OPTIMIZING SAFETY IN SHORT HIGH-SLOPE ROAD TUNNELS: SMOKE PROPAGATION AND VENTILATION SYSTEM RESPONSE

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ABSTRACT

This study focuses on fire protection in short, steep road tunnels, with an emphasis on ensuring passenger safety during evacuation. It introduces a ventilation system designed to address the challenges posed by rapid smoke flow. The system includes a reversible ventilation system in the traffic tunnel tube, accommodating bi-directional traffic, and an overpressure ventilation system in the pedestrian evacuation tunnel.

An early smoke detection feature is integral, rapidly activating the tunnel and the overpressure-protected evacuation gallery ventilation systems, ensuring early warning and passenger safety. The study employs advanced numerical simulations using the OpenFOAM software [1], focusing on a fire scenario with a heat-release rate of 120 MW within the initial 10 minutes, a critical evacuation period. Simulations consider traffic congestion and vehicle shapes.

The findings provide insights into 3D time-dependent smoke propagation within the tunnel, accounting for its unique structure, vehicular obstructions, and buoyant effects from thermal energy release. Results also offer information on the stack effect progression and smoke propagation velocities, crucial for the effective operation of the ventilation system, ultimately enhancing passenger safety during evacuation.

Keywords: road tunnel, steep tunnel, tunnel ventilation, fire, smoke propagation.

1. INTRODUCTION

The focus of this paper is the ventilation system of the Dugi Rat Tunnel, situated on a state road on the Croatian coastline. This tunnel complex consists of two tunnel tubes, each serving distinct functions. The traffic tube spans 852.46 m and facilitates two-way traffic with a single lane for each direction. The evacuation tunnel, spanning 540.2 m, is primarily designated for passenger safety during unforeseen incidents. These two tunnel tubes are interconnected through three cross passages, specifically designed to accommodate pedestrians.

In the process of designing the ventilation system for the Dugi Rat Tunnel, the project team adhered to rigorous safety standards and guidelines. A notable reference point in this endeavor was the application of Swiss guidelines, specifically ASTRA 13002 [2], which addresses ventilation of safety corridors (galleries) in road tunnels. The significance of these guidelines lies in their incorporation of overpressure ventilation for the evacuation tunnel, a critical component for passenger safety. Additionally, ASTRA 13004 [3], focusing on fire detection in road tunnels, played a pivotal role in shaping the design and implementation of the tunnel's safety measures.

This paper deals with the specific details of the ventilation system's design, with a particular emphasis on how to ensure user safety and efficiency of the tunnel ventilation system. Furthermore, the paper discusses how the designed tunnel ventilation system and the number of fans for a fire scenario were rigorously validated and optimized through comprehensive CFD (Computational Fluid Dynamics) modeling and simulations.

2. MANAGEMENT OF THE VENTILATION SYSTEM OPERATION

2.1. Regular work regime

During the regular work regime, the planned longitudinal ventilation system operates in automatic mode and consists of 8 reversible axial jet fans, organized into 4 pairs (batteries). The intensity of ventilation is determined by the level of pollution, with carbon monoxide (CO) as the predominant gas pollutant, and the reduction of visibility due to the emission of smoke and soot. The ventilation system must adhere to the stricter of the two mentioned criteria. The measurement of CO concentration and visibility is conducted at 2 measuring points using combined visibility and CO sensors.

For reliable velocity measurement and as a precaution against potential damage, 3 combined velocity and flow direction sensors are installed. Airflow speed in the tunnel is kept within a specified range, typically under 10 m/s, regulated by the ventilation SCADA system.

Due to the increased risk of rapid smoke propagation in the tunnel, caused by the high longitudinal slope of 4%, 8 sensors for early smoke detection will be installed. These sensors play a crucial role in controlling the ventilation system during fire incidents (more details in Section 2.2). The measurement data generated by these sensors is remotely transmitted to the control and monitoring center. Based on the measurement data, individual fans, batteries, or groups of batteries are automatically activated, utilizing specialized software that manages the operation of the ventilation system.

Operating criteria for ventilation system were selected according to the Austrian guidelines RVS 09.02.31 [4].

2.2. Fire regime

During the fire regime, two points of interest will be discussed: the traffic tunnel tube and parallel evacuation tunnel tube for pedestrians.

