field pressure sensors and numerical simulation (Kim and Kim, 2007; Niu et al., 2017; Li et al., 2022).

Limitations and future directions

The current research on subway passengers' comfort still has limitations and is expected to be improved by the forthcoming work. As can be seen from Table 1, most of the work has focused on exploring the correlation between a single environmental element and comfort level. However, comfort is a synthesis of physical, physiological and psychological reflections, and is jointly affected by various factors in the passengers' environment. Therefore, it is essential to consider the integrated effect of multiple elements when evaluating passengers' comfort. At this stage, it is already possible to monitor environmental parameters through gauges, record physiological indicators through wearable sensors, and access subjective evaluations through questionnaire surveys. The next challenge is how to judiciously incorporate the collected data sets to develop a comprehensive comfort evaluation model with multi-element coupling. There have been several active attempts to assign subjective and objective weight coefficients for each environmental element by fuzzy analytic hierarchy process and rough set theory, so as to establish a comprehensive comfort evaluation index (Huang and Shuai, 2018; Ebrahimi and Bridgelall, 2021).

Improving the service level of the rail transit industry to enhance subway passengers' comfort is still a critical issue to be addressed. Based on the above-mentioned comprehensive comfort theory, the significance of each environmental element can be ranked, so that corresponding mitigation measures can be targeted. The progressive improvement of the subway environmental control system can start from the following aspects: heating, ventilation and air conditioning (HVAC) systems, train shock absorption modules, air tightness regulation, lighting equipment, air purification devices, building materials, etc.

The HVAC system is a key link to control the thermal environment and air quality of the subway space, while it is the major energy consumer of the subway system (Guan et al., 2018). More efforts are needed to achieve reduced energy consumption in HVAC systems while maintaining inherent functionality and passenger comfort. A recent study has reviewed ten energy-saving strategies for HVAC systems and suggested highlights for future work (Yu et al., 2021). The proper use of passive ventilation strategies as well as variable frequency devices is expected to contribute to the construction of a sustainable metro network.

Conclusion

The subway has emerged as an indispensable means of transportation for inhabitants in metropolitan areas. With the improvement of living standards, passengers' requirements for subway transportation are not limited to safety and convenience. A comfortable environment has gradually become a focus of people's attention. This paper systematically reviews the achievements of the past 2 decades on the topic of subway passengers' comfort. Six environmental elements that have significant impacts on comfort level are identified, covering thermal environment, vibration, noise, lighting, air quality, and air pressure. Moreover, measurement schemes, calculation models, and evaluation methods for each element are summarized according to the relevant standards and references. At present, considerable research has been devoted to elucidating the relationship between a single element and passengers' comfort, while the establishment of a comprehensive comfort evaluation model coupled with multiple elements still needs further effort. In addition, the HVAC system plays an important role in the subway environmental control system and consumes a large amount of energy. The rational employment of passive ventilation strategies and variable frequency devices will help to build a comfortable, healthy and sustainable subway network.

Author contributions

WY: Conceptualization, Writing-Original draft preparation; XM: Conceptualization, Methodology; HZ: Methodology; CY: Investigation; QC: Investigation; SO: Writing-Review and editing; XC: Supervision, Writing-Review and editing.

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Conflict of interest

HZ was employed by the Company China State Construction Silkroad Construction Investment Group Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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