

## Article

# Numerical Assessment of Smoke Spread and Evacuation Safety for a Battery Electric Vehicle Fire in a Single-Lane Road Tunnel

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## Abstract

This study investigates the smoke spread characteristics and occupant evacuation safety of a 15 MW battery electric vehicle (BEV) fire in a 1.5 km small-bore single-lane road tunnel. Owing to its minimized cross-section (a single 3.0 m lane within a 3.7 m inner diameter), no fire protection or evacuation facilities can be accommodated, and its fire safety therefore requires performance-based verification. Fire Dynamics Simulator (FDS) was used to simulate the fire under different longitudinal ventilation velocities, and the smoke temperature, visibility and CO concentration were examined. Based on these indices, the available safe egress time (ASET) was determined, while the required safe egress time (RSET) was obtained from Pathfinder evacuation simulations for a worst-case congestion scenario involving 420 occupants, so as to evaluate whether the evacuation distance of the 1.5 km tunnel is adequate. The results show that under natural ventilation, the upstream section 645–750 m violates the  $RSET < ASET$  criterion; under 1 m/s longitudinal ventilation, the failure zone shrinks to 740–750 m; at 2 m/s and 3 m/s, the upstream region remains tenable throughout the 900 s simulation and all occupants can evacuate safely. A longitudinal ventilation velocity of at least 2 m/s is therefore required to ensure safe upstream evacuation in this tunnel. The conclusions are drawn for the present worst-case configuration and are intended for the pre-construction performance-based verification of similar single-lane tunnels without evacuation facilities.

**Keywords:** tunnel fire; electric vehicle; smoke spread; evacuation simulation; numerical simulation



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## 1. Introduction

Road tunnels are an essential component of modern transportation networks. Owing to their long, narrow, and semi-enclosed configuration, fire development inside a tunnel differs considerably from that of open-air fires [1,2]. In recent years, the rapid worldwide adoption of battery electric vehicles (BEVs) has introduced new and complex challenges for tunnel fire safety [3]. Full-scale fire tests have demonstrated that the peak heat release rate of a BEV fire can exceed 10–15 MW, with extremely rapid fire growth [4–6], while the combustion of lithium-ion batteries releases toxic species that pose a severe respiratory hazard to occupants remaining at the scene [7–9]. These characteristics suggest that design fire models derived from conventional vehicle fire data may underestimate the threat to occupant tenability when a BEV fire occurs in a tunnel environment. Consequently, a thorough understanding of the smoke spread characteristics of electric-vehicle-induced

fires is essential for the performance-based design of tunnel ventilation and emergency response systems [10].

Over the past decade, the global BEV fleet has grown at an unprecedented rate. BEVs are therefore no longer a marginal component of tunnel traffic, but an increasingly significant one. BEV fire accidents exhibit distinctive characteristics: fires originate from thermal runaway of the lithium-ion battery, which propagates rapidly between cells and leads to extremely fast fire growth; full-scale fire tests have measured peak heat release rates exceeding 10–15 MW [4–6]; the combustion products contain highly toxic species such as hydrogen fluoride (HF), in addition to elevated soot and CO yields [7–9]; and the battery may re-ignite hours or even days after the initial extinction.

Compared with conventional internal-combustion-engine vehicle fires, BEV fires differ in four main respects. First, the fire growth is much faster owing to thermal runaway propagation between battery cells. Second, the peak heat release rate of a fully involved BEV can reach or even exceed that of a conventional fuel vehicle within a considerably shorter time [4–6]. Third, the combustion products differ: in addition to CO and soot, BEV fires release fluoride-containing toxic gases such as HF, whose total emission from an electric car fire has been reported to be about twice that of an identical conventional car [5,8]. Fourth, BEV fires are more difficult to extinguish and may re-ignite. Recent full-scale fire tests of BEVs in road tunnels and under open conditions [4,6,9], as well as numerical studies of electric vehicle fires in tunnels [11,12], confirm these differences and indicate that design fire models derived from conventional vehicle fire data may underestimate the threat to occupant tenability.

Single-lane road tunnels with a minimized cross-section represent a distinct challenge in this respect. A typical single-lane tunnel, such as the LVCC Tunnel in Las Vegas, is 2.7 km long and allows only one vehicle to pass at a time. In such tunnels, the bored cross-section accommodates only a single vehicle lane, with space for only one passenger car (Figure 1a), leaving no space within the cross-section for the fire protection and evacuation facilities required by conventional road tunnel codes, such as emergency walkways, lay-bys and cross-passages. Chinese codes, for instance, require a continuous emergency parking strip of at least 2.5 m for single-lane urban underground road ramps, corresponding to a minimum pavement width of about 6.5 m—more than twice the carriageway width available in such tunnels. Consequently, neither prescriptive code provisions nor established design experience can be applied directly; whether such tunnels can satisfy evacuation safety requirements under fire conditions must be verified through performance-based numerical analysis under the most unfavorable credible fire and congestion scenarios.

Longitudinal ventilation is one of the most widely adopted smoke control strategies in road tunnels. By establishing a unidirectional airflow, it suppresses smoke back-layering and confines the hazardous zone to the region downstream of the fire, thereby maintaining a tenable environment upstream for occupant evacuation [13,14]. The effectiveness of this strategy hinges critically on the ventilation velocity: a velocity that is too low fails to prevent smoke from spreading upstream, whereas an excessively high velocity can intensify fire development and turbulence, transporting heat and toxic smoke to more distant downstream regions [15,16]. For conventional vehicle fires, the critical velocity required to suppress back-layering has been extensively investigated [17,18]. In contrast, quantitative studies on the minimum ventilation velocity that guarantees safe upstream evacuation under BEV fire conditions remain scarce [11,12].

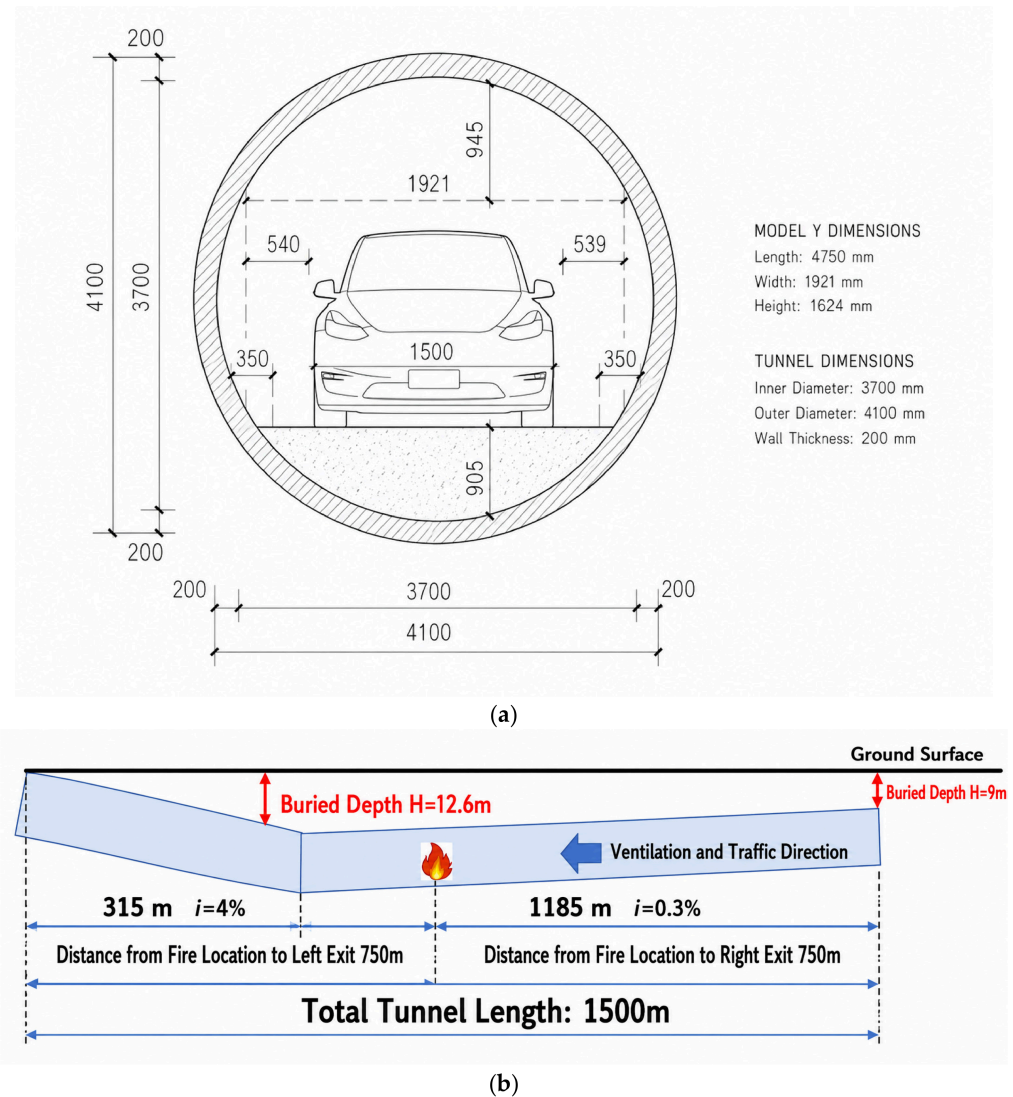


**Figure 1.** Case-study tunnel: (a) cross-section (dimensions in mm); (b) longitudinal V-shaped profile.

Evacuation safety assessment for tunnel fires is generally conducted within the available safe egress time (ASET) and required safe egress time (RSET) framework [19]. ASET is defined as the time from ignition until the environmental conditions at a given location become untenable for occupants, whereas RSET is the time required for occupants to detect the fire, respond to the alarm, and travel to a place of safety [20]. Safe evacuation is achieved only when ASET exceeds RSET at every point along the egress path. In long tunnels, smoke spread is a time-varying and spatially non-uniform process; a position-resolved evaluation is therefore necessary, in which ASET and RSET are computed as functions of longitudinal position along the tunnel to identify local failure zones that would readily be overlooked by a spatially averaged approach [21]. For the self-evacuation phase, the World Road Association (PIARC) specifies allowable values for air temperature, visibility, and carbon monoxide concentration in road tunnels during fire events [22]. In the present study, these allowable values are compared with the computed results at a height of 2 m above the lane surface to evaluate the evacuation and rescue environment inside the tunnel; evaluation at this occupant characteristic height is consistent with established engineering practice [23].

