Application of the tunnel fire scenario dynamic reconstruction based on Intelligent Disaster Prevention Platform in Shanghai

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Abstract. Effective evacuation and fire-fighting response require an accurate, prompt and dynamic reconstruction and visualization of tunnel fire scenarios. This paper aims to introduce the application of the Intelligent Disaster Prevention Platform integrating tunnel fire knowledge with the machine learning approach in Shanghai tunnels. The platform can provide key fire parameters consisting of fire location, real-time heat release rate, temperature distribution and smoke movement, and reconstruct the tunnel fire scenario. The platform uses machine learning algorithms and the tunnel fire knowledge base to conduct in-depth mining and analysis of multi-source heterogeneous monitoring data of tunnel disaster prevention equipment, including four modules: environmental parameters perception, intelligent fire warning, fire scenarios reconstruction and personnel dynamic evacuation, so as to provide scientific decision support for intelligent fire firefighting. Meanwhile, the platform has been demonstrated and applied in many urban underground roads in Shanghai, such as Hongmei South Road Tunnel, Yan'an East Road Tunnel and Dalian Road Tunnel, which significantly reduces the false alarm rate of tunnel fires and provides early warning in fire accidents. The relevant experience can provide guidance for underground infrastructure.

1. Introduction
The urban underground road is developing towards the trend of long and large, multiple entry and exit, and composite function, which puts forward higher requirements for the construction and operation safety of urban tunnels. For road tunnels, because of its confined space and insufficient exits, fires usually result in fast temperature rise, high peak temperature and severe accumulation of hot toxic smoke within the tunnels. High temperatures seriously damage tunnel lining structures and operation equipments installed within the tunnels such as video monitor, signal board and lighting. Hot smoke, which is the most fatal factor on emergency evacuation and rescue in tunnel fires[1] not only reduce visibility, block safe evacuation and fire-fighting, but also cause passengers and firefighters death[2]. There have been numerous serious tunnel fires worldwide, revealing massive casualties as well as severe property damages. Since 2020, there have been several tunnel fire accidents in Shanghai. For example, the vehicle fire accident occurred in Shanghai Hongmei South Road Tunnel on November 17, 2020. The vehicle burned for 30 minutes and was extinguished by firefighters. On March 25, 2021, a car fire accident occurred in Shanghai Yan'an East Road Tunnel. The vehicle burned for 25 minutes and was extinguished by firefighters. On April 13, 2021, a car fire accident occurred in the Shanghai Waihuan Tunnel. The vehicle burned for 25 minutes and was extinguished
by firefighters. These three tunnel fire accidents caused no casualties due to the accurate early warning of the tunnel fire alarm system, the timely handling of the management personnel, and the linkage response of the tunnel disaster prevention facilities and equipment. Relevant fire emergency treatment methods and tunnel fire rescue experience and lessons can provide guidance for other tunnels.

Figure 1. Tunnel fire accidents in Shanghai (a: Hongmei South Road Tunnel fire accident; b: Yan'an East Road Tunnel fire accident; c: Waihuan Road Tunnel fire accident).

The prompt and effective evacuation and fire rescue depends on quick and accurate fire detection and alarm, effective emergency ventilation and smoke control as well as appropriate fire-fighting strategies and emergency management, which all are clearly related to real-time situation within the accident tunnel. Several reliable methods and advanced equipments have been developed to detect tunnel fires, and lots of notable research works were also conducted on tunnel fire detection and alarm[3]. Furthermore, temperature characteristics, smoke movement and control as well as fire suppression, etc in a tunnel fire have been fruitfully carried out through theoretical analysis, numerical simulation, laboratory experiment and field tests[4][5][6]. It seems that we have had a deep understanding on tunnel fire characteristics and how to control fire.

However, for actual tunnel fires, because of complicated field situation it may perform considerable different behaviour comparing to presupposed fire scenarios (e.g., fire location and size, temperature development and smoke movement). Further, due to high temperature, dense smoke and loss of lighting, it is difficult to access into accident tunnel and to get sufficient information on fire development within the tunnel. In most cases, because of lack of information on fire situation within tunnel, the accident tunnel looks like a ‘grey box’ or even a ‘black box’ for evacuation, emergency ventilation, fire-fighting and field emergency management. Insufficient information on fire impede effective and prompt fire-fighting, even may lead to wrong decision on emergency fire-fighting and rescue. For example, in the Mont Blanc Tunnel fire, inappropriate ventilation strategy conducted by tunnel operators results in severer fire processing because supplying fresh air to fire location instead of extracting smoke.

