

Article

Analysis of Smoke Spreading Pattern and Fire Safety in T-Type Subway Interchange Station

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Abstract

This study analyzes the flow and dispersion characteristics of fire smoke within the complex spatial structure of a T-type subway interchange station to clarify the impact of geometric parameter variations on the smoke spread timeline and evacuation environment. A three-dimensional numerical model of a typical T-type interchange station was constructed based on field survey data, with key variables defined as the height difference (H) between the platform and concourse layers and the horizontal distance (L) from the fire source to the track intersection. Through the simulation of multiple fire scenarios, the relationship between the smoke front arrival time (T) and the critical danger time (T_s) at key evacuation nodes was quantified in relation to the structural parameters. The results demonstrated significant linear correlations between vertical smoke spread and horizontal diffusion to adjacent tracks with H and L , respectively. Conversely, smoke intrusion at the transfer stairway exhibited nonlinear behavior driven by geometric constraints. The study notably highlights the dual effect of the height difference (H) on smoke spread. Significantly, the study highlights the dual effect of the height difference (H) on evacuation safety. While an increased height difference delays the initial vertical ascent and enlarges the smoke reservoir capacity, thereby extending the available safe egress time, it simultaneously elongates the physical evacuation path. Consequently, a trade-off emerges between the dispersion delay benefit and the increased evacuation distance. Strategies proposed based on the model analysis include the control of the vertical height difference to $H \leq 11$ m, the installation of smoke barriers, and the optimization of the smoke control system in the transfer corridors. These findings provide a theoretical basis and quantitative evidence for the optimization of smoke control systems and emergency evacuation design in T-type subway interchange stations.

Keywords: T-type subway interchange station; smoke control; geometric effects; smoke-front arrival time; critical danger time; evacuation safety



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1. Introduction

Subway interchange stations serve as critical hubs in urban rail transit networks, facilitating rapid mass transit and passenger transitions. With the rapid expansion of global urbanization, underground rail networks have grown exponentially. In China alone, the operational mileage exceeded 10,000 km by the end of 2024, involving 326 lines across 59 cities [1]. Consequently, the topology of stations has evolved from simple linear layouts to complex node-based interchanges. Among these, T-type and L-type configurations account for a significant proportion, such as 38% in Beijing, due to their efficient utilization

of underground space in land-scarce urban centers [2]. However, this spatial complexity introduces severe vulnerabilities. Historical catastrophes, such as the Daegu and Baku subway fires, have underscored the lethal threat posed by smoke accumulation and thermal toxicity in enclosed underground environments [3].

Extensive research has been conducted to mitigate these risks, evolving from fundamental tunnel flow dynamics to complex station ventilation strategies. Early investigations primarily focused on validating numerical methods and understanding basic tunnel fire physics. For instance, Woodburn et al. [4] and Hu et al. [5] established the reliability of Computational Fluid Dynamics (CFD) in predicting buoyancy-driven smoke flow in tunnels. Building on this foundation, subsequent studies shifted focus to the optimization of smoke control systems. Wang et al. [6] and Long et al. [7] utilized FDS (Version 6.8.0) to evaluate the efficacy of hybrid ventilation modes and revealed that the coordinated operation of platform and tunnel ventilation fans significantly enhances exhaust efficiency. Similarly, Zhong et al. [8] and Yang et al. [9] investigated the impact of exhaust vent layouts through full-scale experiments and numerical analysis. Furthermore, recent studies have increasingly integrated advanced digital tools; for instance, Zhang et al. [10] utilized BIM technology to visualize fire smoke distribution and optimize safety evacuation paths. Regarding the impact of geometric features, Gao et al. [11] quantified the influence of tunnel slope on one-dimensional smoke spread and demonstrated that structural variations significantly alter temperature distributions.

Despite these advancements, a critical gap remains regarding the smoke transport mechanisms in complex interchange geometries. While previous studies have extensively covered standard island stations or Cross-type interchanges [12–14], the specific dynamics of T-type stations remain under-explored. Unlike the multi-directional dispersion in Cross-type nodes, T-type stations feature a single-sided vertical coupling at the track intersection. As noted by Li et al. [15] and Klotz [16] in their studies on vertical shafts, connections in underground structures often induce a strong stack effect. In T-type stations, this geometry acts as a funnel that concentrates the buoyancy-driven smoke mass flux from the lower platform directly into the transfer bottleneck [17]. This mechanism differs fundamentally from the distributed dispersion observed in linear stations and leads to the eventual formation of a stagnation layer driven by the stack effect. Although Roh et al. [18] analyzed evacuation performance in T-type stations, quantitative correlations between this unique flow behavior and geometric parameters, specifically the height difference (H) and transfer distance (L), are still lacking.

To address this deficiency, this study establishes a full-scale numerical model to systematically analyze smoke dispersion in T-type interchange stations when the fire source is located at the center of the platform layer. This study introduces the vertical height difference (H) between the concourse and platform layers, and the horizontal distance (L) from the fire source to the track intersection as key variables. Multiple fire scenario simulations are conducted to quantitatively analyze the relationship between the smoke front arrival time (T), the critical danger time (T_s), and the building structural parameters. By identifying the governing patterns of smoke spread, this study aims to provide a theoretical foundation and quantitative evidence for the optimization of smoke control systems and evacuation designs in T-type subway interchange stations.