The primary question addressed here is whether a single-lane tunnel without fire protection and evacuation facilities (e.g., cross-passages) can still satisfy evacuation safety requirements under fire conditions. To this end, the present study conducts a coupled numerical simulation of smoke spread and occupant evacuation for a 15 MW BEV fire

at the mid-length of a 1.5 km single-lane circular tunnel. The tunnel features a V-shaped longitudinal profile with maximum and minimum gradients of 4% and 0.3%, respectively. Fire Dynamics Simulator (FDS) is employed to model smoke temperature, visibility, and CO concentration at a height of 2 m under four longitudinal ventilation scenarios: natural ventilation, and mechanical longitudinal ventilation at 1 m/s, 2 m/s, and 3 m/s. The resulting position-resolved ASET profiles are compared against RSET values obtained from Pathfinder evacuation simulations for a worst-case full-load congestion scenario involving 420 occupants in 105 queued vehicles. As the case-study tunnel is still at the planning stage, the present study constitutes a pre-construction, performance-based verification: its purpose is to examine whether, in the extreme case that no fire protection or evacuation facilities can be accommodated, longitudinal ventilation using only the two portals can still satisfy the occupant evacuation requirements under the most unfavorable credible fire and congestion scenarios. The specific objectives are to:

- (1) Quantify the smoke spread characteristics and tenability limits under each ventilation condition.
- (2) Identify the longitudinal zones where evacuation safety criteria are violated.
- (3) Determine the minimum longitudinal ventilation velocity required to ensure safe upstream evacuation in this tunnel configuration.

The remainder of this paper is organized as follows: Section 2 describes the tunnel geometry, numerical modelling approach, fire scenario design, and the ASET and RSET calculation methodology. Section 3 presents and discusses the simulation results for each ventilation scenario. Section 4 summarizes the main conclusions and recommendations for future work.

## 2. Materials and Methods

### 2.1. Tunnel Description

The case-study tunnel is a single-lane road tunnel with a total length of 1.5 km. The bored cross-section is circular, with an outer diameter of 4.1 m and an inner diameter of 3.7 m, and the carriageway width is 3.0 m (Figure 1a). The tunnel adopts a V-shaped longitudinal profile: the 1185–1500 m section has the maximum gradient of 4%, while the remaining 1185 m section has a gradient of 0.3% (Figure 1b). The fire source is located at the tunnel midpoint (+750 m).

Only the carriageway space is considered in the tunnel cross-section, and no evacuation facilities are provided within the 1.5 km length. International codes recommend pedestrian cross-passage spacing of 100–300 m and vehicular cross-passage spacing of 900 m; in non-urban areas, pedestrian cross-passage spacing may be extended to approximately 400 m. Chinese codes specify pedestrian cross-passage spacing of 250–300 m (maximum 500 m) and vehicular cross-passage spacing of 750–1500 m. Given these constraints, a performance-based fire and evacuation analysis is required for this particular tunnel project.

### 2.2. Numerical Model and Mesh

Fire simulations were performed with the Fire Dynamics Simulator (FDS, version 6.7.0, National Institute of Standards and Technology, USA). The tunnel was modelled as a 1500 m long duct with a cross-section of 3.7 m × 2.8 m (width × height), preserving the original cross-sectional area and the V-shaped gradients of 4% and 0.3%. Both portals were set as open boundaries at ambient conditions (20 °C, 101.325 kPa). The circular bored cross-section (inner diameter 3.7 m) was simplified to a rectangular section of 3.7 m × 2.8 m, preserving the cross-sectional area for smoke flow (10.75 m<sup>2</sup> versus 10.36 m<sup>2</sup>, a deviation of less than 4%). The hydraulic diameter decreases slightly from 3.7 m to 3.19 m; the

resulting increase in wall friction and heat loss makes the simulated smoke spread slightly slower, i.e., the ASET values are slightly conservative, which is acceptable for a safety-oriented verification. Moreover, a Cartesian FDS mesh represents the rectangular section exactly, whereas a circular boundary would suffer from stair-step approximation errors. The influence of this simplification on the results is therefore considered minor and slightly conservative.

Mesh resolution strongly affects the accuracy of FDS results. For buoyant plumes, the adequacy of the mesh is commonly assessed using the non-dimensional mesh resolution index, defined as:

$$\frac{D^*}{\delta x}, \text{ with } D^* = \left( \frac{\dot{Q}}{\rho_{\infty} c_p T_{\infty} \sqrt{g}} \right)^{\frac{2}{5}} \quad (1)$$

where  $D^*$  is the characteristic fire diameter,  $\delta x$  is the nominal mesh cell size,  $\dot{Q}$  is the heat release rate,  $\rho_{\infty}$  the ambient density,  $c_p$  the specific heat of air,  $T_{\infty}$  the ambient temperature and  $g$  the gravitational acceleration. The FDS User's Guide recommends  $4 \leq D^*/\delta x \leq 16$ , and a range of 8–10 offers a good compromise between accuracy and computational cost. For the present 15 MW fire, a mesh size of 0.3 m was adopted after balancing accuracy and computational cost; local mesh refinement was applied only in the vicinity of the fire source. Prior to the production runs, a mesh independence analysis was carried out comparing uniform mesh sizes of 0.2 m, 0.3 m, 0.4 m and 0.5 m. Balancing numerical accuracy against computational cost, the 0.3 m mesh was finally adopted for the whole domain, with local refinement applied only in the core region of the fire source. The computational domain consists of 1,778,400 cells in total. In order to accurately reproduce the smoke motion at the transition point of a V-shaped profile, the entire tunnel model was rotated by an angle corresponding to a 0.3% gradient (the gentler slope), so that the gentler section became horizontal and served as the horizontal computational domain. Meanwhile, the steeper section was geometrically modeled with a gradient of 4.3% (4% + 0.3%). Finally, the gravity vector was uniformly rotated throughout the computational domain by an angle corresponding to the 0.3% gradient of the gentler section, so that stair-stepped cells on the gentle-slope side were minimized while the geometric transition at the lowest point of the V-shaped profile was preserved in the model. The resulting FDS model is shown in Figure 2.

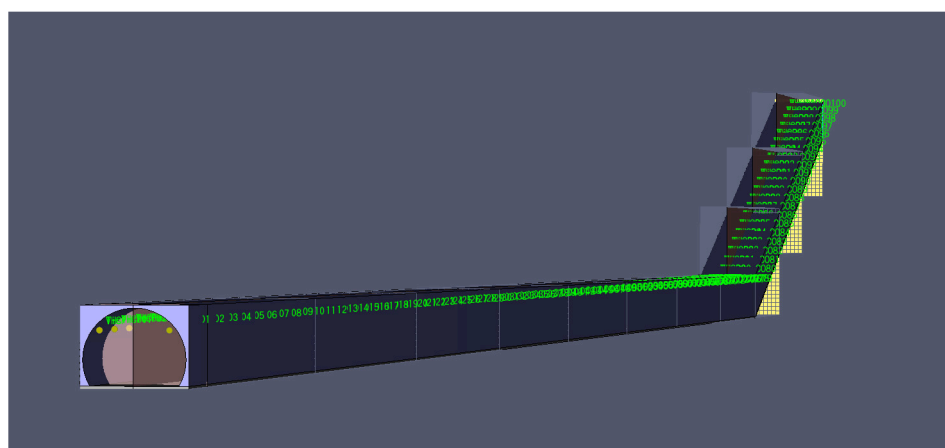


**Figure 2.** FDS computational model of the 1.5 km single-lane tunnel.

Numerical simulations were performed for a 15 MW BEV fire scenario in the 1500 m tunnel with the fire source located at the mid-point (+750 m). The main objective was

to investigate smoke spread under different longitudinal ventilation conditions; the four simulation scenarios are summarized in Table 1.

**Table 1.** FDS fire simulation scenarios.

| Scenario | Fire Location and Size | Ventilation         | Output                        |
|----------|------------------------|---------------------|-------------------------------|
| 1        | +750 m, 15 MW (BEV)    | Natural ventilation | Smoke control effect, ASET(x) |
| 2        | +750 m, 15 MW (BEV)    | Longitudinal, 1 m/s | Smoke control effect, ASET(x) |
| 3        | +750 m, 15 MW (BEV)    | Longitudinal, 2 m/s | Smoke control effect, ASET(x) |
| 4        | +750 m, 15 MW (BEV)    | Longitudinal, 3 m/s | Smoke control effect, ASET(x) |

The burning vehicle was modelled based on the dimensions of a Tesla BEV (4.7 m × 1.9 m × 1.6 m). The battery was represented as a ternary lithium cell (equivalent formula  $C_{6.3}H_{7.1}O_{2.1}N_1$ ); the combustion reaction in FDS was defined according to the burning characteristics of ternary lithium batteries. Soot yield and CO yield were set to 0.1 kg/kg and 0.1 g/g, respectively, based on full-scale BEV fire test data reported in the literature [4,6,7,9]. The peak heat release rate was set to 15 MW, and the fire growth coefficient was taken from Kang et al. [6] (range 0.0085–0.020); the resulting HRR curve is shown in Figure 3. This value corresponds to the upper bound of peak values measured in full-scale BEV fire tests reported in the literature, including tests conducted in road tunnels [4–6]. As this study is a pre-construction performance-based verification of a tunnel without fire protection or evacuation facilities, the design fire was taken as the most unfavorable credible scenario.

