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A Review of Tunnel Fire Evacuation Strategies and State-of-the-Art Research in China

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Abstract:

After over thirty years of fast economic development and massive construction of infrastructures, China now owns the largest total length of tunnels in the world. However, many tunnels are overloaded with a large traffic volume and vulnerable to fire accidents in operation. Once a fire occurs in the tunnel, the occupants face a dangerous and confined environment and need to evacuate before reaching untenable conditions. Failure in fire evacuation will cause severe injuries and casualties under high-temperature and toxic fire smoke, and many past fire accidents have taught us lessons. Driven by the need for tunnel fire safety in China, many new researches are conducted related to fire evacuation in tunnel environments including full-scale experiments, and new evacuation strategies are carried out with sophisticated tunnel designs and regulations. Hence, this work aims to review these latest developments and studies in China towards better and safer evacuation in tunnel fires. In specific, the paper summarized the evacuation issues in tunnel fires generally and pointed out the unique issues in China. Aiming these issues, the paper then introduced recent evacuation strategies and evacuation research in China respectively. Typical tunnel fire accidents and full-scale tunnel fire evacuation tests in China were discussed in detail as case studies. Detailed evacuation strategies and the exposed issues were analyzed in those tunnel fire accidents emphatically, while evacuation findings of human behavior such as evacuation choices and trajectories were presented according to several field tunnel fire evacuation conducted by the authors. Finally, we highlight the research advances and challenges of fire evacuation in tunnels, as well as the need and directions for future research.

Keywords: *Tunnel fire safety; Evacuation; Case study; Full-scale experiments; Human behavior*

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1. Introduction

Tunnels have predominantly been constructed in China to solve heavy traffic congestion, including underwater tunnels, road tunnels and metro tunnels. According to the 2020 Transportation Industry Statistics Bulletin, China has owned the largest number of road tunnels in the world so far. The total length and scale of tunnels in China are the longest and the largest in the world, and the geological conditions and structural forms are the most complex [1]. By 2020, there have been 21,316 constructed tunnels with a total length of 21,999 km, which has an increase of 247% in terms of number and 458% in terms of length compared to 2009 [2]. Fig. 1 shows the increasing trend of the number and the total length of road tunnels in China from 2009 to 2020, and some selected tunnels are listed in Table 1.

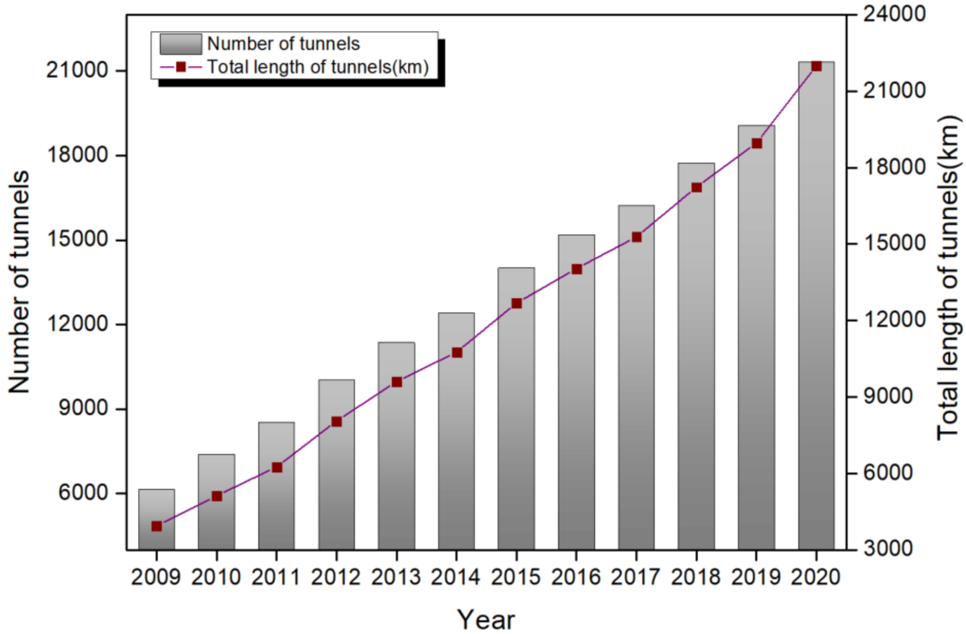

Fig. 1. Number and total length of road tunnels in China from 2009 to 2020

Table 1. Some recent extra-long tunnels (over 10 km) in China.

Type of tunnel	Tunnel name	Location (Province)	Year of opening	Length (km)
Underwater tunnel	Shouxihu Tunnel	Jiangsu	2013	4.4
	Hong Kong-Zhuhai-Macao Bridge	Guangdong	2018	18.4
	Taihu Tunnel	Jiangsu	2021	10.8
Road tunnel	Muzhailing Tunnel	Gansu	2016	19.1
	Tiantaishan Tunnel	Shannxi	2020	15.6
	Shiziping Tunnel	Sichuan	2020	13.2
	Qingyun Tunnel	Fujian	2013	22.2
	West Qinling Tunnel	Gansu	2016	28.2
	Songshan Tunnel	Guangdong	2017	38.8
Metro tunnel	Xi’an No. 2 Line	Shannxi	2014	26.5
	Shenzhen No. 9 Line	Guangdong	2016	25.4
	Nanjing No.4 Line	Jiangsu	2017	29.8

Tunnel fire is one of the most common and destructive hazards in tunnels and frequently causes devastating loss and severe casualties [3,4]. The long-distance and complex structures of tunnels will worsen the evacuation conditions in tunnel fires furthermore. For example, there were 40 deaths and 12 injuries in Jinji Road Tunnel fire in Shanxi Province in 2014; and another 36 casualties in Maoliling Road Tunnel Fire in Zhejiang Province in 2019, as shown in Fig. 2 [5]. Table 2 lists some recent tunnel fire accidents in China and their details.

Fig. 2. Severe tunnel fire accidents in China in recent years, (a) Jinji Road Tunnel fire (Mar 2014), and (b) Maoliling Road Tunnel fire (Aug 2019)[6,7].

Table 2. Selected major tunnel fire accidents in China over the last 20 years [2,5].

Year	Location (Province)	Tunnel name	Cause	Casualties
2010	Jiangsu	Huishan Tunnel	Arson	24 deaths, 19 injuries
2011	Gansu	Qidaoliang Tunnel	Tankers rear-ended	4 deaths, 1 injury
2012	Taiwan	Xueshan Tunnel	Collision	2deaths, 22 injuries
2012	Gansu	Taohua Tunnel	30 t nitrobenzene deflagration	3 injuries
2014	Shanxi	Jinji Tunnel	Collision & methanol leakage	40 deaths, 12 injuries
2017	Hebei	Zhangshi Tunnel	Collision	3 deaths, 15 injuries
2017	Shandong	Taojiakuang Tunnel	Arson	13 deaths (11 children)
2019	Fujian	Maoliling Tunnel	Self-ignition of tires	5 deaths, 31 injuries
2020	Hunan	Xuefengshan Tunnel	Semi-trailer ignition	None

In tunnel fires, heat, hot smoke, and toxic gases from the flame (e.g., burning vehicles and gasoline) will spread along the tunnel to lower the visibility and form a hazardous environment, imposing life threats to the occupants inside the tunnel [8–10]. The tunnel fire usually burns more fiercely than an open-space fire, because in the enclosed space, the heat feedback from the smoke layer enhances, limited oxygen can smother occupants, and the chemical goods carried by trucks in tunnels add the chance to trigger explosions [11]. Occupants have to evacuate outside the tunnel or find shelters at the early stage of the fire before it gets worse [12]. During the evacuation, they suffer difficulty when finding correct exits and paths as they are unfamiliar with tunnel layouts and seldom have the chance to walk in tunnels in daily life [13]. The smoke layer not only reduces the environmental visibility and weakens human mobility, but also causes panic to make unreasonable and even lethal decisions.

Along with the fast development of tunnel construction, the size and complexity of the tunnels have boosted, such as from two lanes to multi-lanes and from one layer to multi-layers, and the change affects the occupants' evacuation furthermore with an increasing sense of strangeness to tunnels [14]. Considering the high density of occupants and the difficulty of evacuation in tunnel fires, fire engineers and scientists are devoted to improve the safety of evacuation in tunnel fires. In practice, they have developed and applied several fire-safety measures and methods.

For instance, several smoke control systems have been invented like longitudinal ventilation, natural ventilation and point smoke extraction to control smoke in fire [15–18], as shown in Fig. 3. These systems could control the fire and smoke efficiently and provide more time for occupants to evacuate. Meanwhile, the evacuation strategies for each system should vary accordingly. For example, the reverse smoke flow should be taken seriously for the longitudinal systems while extra measurements are to be considered for the vehicles and people downstream in case they are trapped there. For natural ventilation, the requirements of lights for evacuation visibility could be lower considering the sunlight through the vertical shafts. Moreover, the installation of exit signages is set in tunnels to guide evacuation by providing evacuation directions and information [19,20].

However, the research of evacuation in tunnel fires is relatively new and less compared to fire dynamics studies. Despite gaining more attention recently since the 2000s, the evacuation theory, modelling, and practical measures in tunnel fires still need more improvement, particularly because we still have insufficient understanding of the human behaviors in tunnel fires [21,22]. Some previous research have many limitations, for example, the missing evidence of fire accidents recording because the video was easily lost in high-temperature fire scene, and the view on human motion was blocked by dense smoke [12]. In addition, there are rare chances to learn human behaviors in a real tunnel fire environment without video footage. Conducting a full-scale fire test in a real tunnel is problematic, considering the great expense to stop the traffic and call for a lot of vehicles and participants, as well as the safety and health risks of people near a large tunnel fire. Therefore, there were only a limited number of full-scale experiments of evacuation conducted like in Sweden and in Rome in the experimental tunnels [19,23]. Those restrictions and adverse factors have slowed down the progress of evacuation research in tunnel fires to some extent. In contrast, a great number of newly-built tunnels in China have brought about huge challenges of evacuation issues, while also increasing the chances of studying evacuation in tunnel fires by conducting full-scale experiments [14,24].