2. T-Type Interchange Station

2.1. Structural Features

A detailed survey was conducted on several representative T-type subway interchange stations in Xi'an, including Xiaozhai Station, Beidajie Station, Wulukou Station, and Lijiacun Station. By integrating field measurements with behavioral observations and adhering

to relevant local codes, this study summarized the common characteristics regarding the spatial layout and equipment configuration of T-type interchange stations. The survey prioritized key elements such as platform structural features, transfer line layouts, and the arrangement of ventilation and smoke exhaust facilities. Additionally, data regarding passenger flow density and direction during off-peak and peak periods, as well as the configuration of fire evacuation guidance measures, such as emergency broadcasts, evacuation signage, and the accessibility of fire safety facilities, were obtained from the local subway operator. These empirical data provide the foundation for subsequent modeling and fire scenario settings.

T-type interchange stations typically comprise two intersecting lines. The main line generally adopts an island platform located at the second underground level (B2) with a width of 12–14 m, while the branch line is situated at the third underground level (B3), utilizing either island or side platforms with a width of 10–12 m depending on passenger demand. The transfer node is positioned at the track intersection and connects different lines via a transfer concourse or corridor. Two primary transfer modes were identified, namely vertical transfer, which achieves cross-level connection via staircases and escalators with a vertical height difference of 5–8 m, and horizontal transfer, which utilizes corridors for inter-level connection.

Regarding the configuration of ventilation and smoke control systems, the designated smoke extraction rates for the platform and concourse levels are $60 \text{ m}^3/\text{s}$ and $50 \text{ m}^3/\text{s}$, respectively. These parameters are based on the Chinese National Standard GB 51298-2018 [19], representing the rated capacity of the semi-transverse ventilation system designed to handle a 10 MW shielded fire event. Specifically, the Line 3 platform utilizes a semi-transverse smoke exhaust system. Two overhead exhaust ducts run parallel to the tracks along the station length. A total of 48 exhaust louvers with dimensions of $1.0 \text{ m} \times 0.4 \text{ m}$ are symmetrically distributed with a spacing of 5.0 m. In the simulation, each vent is assigned a volumetric outflow rate of $1.25 \text{ m}^3/\text{s}$, corresponding to a face velocity of approximately 3.1 m/s, ensuring effective smoke capture. Similarly, the concourse level is equipped with a ceiling-mounted mechanical extraction system, where 40 exhaust vents ($1.0 \text{ m} \times 0.4 \text{ m}$) are arranged in two rows above the central corridor to deliver a total exhaust capacity of $50 \text{ m}^3/\text{s}$. Smoke containment walls with a height of 0.5 m and spacing of 20 m are installed at the ceiling. The fire safety system covers automatic sprinkler and fire alarm devices. Emergency evacuation facilities require a stairway width of 1.8 m (unidirectional) or 2.4 m (bidirectional), with a step height of 0.15 m. Passenger service facilities include barrier-free elevators and guidance signage.

2.2. Station Overview and Model Construction

This study investigates a typical T-type interchange station in Xi'an that serves as the underground hub for Lines 2 and 3. The Line 2 platform, which is oriented North–South at the B2 level, features a standard section width of 21.5 m, platform dimensions of $12.0 \text{ m} \times 112.0 \text{ m}$, and a maximum depth of 17.1 m. The Line 3 platform, situated at the B3 level and oriented East–West, has a standard section width of 21.7 m, dimensions of $11.5 \text{ m} \times 113.5 \text{ m}$, and a maximum depth of 23.2 m. The station comprises six entrances. Connection between the Line 2 platform and the concourse is achieved via two escalators, one downward escalator, and a staircase with 11 steps. The Line 3 platform is equipped with a west-side unidirectional downward transfer stairway restricted to Line 2 transfers and central escalator groups. Inter-line transfers require routing through the concourse due to the absence of direct platform connections.

To facilitate the establishment and adjustment of the numerical model, a comprehensive analysis of evacuation safety parameters was conducted based on extensive surveys of

similar regional stations. Key architectural features of three critical nodes derived from this survey are illustrated in Figure 1. Subsequently, a full-scale (1:1) three-dimensional model was developed to reproduce the spatial structures of the concourse and platform layers. The modeling process prioritized key evacuation nodes, including escalator entrances and transfer stairways, to ensure geometric alignment with measured data, with an error margin of less than 5%. The model overview, the layout of the station level, and the location of key evacuation points are presented in Figure 2, Figure 3, and Figure 4, respectively.