Therefore, sufficient real-time information is urgently required to facilitate effective rescue and fire-fighting in site and to properly adjust ventilation strategies. For example, the appropriate fire suppression system (e.g., sprinklers or water mist systems) should be activated according to correct fire location; emergency ventilation should be checked and adjusted to effectively control smoke movement according to fire size and real smoke movement direction, velocity and diffusion range within the tunnel; emergency management strategies should be dynamic changed according to real-time actual fire development within tunnel to correctly and promptly instruct opening/closing proper cross-passages between tunnels, to instruct passengers to safe evacuation through broadcasting, to show right signal, and to instruct firefighter to access into tunnel and suppress fire through appropriate access points.

Recently, new technologies such as the Internet of Things and artificial intelligence have empowered traditional infrastructure, providing more intelligent means to improve the safety and efficiency of the
operation of long underground roads[7][8][9]. The real-time tunnel fire VR simulator system was
developed based on a highly reliable CFD simulation to provide wide-ranging second-hand experience
to the general public or inexperienced firefighters or commanders, enabling them to make prompt
decisions and safe and organized responses in actual fire situations[10]. Li et al. examined a method
for simulating underground fire disasters based on Cellular Automata. The feasibility of the Cellular
Automata model for underground mine fire disasters, and its visualization effects were tested and
verified through a case study[11]. But the existing studies were all based on numerical simulation
scenarios to verify the effectiveness of the proposed methods. The fixed ventilation velocity and other
parameters assumed in the numerical simulation scenarios do not match the response of the ventilation
system and the firefighting equipment in the real tunnel fire scenario. This paper aims to introduce the
basic framework and the application of the Intelligent Disaster Prevention Platform in Shanghai
tunnels. The main innovation of the platform is to fully combine knowledge-driven methods and data-
driven methods to achieve complementary advantages. At the same time, it has sufficient
generalization ability and computational efficiency.

2. Framework of the Intelligent Disaster Prevention Platform.
As shown in Fig. 1, the basic idea of the proposed method is to construct and to visualize real-time
temperature field and smoke movement within an accident tunnel based on available limited
temperature and ventilation information. The new method consists of four modules: environmental
parameters perception, intelligent fire warning, fire scenarios reconstruction and personnel dynamic
evacuation.

Figure 2. Framework of the Intelligent Disaster Prevention Platform.
In an accident tunnel, the available temperature information can be gathered from the disaster
prevention equipment of tunnel (Fibre Bragg Grating) installed under tunnel ceiling. These gathered
limited discrete temperature and ventilation information are input to developed model and algorithm to
further analyse. Based on the input temperature and ventilation information, and FBG configuration
and tunnel geometry, fire location, real-time continuous longitudinal and vertical temperature
distributions are established. Further, smoke movement is determined as well. Several key parameters
such as maximum temperature, smoke flow range, direction and velocity, presence and length of back-layering, and fire development are determined. Take the key parameter fire source position as an example. The fire location is determined by temperature sensors under tunnel ceiling, depending on the position of maximum temperature of the sensors. When there is no longitudinal ventilation velocity within tunnel, fire location is assumed that it is coincide with the position of maximum temperature of the sensors. Furthermore, the errors of fire location depend on the spatial interval of temperature sensors[12][13]. Finally, all of aforementioned fire information such as temperature distribution and smoke movement are dynamically visualized and present in computer screen.

The proposed method is contributed to transform accident tunnel from a ‘grey box’ or ‘black box’ to a ‘white box’. The gathered information can be used to direct effective emergency ventilation and smoke control, prompt and proper evacuation and fire rescue, and appropriate fire-fighting strategy. The visualization of fire within tunnel will facilitate manager to know well the real-time fire situation in tunnel and to conduct correct decision-making and appropriate emergency management.

3. The application of the Platform in Shanghai Hongmei South Road Tunnel

3.1. Basic information of system application

The Shanghai Hongmei South Road Tunnel is a double-hole long road tunnel with a total length of 5260 meters. The Intelligent Disaster Prevention Platform of Hongmei South Road Tunnel can respond to fires sensitively, accurately identify fires, and accurately determine the location of the fire. Under the condition that the false alarm rate is less than 1 time/year 2km tunnel, the 0.5MW tunnel fire can be alarmed within 30 seconds. Normally, the system monitors the temperature of the tunnel with full coverage at a frequency of once per second, with a temperature measurement accuracy of +/−0.5 °C.