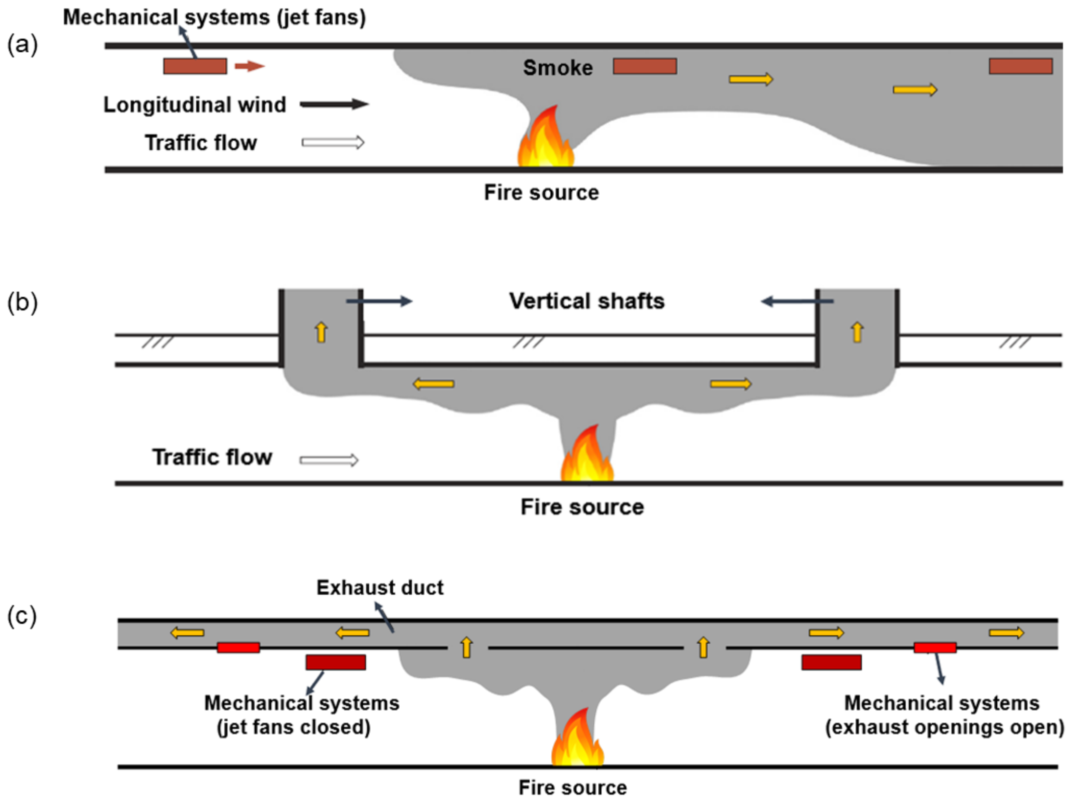

Fig. 3. Schematic diagram of three mainstream smoke control systems, (a) Longitudinal ventilation system, (b) Natural ventilation system, and (c) Point smoke extraction system [48].

With the great support of local and state governments, Chinese researchers have made huge progress in evacuation strategies and research over the past years, and it is essential to summarize the achievement and point out the shortage [25–27]. Thus, this paper reviews the latest development of evacuation research in tunnel fires in China. In specific, Section 2 introduces the issues of evacuation in tunnel fire, and Section 3 and 4 discusses the current findings of evacuation strategies and research respectively. Section 5 and 6 then analyzed evacuation case studies of tunnel fire accidents and full-scale experiments accordingly. Section 7, then, discusses the unique challenges and perspectives in China and proposes corresponding suggestions including emerging technologies and adequate education. The paper's aims include reviewing the past findings of evacuation in tunnel fires in China, and attaching research importance to the field of evacuation.

2. The issues of evacuation in tunnel fires

2.1. General issues and challenges of evacuation

Tunnel fires have gained worldwide attention from fire researchers due to the devastating and destructive damage to both tunnels and the lethal threats to occupants, including the structural collapse by fire and toxic fire smokes. Many researchers are devoted to enhancing the resistance of tunnels to fire. Some develop flame-retardant materials on tunnel linings, and others investigate the fire and smoke dynamics to better evaluate the fire scene and hazards [28]. Compared to advancing the tunnel structure resilience in fire and venting fire smoke out of the tunnel, it is even more important to improve occupants' safety and resilience to a severe fire environment of high temperature and toxic smoke. Moreover, some unique characteristics and risks can aggravate to worsen the conditions of evacuation in a tunnel fire environment, compared to evacuation in other types of buildings.

(1) Tunnels are long and narrow, creating a special confined space. Unlike fires in open sites or inside a large atrium, the fires in tunnels burn more fiercely in the enclosed space under the enhanced heat feedback from the hot smoke layer and heated walls, while the convective heat dissipation are poor under limited inlet fresh air [29]. A huge amount of hot and toxic fire smoke will quickly accumulate inside the tunnel, and the visibility in the tunnel will decrease. High temperature, toxic smoke and low visibility affect occupants' movement performance to a larger extent that may result in serious casualties [15], as verified by many past accidents (see Table 2). Sometimes, the ventilation and smoke control systems may be out of order or failed to switch on in fire, which could deteriorate the evacuation environment in tunnel fires furthermore.

(2) The connection of tunnels with the outer environment is normally poor. Thus, the occupants inside the tunnel have few approaches to obtain fire and accident information [30]. The occupants could not see the outside due to limited exits in tunnels and nontransparent structures, as shown in Fig. 4. Moreover, they have trouble knowing the accidents' dynamics and consequences, locating themselves or learning the development because the GPS signal could be extremely weak and inaccurate under the ground [31]. All these factors can lead to a slow response or incorrect evacuation of occupants themselves.

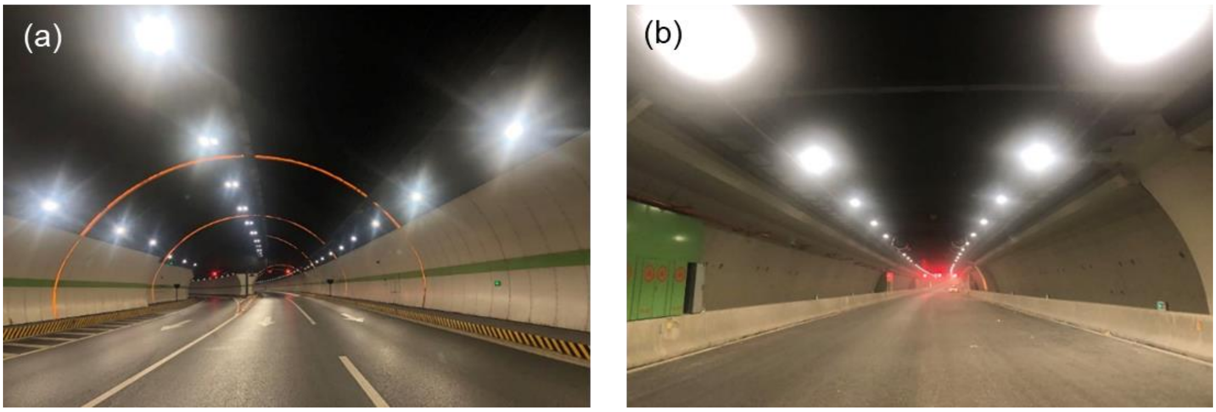

Fig. 4. The non-transparent structure of normal tunnels, (a) Beidi Road Tunnel in Shanghai, and (b) Zizhi Road Tunnel in Zhejiang Province.

(3) Poor assistance of professional emergency services. Fire brigade in a tunnel fire may be more difficult than the buildings on the ground, and it also takes a much longer time [32]. Obtaining the precise location of the fire needs a longer time with the interference of smoke. In addition, due to limited exits in tunnels and the traffic congestion caused by the fire, trapped vehicles are piling on the road, and fire engines often have trouble entering the tunnel and passing through the trapped vehicles, as shown in Fig. 5(a). What makes things worse, many tunnels are in remote locations like mountain tunnels, underwater tunnels, crossing-cities tunnels suffer more difficulties in obtaining the emergency response and rescue processes due to the long distance to fire stations, as shown in Fig. 5(b), and old tunnels may meet more safety issues due to their poor technical installations and smaller size of cross-section, which may restrict the entering of fire engines.

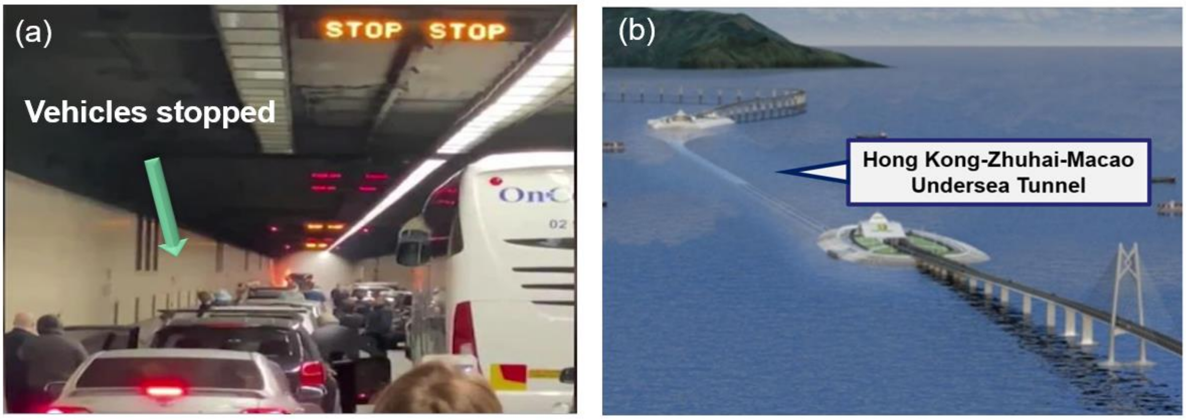

Fig. 5. Problems of firefighting in a road tunnel fire, (a) Traffic jam in the tunnel due to a car fire, and (b) Undersea tunnels (Hong Kong-Zhuhai-Macao Undersea Tunnel) [33,34].