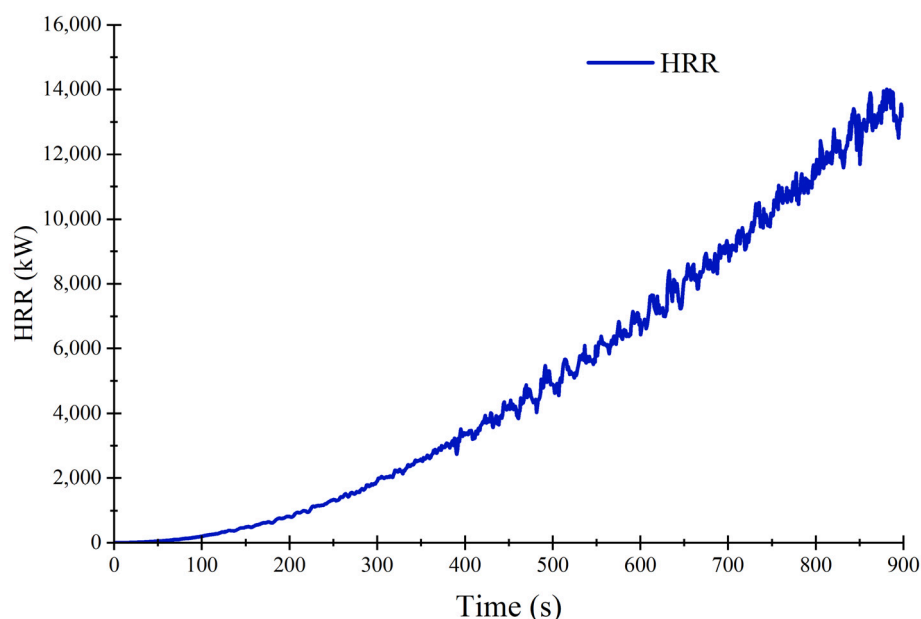


**Figure 3.** Heat release rate curve of the 15 MW BEV design fire used in the simulations.

PIARC divides fire development into a Self-Evacuation Phase and a Fire-Fighting Phase, recommending that the self-evacuation phase not exceed 15 min. The Chinese Code for Design of Road Tunnel also recommends that occupant evacuation time under fire conditions be less than 15 min. Consequently, the total simulation duration was set to 900 s after ignition.

### 2.3. Evacuation Safety Criteria

Whether the tunnel smoke control system can provide an environment meeting safe evacuation requirements is a key criterion for judging whether the system achieves its

design objective. Two assessment indicators are involved: first, whether the time required for occupant evacuation is shorter than the time until conditions become untenable ( $RSET < ASET$ ); second, whether the environmental parameters inside the tunnel under smoke control satisfy the safe evacuation environment criteria. Different countries specify different environmental criteria for tunnel evacuation safety (ASET criteria), but the governing parameters are mainly determined in terms of visibility, temperature and smoke toxicity.

Following the PIARC permissible values for air temperature, visibility and carbon monoxide concentration in underground roads during a fire, the evacuation and rescue environment is evaluated against the computed results at 2 m above the carriageway. Table 2 lists the permissible values provided by PIARC. In addition, fire protection design handbooks indicate that humans exposed to temperatures above 318 K (45 °C) experience pain, thermal injury to the skin and respiratory system, and first-degree burns [19,24]. Effective smoke extraction that keeps the air temperature below 318 K within the occupied zone 2 m above the carriageway therefore helps to create a safer environment for evacuation and rescue.

**Table 2.** Permissible values of air temperature, visibility and CO concentration in road tunnels (PIARC).

| Control Parameter | Air Temperature | Minimum Visibility | CO Concentration |
|-------------------|-----------------|--------------------|------------------|
| Permissible value | <80 °C (353 K)  | >7–15 m            | <225 ppm         |

Table 3 presents the criteria used in four countries for determining the time to untenable conditions. In China, the commonly adopted criteria are the “life safety criteria” of the Fire Engineering Guidelines and the “available safe egress time assessment criteria” in Volume 3 of the China Fire Protection Handbook.

**Table 3.** ASET criteria in different countries.

| Country                   | Convective Heat                                              | Radiant Heat (kW/m <sup>2</sup> )                            | Smoke Obscuration                                                                   |
|---------------------------|--------------------------------------------------------------|--------------------------------------------------------------|-------------------------------------------------------------------------------------|
| New Zealand [25]          | Smoke layer temperature $\leq$ 65 °C, exposure time > 30 min | <2.5 (gas layer temperature 200 °C)                          | Extinction coefficient < 0.5 m <sup>−1</sup> , visibility 2 m                       |
| United Kingdom (BSI) [26] | Smoke layer temperature < 60 °C, exposure time > 30 min      | <2.5, exposure time > 5 min                                  | Extinction coefficient < 0.1 m <sup>−1</sup> , visibility 10 m                      |
| Australia [27]            | Smoke layer temperature < 60 °C, exposure time > 30 min      | <2.5, exposure time > 5 min                                  | Extinction coefficient < 0.1 m <sup>−1</sup> , visibility 10 m                      |
| China [24]                | Space below 2 m: <60 °C (sustained for 30 min)               | Space above 2 m: <2.5 kW/m <sup>2</sup> (temperature 180 °C) | Large spaces: visibility > 10 m below 2 m; small spaces: visibility > 5 m below 2 m |

The following criteria are adopted to judge the effectiveness of the tunnel smoke extraction system in the numerical simulations:

- (1) Temperature criterion: during the evacuation period, the temperature at 2 m height in the tunnel shall not exceed 60 °C.
- (2) Visibility criterion: the visibility at 2 m height shall not be less than 10 m.
- (3) Carbon monoxide criterion: the CO concentration at 2 m height shall not exceed 225 ppm. Fire products are complex and variable, depending strongly on the burning material and ambient conditions, making it very difficult to predict their composition and concentration. A widely used engineering simplification is therefore adopted: if the visibility of a light-emitting object is not less than 10 m, the volume fractions of the various toxic combustion products are considered unlikely to reach the human

tolerance limit within 30 min; this criterion is used in combination with the visibility criterion. It is acknowledged that battery electric vehicle fires emit additional toxic species that are not explicitly modelled here; in particular, hydrogen fluoride (HF) represented the largest difference in combustion gases between electric and conventional vehicles in large-scale fire tests [7], and the total HF emission of an electric car has been reported to be about twice that of an identical conventional car (0.7 kg versus 0.4 kg) [8]. The explicit resolution of HF and other toxic emissions of new energy vehicle fires will be addressed in our subsequent experimental and numerical studies.

When the tunnel fire environment reaches any one of the above three criteria, the fire is regarded as hazardous; the time to reach the hazardous state minus the ignition time is the available safe egress time for occupants.

#### 2.4. Calculation of Available Safe Egress Time and Required Safe Egress Time

If the fire spreads faster than the occupants can escape (i.e.,  $ASET < RSET$ ), safe evacuation cannot be achieved; otherwise, occupants can evacuate safely. ASET is the available safe egress time, i.e., the time for the fire hazards to develop until occupants lose their ability to escape. RSET is the required safe egress time, i.e., the time from ignition until all trapped occupants reach a place of safety.

For a tunnel 1.5 km in length, longitudinal smoke spread along the ceiling takes a relatively long time. A refined evacuation analysis is therefore adopted, in which RSET is calculated separately at different longitudinal positions. ASET and RSET are treated as functions of the position parameter, i.e.,  $RSET(x) < ASET(x)$ , where  $x$  denotes the position.

The time required for occupant evacuation consists of the detection and alarm time, the occupant response time, and the evacuation movement time.

$$T_{RSET} = T_{det} + T_{act} + T_{eva} \quad (2)$$

where  $T_{det}$  is the detection and alarm time,  $T_{act}$  the occupant response time, and  $T_{eva}$  the movement time, including queuing at exits. Vehicle fires in tunnels develop rapidly and are easily noticed, and road tunnels are normally equipped with automatic alarm systems; the alarm time was therefore set to 60 s and, considering the age structure and physical and mental state of vehicle occupants, the response time was also set to 60 s. It should be noted that applying a uniform alarm and response time to all occupants is an engineering simplification: in reality, direct eyewitnesses of the fire outbreak can react almost immediately, whereas occupants far from the fire must wait for the alarm triggering and the emergency announcement, so that pre-movement times differ between occupants at different locations. This differentiation is not resolved in the present study and is identified as future work (Section 4). Figure 4 shows the timeline of each component of safe evacuation during a tunnel fire.

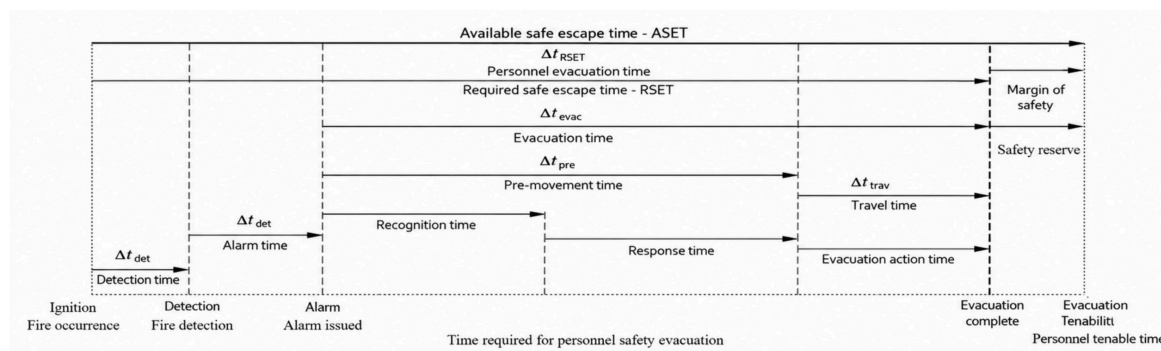


**Figure 4.** Timeline of safe evacuation components during a tunnel fire.

The unimpeded walking speed of occupants under fire conditions is influenced by visibility, smoke irritation, occupant density and individual physical condition. Full-scale tunnel evacuation experiments have reported walking speeds of approximately 1.0–2.0 m/s under clear or low-smoke conditions, decreasing markedly as visibility deteriorates [28,29]. PIARC recommends that the movement speed of occupants in a tunnel during a fire be taken as 0.5–1.5 m/s [22]. In this study, the walking speed was assumed to follow a normal distribution with a mean of 1.25 m/s and a standard deviation of  $\sigma = 0.1$  m/s, truncated at  $1.25 \pm 3\sigma$ .