When a fire occurs in the traffic tunnel tube and the alarm is confirmed, the overpressure ventilation system of the evacuation tube is activated, and the ventilation system operates depending on which of the 3 action zones the fire occurred in (see Fig. 1).

If a fire occurs in the 1st operating zone (from 0 to 190 m), the ventilation system automatically activates the farthest jet fans - specifically, fan batteries no. 4 and 3 - directing air flow towards the lower portal. The precondition for this is that their neighboring smoke sensors, SS-7, and SS-5, are not triggered by smoke. This strategy is known as the "Fire-eject" [5] from the tunnel, designed to prevent smoke from spreading by buoyancy towards the higher portal, which would fill a large part of the tunnel and in this way achieve a "chimney effect" with a high buoyancy smoke flow. This flow can pose danger or even entirely prevent the evacuation of passengers. In the smoke-free section of the tunnel tube, the airflow speed should be greater than or equal to the critical flow velocity, v_C. For the given conditions of an undeveloped fire and the tunnel's geometry, the critical flow velocity, v_C, is 2.9 m/s.

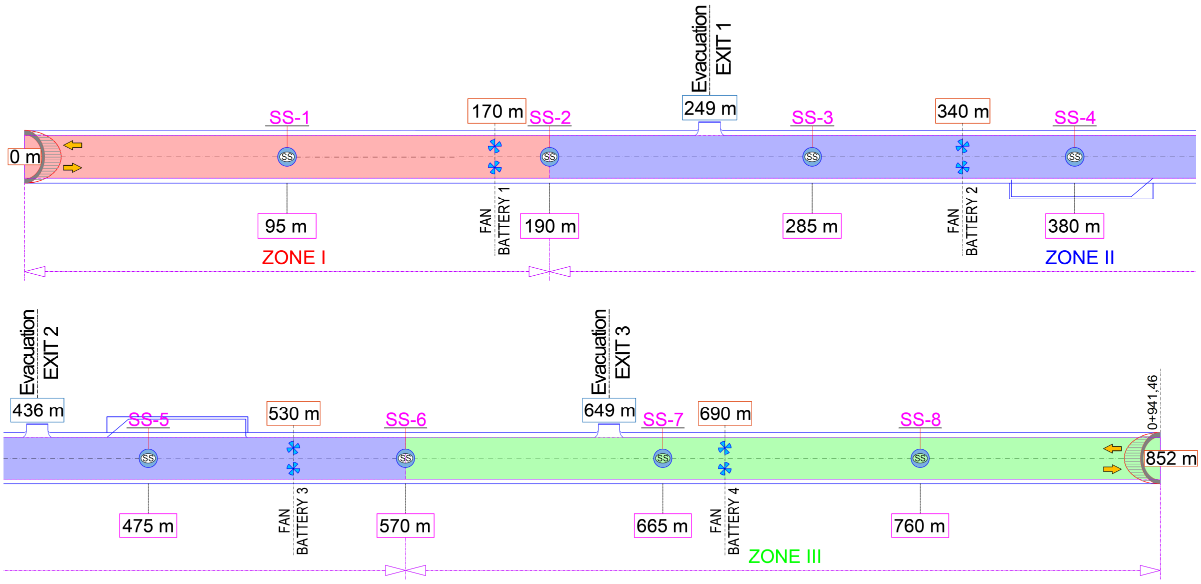

Figure 1: Diagram of the action zones of the ventilation system and sensors for early fire detection
Source: CTP Projekt d.o.o.

If a fire occurs in the 2nd operating zone (from 190 to 570 m), the ventilation system is automatically switched off and does not participate in the smoke control process. Insights from fires in similar tunnels [6], along with the results of the CFD analysis of fire and smoke development made for Dugi Rat Tunnel, revealed high velocities of smoke propagation towards the higher portal of the tunnel. Specifically, the buoyant smoke propagation velocities, as per the results of CFD modeling, reached up to 4.7 m/s for fires with a heat release rate (HRR) of 20 to 120 MW, as detailed in Section 3. Given this data, the designer believes that involving ventilation during rapid smoke propagation could only contribute to additional smoke turbulence and expedite the filling of the tunnel tube with smoke across its entire cross-section. Moreover, the ventilation management system is too slow to be able to efficiently handle ventilation in fire conditions in a short tunnel with a relatively large longitudinal slope, such as the Dugi Rat Tunnel.