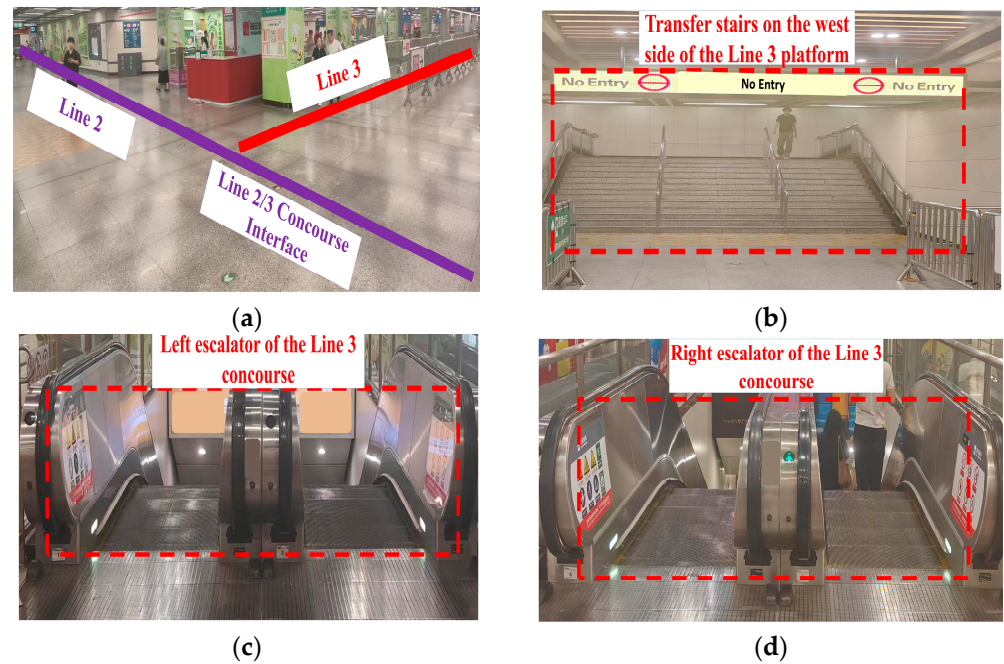


Figure 1. Key architectural nodes of the surveyed T-type interchange station. (a) The concourse interface between Line 2 and Line 3; (b) Transfer stairway on the west side of the Line 3 platform; (c) Left escalator entrance at the Line 3 concourse; (d) Right escalator entrance at the Line 3 concourse.

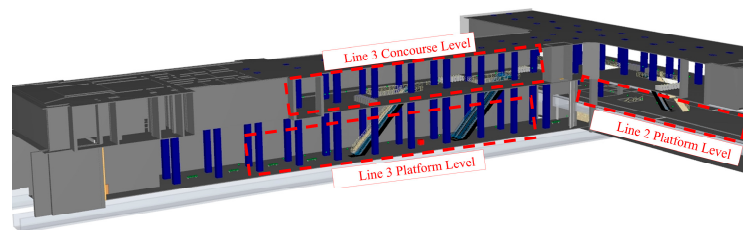


Figure 2. Overview of the T-interchange model.

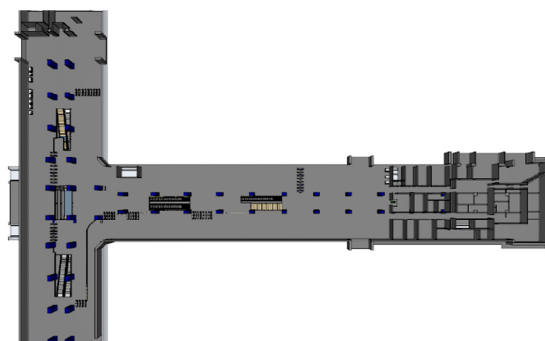


Figure 3. Layout of station level.

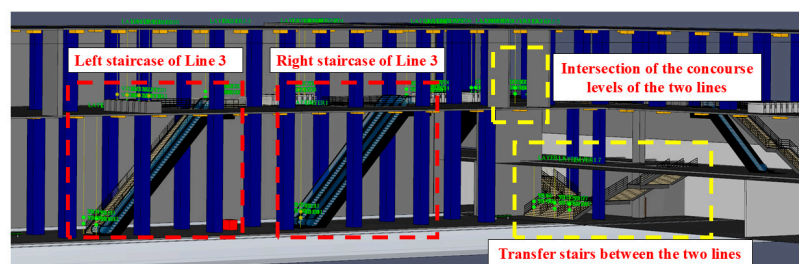


Figure 4. Location of key evacuation points.

3. Numerical Model Setup

3.1. Model Configuration and Grid Sensitivity

A three-dimensional fire model was developed using the Pyrosim software (2023.2) [20], where the computational domain was discretized using a structured mesh. The fire characteristic diameter (D^*) was calculated as approximately 2.4 m based on the heat release rate. Regarding the boundary conditions, the external surfaces of the computational domain were set to OPEN with an ambient pressure of 101,325 Pa. While the station tunnel ends were modeled as closed walls to delineate the specific interchange zone, the station entrances and exits remained open to the atmosphere. This setup allows for natural air replenishment, or make-up air, driven by the negative pressure differential created by the mechanical exhaust system, ensuring mass conservation and pressure stability within the simulation domain.

According to the FDS guidelines, the recommended grid resolution (D^* / δ_x) ranges from 4 to 16 [21], which corresponds to grid sizes between 0.15 m and 0.60 m. To scientifically determine the optimal grid size, a rigorous quantitative grid independence analysis was performed using four distinct mesh sizes of 0.8 m, 0.6 m, 0.5 m, and 0.3 m. The finest mesh of 0.3 m was utilized as the numerical reference solution. Grid sensitivity was assessed by calculating the relative error (ϵ) for two critical safety parameters, specifically the Peak Ceiling Temperature Rise (ΔT_{max}) directly above the fire source and the Visibility Threshold Time (t_{vis}) at the transfer stairway, defined as the time required for visibility to drop below 10 m.

The comparison results indicated that the coarse 0.8 m grid resulted in a T_{max} of 137.31 °C and a t_{vis} of 98.5 s. When compared to the reference solution (0.3 m mesh), which yielded a T_{max} of 156.89 °C and a t_{vis} of 113.96 s, the relative errors were 14.3% for temperature rise and 13.6% for visibility time. These deviations exceed the acceptable engineering tolerance and confirm that 0.8 m is too coarse to accurately capture the plume dynamics and numerical diffusion. Conversely, the 0.6 m grid yielded a T_{max} of 146.35 °C and a t_{vis} of 106.2 s. The relative errors significantly decreased to 7.7% for temperature and 6.8% for visibility. These values distinctively fall within the standard 10% error margin for fire engineering simulations, which indicates reliable convergence. Further refining the grid to 0.5 m resulted in a T_{max} of 147.99 °C and a t_{vis} of 107.0 s, corresponding to errors of 6.5% and 6.1%. Although the 0.5 m mesh offers a slight improvement in accuracy compared to the 0.6 m mesh with an error reduction in less than 1.2%, it entails a substantial increase in computational cost due to the cubic relationship between grid size and total cell count. Consequently, the 0.6 m mesh was adopted as the optimal choice to balance computational efficiency and numerical accuracy for this large-scale station model.