In summary, a safe and reliable evacuation in tunnel fire scenarios is a significant challenge, considering the unique features of the tunnel environment and the following troubles. Fire engineers and scientists have to conduct thorough research to understand human behavior in tunnel fires, and then design functional, reliable and scientific strategies and regulations to guarantee occupants' safety in case of a tunnel fire.

2.2. Specific issues of tunnel evacuation in China

Evacuation in tunnel fires in China shares all similar issues of evacuation in other countries due to the characteristics of tunnels and occupants' poor connection from the outside. However, there are some unique features in China that may lead to different problems and more challenges in the evacuation processes, and we need to pay special attention to guaranteeing safety in case of tunnel fires.

(1) Extremely high traffic flow. A great number of urban tunnels are constructed in large cities in China to solve traffic pressure and therefore load high-density occupants [35]. For instance, the traffic volume of the Dalian Road Tunnel in Shanghai reaches 30,000 vehicles per day [36]. It is easy to catch a fire accident in such traffic pressure. Moreover, due to the high traffic pressure day and night, it is difficult to close the tunnels for a certain period of time for daily maintenance. Hence, the installations for evacuation have a larger possibility of failure in tunnel fires.

(2) Massive tunnels across mountains. China is a mountainous country, especially in the western part, where tunnels are built to solve the traffic inconvenience. Those tunnels are commonly built at extreme lengths in order to connect areas on different sides of mountains, like most extra-long tunnels (over 10km) in China located in western provinces, namely Sichuan, Shanxi and Shaanxi, as listed in Table 3.

Table 3. Some extra-long tunnels (over 10 km) in China

No.	The name of the tunnel	Location (Province)	The length of the tunnel (m)	Maximum depth (m)
1	Zhongnanshan Tunnel	Shaanxi	18,020	1,640
2	Jinpingshan Tunnel	Sichuan	17,504	2,375
3	Maijishan Tunnel	Gansu	12,229	500
4	Baojiashan Tunnel	Shaanxi	11,185	660
5	Nibashan Tunnel	Sichuan	10,007	1,650
6	Xishan Tunnel	Shanxi	13,654	452
7	Baotashan Tunnel	Shanxi	10,480	600
8	Hongtiguan Tunnel	Shanxi	13,122	610
9	Yunshan Tunnel	Shanxi	11,387	743
10	Xinerlangshan Tunnel	Sichuan	13,459	1,500
11	Micangshan Tunnel	Shannxi & Sichuan	13,833	1,055
12	Tianshan Tunnel	Xinjiang	22,035	1,113
13	Tiantaishan Tunnel	Shannxi	15,560	973
14	Muzhailing Tunnel	Gansu	15,221	638
15	Shiziping Tunnel	Sichuan	13,156	1,500
16	Baima Tunnel	Sichuan	13,013	1,092
17	Guigala Tunnel	Xizang	12,798	1,000

Specifically, China owns the longest tunnel in high altitudes (over 4,000m), including Xueshan No.1 Tunnel and Changlashan Tunnel [37,38]. Besides, those tunnels are usually built in extremely adverse geological conditions, like over 90% tunnels' maximum depths are over 500 m, which leads to insufficient evacuation, if there are extra-long evacuation paths to the ground.

(3) Driving large-scale trucks illegally. Due to the fast development of construction and other industry, large-scale trucks occupy the traffic volume prominently in China. While some tunnels are allowed to load large-scale trucks carrying chemical goods, construction materials, etc., large-scale trucks issues are always one of the top concerns of tunnels. Once they are in fire, they could easily destroy the tunnel due to their large scales and hazardous goods loaded, especially for those tunnels with poor infrastructure maintenance. In the meantime, drivers are easy to get tired during long driving, which may trigger an accident and causes serious consequences. Thus, the regulations for large-scale trucks in tunnels should be set more strictly, and related driving training should be enhanced particularly.

(4) More urban traffic link tunnels (UTLTs) in the urban area. UTLTs are a new form of urban tunnels, which usually connect several tunnels, underground parks or underground commercial districts, and have been increasingly merged into urban traffic systems. Different from common tunnels, UTLT has several exits with shorted distances, Thus, pedestrians may be easier to find exits with clear guidance or get lost with conflict or confusing guidance. UTLTs could be served as traffic nodes in urban area, and with more turns and exits, drivers are more likely to get crashed or scratched mutually. Though there are few severe fires in UTLTs so far, more fire and evacuation research should focus on this field and enhance our knowledge[39–41].

3. Strategies of tunnel fire evacuation in China

Scientific and effective evacuation strategies is the premise of occupants' safe evacuation in a tunnel fire. Generally, the strategies' design is based on two mainstream design modes, namely prescriptive code design (PCD) and performance-based design (PBD) [42]. PCD regulates the detailed design parameters for various structure forms, and engineers are required to use these as their design standards. The code determines the distance of exits and the size of each exit. For instance, the distance of two adjacent exits should be no longer than 300 m in road tunnels longer than 1500 m.

In contrast, PBD often addresses the fire safety of new tunnel designs and environments that are not covered in the existing fire codes. PBD is a goal-based method, and engineers decide the details of evacuation settings based on the tunnel's capacity and potential evacuation performance via numerical simulation and theoretical analysis themselves. Despite not following the codes or having no code to follow, the PBD needs the approval from authority having jurisdiction (AHJ) to ensure fire safety is fulfilled. Although the PBD has more flexibility, it is costlier and more time-consuming in the design, documenting and review processes and potentially has a higher risk in case of unexcepted fire incidents. Nevertheless, the PBD will provide important data and support for upgrading the fire codes in future [43]. In mainland China, there is a tendency and preference for applying and upgrading the detailed prescriptive code to reduce the design flexibility and performance-based approaches under the civil law legal system [44].The evacuation strategies consist of two main parts, namely evacuation design of structures, and facilities/systems for the purpose of evacuation in tunnel fire. The below sections introduced two parts respectively.

3.1. Evacuation design of structures in tunnel fire

Considering PBD relies greatly on the ability of engineers, most countries still apply prescriptive codes as the evacuation design for most tunnels essentially. Some new tunnels with innovative designs, ultra-large lengths, and complex structures have to choose PBD, when there are no related regulations to follow. Evacuation in tunnel fire is a new topic, and the regulations to design structures have learned a lot from evacuation in buildings. The regulations in the early years were derived from "Handbook on Building Fire Codes" and "SFPE Handbook of Fire Protection Engineering". With the development of tunnel fires, more books and codes aiming at tunnel fires appeared like "Tunnel Fire Dynamics" and "The Handbook of Tunnel Fire Safety", and those summarized data and empirical correlations have provided engineers with the layouts of tunnels for evacuation and the evacuation equipment and systems etc. Those regulations instruct engineers to design tunnels' structure by satisfying the requirement of evacuation in tunnel fires. Regulations improve gradually with the findings of evacuation in tunnel fires, so nowadays there are increasing outcomes in this field[45,46].

Considering the different characteristics of urban tunnels and mountain tunnels (usually in rural areas), the regulations of structures are commonly formulated separately in China. For urban tunnels, there are specific requirements for the evacuation path's length and size, the distance of exits and technical installations, including water suppression and alarming and smoke control systems. The principal regulations are the National Standard GB 50016-2014: Code for fire protection design of buildings". Its latest version was drafted by Tianjin Fire Research Institute and co-issued by the Ministry of Housing and Urban-Rural Development and the General Administration of Quality Supervision, Inspection and Quarantine in 2018. Other related regulations with more details include GB 50157-2013: Code for Design of Metro, JTG D70-2-2014: Specifications for Deisign of Highway Tunnels, TB 10003-2016: Code for Design of Railway Tunnel etc. (covers see Fig. 6), and their comparisons are listed as Table 4 [47–50]

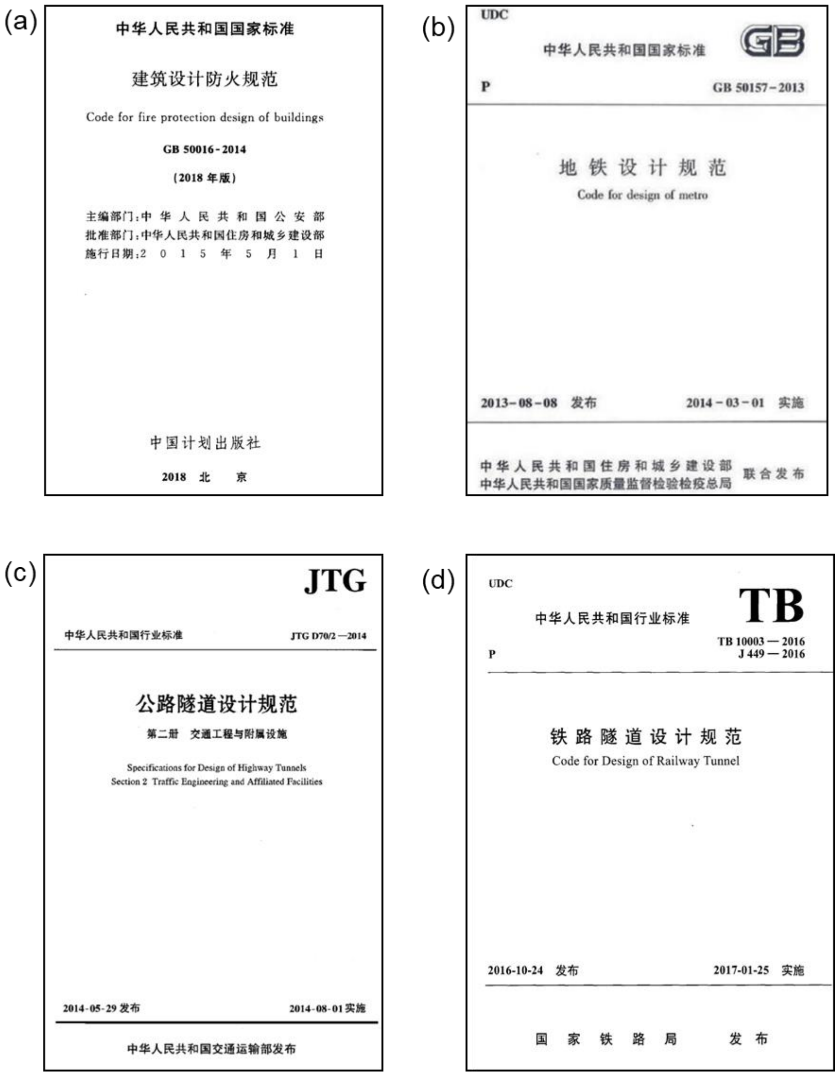

Fig. 6. Covers of related tunnel fire safety codes [49–52].