If a fire occurs in the 3rd operating zone (from 570 to 852 m), the ventilation system automatically activates the fans of battery no. 1, and then battery no. 2, with the flow directed towards the higher portal, provided that their neighboring smoke sensors, SS-2 and SS-4, are not triggered by smoke. This sequential activation aims to align the operation of the ventilation system with the natural direction of smoke flow towards the higher portal, with the goal of containing smoke within the shorter part of the tunnel. The airflow velocity, maintained by the ventilation system, should range from 1.5 to 2.0 m/s towards the upper portal. This setup is designed to counteract the potential influence of the wind, which might otherwise direct the airflow towards the lower portal, potentially causing smoke to accumulate in the longer part of the tunnel. If the air flow velocity in the initial phase of the fire exceeds 2 m/s towards the upper portal, the ventilation system will not be activated.

The implementation of overpressure ventilation in the evacuation tube is a crucial measure for active fire protection in the Dugi Rat Tunnel. This measure is designed to ensure the safety of passengers throughout the entire evacuation process to a secure open space. The overpressure ventilation system's primary objective is to prevent smoke infiltration from the fire-endangered tunnel tube into the evacuation tunnel. By doing so, it maintains a safe passage for the evacuation of passengers, even in conditions of rapidly expanding smoke buoyancy toward the higher portal of the traffic tunnel tube, influenced by the fire.

Figure 2 illustrates a cross-section of an emergency exit featuring two partitions. The first partition is fireproof, situated between the traffic tunnel and the crosswalk (exit) for pedestrians, which maintains a 25 Pa overpressure. The second partition is positioned between the crosswalk and the evacuation tube, which maintains a higher overpressure of 50 Pa. Each partition within the three crosswalk exits is equipped with two pressure relief dampers. Additionally, the fireproof partition is fitted with smoke dampers, designed to open exclusively during the activation of the overpressure system.

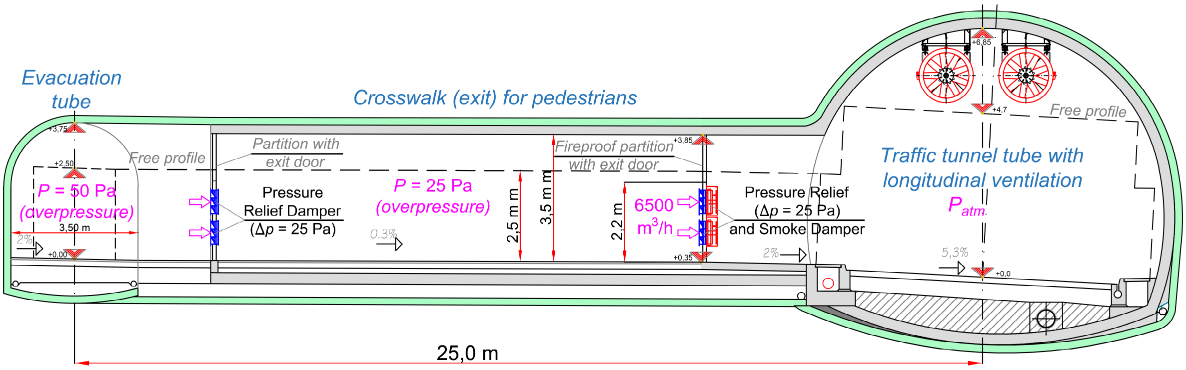

Figure 2: Cross-section of the traffic tunnel tube and the evacuation tunnel for pedestrians
Source: CTP Projekt d.o.o.

A mechanical ventilation system, designed to provide a high-capacity and reliable supply of fresh air in fire conditions, is employed to establish an overpressure condition along the entire length of the evacuation tunnel. The primary components of this system are two ventilation units situated in the engine room above the air-lock room (smokeproof enclosure) at the exit of the evacuation tube. One ventilation unit functions as the primary unit, while the other serves as a stand-by unit, activated only in the event of a failure or error in the primary ventilation unit. The role of the primary ventilation unit can be programmatically altered as part of the ventilation management system.