3.2. Fire Scenarios and Safety Criteria

The simulated fire scenarios were defined as severe accidental fires or typical arson incidents resulting in the full combustion of a single subway carriage, including luggage and interior linings. Extreme public safety incidents, such as terrorist attacks involving

explosives, were excluded from this study. A peak Heat Release Rate (HRR) of 10 MW was selected, which aligns with the design fire curves for modern steel/aluminum metro carriages specified in EN 45545-2 [22] and engineering practices under NFPA 130 [23]. This value represents a worst-case design scenario for the standard evacuation system, corresponding to the flashover phase of a single carriage, while excluding catastrophic multi-carriage events exceeding 20 MW. The fire growth followed an ultrafast t^2 curve ($\alpha = 0.1876 \text{ kW/s}^2$), representing the most severe condition for evacuation design. The ambient temperature was set to 20.0 °C. The fire source was positioned at the center of the Line 3 platform (a typical high-risk area), with 15 monitoring points deployed at key evacuation nodes—including the concourse escalator entrance, track intersection, and transfer stairways—to record temperature, visibility, and smoke layer height.

Three critical parameters were selected as safety criteria based on their impact on personnel safety:

- (1). Temperature Threshold: Previous research [24] indicates that respiratory function is severely impaired at temperatures exceeding 65.0 °C at a height of 1.6 m. Consequently, 1.6 m was adopted as the monitoring baseline to cover the respiratory zone.
- (2). Critical Visibility: With an initial visibility of 30.0 m, a conservative threshold of 10.0 m at a height of 1.6 m was adopted as the evacuation safety criterion, referencing critical values for both small and large spaces [25].
- (3). Smoke Layer Height: A critical threshold of 1.6 m (eye-level upper limit) was established to ensure the smoke layer remains above this height. Detectors were installed at key nodes to monitor real-time height variations, enabling a comprehensive risk assessment in conjunction with temperature and visibility data.

4. Results Analysis and Discussion

4.1. Simulation Scenarios and Parameter

In the numerical model, the fire source was positioned at the center of the Line 3 platform and flanked by automatic escalators. A transfer stairway located between the west side of Line 3 and Line 2 serves as a unidirectional pedestrian access from the concourse to the platform. Preliminary simulations revealed a significant correlation between smoke spread characteristics and the arrival time at key nodes with two geometric variables: the vertical height difference (H) between the platform and concourse layers and the horizontal distance (L) from the fire source to the track intersection. Consequently, based on extensive surveys of T-type interchange stations, H and L were introduced as the key structural parameters to investigate the governing mechanisms of smoke dispersion in stations with varying geometric configurations. The variation ranges were defined as H ranging from 8.9 m to 12.9 m with an increment of 1.0 m and L ranging from 20.0 m to 60.0 m with an increment of 5.0 m. Distinct scenarios were established in the numerical simulations by varying H and L while maintaining the constant relative position of the fire source and adjacent escalators.

Considering the impact of fire on personnel safety, the automatic escalators, the concourse track intersection, and the west-side transfer stairway were identified as critical evacuation bottlenecks. The smoke arrival times at these three nodes were denoted as T_1 , T_2 , and T_3 , while the critical danger times for smoke to cause injury were denoted as T_{s1} , T_{s2} , and T_{s3} , respectively. A series of CFD simulations were conducted to generate comprehensive datasets from which mean values were derived. Table 1 defines the key parameters for the simulations. For scenarios with constant H and variable L , critical timing data for smoke spread to the concourse are summarized in Table 2. Correspondingly, Tables 3 and 4 present the critical timing data for smoke spread to the Line 2 concourse (constant H , variable L) and the west-side transfer stairway (constant H , variable L), respectively.

Table 1. Definition of simulation parameters.

Parameters	Definition
H	Vertical height difference between the concourse and platform levels
L	Straight-line distance between the fire source and the intersection of the two lines in the T-type interchange station
T_1	Time from ignition until smoke spreads to the Line 3 concourse level
T_2	Time from ignition until smoke spreads to the Line 2 concourse level
T_3	Time from ignition until smoke spreads to the transfer stairs on the west side of the Line 3 platform
T_{s1}	Critical time when smoke conditions at the Line 3 concourse level pose a threat to personnel safety
T_{s2}	Critical time when smoke conditions at the Line 2 concourse level pose a threat to personnel safety
T_{s3}	Critical time when smoke conditions at the transfer stairway on the west side of the Line 3 platform pose a threat to personnel safety

Table 2. Summary of simulation results for T_1 and T_{s1} ($L = 40$ m).

Operating Conditions	H/m	T_1/s	T_{s1}/s
1	8.9	49.5	51.8
2	9.9	50.7	49.1
3	10.9	56.9	54.7
4	11.9	57.5	65.2
5	12.9	64.3	71.0
6	13.9	68.8	75.7
7	14.9	72.7	82.8

Table 3. Summary of simulation results for T_2 and T_{s2} ($H = 11.9$ m).