Figure 3. Fire test of intelligent disaster prevention platform of the Hongmei South Road Tunnel. (a: Tunnel longitudinal temperature distribution diagram; b: tunnel full-scale fire tests; c: Tunnel fire source location and smoke field visualization; d: visualization of tunnel fire temperature data)

Without the addition of tunnel hardware equipment, the platform is based on fire theory, data mining, and digitization. In the fire accidents, it provides tunnel managers and fire rescue departments with a large amount of key information and real-time status in the tunnel (such as the fire source location, fire scale, temperature field distribution, smoke movement, etc.), which solves the problem of the inability
to know the real-time status of the tunnel (the camera in the tunnel is blocked by smoke) and the inability to reliably guide fire-fighting and rescue evacuation.

3.2. The Fire Accident in Shanghai Hongmei South Road Tunnel

At 5:41 on November 17, 2020, Hongmei South Road Tunnel Central Control found that a car spontaneous combustion incident occurred at the camera No. 49 of the East Line Tunnel through the monitoring picture. At 5:45, the Hongmei South Road Tunnel Fire Alarm System issued a fire warning. However, the Intelligent Disaster Prevention Platform issued a fire warning through the fire differential temperature early warning algorithm at 5:22. The tunnel central control immediately notified the inspectors to rush to the scene and immediately dialed 119 and 110 to report to the police. The on-site firefighting linkage system water spray, foam, fan, and broadcasting all started normally. This tunnel fire accidents caused no casualties due to the accurate early warning of the tunnel fire alarm system, the timely handling of the management personnel, and the linkage response of the tunnel disaster prevention facilities and equipment.

![Figure 4](image.png)

**Figure 4.** The comparison of alarm time between fire alarm system and Intelligent Disaster Prevention Platform in the Hongmei South Road Tunnel.
(a: Tunnel existing fire alarm system; b: Intelligent Disaster Prevention Platform)

Analysing the entire fire accident emergency response process, the following experience is worth learning:
1. The platform is only used for research and testing of scientific research projects, and is independent of the tunnel fire alarm system and equipment of Hongmei South Road Tunnel. Various alarm signals are not transmitted to the fire alarm controller, and it does not participate in the fire-fighting rescue and escape linkage after a fire occurs.
2. Because the tunnel central control system includes the fire alarm system, video monitoring system and fire-fighting system, the internal local area network is basically adopted. The time between the various subsystems is not uniform, which causes certain difficulties for the assessment of emergency response after a fire and the analysis of time nodes.
3. The Hongmei South Road tunnel fire accident caused a blockage of vehicles upstream of the fire source. The exhaust of longitudinal ventilated tunnels causes fire smoke to be discharged from the exit, which puts the fire trucks and firefighters who want to enter the tunnel in the reverse direction and close to the fire source in danger. Fire rescue vehicles could not reach the scene, and firefighters could only run into the tunnel.
4. The driver of the burning vehicle opened the hood to check the smoke in the early stage of the car fire. This action accelerated the burning of the vehicle and expanded the scale of the fire.
After this fire accident, the intelligent disaster prevention system platform has been continuously updated and expanded with new functions. Through the establishment of domestic and foreign tunnel fire databases, the basic information of tunnel fires is sorted according to a unified data template, and
the proportion of causes of tunnel fire accidents is analyzed to provide guidance for tunnel disaster prevention. At the same time, the dynamic evacuation plan for personnel was updated. After the fire broke out, the three-dimensional threat situation field of the tunnel and the optimal path for evacuation of personnel were updated and calculated according to the real-time information of the tunnel fire field.

4. Conclusions
The platform provides a dynamic fire evacuation and rescue plan based on the development situation and real-time status of the fire in the tunnel. Compared with the existing fixed and textual fire evacuation plan, it improves the efficiency of fire-fighting and evacuation and rescue work at the fire scene. In the future, the system platform will continue to accumulate data on the service period of the tunnel, update the corresponding fire algorithm model, and help the safe and efficient operation of the Shanghai tunnel.

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