The worst-case congestion scenario was analyzed: a fire involving a single BEV at the tunnel mid-length, with all traffic jammed upstream. The evacuation situation under this full-load congestion scenario is illustrated in Figure 5. This scenario is a deliberately chosen worst-case bound for the pre-construction verification: its purpose is to examine whether, without any escape passages or fire protection systems, longitudinal ventilation using only the two portals can still satisfy the evacuation requirements under the most unfavorable traffic state, rather than to predict normal tunnel operation. Vehicles were assumed to queue with a spacing of 2 m. This spacing represents a typical stopped, bumper-to-bumper queue in congested tunnel traffic: with the 4.7 m vehicle length, it corresponds to the densest stationary state of jammed single-lane traffic, in which vehicles cannot move and occupants must evacuate on foot through the gaps between vehicles. This gives 105 vehicles within the 750 m upstream section. The number of occupants per vehicle was fixed at four (full load). Although the real occupancy per vehicle is a random variable with a lower mean, the full-load assumption constitutes the upper bound of that distribution: it maximizes the total evacuee population (420) and hence the required safe egress time, so that any realistic random occupancy pattern is enveloped by the analyzed scenario. In other words, if safe evacuation is demonstrated under the full-load assumption, it is guaranteed for any random occupancy with a reasonable mean (Table 4).

Because the single lane is narrow, occupants can only escape through the gaps between vehicles, which reduces the effective movement speed; occupants evacuate upstream, i.e., against the direction of smoke spread. Measuring points were placed every 15 m along the evacuation path, and the time at which the last occupant passes each point defines the position-resolved RSET(x). Safe evacuation at position x requires  $RSET(x) < ASET(x)$ .

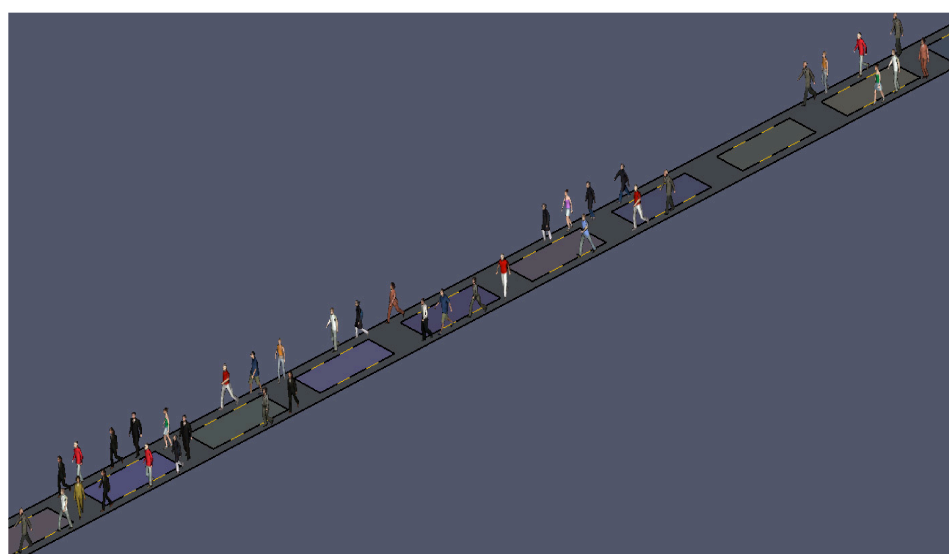


**Figure 5.** The situation regarding the evacuation of people from the tunnel (full load).

**Table 4.** Parameters of the evacuation simulation (full-load congestion scenario).

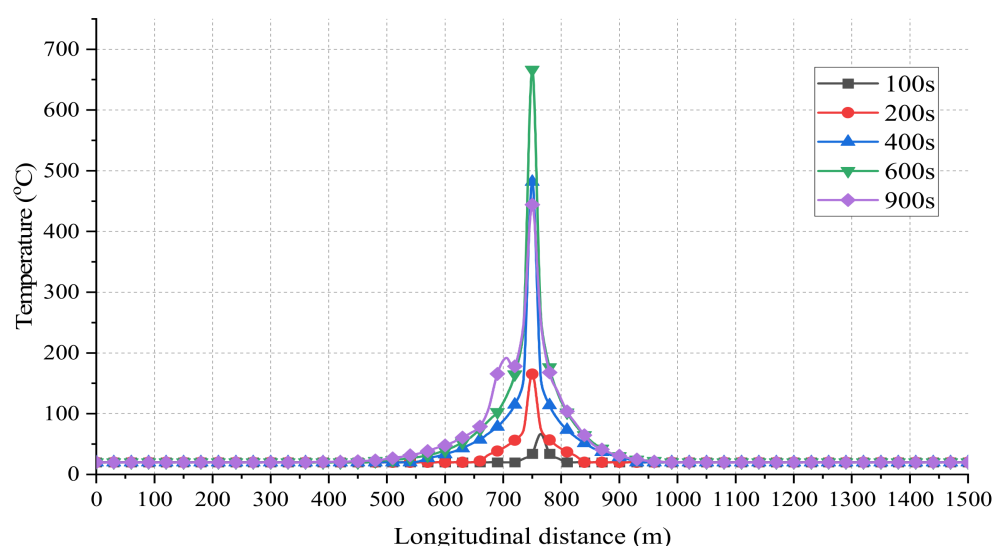
| Item                         | Value                                                                   |
|------------------------------|-------------------------------------------------------------------------|
| Carriageway width            | 3.0 m + 2 × 0.17 m                                                      |
| Maximum tunnel width         | 3.7 m                                                                   |
| Vehicle dimensions (BEV)     | 4.7 m × 1.9 m (L × W)                                                   |
| Vehicle spacing (congestion) | 2 m                                                                     |
| Occupants per vehicle        | 4 (full load)                                                           |
| Number of vehicles           | 105                                                                     |
| Total evacuees               | 420                                                                     |
| Alarm + response time        | 60 s + 60 s                                                             |
| Walking speed                | Normal ( $\mu = 1.25$ m/s, $\sigma = 0.1$ m/s), truncated $\pm 3\sigma$ |

### 3. Results and Discussion

#### 3.1. Natural Ventilation

Under natural ventilation (no mechanical ventilation activated), the buoyant smoke rises to the ceiling and spreads longitudinally in both directions. Because the fire is located at the middle of the tunnel, the longitudinal temperature distribution is initially almost symmetric; once the smoke front enters the 4% slope section; however, the stack effect distorts the temperature and visibility distributions and accelerates the spread toward the uphill portal.

At the characteristic height of 2 m (Figure 6), the temperature exceeded the 60 °C criterion within approximately 15 m of the fire at 200 s, and within approximately 100 m of the fire after 600 s. Visibility (Figure 7) dropped below 10 m within approximately 30 m of the fire at 100 s and within approximately 90 m after 200 s. The CO concentration (Figure 8) exceeded 225 ppm within approximately 75 m of the fire at 200 s and within approximately 195 m at 400 s, making CO the controlling criterion at greater distances from the fire. Combining the three criteria (Figure 9), the sections 0–350 m and 990–1500 m remain tenable throughout the 900 s simulation, whereas ASET(x) decreases steeply toward the fire, reaching only a few tens of seconds in its immediate vicinity.