Operating Conditions	L/m	T_2/s	T_{s2}/s
8	30	128	182
9	35	164	213
10	40	174	255
11	45	194	257
12	50	207	289
13	55	266	311
14	60	270	322

Table 4. Summary of simulation results for T_3 and T_{s3} ($H = 11.9$).

Operating Conditions	L/m	T_3/s	T_{s3}/s
8	30	105	103
9	35	106	105
10	40	108	106
11	45	112	108
12	50	117	114
13	55	126	122
14	60	128	125

4.2. Influence of Structural Parameters on Spread Timing

Analysis of the relationships of T_1 and T_{s1} with H , and T_2 , T_{s2} , T_3 , and T_{s3} with L , revealed distinct linear trends. Linear fitting yielded low residual fluctuations, while nonlinear alternatives (e.g., power functions) demonstrated no significant improvement in goodness of fit (R^2). Consequently, linear regression was adopted to quantify these correlations.

4.2.1. Height Difference (H)

In this study, T_1 denotes the smoke arrival time at the concourse, while T_{s1} represents the critical time for threat onset. To quantify the influence of H on these parameters, linear fitting was performed on the simulation data. The fitting curves and data distribution are presented in Figure 5. The relationships derived from the linear regression analysis are expressed in Equations (1) and (2).

$$T_1 = 4.0 H + 12.0, R^2 = 0.974 \quad (1)$$

$$T_{s1} = 5.8 H - 4.7, R^2 = 0.946 \quad (2)$$

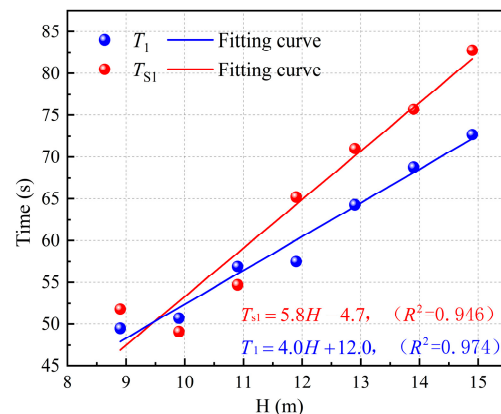


Figure 5. Linear fitting of vertical dispersion timing (T_1 and T_{s1}) against height difference (H).

A strong positive correlation was observed between T_1 and H , which indicates that the smoke arrival time increases with the vertical height difference. Specifically, as H increased from 8.9 m to 12.9 m, T_1 rose from 49.5 s to 64.3 s, representing a 29.8% increase. The slope of 4.0 s/m implies a vertical dispersion delay of approximately 4.0 s per meter of height increase. This latency is primarily attributed to the extended vertical trajectory of the smoke plume, which necessitates a longer duration for stratification and stabilization.

Significantly, the regression analysis reveals that the slope for the critical danger time T_{s1} (5.8 s/m) exceeds that of the smoke arrival time T_1 (4.0 s/m). This discrepancy indicates that as the height difference (H) increases, the safety margin, defined as the time interval between initial smoke arrival and the onset of critical conditions ($T_{s1} - T_1$), widens. Physically, this phenomenon is attributed to the enlarged smoke reservoir capacity inherent in deeper stations. While the smoke plume travels a longer vertical distance (delaying T_1), the increased upper-level volume requires a greater mass of smoke to fill before the smoke layer descends to the critical respiratory height. Consequently, the buffer time available for early evacuation expands with station depth.

However, this temporal gain presents a dual effect in the context of total evacuation safety. While a larger H delays the onset of hazardous conditions (increasing the Available Safe Egress Time, ASET), it simultaneously extends the physical vertical evacuation distance for passengers (increasing the Required Safe Egress Time, RSET). Therefore, the design of H represents a critical trade-off. Based on the intersection of dispersion delay and evacuation efficiency, a recommended upper limit of 11.0 m is proposed to optimize this balance. For deep stations where large H is unavoidable, simply relying on the passive buffer is insufficient; enhancement of lower-level mechanical smoke extraction is imperative to prevent the stagnation layer from settling before evacuation is complete.

4.2.2. Horizontal Distance (L)

In this analysis, T_2 denotes the smoke arrival time at the Line 2 concourse, while T_{s2} represents the critical time for threat onset. L signifies the horizontal distance between the fire source and the track intersection. Linear regression was performed on the simulation datasets for both T_2 and T_{s2} against L , and the fitting curves and data are presented in Figure 6. The relationships are expressed in Equations (3) and (4).

$$T_2 = 4.7 L - 13.0, R^2 = 0.952 \quad (3)$$

$$T_{s2} = 4.6 L + 52.0, R^2 = 0.967 \quad (4)$$

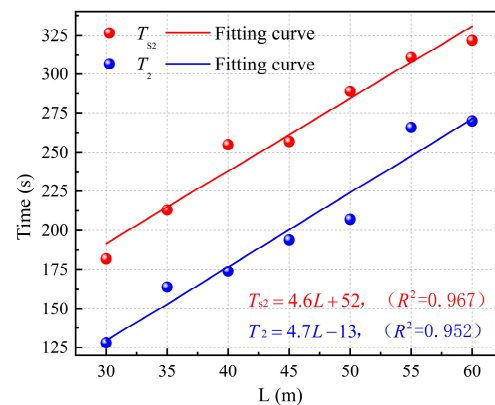


Figure 6. Linear fitting of dispersion timing to adjacent tracks (T_2 and T_{s2}) against horizontal distance (L).