Table 4. Related tunnel fires codes and comparisons in China.

Code No.	Code Name	Year	Major and shortage
GB 50016-2014	Code for fire protection design of buildings	2018	Covers urban transportation and its fire water supply, fire extinguishing facilities, ventilation and smoke exhaust, fire automatic, alarm system, power supply, but no metro/railway tunnels, pipelines and cable tunnels
GB 50157-2013	Code for design of metro	2013	Covers metro station but not for tunnels between each station
JTG D70-2-2014	Specifications for Design of Highway Tunnels	2014	Covers fire design scales, firefighting facility configuration requirements, and water mist system setup requirements, but this code is local-level and not mandatory or universal.
TB 10003-2016	Code for Design of Rai1way Tunnel	2016	Divide railway tunnels into four types but no detailed requirements of fire safety

For example, these codes define the distance of two adjacent evacuation paths and exits inside the tunnel should be between 250 – 300 m. Nevertheless, these requirements are often different from other countries, and some comparisons of distances are listed in Table 5. For example, the clear width of the evacuation path should be no less than 1.2 m and the clear height no less than 2.1 m. Besides, there should be fire prevention procedures from the tunnel to the evacuation path, like a fire door no less than Grade B. Such guidelines could be referred to Chapter 12 in GB 50016-2014 [53–55].

Table 5. Recommended values for the distance between adjacent evacuation paths.

Country or Region	Code	Distance (m)	Width (m)	Other related regulations
China	GB 50016-2014	250-300	1.2	Both ends with fireproof door (> Grade B)
USA	NFPA 502	<300	1.12	Both end with a fireproof door (Grade: Time>1.5h), decoration: Grade A
EU	Directive 2004/54/EC	New: < 150 In use: < 250	—	With emergency phones and two fire extinguishers Adding more paths if traffic volume > 2,000 vehicles per day

However, the recent increasing extra-long tunnels in China and the vulnerability of evacuation issues for extra-long tunnels add significant challenges in designing safe and reliable fire evacuation. The national code requires that tunnels over 20 km have to design under performance-based approaches and be evaluated separately, apart from satisfying the existing regulations. Extra-long tunnels often appear in mountainous area with flexible forms and varied sizes. Like the PBD in buildings, it calculates the Available Safe Egress Time (ASET) in various tunnel fire scenarios and the Required Safe Egress

Time (RSET) under different occupancy densities and exit routes. Eventually, the design should satisfy "ASET > REST" or a ratio of ASET/REST and balance the economic considerations [56]. However, due to the understanding of human behavior in fire, particularly in the tunnel fire environment, being far from thorough at the moment, the calculation is more or less an estimation. Despite the research challenges, we need to investigate human behavior to ensure our design is in accordance with reality. Therefore, such assistance could be effective and efficient for occupants' evacuation in a tunnel fire.

3.2. Evacuation facilities and systems in tunnel fire evacuation

Apart from regulations on the evacuation structures' design such as the paths and exits, nowadays, there are more measures to enhance the evacuation in tunnel fires by involving professional evacuation facilities and systems, such as effective smoke control systems and early-warning systems [57,58]. Smoke control systems are widely applied in tunnels to control smoke in the fire, as shown in Fig. 3. Moreover, some intelligent early-warning systems are equipped in newly-built tunnels, and the regulations are listed in Table 6.

Compared to USA or Germany, the regulations of alarm detection systems are not detailed in terms of types and functions in China. However, new and advanced systems nowadays are fast applied in China actively in newly-built tunnels, and they could detect the fire location, give the alarms to the central control systems, and predict fire development [59,60]. Some tunnels are equipped with fiber grating sensors or dual-wavelength sensors, which could monitor the temperature of the tunnel every second. Once there is a fire, the environmental temperature will increase, the sensors will report it, and the central system will analyze it with other systems like video monitors. When it confirms there is a fire, the broadcast system will ring the alarm and warn the occupants to evacuate in time. Moreover, some relative systems will start to work like foam-water spray.

Table 6. Regulations of Fire early-warning facilities.

Country or Region	Code	Distance (m)	Detection time (s)	Other related regulations
China	GB 50016-2014	50	60	Tunnel, control room and substation should all be equipped.
USA	NFPA 502	90 m (manual alarm) Within 15 m (auto alarm)	90	Type B, C and D tunnel should be equipped with manual and tunnel with water-based fire extinguishing system should be with auto.
EU	Directive 2004/54/EC	—	—	All tunnels should be equipped with fire alarming systems but control room is optional
Germany	RABT-2003	50	30	Tunnels over 400m or with mechanical ventilation systems should be equipped. The detection time is aimed at 5 MW fire with 6m/s airflow

In addition, some intelligent tunnels could also add evacuation guiding systems [61,62]. They could monitor the real-time evacuation in the tunnel and give corresponding guidance, according to the potential congestion or block by the fire. Moreover, they are supposed to adjust technical installations according to the fire dynamics, such as changing the guiding direction of information signs. Those advanced systems applied in China recently improved the evacuation in a tunnel fire. With the fast development of complex tunnel constructions in China, it is clearly regulated that there should be warning systems to stop vehicles from entering the tunnel 100-150 m outside the tunnel entrance, and there should be automatic fire alarm systems for tunnels over 500 m (loading trucks with chemicals) or tunnels over 1500 m (no trucks with chemicals allowed). Largely owing to the development of research in evacuation, all those measurements are widely applied and aim at controlling the fire spread, diminishing the harm of fire, warning occupants to evacuate in a short time and guiding their evacuation correctly and efficiently.

4. Evacuation research in tunnel fires

4.1. Overview of evacuation research in tunnel fires

The research of evacuation in tunnel fires has exploded in the 21st century though there were a handful of scientists stepped into this field since the 1990s. For example, Sime claimed drivers preferred to drive back to the original entrance when they met emergencies. Evacuation in tunnel fires, then, has developed from evacuation in buildings and learned human beings' speed and walking behaviors on the ground, ramps and staircases [63–66]. Afterwards, a diverse range of studies concerning this topic has been conducted, including human behavior, human psychology and guidance from technical installations [67–69].

Specifically speaking, scientists have investigated walking behaviors, including their speed and postures in tunnels with the influence of fire smoke and low visibility and their congestion in front of exits along with driving behaviors in the tunnel during the information processing and movement [23,70–75]. In addition, research from social psychology has paid attention to social influence and their help and support mutually [76]. They have confirmed the formation of social influence, and they are devoted to understanding the mechanism of social behavior in evacuation and taking advantage of it furthermore [77,78]. Moreover, some scientists tested several technical installations in the tunnel and confirmed their guidance during evacuation. They also improved the settings, including information signs, alarming and lighting to assist the evacuation better [19,20,79,80]. All those researches have filled in the gaps of evacuation in tunnel fires in a large extent. However, most research focused on a specific topic like the relation between walking speed and crowd densities and rarely have had a chance to study the whole fire evacuation process in field. The lack of research mainly results from the limited chance to study human behavior in a real, full-scale tunnel, resulting in a shortage of knowledge in reality. The problem becomes extremely severe when some special tunnels are constructed and put into use since we could predict the evacuation behavior in normal tunnels, but hard to infer to special tunnels like extra-long tunnels or tunnels in high altitudes. While there are still several limitations of current evacuation research in tunnel fire, the research has achieved significantly in China so far. It deserves a summary point by point and it will help us to learn the strength and weakness of research in tunnel evacuation in fire. Some representative researches are introduced below.

4.2. Chinese Research organizations and representative researchers

Along with the increasing tunnel constructions in China these years, local researchers have paid huge attention to tunnel fires both from higher educations and research institutes. Four Fire Research Institutes in China, namely Tianjin, Shanghai, Shenyang and Sichuan Fire Science and Technology Research Institute of MEM are directly led by Ministry of Emergency Management of the People's Republic of China. Among them, Tianjin Institute are specialized in auto fire extinguishing systems, fire dynamics modeling and industry standards development; Shanghai in firefighting service including firefighters' suits, rescue facilities and daily training; Shenyang in fire scene inspection and material evidence identification as well as firefighting communication; and Sichuan in quality supervision and inspection of fireproof materials, and fire and explosions research [81–85]. Meanwhile, researchers from higher education emphasize on research in evacuation in tunnel fires and they have conducted experiments in tunnel fires, calibrated human behavior models, and optimized evacuation facilities. Among them, the University of Science and Technology of China (USTC), Tongji University, and Southwest Jiaotong University, have been the most active in this field[24,25,86–92]

4.3. Research topics classification in China

The topics related to evacuation in fire of recent years (from 2010) are summarized and illustrated shown as Fig. 7 by the authors. The figure draws the detailed topics and their connections according to 387 pieces of research work in recent years with the keywords including "tunnel", "fire" and "evacuation". Those works were searched from Web of Science Core Collection. From the connection figure, the topics was divided into three main clusters with three colors clearly. The red cluster focus on characteristics of fire and smoke control systems such as ventilation modes, temperature distributions and smoke movement, sharing great similarities with fire dynamics, while the blue focus on the occupants' performance in emergency and has a close relationship with the green. The green is centralized with evacuation with safety issues and risks. Some typical research and findings in China are as below.