3. NUMERICAL SIMULATION OF SMOKE PROPAGATION AND VENTILATION SYSTEM RESPONSE

3.1. Numerical model

The numerical simulations were conducted using the OpenFOAM (v2112) open-source simulation toolbox [1], primarily utilized for solving problems in the field of continuum mechanics, particularly in computational fluid dynamics. The simulations utilized a transient model for buoyant, turbulent flows of compressible fluids. The fire scenario within the tunnel was simulated as a variable source of both heat and smoke. The model does not consider the chemical reactions due to combustion; instead, it treats the smoke as a passive scalar represented by carbon dioxide concentration levels. The carbon dioxide is propagated through the computational domain using a standard transport equation that incorporates the effects of both advection and diffusion.

In the context of fire modeling, the study adopts a strategy where a specified fraction of the total heat generated is assumed to escape into the environment via radiation without affecting the gas within the tunnel (approx. 30%). The remaining energy is transferred to the surrounding gas. Figure 3 presents the employed HRR curve, in the initial phase of fire, where the thermal power increases quadratically. The used scenario of 120 MW primarily defines the fire growth coefficient (α) for the HRR calculation. However, within the scope of interest of this study, which is the initial 10 min., the fire does not reach the full fire load of 120 MW.

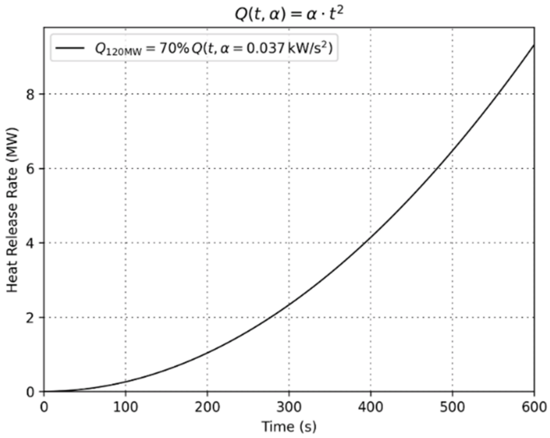

Figure 3: HRR curve - thermal power increase

Figure 4 depicts the simplified geometry of the traffic tunnel, serving as the base for creating the computational mesh. The mesh consists of approx. 2.5 million cells, each with a mean dimension of 0.3 m. The volumetric heat source is positioned 230 m from the tunnel's lower entrance. Table 1 presents the temporal behavior of the heat source, i.e., volume of the fire as a function of time. Additionally, the simulations account for the impact of traffic congestion. To mirror the bidirectional traffic, vehicles are strategically placed at 15-meter intervals in both directions relative to the fire's origin, with 15% of lorries in total vehicle volume.

In the simulation of the Fire-eject strategy, axial fans were modeled as volumetric sources of momentum. This involved assigning specific velocity values to the computational cells within the fan regions, based on specifications provided in the manufacturer's datasheet.

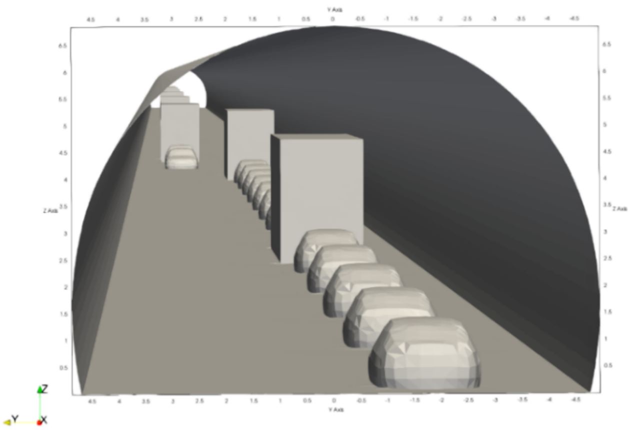

Figure 4: Simplified geometry of the traffic tunnel

Table 1: Behavior of the volumetric heat source

	$0 < t \leq 200$	$200 < t \leq 400$	$400 < t \leq 600$
$V(t)$	12 m^3	36 m^3	60 m^3

3.2. Ventilation-off strategy

This analysis provides insights into smoke propagation and the progression of the stack effect within the tunnel for the previously defined 120 MW fire scenario when the ventilation system does not participate in the smoke control process. Figure 5 illustrates the regions impacted by smoke along the longitudinal section for various time intervals (100, 200, 300, 400, 500, and 600 seconds). Zones with a carbon dioxide concentration exceeding 0.1% are indicated in black. Results at 400 and 500 s suggest that the stack effect is becoming powerful enough to push the already propagated smoke (from the lower section) towards the upper portal.