**Figure 6.** Temperature distributions at different times at 2 m above the ground (natural ventilation).

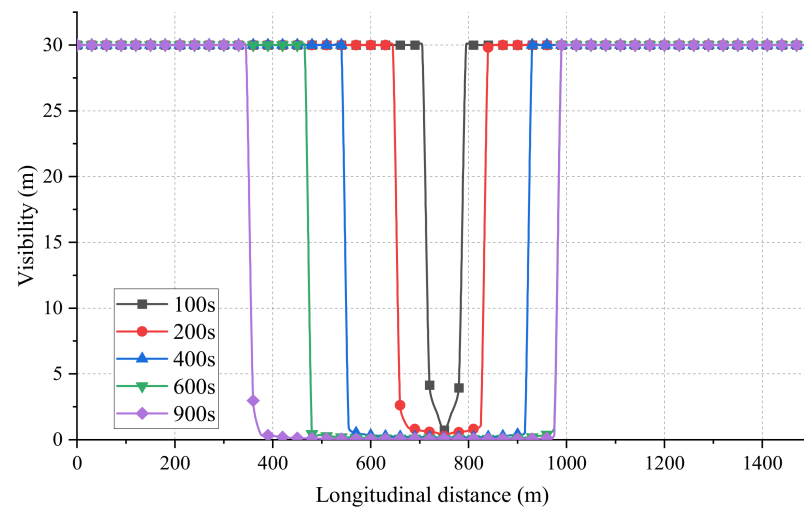


**Figure 7.** Visibility distributions at different times at 2 m above the ground (natural ventilation).

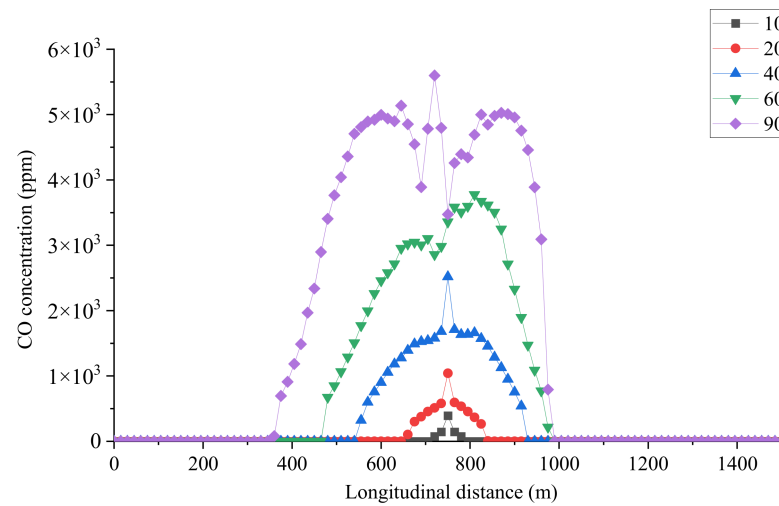


**Figure 8.** CO concentration distributions at different times at 2 m above the ground (natural ventilation).

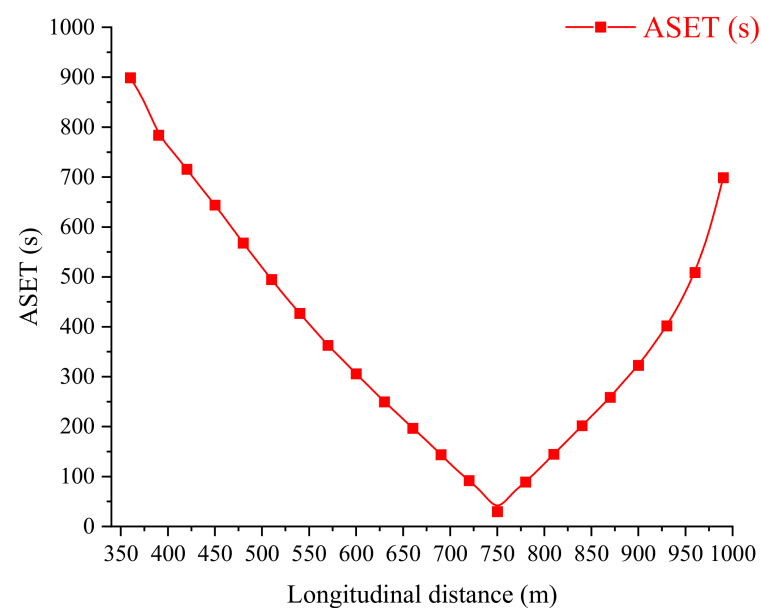


**Figure 9.** Distribution of available safe egress time (ASET) along the tunnel (natural ventilation).

### 3.2. Longitudinal Ventilation of 1 m/s

With a longitudinal velocity of 1 m/s, smoke back-layering is substantially reduced but not fully suppressed, and the hazardous region shifts downstream. At 2 m height (Figure 10), temperatures above 60 °C were confined to 750–780 m at 200 s and extended to 750–900 m after 600 s. Visibility below 10 m was observed over 735–780 m at 100 s and 720–870 m after 200 s (Figure 11); CO above 225 ppm covered 735–855 m at 200 s and 690–1050 m at 400 s (Figure 12). The upstream section 0–680 m remains tenable at all times (Figure 13), but a short region immediately upstream of the fire still becomes untenable within the evacuation window.

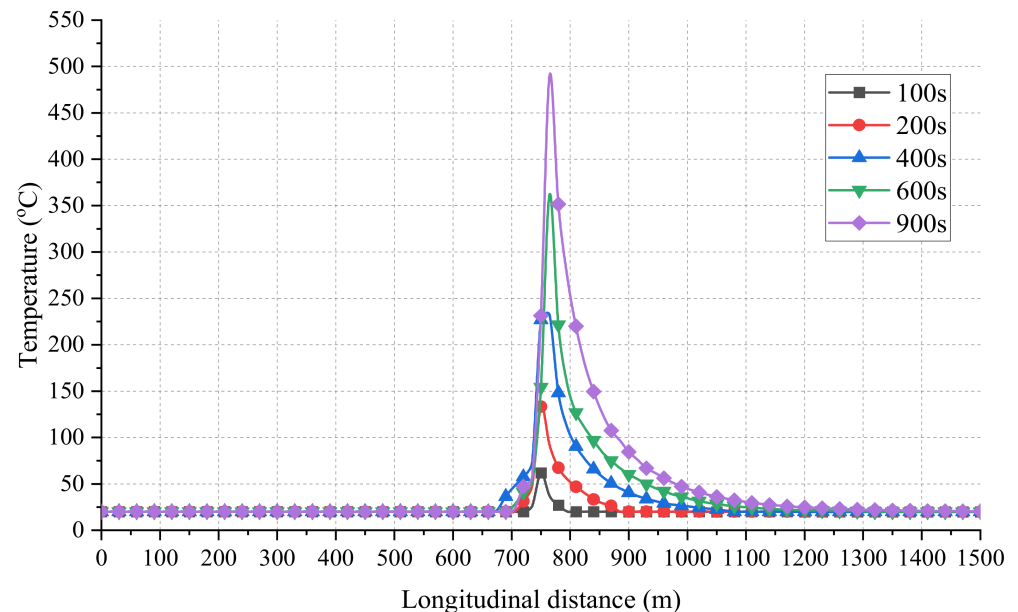


**Figure 10.** Temperature distributions at different times at 2 m above the ground (longitudinal ventilation, 1 m/s).

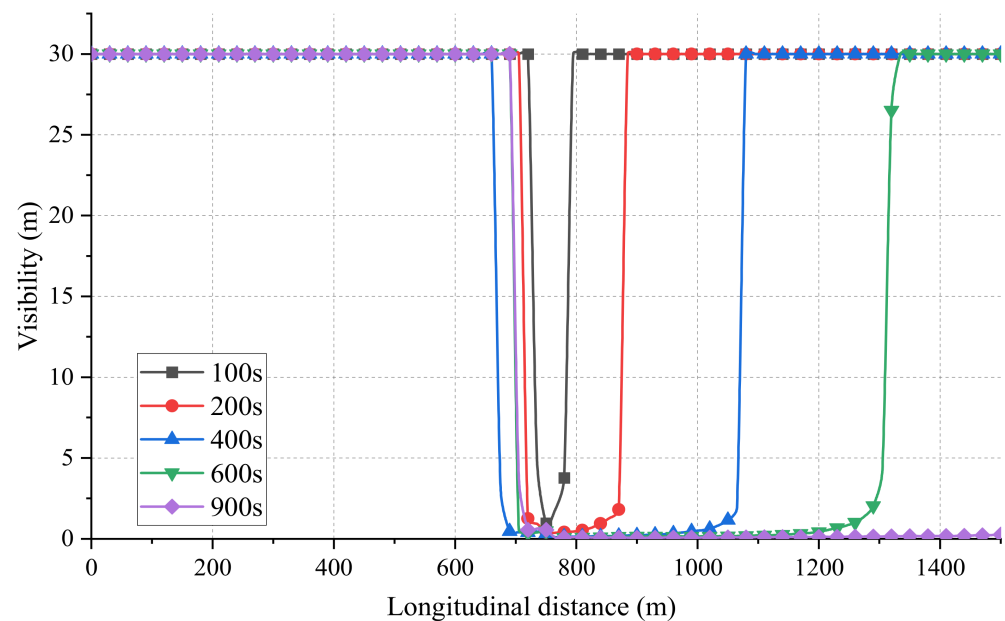


**Figure 11.** Visibility distributions at different times at 2 m above the ground (longitudinal ventilation, 1 m/s).

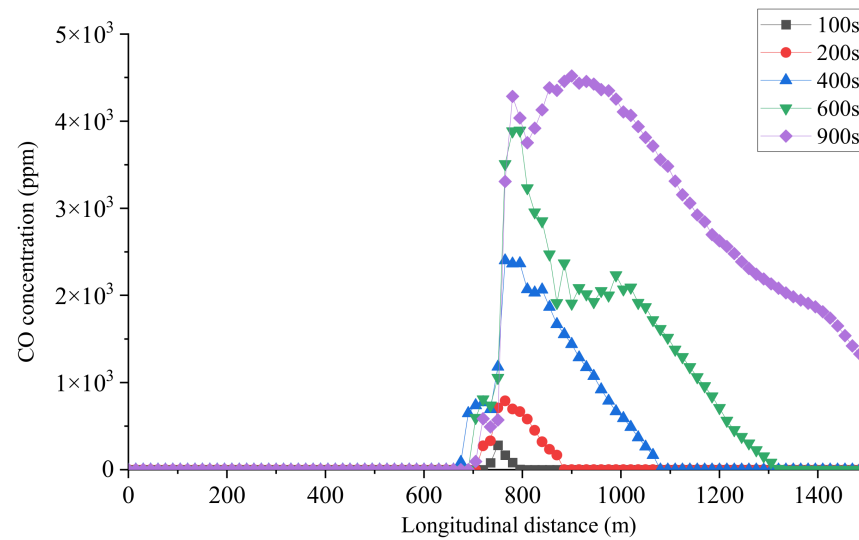


**Figure 12.** CO concentration distributions at different times at 2 m above the ground (longitudinal ventilation, 1 m/s).