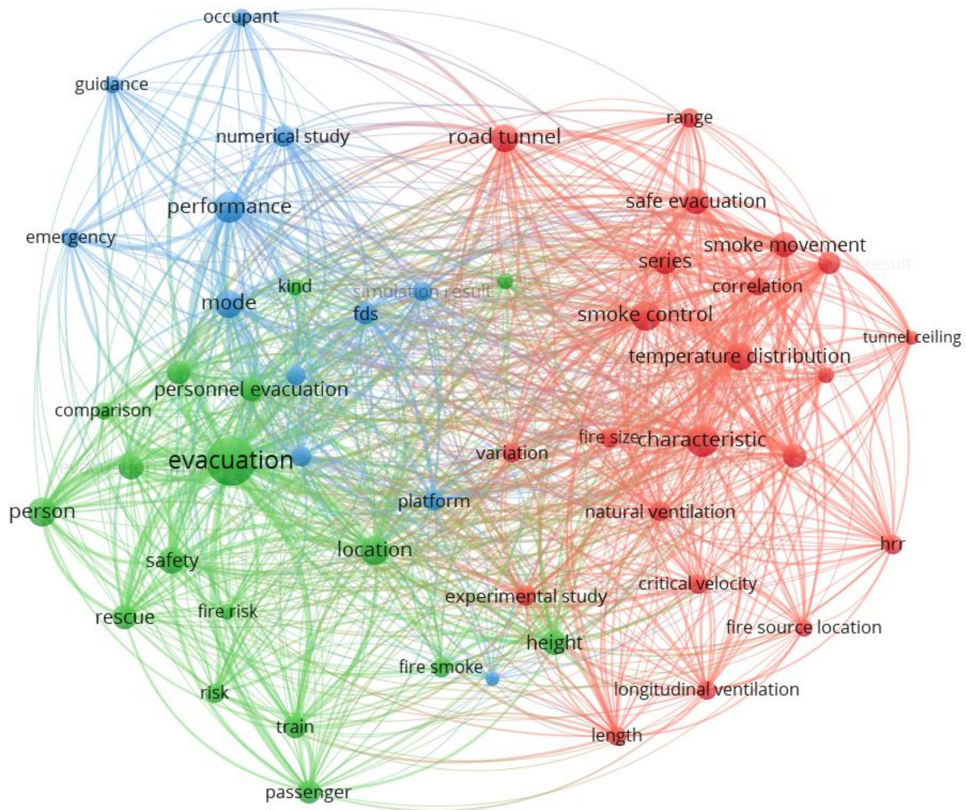

Fig. 7. The topics related to tunnel fire evacuation in recent years (from Web of Science Core Collection).

4.4. Representative research from USTC in China

Compared to overseas research, one of the main contributions from Chinese research are some full-scale evacuation experiments. It is commonly hard to conduct full-scale evacuation experiments in tunnel fires because most tunnels are open for 24/7 and the limited closed period is applied to maintenance service. However, thanks to the massive construction of tunnels, it is possible and feasible to conduct full-scale experiments before the tunnel is put into use officially and it has been applied in several tunnels [14,20,87,88]. Those studies not only tested the evacuation capacity of some extra-long or special tunnels but also provide valuable research data of human evacuation for further evacuation modelling setting and calibration. Some typical studies are introduced briefly below.

Song and his team in USTC have investigated human behavior for several years and they have made a great contribution on the detailed human behavior like their speed and pace in different scenarios [26,66,93–95]. Though their research is not targeted at human behavior in tunnel, their findings still help to know human reaction in a general aspect. For instance, they have conducted experiments like crowds flow with background music or on staircases and calibrated movement models [36,93,96,97]. Their experiments showed that pedestrians stop longer with music and stop-and-go behavior is more frequently. From experiments on staircases, they found that participants who stand in front of the queue accelerate before merging with participants coming from upstairs, and the speeds of participants from upstairs are reduced when participants join the flow. Pedestrians would like to choose inner side stairs rather than outside stairs when stairs are divided into two parts, as shown in Fig. 8. They also studied the evacuation process, like route choice around obstacles, and they found that crowd densities and distance to exits influenced human decisions [90,98].

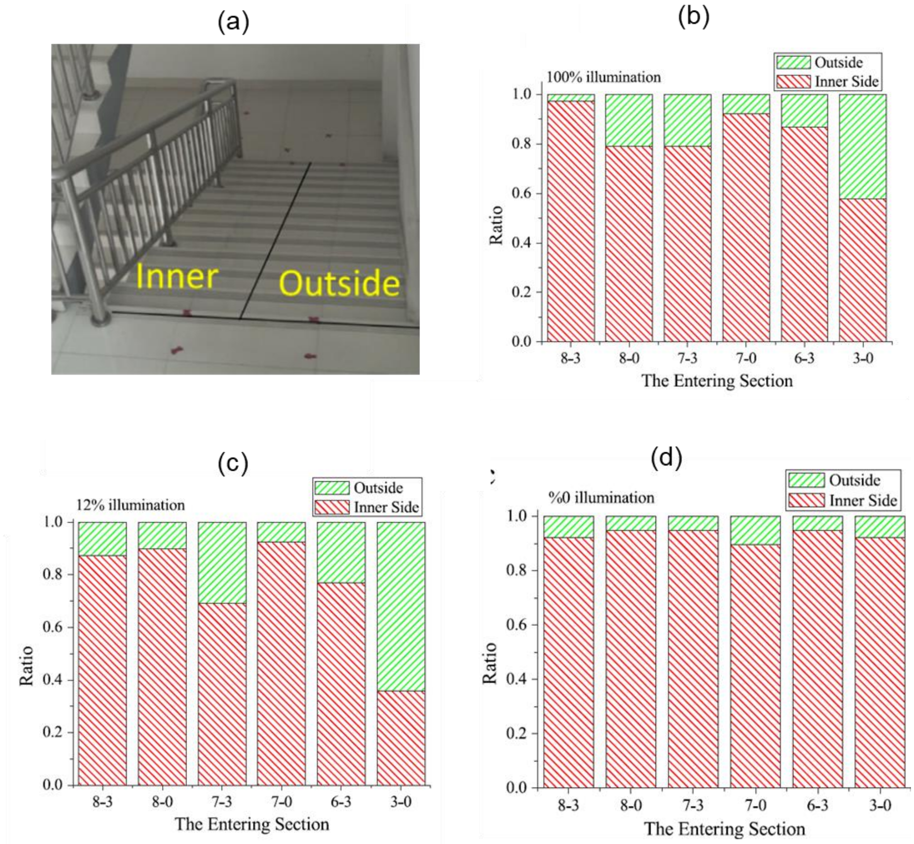

Fig. 8. The preference of inner and outside under different illumination, (a) Inner and outside of staircases, (b)100% illumination, (c) 12% illumination, and (d) 0% illumination [66].

From their experiments and simulations, two identical exit doors were not used evenly during evacuation. They also found pedestrians prefer a route with fewer people and nearer to them. The preference will rise with the increase of route distance and pedestrian's density. During the investigation, they also paid attention to the vulnerable like the elderly [99]. The speed of the elderly is always lower than the young people and the free speeds are about 1.28 m/s of the elderly and about 1.40 m/s of the young, respectively in the laboratory experiments, as shown in Fig. 9.

Those researches help to have a better understanding of human behavior on the ground and in the buildings with different structure forms. On one hand, those findings build a foundation to study human behavior in tunnel fires such as the basic walking velocity and preferred evacuation trajectories. On the other hand, some structures namely staircases have started to apply in complex tunnels. For example, some newly-built tunnels are constructed with two layers and the evacuation routes are staircases connecting two layers mutually, and the findings of evacuation via staircases could benefit the evacuation in tunnel fire.

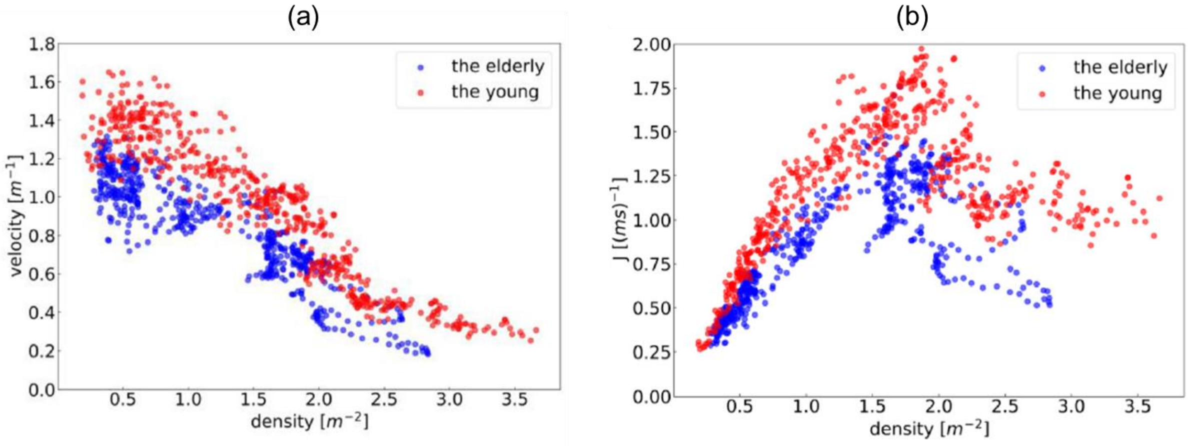

Fig. 9. Comparison of the fundamental diagrams of unidirectional flow of the elderly and youths, (a) velocity and density, and (b) flow and density [99].

4.5. Representative research from Tongji University in China

Zhang et al., in Tongji University have focused on evacuation in tunnel fires in recent years. They have done evacuation research in tunnel fires via several full-scale experiments in real tunnels both in urban area (Fig. 10) and in mountainous area (Fig. 11). They did field evacuation experiments in urban tunnels with natural ventilation, and confirmed the positive influence of natural ventilation in evacuation due to the big ceiling openings. Moreover, they have discovered the movement rules in long evacuation paths in mountainous tunnel and optimized technical installations to assist evacuation better including information signs and alarms[14,20]. For instance, they divided occupants' movement into four stages according to the distance in a long evacuation path in a high altitude and also measured the reaction time.