A strong positive correlation exists between T_2 and L with a slope of 4.7 s/m, which indicates a dispersion delay of approximately 4.7 s per meter of distance increase. This result suggests that increasing L significantly retards smoke diffusion to adjacent tracks. At minimal L where the fire source is near the intersection, the high velocity within the turbulent jet core preserves kinetic energy, which facilitates rapid entrainment into the concourse and subsequent intrusion into Line 2. Conversely, at larger L , kinetic energy decay is accelerated by frictional resistance and entrainment effects within the long-distance channel, thereby significantly reducing the dispersion rate. This trend aligns with recent findings by Su et al. [26], who observed that smoke propagation in confined cross-passages is strictly governed by critical velocity thresholds. From a theoretical perspective, the observed linear correlation is consistent with the characteristics of confined corridor flow. Unlike radial ceiling jets in unconfined spaces where velocity decays rapidly, the smoke flow within the station corridor is laterally constrained by the walls. In this regime, provided the exhaust rate and fire buoyancy are constant, the smoke front maintains a relatively stable mean velocity over the studied distance. Consequently, the travel time increases linearly with the path length. However, it must be emphasized that these regression equations are empirical models derived under specific standardized engineering conditions. In this study, key parameters such as the Heat Release Rate (HRR, 10 MW) and smoke exhaust capacity (60 m³/s) were set strictly according to the Chinese National Standard GB 51298-2018 [19]. It is worth noting that these settings are also consistent with major international protocols, such as NFPA 130 [22] and EN 45545 [21], making the simulated scenarios representative of modern global subway systems. In actual engineering projects, these operating parameters are typically prescriptive and constant, whereas geometric parameters (H , L) vary significantly due to site-specific geological constraints. Therefore, these equations effectively quantify the impact of geometric variations under standard design scenarios. While the specific coefficients may adjust with different fire loads or

ventilation schemes, the identified linear trend offers a valuable reference for preliminary engineering design.

Correspondingly, T_{s2} exhibits a similar linear growth trend with a slope of 4.6 s/m. Notably, the intercept for T_{s2} is approximately 52.0 s, whereas T_2 has a theoretical negative intercept. This difference reflects that the smoke concentration requires accumulation time to reach hazard thresholds after arrival. The substantial intercept for T_{s2} reflects the inherent path latency associated with the tortuous trajectory from the platform through the escalator to the Line 3 and Line 2 concourses. Although a larger L delays arrival, the risk of visibility loss upon arrival remains significant due to cooling-induced sinking and compromised smoke extraction.

In engineering applications, the determination of L correlates with the transfer passage length and station layout. While extended transfer passages with a larger L function as natural smoke barriers to delay diffusion, they simultaneously elongate evacuation paths and may induce smoke recirculation and retention. Overly long passages are prone to intermediate cooling, sedimentation, and local backflow. Consequently, the installation of segmented smoke containment walls in long passages is recommended to effectively disrupt long-distance horizontal smoke transport.

4.2.3. Geometry at Staircases

In this analysis, T_3 denotes the smoke arrival time at the west-side transfer stairway, while T_{s3} represents the critical time for hazard onset. L signifies the horizontal distance from the fire source. Linear regression was performed on both T_3 and T_{s3} against L , and the results are presented in Figure 7. The fitting relationships are expressed in Equations (5) and (6).

$$T_3 = 0.84 L + 77.0, R^2 = 0.935 \quad (5)$$

$$T_{s3} = 0.77 L + 77.0, R^2 = 0.916 \quad (6)$$

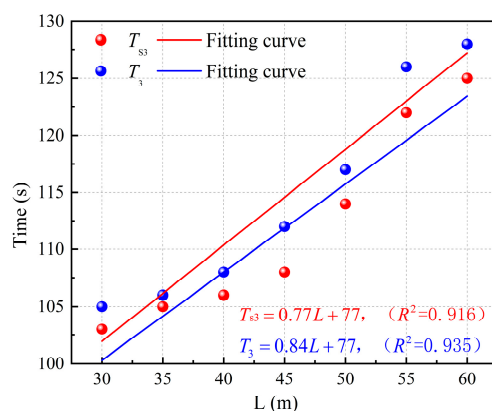


Figure 7. Linear fitting of dispersion timing at the transfer stairway (T_3 and T_{s3}) against horizontal distance (L).

A relatively weak correlation characterizes the relationship between dispersion timing and L . As L increased from 30 m to 60 m, T_3 rose from approximately 102 s to 127 s. The slope of 0.84 s/m is significantly lower than that observed in other zones, such as 4.7 s/m for T_2 , which indicates that the influence of horizontal distance on dispersion timing is marginal in this region. Similarly, T_{s3} exhibits a minimal slope of 0.77 s/m. This observation confirms that the horizontal fire source positioning is not the dominant factor governing dispersion timing in this zone. Instead, smoke spread is primarily controlled by local geometric constraints, manifesting as a distinct flow bottleneck effect.

As demonstrated by Chen et al. [27] in their analysis of stair area airflow, the complex interaction between buoyancy and geometric constraints creates local turbulence that defies

simple linear predictions. The narrow entrance of the transfer stairway and surrounding walls constitute strong flow obstructions that force the smoke to bypass or surmount obstacles prior to entry. This geometric interaction significantly attenuates the correlation between dispersion time and distance L . Furthermore, significant smoke recirculation was observed. Following buoyancy-driven accumulation at the platform ceiling, the smoke plume is obstructed by the wall above the stairway, which results in cooling, descent, and subsequent backflow towards the platform center. Over time, the high-density, low-temperature smoke fills the stairway volume and leads to a rapid deterioration of visibility.