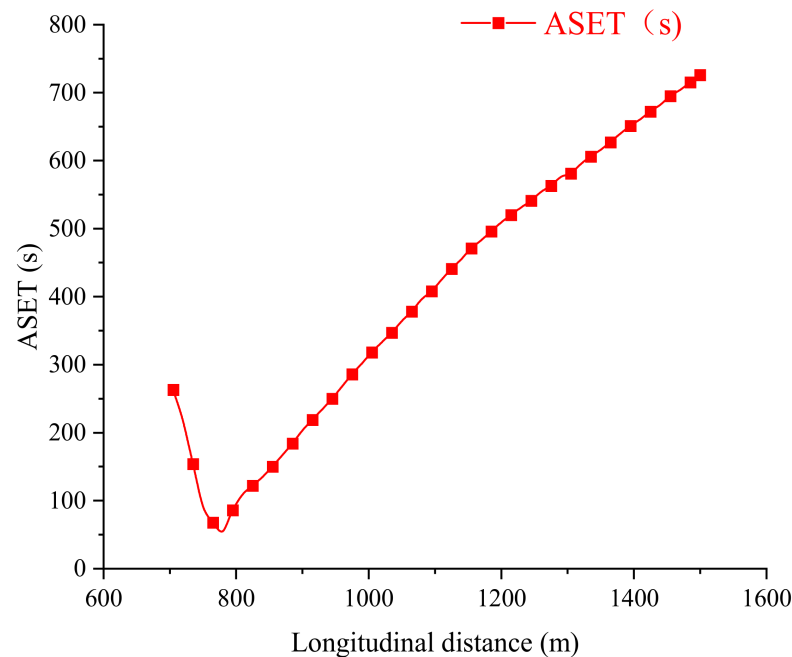


**Figure 13.** Distribution of available safe egress time (ASET) along the tunnel (longitudinal ventilation, 1 m/s).

### 3.3. Longitudinal Ventilation of 2 m/s

At 2 m/s, smoke back-layering upstream of the fire is fully suppressed: the upstream section 0–750 m remains completely free of smoke and tenable during the whole simulation. At 100 s the temperature at 2 m height was below 60 °C along the entire tunnel; by 600 s temperatures above 60 °C were restricted to the downstream section 765–960 m (Figure 14). Visibility fell below 10 m over 765–930 m at 200 s, and after 600 s the entire downstream section from 765 m to the exit portal (1500 m) became untenable in terms of visibility (Figure 15); the same downstream section exceeded 225 ppm CO after 600 s (Figure 16). Consequently, ASET(x) exceeds the simulation duration everywhere upstream of the fire and increases monotonically downstream of it (Figure 17).

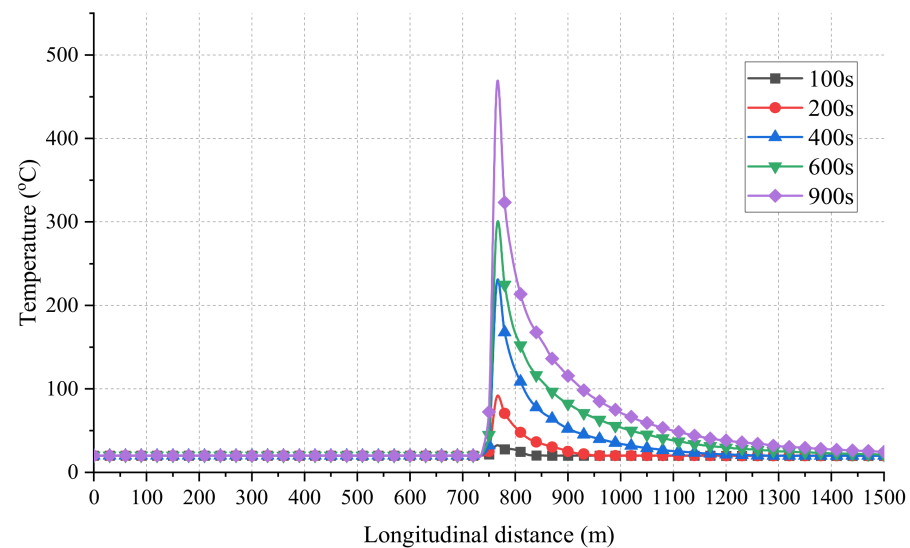


**Figure 14.** Temperature distributions at different times at 2 m above the ground (longitudinal ventilation, 2 m/s).

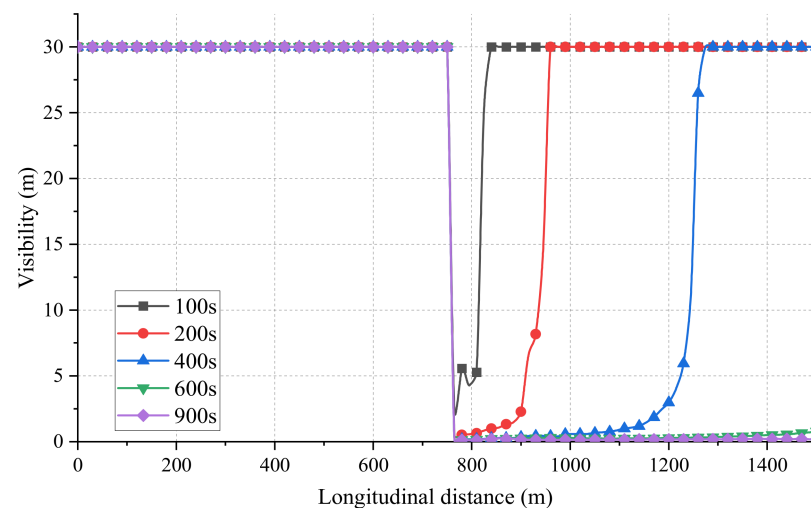


**Figure 15.** Visibility distributions at different times at 2 m above the ground (longitudinal ventilation, 2 m/s).

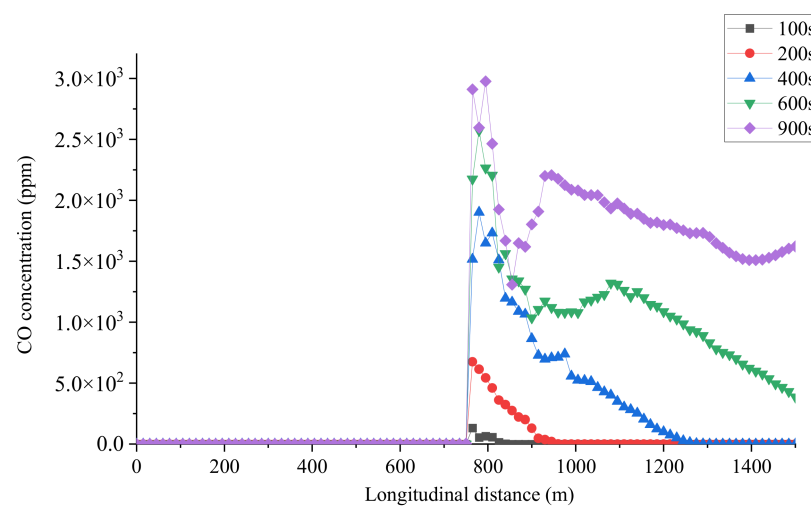


**Figure 16.** CO concentration distributions at different times at 2 m above the ground (longitudinal ventilation, 2 m/s).

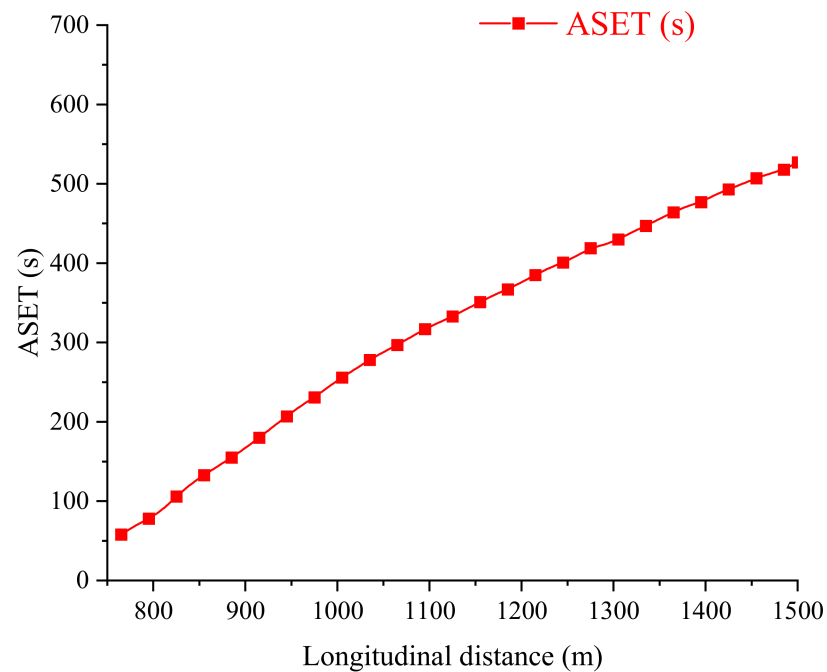


**Figure 17.** Distribution of available safe egress time (ASET) along the tunnel (longitudinal ventilation, 2 m/s).

### 3.4. Longitudinal Ventilation of 3 m/s

At 3 m/s the overall pattern is similar to that at 2 m/s, with the hazardous region confined slightly further downstream. Temperatures above 60 °C at 2 m height covered 765–1005 m at 600 s (Figure 18); visibility below 10 m covered 765–945 m at 200 s and, after 600 s, the whole downstream section to the exit portal (Figure 19); CO above 225 ppm covered 765–855 m at 200 s and the whole downstream section after 600 s (Figure 20). The upstream section 0–750 m again remains tenable at all times (Figure 21). Increasing the velocity from 2 to 3 m/s therefore brings no additional benefit for upstream evacuation, while it transports heat, smoke and CO further downstream.