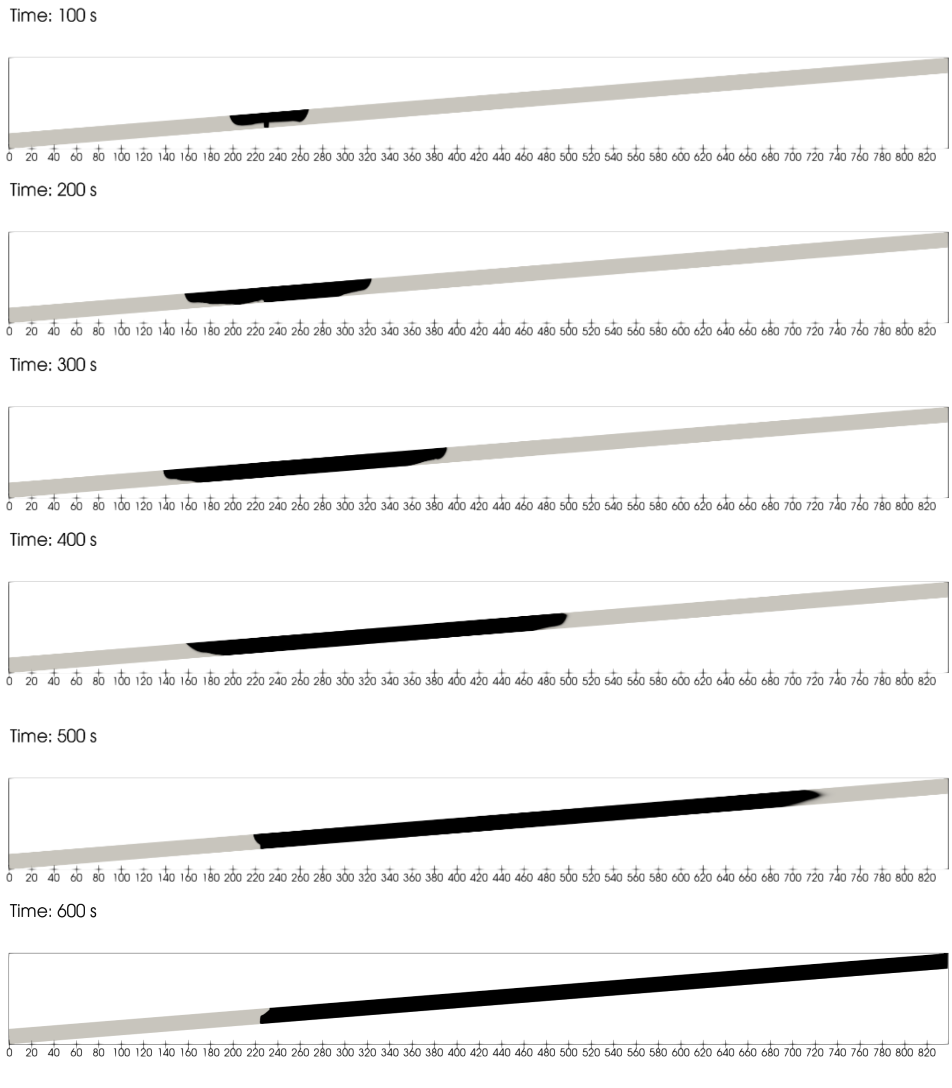

Figure 5: Smoke propagation and progression of the stack effect within the tunnel for a 120 MW fire scenario

3.3. Fire-eject strategy

To compare the smoke behavior between the Fire-eject strategy and the Ventilation-off strategy, we utilize the same fire setup, maintaining consistency in terms of location and Heat Release Rate (HRR) curve. Despite the chosen location being situated outside the 1st zone of action as illustrated in Figure 1, where the Fire-eject strategy would typically be activated, this is a deliberate choice aimed at demonstrating the ventilation system's capability to manage slightly greater distances when ejecting smoke.

However, when smoke reaches the closest sensors, SS-2 and/or SS-3, approximately 140 s, in accordance with the management strategy outlined in Section 2, the control system activates fan batteries 3 and 4. These fans start to push the smoke towards the lower portal. To ensure an adequate safety margin, the simulation incorporates a 20 s delay, and a 10 s ramp-up time for the axial fans.