In addition, they tested the guidance of technical installations, including information signs, lights and alarms, and the results showed they guided evacuation in an emergency. Among them, signs were generally regarded as the most functional and the side effect of alarms were observed. On the one hand, those findings tested the evacuation performance of those tunnels in fire and helped to improve evacuation strategies and settings. On the other hand, those studies learned the applicability of human behavior from normal conditions to tunnel fires and studied the difference between them. Those findings perfect the understanding of human behavior in fire and lead to guidance on evacuation planning and treatment in tunnel fires. Full-scale experiments in tunnels are one of the most authentic ways to study evacuation in tunnel fires, second to fire accidents, but only a few have been accomplished due to the difficulty and restrictions of preparation. Two case studies of full-scale evacuation experiments in tunnel fires along with two fire accidents, are introduced in the following chapter [20,24] .

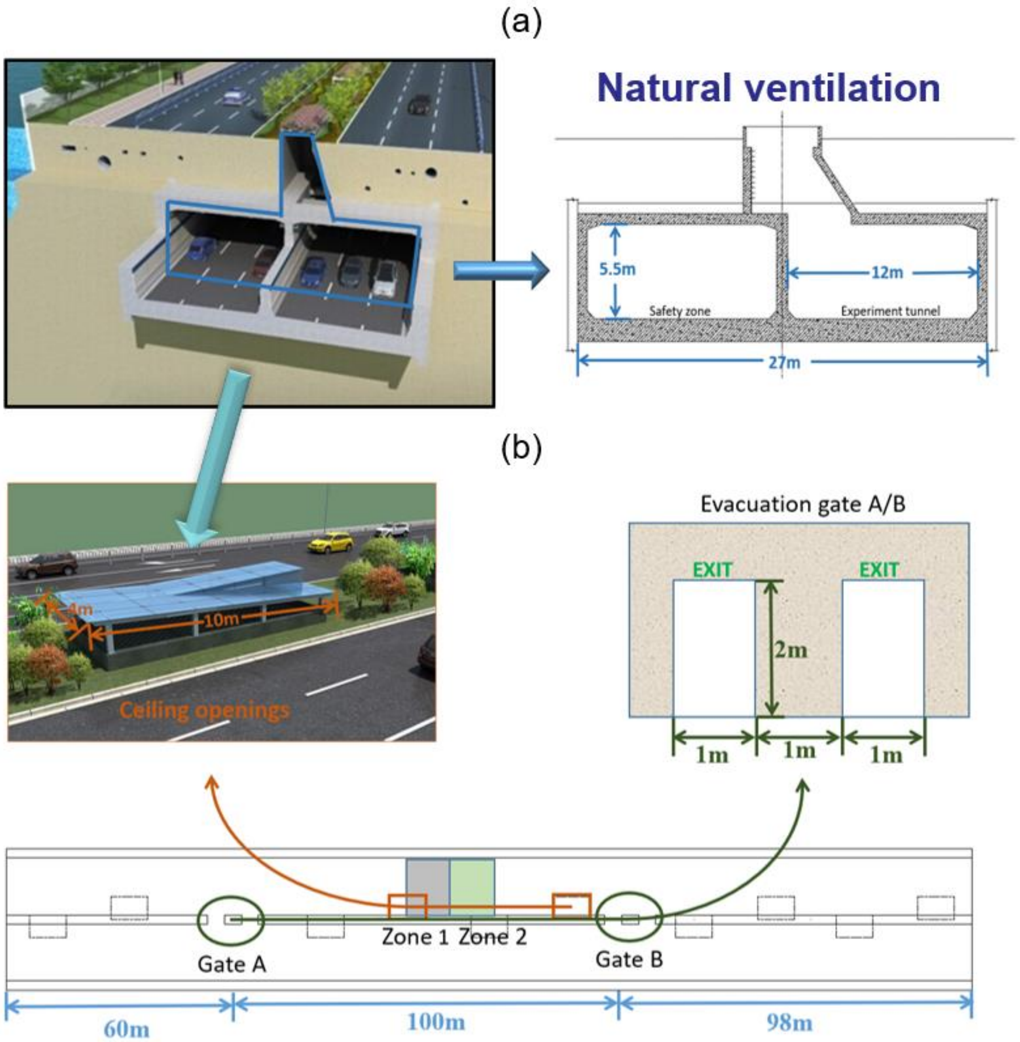

Fig. 10. The structure of the Beidi Tunnel, (a) The dimensions and cross-section, and (b) The size and layout of evacuation routes [22].

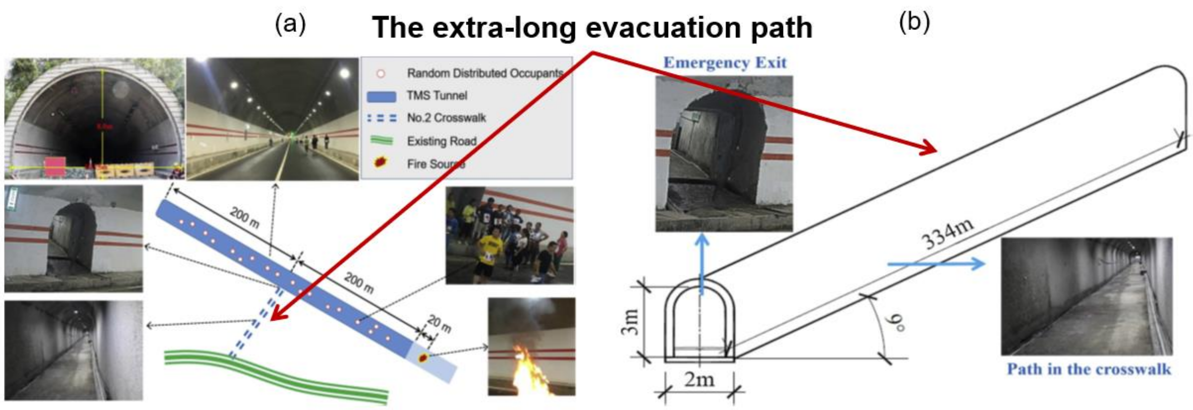

Fig. 11. Tengmieshan Road Tunnel and its extra-long evacuation path [14], (a) Tengmieshan Road Tunnel and the fire evacuation experiment, and (b) The extra-long evacuation path.

5. Case studies of tunnel fire accidents and evacuation

Cases of tunnel fire accidents and evacuation are reviewed in this section. The causes of fire accidents, evacuation strategies, evacuation performance and progress are analyzed and discussed specifically. The analysis of evacuation in real accidents are vital to understand the status quo of evacuation and expose the shortage of evacuation strategies and research currently. In specific, three tunnel fire accidents in China, namely, the Jinji Road Tunnel fire, Maoliling Road Tunnel fire, and Xuefengshan Road Tunnel fire, are reviewed in this section, while the former two caused great casualties, and the last one had no death. This section explored great challenges in fire evacuation and rescue process of three fire incidents, and discussed their different evacuation consequences. In addition, it revealed unique evacuation needs that deserve more future research.

5.1. Case 1: Jinji Road Tunnel fire in 2014

The fire accidents started from two articulated trucks transporting methanol colliding with each other in Jinji Road Tunnel in Shanxi Province, China, on 1st Mar 2014, as shown in Fig. 12 [15]. The methanol in front of the vehicle leaked and caught fire., and two other hazardous chemical transport vehicles and 31 vehicles, including some coal trucks, were ignited and detonated. The fire caused 40 deaths, 12 wounded, 42 vehicles destroyed, and over US$11 million in direct financial loss [100].

There are several causes of the tragedies both from the drivers' aspects and the evacuation strategies. From the drivers' part, causes include the drivers' dereliction and lacking of safe driving knowledge during the transportation, and the transport company's lax management of heavy trucks. Their improper and nonstandard behavior triggered this fire. Meanwhile, from the evacuation strategies, there were not efficient and effective measurements to guide and assist the evacuation, which caused 40 deaths eventually.

Fig. 12 Jinji Road Tunnel fire in 2014[101].

In specific, firstly, there were no functional smoke control systems when the tunnel was in fire, and the smoke spread fiercely and rapidly in the tunnel. The occupants had great difficulty to evacuate from the tunnel, and the firemen could not enter into the tunnel due to the dense smoke and terrible visibility. Secondly, some other firefighting facilities did not work such as the smoke detectors did not detect the accident nor rang the alarms, and the fire hydrant was out of water, which brought about problems for the fire brigade. In addition, the information signs were not clear and did not point to the nearest exits, and some evacuation exits in the tunnel could not open. Hence, the occupants had to evacuate from two ends of the tunnel, which cost a much longer time, and some could not evacuate before the fire spread.

While the accident did not result from occupants' improper evacuation behavior principally, it exposed two aspects of issues about driving education in tunnel fire and evacuation strategies of tunnel systems. On one hand, strict rules and rigorous training in driving should be carried out for tunnel safety. Proper operations of drivers to fire could decrease the chance of traffic accidents and tunnel fire's consequence largely. On the other hand, it is crucial to ensure the normal operation of evacuation strategies so that it could provide suitable environment and guide occupants to evacuate from tunnel fires. Otherwise, it has a large possibility to result in great casualties. It calls on more research attention to enhance the evacuation strategies such as the reliability of firefighting facilities and the availability of evacuation guidance.

5.2. Case 2: Maoliling Road Tunnel fire in 2019

The fire accident in Maoliling Tunnel started from the fourth inner tire burst of a semi-truck at 18:24 on 27th Aug, 2019, right after two minutes of driving into the tunnel (see Fig. 13). The driver stopped the truck in the slow lane later, and the location was almost the middle of the tunnel (1,775 m to the tunnel entrance, and 1810m to the tunnel exit). After the fire started, the driver tried to put out the fire with the vehicle fire extinguisher, and three traffic police noticed the fire during the patrolling. They joined the firefighting with the driver and requested reinforcements. However, the synthetic leather in the truck burned and contributed to the serious fire in a short period. As a result, there were 5 deaths and 31 injuries from this fire accident.