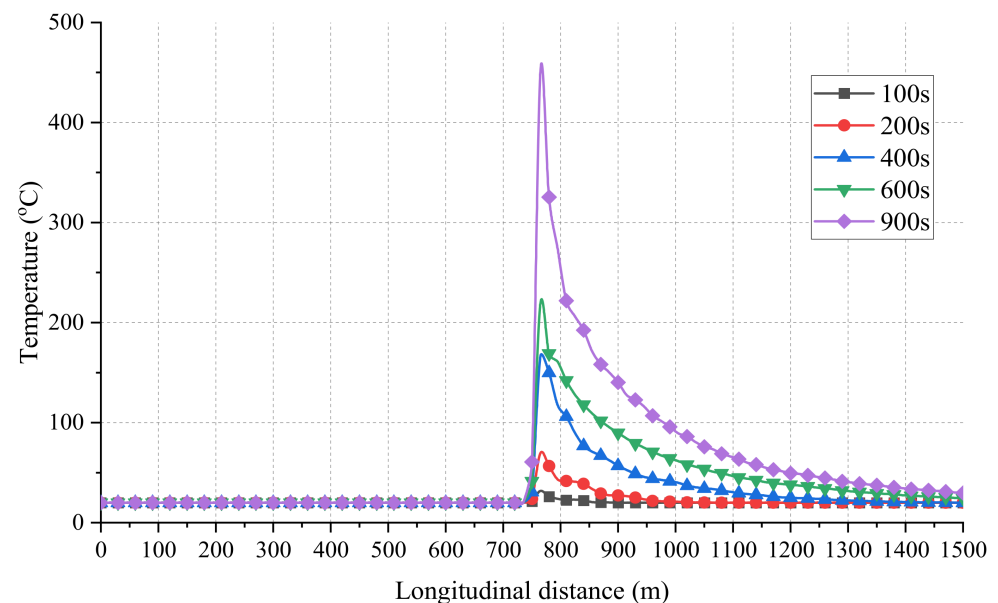


**Figure 18.** Temperature distributions at different times at 2 m above the ground (longitudinal ventilation, 3 m/s).

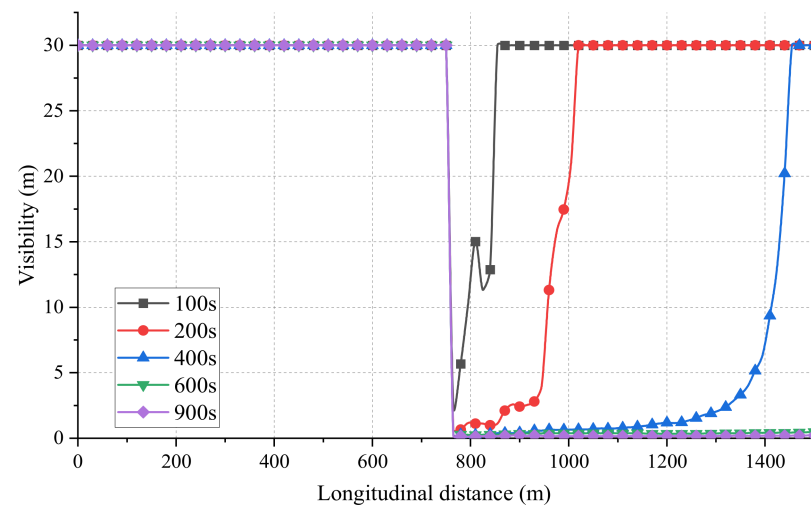


**Figure 19.** Visibility distributions at different times at 2 m above the ground (longitudinal ventilation, 3 m/s).

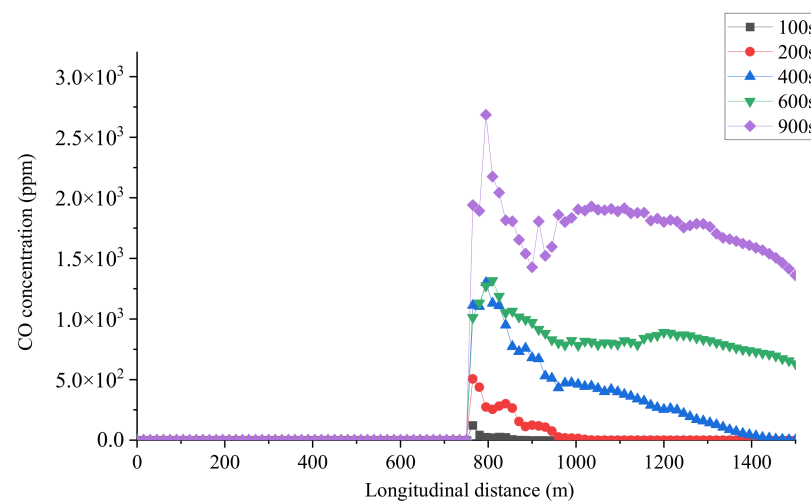


**Figure 20.** CO concentration distributions at different times at 2 m above the ground (longitudinal ventilation, 3 m/s).

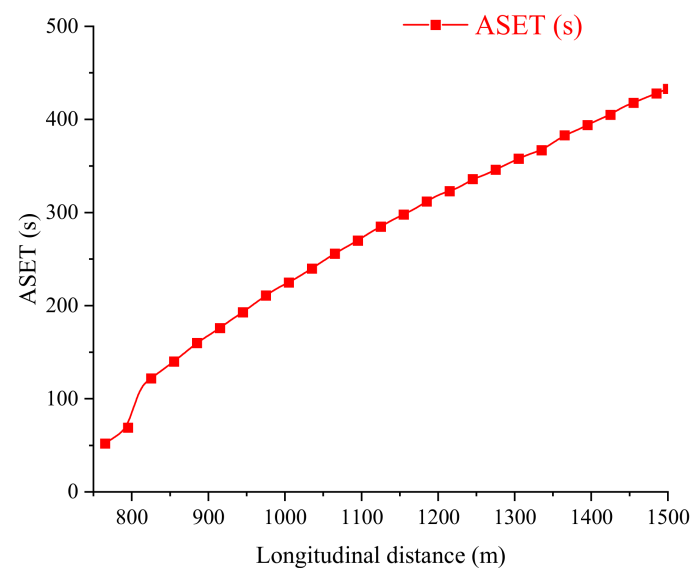


**Figure 21.** Distribution of available safe egress time (ASET) along the tunnel (longitudinal ventilation, 3 m/s).

### 3.5. Position-Resolved ASET/RSET Comparison

The fire simulations in Sections 3.1–3.4 show that, for longitudinal velocities of 2 m/s and above, the entire upstream section (0–750 m)—where all 420 occupants are located in the congestion scenario—remains tenable throughout the 900 s self-evacuation phase. The refined evacuation assessment therefore focuses on the natural ventilation and 1 m/s scenarios.

In the full-load congestion scenario, the simulated movement time of all 420 occupants to the upstream portal is 758.8 s; adding the 60 s alarm and 60 s response times gives a total RSET of 878.8 s for the occupant closest to the fire. The position-resolved comparison of RSET(x) and ASET(x) along the upstream section is shown in Figure 22. Under natural ventilation, occupants in the section 645–750 m (i.e., within about 105 m upstream of the fire) experience  $RSET(x) > ASET(x)$  and cannot evacuate safely; the tenability limit is reached before they have moved far enough away from the fire. At 1 m/s, the failure zone shrinks to 740–750 m, i.e., only the occupants of the one or two vehicles closest to the fire remain at risk. At 2 m/s and 3 m/s,  $ASET(x) > 900$  s everywhere upstream and  $RSET(x) < ASET(x)$  is satisfied for all occupants. Table 5 summarizes the hazardous regions identified for each scenario.

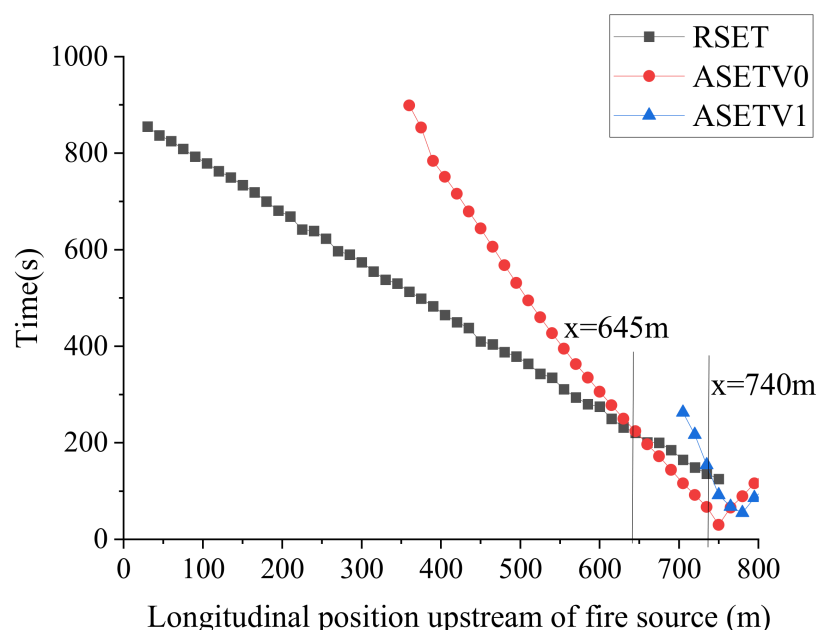


**Figure 22.** Comparison of RSET and ASET in the region upstream of the fire under the full-load occupancy scenario.

**Table 5.** Summary of hazardous regions at 2 m height and evacuation assessment for the four scenarios (900 s simulation).

| Scenario            | Region > 60 °C (t = 600 s) | Region < 10 m Visibility (t = 200 s) | Region > 225 ppm CO (t = 200 s) | Evacuation Failure Zone (RSET > ASET) |
|---------------------|----------------------------|--------------------------------------|---------------------------------|---------------------------------------|
| Natural ventilation | 650–850 m                  | 660–840 m                            | 675–825 m                       | 645–750 m (upstream)                  |
| 1 m/s               | 750–900 m                  | 720–870 m                            | 735–855 m                       | 740–750 m (upstream)                  |
| 2 m/s               | 765–960 m                  | 765–930 m                            | 765–870 m                       | None (upstream safe)                  |
| 3 m/s               | 765–1005 m                 | 765–945 m                            | 765–855 m                       | None (upstream safe)                  |

## 4. Conclusions

This study assessed, by coupled FDS and Pathfinder simulation, the smoke spread and evacuation safety of a 15 MW BEV fire at the mid-length of a 1.5 km single-lane,

V-shaped road tunnel without evacuation facilities, under four ventilation scenarios. The main conclusions are as follows:

- (1) The fire source configuration of this study differs from previous tunnel fire simulations: the smoke production rate and CO production rate of an BEV fire are higher than those of a conventional fuel vehicle fire. The burning vehicle was modelled on the characteristics of a Tesla BEV, with the battery represented as a ternary lithium battery; the combustion reaction in FDS was defined according to the combustion characteristics of ternary lithium batteries, and the smoke and CO production rates were set with reference to full-scale BEV fire tests reported in the literature.
- (2) Tenability criteria at the 2 m characteristic height were established as temperature  $\leq 60$  °C, visibility  $\geq 10$  m and CO  $\leq 225$  ppm, combining PIARC permissible values and Chinese practice; the visibility criterion simultaneously bounds the overall smoke toxicity within the evacuation window.
- (3) A position-resolved ASET(x)/RSET(x) assessment was applied over the full tunnel length. Under natural ventilation, the upstream section 645–750 m violates RSET(x) < ASET(x) and does not satisfy evacuation requirements; at 1 m/s the failure zone shrinks to 740–750 m; at 2 m/s and 3 m/s the entire upstream section (0–750 m) remains tenable and all 420 occupants complete evacuation in 878.8 s (including 120 s of alarm and response time). A longitudinal ventilation velocity of at least 2 m/s is therefore required to guarantee safe upstream evacuation in this tunnel.