In engineering practice, the determination of L is coupled with the transfer passage length and station layout. Given the risks of high-concentration smoke accumulation induced by geometric constraints, sole reliance on planar layout adjustments proves insufficient for enhancing stairway safety. Consequently, the installation of mechanical pressurization systems or barriers at these critical bottleneck nodes is recommended to mitigate risk.

4.3. Smoke-Spread Characteristics and Model Verification

This section analyzes the smoke dispersion characteristics within a T-type interchange station as visualized via visibility slice contours in Figure 8. The analysis emphasizes the impact of the vertical height difference (H) and horizontal fire source location (L) on the dynamics of dispersion.

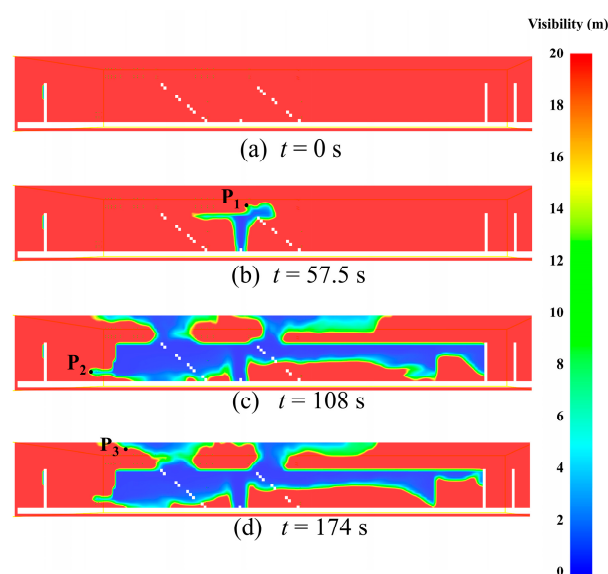


Figure 8. Dynamic evolution of 2D visibility slices at $Y = -10.5$ m. From top to bottom: (a) Initial state at $t = 0$ s; (b) Smoke front reaches the Line 3 concourse detection point (P_1 , corresponding to T_1) at $t = 57.5$ s; (c) Smoke reaches the west-side transfer stairway (P_2 , corresponding to T_3) at $t = 108$ s; (d) Smoke intrudes into the Line 2/Line 3 interface (P_3 , corresponding to T_2) at $t = 174$ s.

4.3.1. Dynamic Smoke Evolution

The visibility distribution contours illustrate a distinct dynamic evolution process, characterized by the competition between thermal buoyancy and inertial forces. This process is categorized into three physical phases described below.

Phase I involves vertical impingement and ceiling jet formation during the interval of 0–57.5 s. Driven by strong thermal buoyancy, the high-temperature smoke plume ascends rapidly. Upon impinging on the station ceiling, the vertical momentum transitions into horizontal momentum to form a radial ceiling jet. By $t = 57.5$ s (Figure 8b), the smoke front has migrated through the escalator shaft and reached the detection point P_1 at the Line 3 concourse.

Phase II is characterized by stack effect driven spread between 57.5 s and 108.0 s. Following the ascent, the smoke spreads horizontally along the concourse ceiling. The vertical escalator shaft acts as a chimney where the stack effect accelerates the upward smoke transport and induces localized turbulence. By $t = 108.0$ s (Figure 8c), the smoke layer has propagated to the west side and fully engulfed the transfer stairway (P_2), resulting in significant visibility degradation in the upper zones indicated by the blue regions.

Phase III involves destratification and gravitational settling from 108.0 s to 174.0 s. As the smoke spreads further, heat exchange with the cool walls and mixing with ambient air induce a cooling effect that increases the smoke density. This process leads to destratification, where the cooler and denser smoke loses thermal stability and settles gravitationally. By $t = 174.0$ s (Figure 8d), a thick stagnation layer has accumulated at the floor level and transgressed the boundary into the Line 2 concourse (P_3). Figure 8d clearly shows that visibility at the intersection drops rapidly below the safety threshold due to the limited smoke extraction capacity relative to the high mass flux.

4.3.2. Regression Model Verification

A representative scenario ($H = 11.9$ m, $L = 40.0$ m) was selected to verify the reliability of the established smoke dispersion prediction models, specifically the linear relationships between T_1 and H , T_2 and L , and T_3 and L . This selection also provides visual evidence for the data listed in Tables 2–4. While presenting CFD contours for every scenario in the tables would be redundant, this representative case serves to visualize the physical flow patterns underlying the statistical data.

The visibility distribution at the $Y = -10.5$ m slice, as illustrated in Figure 8, visualizes smoke propagation to three critical nodes, specifically the Line 3 concourse, the concourse intersection, and the transfer stairway. The actual smoke arrival times were extracted by analyzing the temporal evolution of these contours. The theoretical predictions yielded by substituting the scenario parameters ($H = 11.9$ m, $L = 40.0$ m) into the constructed linear regression equations were subsequently compared with simulated observations. The model predicted 59.6 s for the Line 3 concourse (T_1), which closely aligned with the simulated time of 57.5 s. Similarly, the prediction for the Line 2/Line 3 intersection (T_2) was 175.0 s, showing negligible deviation from the simulated 174.0 s, while the transfer stairway prediction (T_3) of 110.6 s aligned well with the simulated 108.0 s.