Figure 6 illustrates the smoke distribution at 160, 200 and 250 s, showcasing the capability of the selected ventilation system to successfully stop the development of the stack effect and push the already accumulated smoke within the tunnel towards the lower portal. Furthermore, Figure 7 presents the sampled longitudinal velocity at 271 m from the lower portal, the location of the combined velocity and air flow direction sensor. The solid red line represents the sampled velocity for the Ventilation-off strategy, and the dashed blue line depicts the velocity for the Fire-eject strategy. Both curves have identical behavior until the activation of axial fans. Shortly after the activation, the flow direction sensor would detect a change in the air-flow direction, as demonstrated by the smoke distribution images.

Figure 6: Smoke distribution in the Fire-eject strategy

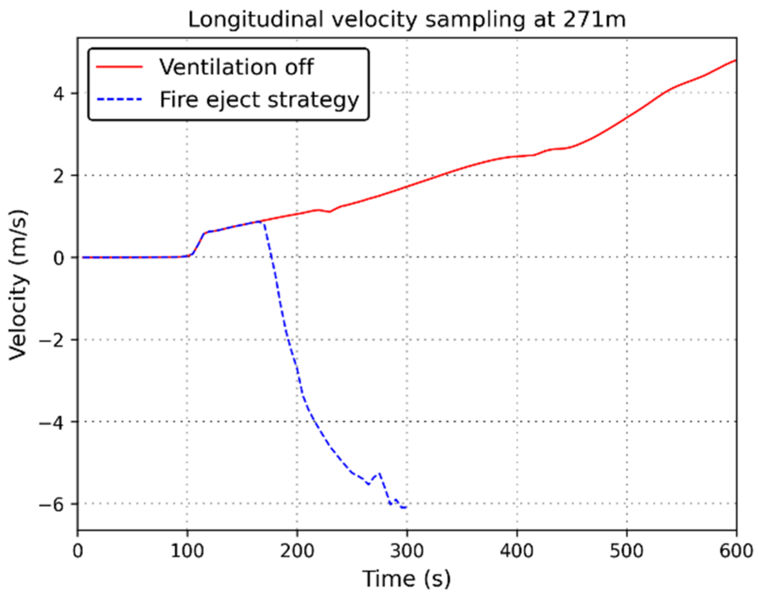

Figure 7: Longitudinal velocity at 271 m from the lower portal

4. SUMMARY AND CONCLUSION

The role of the ventilation system in fire conditions in short steep tunnels is very delicate, primarily due to the rapid propagation of smoke towards the higher portal caused by intense thermal buoyancy. In the Dugi Rat Tunnel, velocities of buoyant smoke flow, determined through Computational Fluid Dynamics (CFD) simulations, can reach up to 4,7 m/s in the observed interval of time (600 s) and corresponding heat release rate. These high velocities of smoke propagation highlight the need for a fast and efficient evacuation of passengers. Active operation of the ventilation system becomes essential when it can justifiably contribute to a better and safer evacuation.

The results presented in this paper demonstrate that, in the initial fire phase with a reliable system for fast smoke detection, the ventilation system can successfully expel smoke from the tunnel using a "Fire-eject strategy." This strategy proves particularly effective when the fire occurs in the lower third of the tunnel tube, representing the most dangerous fire scenario. In other fire scenarios, the potential for the ventilation system to positively contribute to the evacuation process is minimal (e.g., the upper third of the tunnel) or even counterproductive (e.g., the central part of the tunnel). Unrealistic expectations should not be placed on the ventilation system due to its inherent aerodynamic inertia and the limited ventilation resource in short tunnels. Therefore, a reliable passenger protection system should be provided throughout the evacuation process. The overpressure ventilation system of the evacuation tunnel, described in this paper, effectively combines passive and active protection measures for tunnel users.

To fully confirm the described ventilation strategy in short steep tunnels, the effects of surrounding factors, notably the influence of wind on the tunnel portals, must be considered. This requires further numerical simulations that incorporate local climatological parameters and terrain characteristics. Complete validation depends on operational experiences with this relatively complex tunnel tube ventilation system and the overpressure ventilation of the evacuation corridor for passengers, including rapid smoke detection.

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