These conclusions are drawn for the pre-construction performance-based verification of this tunnel configuration: a 1.5 km single-lane tunnel without evacuation facilities, a 15 MW BEV design fire at the mid-length, and longitudinal ventilation as the only smoke control measure. Several limitations should be noted. The BEV fire dynamics parameters were adopted from published full-scale tests, and no experimental validation in this specific tunnel is available because it is still at the planning stage. The congestion scenario with full-load occupancy is a deliberate worst-case bound rather than a prediction of normal tunnel operation. A uniform alarm and response time was applied to all occupants, without differentiating the pre-movement time between direct eyewitnesses of the fire and distant occupants who must wait for the alarm and the emergency announcement. Toxic species other than CO, in particular hydrogen fluoride, were not explicitly modelled. Full-scale fire and evacuation tests combined with virtual-reality behavioral experiments and multi-camera trajectory tracking [30–32], HF toxicity modelling, randomly distributed vehicle occupancy, and differentiated pre-movement times are recommended as future work.

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## References

- Barbato, L.; Cascetta, F.; Musto, M.; Rotondo, G. Fire Safety Investigation for Road Tunnel Ventilation Systems—An Overview. *Tunn. Undergr. Space Technol.* **2014**, *43*, 253–265. [\[CrossRef\]](#)
- Li, J.; Liu, J. Science Mapping of Tunnel Fires: A Scientometric Analysis-Based Study. *Fire Technol.* **2020**, *56*, 2111–2135. [\[CrossRef\]](#)
- Sun, P.; Bisschop, R.; Niu, H.; Huang, X. A Review of Battery Fires in Electric Vehicles. *Fire Technol.* **2020**, *56*, 1361–1410. [\[CrossRef\]](#)
- Sturm, P.; Föfßleitner, P.; Fruhwirt, D.; Galler, R.; Wenighofer, R.; Heindl, S.F.; Krausbar, S.; Heger, O. Fire Tests with Lithium-Ion Battery Electric Vehicles in Road Tunnels. *Fire Saf. J.* **2022**, *134*, 103695. [\[CrossRef\]](#)
- Lecocq, A.; Bertana, M.; Truchot, B.; Marlair, G. Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle. In Proceedings of the 2. International Conference on Fires in Vehicles—FIVE 2012, Chicago, IL, USA, 27–28 September 2012.
- Kang, S.; Kwon, M.; Choi, J.Y.; Choi, S. Full-Scale Fire Testing of Battery Electric Vehicles. *Appl. Energy* **2023**, *332*, 120497. [\[CrossRef\]](#)
- Hynynen, J.; Willstrand, O.; Blomqvist, P.; Andersson, P. Analysis of Combustion Gases from Large-Scale Electric Vehicle Fire Tests. *Fire Saf. J.* **2023**, *139*, 103829. [\[CrossRef\]](#)
- Truchot, B.; Fouillen, F.; Collet, S. An Experimental Evaluation of Toxic Gas Emissions from Vehicle Fires. *Fire Saf. J.* **2018**, *97*, 111–118. [\[CrossRef\]](#)
- Bai, Z.P.; Yu, Y.Y.; Zhang, J.Y.; Hu, H.M.; Xing, M.Y.; Yao, H.W. Study on Fire Characteristics of Lithium Battery of New Energy Vehicles in a Tunnel. *Process Saf. Environ. Prot.* **2024**, *186*, 728–737. [\[CrossRef\]](#)
- Xie, J.; Li, J.; Wang, J.; Jiang, J. Fire Protection Design of a Lithium-Ion Battery Warehouse Based on Numerical Simulation Results. *J. Loss Prev. Process Ind.* **2022**, *80*, 104885. [\[CrossRef\]](#)
- Dessi, R.; Fruhwirt, D.; Papurello, D. A Study on Large Electric Vehicle Fires in a Tunnel: Use of a Fire Dynamics Simulator (FDS). *Processes* **2025**, *13*, 2435. [\[CrossRef\]](#)
- Caliendo, C.; Russo, I.; Genovese, G. A Numerical Evaluation for Estimating the Consequences on Users and Rescue Teams Due to the Fire of an Electric Bus in a Road Tunnel. *Appl. Sci.* **2024**, *14*, 9191. [\[CrossRef\]](#)
- Li, Y.Z.; Lei, B.; Ingason, H. Study of Critical Velocity and Backlayering Length in Longitudinally Ventilated Tunnel Fires. *Fire Saf. J.* **2010**, *45*, 361–370. [\[CrossRef\]](#)
- Oka, Y.; Atkinson, G.T. Control of Smoke Flow in Tunnel Fires. *Fire Saf. J.* **1995**, *25*, 305–322. [\[CrossRef\]](#)
- Wu, Y.; Bakar, M.Z.A. Control of Smoke Flow in Tunnel Fires Using Longitudinal Ventilation Systems—A Study of the Critical Velocity. *Fire Saf. J.* **2000**, *35*, 363–390. [\[CrossRef\]](#)
- Weng, M.C.; Lu, X.L.; Liu, F.; Du, C.X. Study on the Critical Velocity in a Sloping Tunnel Fire under Longitudinal Ventilation. *Appl. Therm. Eng.* **2016**, *94*, 422–434. [\[CrossRef\]](#)
- Tang, W.; Hu, L.H.; Chen, L.F. Effect of Blockage-Fire Distance on Buoyancy Driven Back-Layering Length and Critical Velocity in a Tunnel: An Experimental Investigation and Global Correlations. *Appl. Therm. Eng.* **2013**, *60*, 7–14. [\[CrossRef\]](#)
- Gannouni, S.; Maad, R. Numerical Study of the Effect of Blockage on Critical Velocity and Backlayering Length in Longitudinally Ventilated Tunnel Fires. *Tunn. Undergr. Space Technol.* **2015**, *48*, 147–155. [\[CrossRef\]](#)
- Purser, D. ASET and RSET: Addressing Some Issues in Relation to Occupant Behaviour and Tenability. In *Fire Safety Science*; International Association for Fire Safety Science: London, UK, 2003.
- Chu, G.; Wang, J.; Wang, Q. Time-Dependent Fire Risk Assessment for Occupant Evacuation in Public Assembly Buildings. *Struct. Saf.* **2012**, *38*, 22–31. [\[CrossRef\]](#)
- Gehandler, J.; Eymann, L.; Regeffe, M. Limit-Based Fire Hazard Model for Evaluating Tunnel Life Safety. *Fire Technol.* **2015**, *51*, 585–614. [\[CrossRef\]](#)
- PIARC. Smoke Control in Road Tunnels. In *PIARC Technical Committee C5 Road Tunnel*; PIARC: La Défense Cedex, France, 1999.
- Caliendo, C.; Genovese, G.; Russo, I. A Simultaneous Analysis of the User Safety and Resilience of a Twin-Tube Road Tunnel. *Appl. Sci.* **2022**, *12*, 3357. [\[CrossRef\]](#)
- Fire Department of the Ministry of Public Security of China. China Fire Protection Handbook. In *Fire Planning, Public Fire Protection Facilities and Building Fire Protection Design*; Shanghai Scientific & Technical Publishers: Shanghai, China, 2006; Volume 3. (In Chinese)
- Buchanan, A.H. *Fire Engineering Design Guide*; Centre for Advanced Engineering: Christchurch, New Zealand, 2001.
- DD 240-1; Fire Safety Engineering in Buildings. Guide to the Application of Fire Safety Engineering Principles. British Standards Institution: London, UK, 1997.
- Fire Code Reform Centre. *Fire Engineering Guidelines*, 1st ed.; Fire Code Reform Centre Ltd.: Sydney, NSW, Australia, 1996.
- Fridolf, K.; Ronchi, E.; Nilsson, D.; Frantzich, H. Movement Speed and Exit Choice in Smoke-Filled Rail Tunnels. *Fire Saf. J.* **2013**, *59*, 8–21. [\[CrossRef\]](#)
- Ronchi, E.; Fridolf, K.; Frantzich, H.; Nilsson, D.; Walter, A.L.; Modig, H. A Tunnel Evacuation Experiment on Movement Speed and Exit Choice in Smoke. *Fire Saf. J.* **2018**, *97*, 126–136. [\[CrossRef\]](#)

30. Zhang, Y.; Kinateter, M.; Templeton, A.; Warren, W.H. A Virtual Reality Experiment on Visual and Auditory Guidance for Egress in Road Tunnel Fires. *Fire Technol.* **2025**, *61*, 4527–4555. [[CrossRef](#)]
31. Zhang, Y.; Ding, Y.; Chraibi, M.; Huang, X. Multi-Scale Analysis of Fire and Evacuation Drill in a Multi-Functional University High-Rise Building. *Dev. Built Environ.* **2025**, *21*, 100626. [[CrossRef](#)]
32. Ding, Y.; Chen, X.; Zhang, Y.; Huang, X. Smart Building Evacuation by Tracking Multi-Camera Network and Explainable Re-Identification Model. *Eng. Appl. Artif. Intell.* **2025**, *148*, 110394. [[CrossRef](#)]

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