Fig. 13 Maoliling Road Tunnel Fire in 2019

During the fire accident, the deflagration was a key point. The dense smoke from deflagration soon spread and occupied the whole tunnel and caused several vehicles' collisions and scratches along the traffic flow. Though the tunnel started extra sets of fans to boost blowing the smoke out of the tunnel from the deflagration, the dense smoke and toxic gases caused several casualties in a short period. The fire brigade started to run towards the fire location at 19:02 and rescued over 100 occupants. The fire was controlled at 19:30, and the rescue ended at 20:33.

Overall, the evacuation, firefighting and rescue were rapid, and most of the trapped occupants were either self-evacuated or rescued by fire brigades. However, the dense smoke from the deflagration was the main factor for the casualties. On one hand, the burning production causes several asphyxias of the trapped people, on the other hand, the smoke prevented the rescue vehicles from entering the tunnel . The incident warns us that specific measurements should be prepared for sudden accidents such as deflagration or flashover, and more targeted research are to be conducted for prediction and prevention. It would improve the tunnel safety in fire.

5.3. Case 3: Xuefengshan Road Tunnel fire in 2020

Compared to the great casualties and losses in Jinji Road Tunnel fire and Maoliling Road Tunnel fire, the fire accidents in Xuefengshan Road Tunnel had no deaths due to its timely evacuation and rescue. The fire accident, which happened at K1376+600 in Xuefengshan Road Tunnel on 25th Oct 2020, was triggered by a fire from a semitrailer loaded with electric bikes, and it caused over 300 occupants stuck in the tunnel together with 33 vehicles, as shown in Fig. 14.

Fig. 14. Xuefengshan Road Tunnel Fire in 2020 [102].

When the fire was ignited, the control systems reacted quickly, and the local government organized the evacuation promptly and orderly. The smoke control systems worked along with smoke extraction vehicles, firefight robots etc., to control the fire. During the first stage of self-evacuation, over 250 occupants evacuated from the tunnel following the instructions in the tunnel. There were multiple exits along the 7 km tunnel with intervals of 250 m, and they were the main evacuation route to the safety zones. During the next stage, firefighters entered the tunnel, put off the fire and rescued the left 65 occupants. The successful evacuation of this fire was largely dependent on the scientific evacuation layouts like transverse exits and the effective guidance of evacuation at the start of the fire. To enhance the safety of occupants in tunnel fires, the key point is to understand human behavior in tunnel fires and provide corresponding strategies.

6. Case studies of full-scale tunnel evacuation experiments

Field experiments are useful to study evacuation behavior in tunnel fire while fire accidents expose the shortage of current evacuation strategies and research and point out the research need. Two full-scale field experiments are introduced investigating evacuation performance in tunnel fires conducted by the authors these years. The experiments were conducted in real tunnels and participants evacuated from the experimental tunnels to the safety zones. Their route choices, movement time, reaction to technical installations and speed change were recorded and analyzed to understand human behavior in tunnel fire. The experimental data is rare and valuable due to the high cost of field evacuation experiments and inflexible parameters. Detailed information could be referred to [13,19,23].

6.1. Case 1: Evacuation of Tengmieshan Road Tunnel with extra-long evacuation path

China is a mountainous country, and there are rolling hills in the western part, which brings huge challenges to residents' daily transportation. Hence, some tunnels are constructed to solve this problem, and due to the adverse geological condition, the tunnels sometimes have to be constructed with a steep slope, extra-long evacuation paths and fewer transverse exits. Considering the adverse conditions including tunnels are in high altitude, reduced oxygen, long distance of evacuation and steep slopes, the evacuation conditions may be largely different from normal tunnels. Therefore, Zhang et al., conducted an experimental study of evacuation in tunnel fire in Tengmianshan Tunnel in Yunan Province, China. The study learned the evacuation performance in tunnel fires targeting to tunnels in high altitude and low-pressure areas, and gave instructions and suggestions on evacuation planning of those types of tunnels.

The study was conducted in the Tengmieshan Tunnel, located in the southwest of China, with an average altitude of 1025m and a reduced oxygen content of 19.31% (20.95% in 0m), as shown in Fig. 11. Due to the poor terrain conditions, one evacuation path has to be 334m in length with a 9.0° slope, which may cause trouble to pedestrians' evacuation in case of fire. In this study, a fire of 0.5MW was ignited to produce smoke, decrease the visibility and increase the sense of stress as in real tunnel fires. Pedestrians' behaviors, including their adaption time, speed and physical conditions in the tunnel and extra-long evacuation path, were presented and analyzed. The study tested the evacuation ability of tunnels, i.e., Tengmieshan Tunnel with extra-long evacuation route.

Test results showed that its evacuation paths overall provided a reliable evacuation environment for pedestrians in the face of those adverse factors. Moreover, the study summarized the rules of movement of a long evacuation path like moving stages and trajectories preference on the right side, especially when they approached the end of the path, as shown in Fig. 15. The experiment is regarded as one of initial research on tunnel evacuation at high altitudes, and the experimental data will aid further calibration and validation of numerical modelling of evacuation behavior.

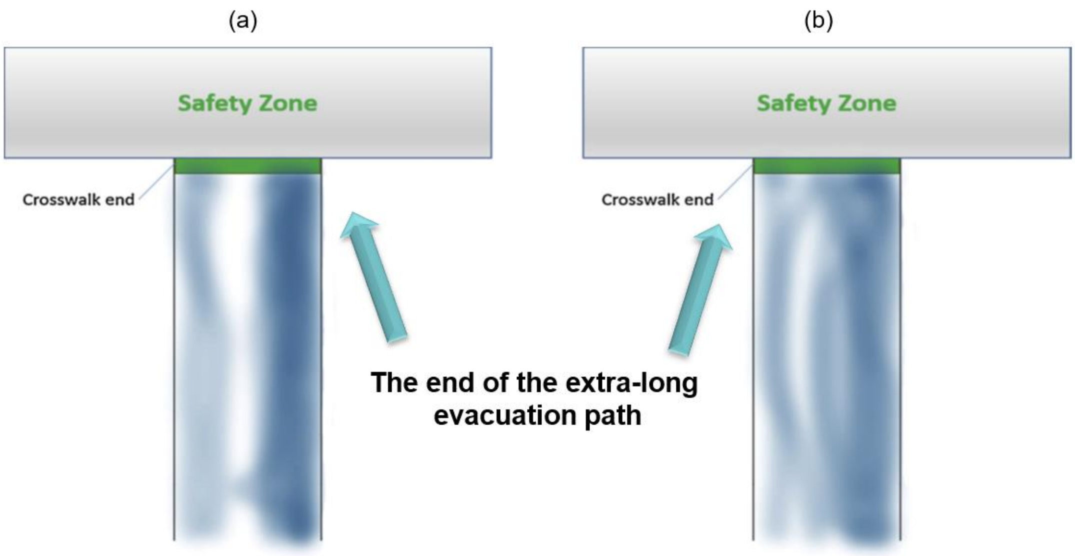

Fig. 15. People's track of last 35 m in the evacuation path in Tengmieshan Road Tunnel [13], (a) female and (b) male.

6.2. Case 2: Evacuation of Beidi Road Tunnel, Shanghai with natural ventilation

Shanghai suffers severe congestion in urban areas while loading significantly large traffic volumes, and tunnels are constructed to relieve the traffic pressure. Due to Shanghai's weak geological condition, most areas could not load deeply-buried tunnels, which dictated that shallow tunnels are preferred. Hence, mechanical ventilation systems are not suitable with the restriction of the tunnel's shallow depth, and some tunnels apply natural ventilation with large openings on the ceilings. Those openings allow natural light into the tunnel and change the enclosed tunnel to a semi-enclosed one. A field experimental study, therefore, was conducted to test the effect of natural ventilation on pedestrians' behavior changes, along with their use of technical installations during the evacuation in tunnels.

The experiment was organized in the Beidi Tunnel, a new six-lane bidirectional urban road tunnel with natural ventilation in Shanghai. The size and the outlook of the tunnel could be referred as Fig. 10. The study showed those vertical shafts could pose a positive influence people's behavior and route choice during evacuation by exhausting smoke and introducing sunlight into the tunnel. According to the evacuation performance and the interview of pedestrians, the openings, on the one hand, provide enough light and maintain good visibility in the tunnel.

On the other hand, sunlight offers a sense of security to pedestrians, and they show an active attitude towards ceiling openings. The study demonstrated the positive function of natural ventilation and the openings on the ceilings. In addition, during the study, firefighters entered the tunnel through the openings, and the time they spent was 40% shorter than they used typical paths (see Fig. 16). It indicated another advantage of natural ventilation - a quicker way to rescue in tunnel fires. This field experiment recorded evacuation behavior in a natural-ventilated tunnel, and investigated specific ventilation mode's influence on evacuation.

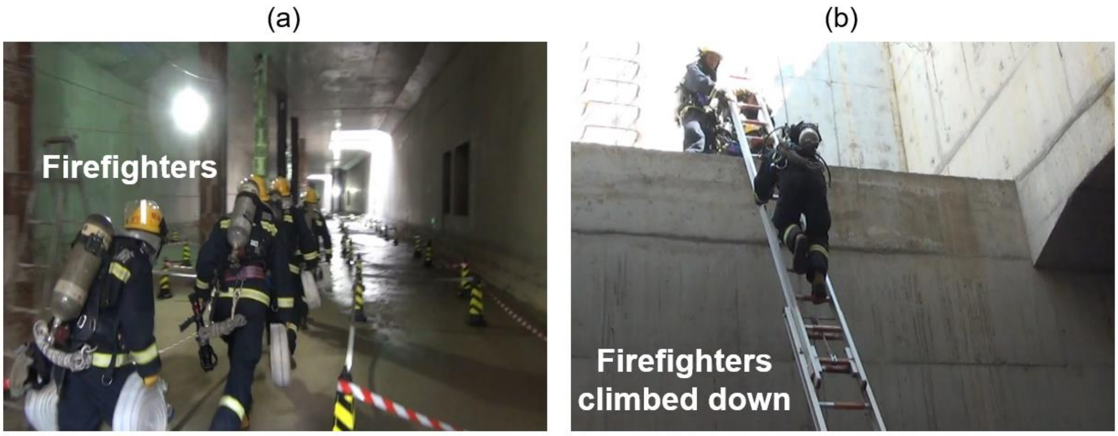

Fig. 16 Firefighters' rescue to the fire location in the tunnel, (a) Normal path through the tunnel, and (b) Entered the tunnel through the vertical shafts.