Furthermore, the regression models for the critical danger time (T_s) were rigorously verified against the CFD simulation results visualized in Figure 9 to ensure the reliability of safety assessments. This figure provides the direct physical interpretation of the critical timing data presented in the tables.

Substituting the scenario parameters ($H = 11.9$ m, $L = 40.0$ m) into the established equations yielded the following comparisons. For the Line 3 concourse (T_{s1}), the regression model predicted a critical time of 64.3 s, which closely aligned with the simulated onset time of 65.2 s and corresponded to a relative error of 1.4%. For the transfer stairway bottleneck (T_{s3}), the theoretical prediction was 107.8 s, which deviated marginally from the simulated 106.0 s with a relative error of 1.7%. Similarly, at the Line 2 concourse interface (T_{s2}), the model predicted 236.0 s versus the simulated 255.0 s, resulting in a relative error of 7.5%. The minimal relative errors between theoretical predictions and numerical results indicate a strong correlation. These visualization results confirm that the linear regression models derived from the multiple simulation scenarios in Tables 2–4 effectively capture the actual smoke dispersion laws. Consistent validation results were observed across other simulation conditions, though visualizations are omitted for brevity to focus on the representative trends. In conclusion, the established quantitative relationships exhibit robust engineering applicability and provide a reliable basis for the prediction of station evacuation timelines.

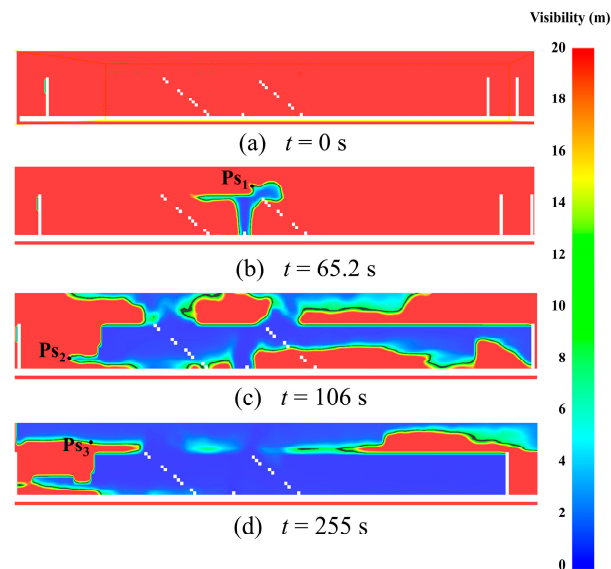


Figure 9. Dynamic evolution of visibility contours at critical danger moments (T_s) for the validation scenario ($H = 11.9$ m, $L = 40$ m). From top to bottom: (a) Initial state; (b) Critical condition reached at Line 3 concourse (P_{s1}) at $t = 65.2$ s; (c) Critical condition reached at transfer stairway (P_{s2}) at $t = 106$ s; (d) Critical condition reached at Line 2 interface (P_{s3}) at $t = 255$ s.

5. Conclusions

This study established a three-dimensional numerical model for a typical T-type subway interchange station to quantify the dynamic evolution of smoke spread. By introducing the vertical height difference (H) and horizontal distance (L) as key variables, the research elucidated the underlying dispersion mechanisms and their implications for evacuation safety.

A primary finding of this work is the dual mechanism that governs vertical smoke dispersion. While an increased vertical drop (H) linearly delays the initial arrival of the smoke front (≈ 4.0 s/m), it provides an even greater delay for the critical danger time (≈ 5.8 s/m) due to the enlarged smoke reservoir effect in the upper concourse. This result suggests that deeper stations possess a stronger passive buffering capacity against smoke layer descent. However, this benefit is counteracted by the increased vertical distance required for passenger egress. Therefore, in deep underground stations, the challenge lies not in the speed of smoke descent but in ensuring that the Required Safe Egress Time (RSET) does not exceed the extended Available Safe Egress Time (ASET).

Regarding horizontal propagation, the smoke intrusion time into adjacent lines exhibits a strong linear correlation with distance (L), which is a characteristic attributable to the confined channel flow regime within the station corridor. In contrast, dispersion at the transfer stairway is governed by local geometric bottlenecks rather than the source distance. This phenomenon makes the stairway a critical vulnerability where high-concentration smoke accumulates rapidly and effectively decouples the hazard onset from the horizontal location of the fire. Although these geometric correlations are derived from a T-type configuration, the identified dual mechanism is driven by fundamental plume physics and is thus broadly applicable to L-type and Cross-type interchanges involving vertical connections. However, horizontal dispersion patterns in Cross-type stations may differ because multi-directional flow bifurcation could accelerate momentum dissipation compared to the constrained single-channel flow observed in T-type structures.

Based on these insights, specific engineering strategies are proposed to enhance fire safety design. Statistical analysis of the danger onset time (T_s) suggests that controlling the vertical height difference to $H \leq 11.0$ m effectively balances the benefits of dispersion delay

against the risks associated with extended evacuation distances. For deep underground stations ($H > 11.0$ m) where this threshold is exceeded, standard smoke containment measures may prove insufficient. Therefore, it is recommended to install rigid draft curtains of sufficient depth, specifically at least 80 cm based on the observed smoke layer profile, at transfer openings to mechanically block the thickened and sinking smoke layer. Furthermore, at critical bottlenecks such as transfer stairways where passive geometric adjustments are ineffective, active mechanical pressurization systems should be deployed to prevent smoke backflow [28]. Future research will focus on coupling these smoke dispersion models with agent-based crowd simulation algorithms [29,30] to evaluate personnel evacuation efficiency under dynamic smoke hazards.

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