7. Challenges and perspectives

Chinese researchers have done great investigations on evacuation in tunnel fires along with the increasing numbers of newly-built tunnels. Those investigations, on the one hand, help engineers to design tunnels and corresponding evacuation strategies, including exits layout and evacuation paths, to ensure the evacuation safety in tunnel fires. On the other hand, they supplement the research of human behaviors in tunnel fires, such as increasing data repository [103] and will aid related research furthermore, such as calibrating and validating human behavior models and smart firefighting [104]. However, there are several challenges in China with the pressing need for advanced research, and by addressing those challenges, it is expected to contribute to the research area through unique strength in China.

Firstly, evacuation in tunnel fires in China is always demanding due to the high traffic volume and the extreme geological construction. Urban tunnels in cities always load a heavy traffic flow day and night, which not only represents the tunnel has a larger possibility to catch an accident, but owns a great number of occupants to evacuate once in fire. Moreover, tunnels' 24-hours operation will probably result in delayed service and the failure of technical installations for evacuation. For rural tunnels, they are built in the mountainous area, where the geological conditions are rough and hardly have the chance to satisfy the common requirement of evacuation settings.

The challenges for their evacuation are larger once some fire accidents are triggered such as by fatigue driving and following collisions. For instance, the interval of exits may be built longer than the regulations, and the evacuation paths may be built longer and steeper. Engineers have to decide if the construction meets the requirements of evacuation themselves. However, considering the understanding of human behavior in tunnel fire, especially in extreme environments, is limited, it is rather challenging to make precise and scientific decision. One major perspective development is to by enhancing the understanding of human behavior in tunnel fire in adverse conditions. Therefore, it could contribute to a precise prediction of evacuation, then satisfy the evacuation requirements of various tunnels either in urban or mountainous areas. Those researches could take advantage of massive newly-built tunnels in China, such as conducting full-scale evacuation experiments before they are put into use. The experimental data is extremely precious to evacuation research.

Secondly, the research history of evacuation in China is relatively short (ten years or so) compared to other countries namely Sweden or USA. Though we researchers learned much from them, there are not a large number of scientists working in this field. Along with the shortage of researchers, the research methods are limited in China. Most people still rely on traditional research methods, and some new ones are not fully introduced, like Virtual Reality (VR) or eye-tracking. Some Chinese researchers have tried to start research using VR and eye-tracking systematically, and the application of those methods will help to build vivid scenarios of tunnel fires and to observe people's responses continuously and accurately, and one aim of this research is to call on more researchers into various research methods and collaborating with each other in the near future. In specific, some emerging technologies, which could be used for evacuation research and application in tunnel fires are introduced and discussed below (see Fig. 17).

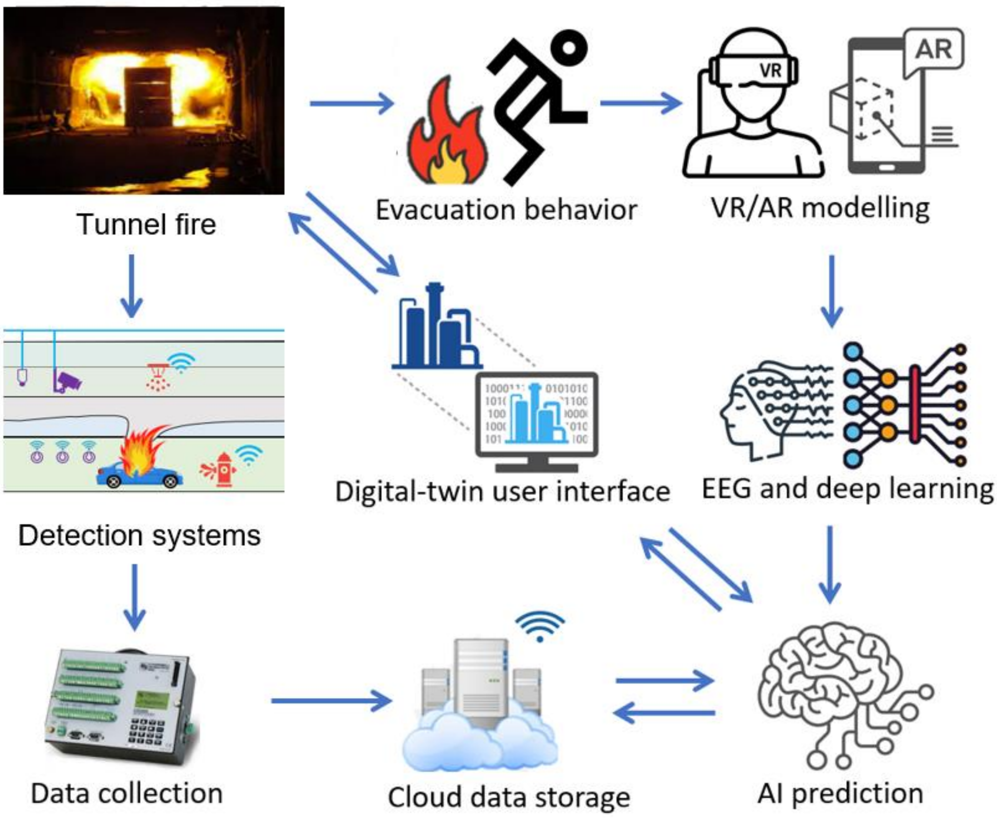

Fig. 17. Emerging technologies in tunnel fire evacuation.

On the one hand, tunnels evacuation performance could be optimized by real-time monitoring and intelligent prediction [105,106]. By installing intelligent and multi-functional detection systems like dual-wavelength or optical fiber grating sensors and monitoring systems, it is feasible to detect the tunnel fire in the early stages and process those data via artificial intelligence (AI) prediction and digital twin technologies. Hence, it is available to predict fire development and evacuation progress. Based on the information, some advanced interference, including dynamic guiding systems, will largely help the evacuation. On the other hand, emerging technologies could be an asset for evacuation research. For instance, virtual reality (VR) and augmented reality (AR) under ethnic consideration are capable of building immersed environment to study human's behavior in a tunnel fire. Moreover, the combination of neuroscience and deep learning is a useful tool to reveal and learn human's response in complex tunnel structures in fire. The reaction of muscles and bodies will be recorded precisely via skin conductivity along with other physiological arousal factors including heart rate, blood pressure, respiration, perspiration. With these data, AI could learn the evacuation preference and explain the rules according to physiological reactions, and then predict the evacuation process accurately and rapidly.

To point out, though more research has conducted in China along with advanced technologies and approaches, the training and education of evacuation is not sufficient in China. There are limited regular evacuation drills both on the ground or underground in China for people to get familiar with the evacuation process and the use of related technical installations. In addition, there are few driving lessons or tests about evacuation about driving through a tunnel and meeting across a fire. The absence of education in evacuation result in the unfamiliarity of tunnel fires and the rational behavior in evacuation, which may bring about unpredictable consequences in tunnel fires. The engineers and researchers will devote themselves to perfecting the driving tests content by adding necessary evacuation education in the future. It is meaningful and essential to enhance evacuation education along with the evacuation research development in China step by step.

8. Conclusions

Tunnels are massively constructed to solve traffic problems in China, and, tunnel fires, one of the most common hazards in tunnels, threaten occupants' life largely. Aiming to this issue, the research on evacuation in tunnel fires is compulsory and significant. The review paper focuses on the evacuation in tunnel fires in China and introduces the development of evacuation strategies and research in tunnel fires in these thirty years. Some main work and achievements include:

1) The paper outlined the common issues of evacuation in tunnel fires worldwide and put forward specific issues in China such as high traffic flow, massive extra-long mountainous tunnels, driving illegally and applications of UTLTs.
2) The paper summarized evacuation strategies in China and other countries from evacuation design of structures and evacuation facilities respectively. Compared to countries/regions namely the United States or the EU, China owns more complex tunnel forms in mountainous area, thus more

challenge in structure design for evacuation. In addition, advanced evacuation systems have been applied in Chinese tunnels while detailed regulations should be supplemented in the codes soon.

3) The paper provided a summary of evacuation research in tunnel fires worldwide and in China. In specific, Chinese research organizations and representative researchers, research topics, and representative research at USTC and Tongji were presented emphatically.
4) The paper reviewed three representative evacuation cases of tunnel fire accidents and two full-scale field evacuation experiments in tunnel fires in China. For fire accidents, we explored great challenges in fire evacuation and rescue process of three fire incidents, and discussed their different evacuation consequences. The evacuation accidents exposed urgent research, and two following field evacuation experiments in tunnel fires conducted by the authors these years were introduced in tunnels with extra-long evacuation paths and in tunnels with natural ventilation.
5) The paper then analyzed the challenges of tunnel evacuation research in China, including its urgent demand due to heavy constructions, short research history and insufficient evacuation education. The authors then proposed corresponding perspectives by introducing emerging technologies in a diagram such as intelligent tunnel monitoring systems, VR/AR immersed evacuation experiments, multiple physiological measurements, and AI training for evacuation prediction

To sum up, the paper introduced the evacuation strategies and research of tunnel fires worldwide and pointed out the differences in China in various aspects. In spite of high requirement and large pressure in tunnel fire evacuation, researchers in China still have done great outcomes and made unique contributions. This review paper is expected to attract more researchers to know about the development of evacuation in tunnel fires in China and call on more researchers' attention to this field in the near future.

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