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Optimizing Fire Safety and Ventilation Strategies for Structural Integrity in Rail Tunnels

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Abstract

Rail systems are vital to the modern urban infrastructure and offer efficient and eco-friendly transportation solutions. The Gaziray Rail System Line in Gaziantep, Türkiye addresses the region's transportation needs while considering potential hazards such as electrical malfunctions and fuel leaks. This study thoroughly assesses fire occurrences and how they affect the structural integrity of tunnel elements, thereby affecting repair costs and continuity of operations. Fire tests and modeling were employed to precisely assess tunnel fire effects, focusing on potential train fires in Gaziray Rail System Line tunnels. This study highlights the importance of vital airflow for effectively directing smoke. It also identifies the ventilation systems required to ensure optimal airflow while maintaining the structural integrity and evacuation pathways. The study identified 18 jet fans with an outlet velocity of 35.7 m/s and flow rate of 40.4 m³/s, which is essential for safe evacuation. The maximum wall temperatures ranged from 774 to 923°C, highlighting the potential fire severity. Recommendations emphasize fire-resistant materials, optimized ventilation systems, and reinforced emergency evacuation measures that are crucial for enhanced safety. Continuous training and awareness efforts ensure swift and secure evacuation during fire incidents, contributing to robust fire safety protocols for the Gaziray Rail Line.

Keywords: Railway Systems; Tunnels; Structural Fire Safety; Simulation; Risk Analysis.

1. Introduction and Theoretical Framework

Public transportation, particularly rail systems, is essential for reducing congestion, improving mobility, and minimizing the environmental impacts in urban areas. As a high-capacity and eco-friendly transit solution, rail systems can significantly lower greenhouse gas emissions, particularly when electrification replaces diesel traction. A study on the Northeast Brazil Railway System [1] highlighted how electrification and renewable energy integration can further enhance sustainability, reinforcing the need for investment in modernized transit networks. These systems offer various advantages, primarily by providing high-speed and regular services, thus mitigating the delays and time losses associated with road traffic issues. Moreover, their operation and maintenance costs are relatively low. Owing to their environment-friendly nature, rail systems assist in reducing carbon footprints, making them an environmentally conscious transportation option. Distinct types of rail systems are available, including light rail transit systems, metro lines, trams, and train lines, each of which is distinguished by its specific features and advantages. For example, metro lines provide high-speed, high-capacity services; however, light-rail systems are known to be extremely economical. Although railway tunnels enhance transportation efficiency by providing weather-protected routes, their enclosed nature raises significant safety concerns. Fire incidents in tunnels pose unique challenges owing to the restricted airflow, rapid heat accumulation, and limited evacuation options. Addressing these risks requires robust ventilation strategies and initiative-

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taking fire mitigation measures. These challenges become particularly critical in emergency situations, where rapid response mechanisms are necessary. Given the enclosed nature of tunnels, fire incidents can pose significant risks to infrastructure integrity and passenger safety, necessitating the development of comprehensive fire-prevention and mitigation strategies. The design and construction of tunnels constitutes a complex process that is crucial for managing traffic flow in cities and enhancing the safety and efficiency of public transportation services.

In recent years, advanced safety management approaches, such as systems thinking, have been integrated into tunnel designs. Bjelland et al. [2] emphasized initiative-taking fire safety management, advocating the use of fire-resistant materials, and optimized ventilation systems to mitigate risks. Their findings highlight that integrating fire-resistant materials and ventilation solutions into tunnel infrastructure can significantly improve resilience. Notably, significant disparities exist between railway and road tunnels [3]. Factors such as the tunnel length, depth, gradient, and orientation significantly affect the construction costs and tunnel durability. Moreover, the tunnel design must consider air quality and ventilation efficiency to ensure optimal safety conditions.

Effective fire ventilation strategies are essential to control smoke propagation and improve evacuation safety. Long et al. [4] explored various ventilation modes in subway stations, emphasizing the role of joint ventilation systems in reducing fire-induced smoke and pollutants. Similarly, Xu et al. [5] demonstrated that optimized ventilation strategies, including mechanical makeup air systems, significantly enhance the smoke extraction efficiency and ensure safe evacuation. These findings highlight the necessity of integrating advanced ventilation mechanisms into tunnel designs to mitigate fire hazards effectively. Although numerous studies have addressed fire safety in railway tunnels, most have focused on individual safety measures or isolated ventilation performances [4–6]. However, a comprehensive analysis integrating multiple fire safety elements, including fire growth, smoke dispersion, ventilation efficiency, and structural integrity, remains limited. This study uniquely combines SES v4.1 simulations with structural integrity assessments to evaluate ventilation strategies under fire conditions. Unlike previous studies that relied on general tunnel fire models, this research was specifically tailored to the Gaziray Rail System tunnel, considering real-world constraints and system specifications.

Tunnels are designed to withstand extreme loading conditions, including accidents and extraordinary events, with a lifespan of approximately 120 years [7]. Among the most significant hazards in tunnel environments are fire incidents, which can escalate rapidly because of confined spaces and limited ventilation. The temperature within a tunnel during a fire can reach 1200°C at the fire source, 900°C in the upper tunnel air layer, and 500–600°C in smoke-dense zones [6, 8, 9]. The thermal properties of tunnel linings and surrounding materials, particularly in the presence of groundwater, significantly influence heat transfer and temperature distribution during fire events [10–12]. A fire results from a combustion process that requires three primary elements: heat, fuel, and oxygen [13, 14]. The behavior of fire in tunnels is inherently nonlinear and governed by two primary factors: the accumulation of hot air in enclosed spaces, which accelerates combustion through radiation heat transfer, and oxygen availability, where limited supply can either suppress or intensify fire growth depending on the ventilation conditions and tunnel structure. Fires in tunnels progress through two distinct stages: pre- and post-flashover. The pre-flashover stage is critical for human survival and evacuation as temperatures remain within tolerable limits. During this phase, open fires, which remain localized and less intense, can occur, or compartment fires, which develop in enclosed spaces and escalate rapidly, posing severe risks to passengers and infrastructure. Once a fire reaches the post-flashover stage, the temperature can exceed 1000°C, causing extensive structural damage and rendering evacuation nearly impossible. At this stage, the flames spread uncontrollably, thereby compromising the integrity of the tunnel walls and ceilings. Given the enclosed nature of tunnels, early fire detection, optimized ventilation systems, and well-planned evacuation procedures are crucial for fire hazard mitigation. Since the 1960s, fire detection and alarm systems have been integral to tunnel safety [15, 16]. Recent advancements in fire safety technologies have further enhanced real-time fire detection, automated suppression systems, and emergency response coordination, thereby significantly improving tunnel fire resilience [17, 18].

Historical tunnel fire incidents have reinforced the importance of implementing fire safety measures. Notably, the Channel Tunnel (France) experienced major fires in 1996, 2006, and 2008, resulting in severe structural damage and operational disruptions [19–21]. These events underscore the necessity of a fire-resistant tunnel design, optimized ventilation mechanisms, and comprehensive risk assessment protocols. Studies such as the 2023 Global Facility for Disaster Reduction and Recovery (GFDRR) report highlight the effectiveness of risk-informed decision-making, advanced suppression systems, and real-time monitoring in reducing casualties and infrastructure damage [22]. Similarly, the 2024 Economics for Disaster Prevention and Preparedness (EDPP) report emphasized the economic and safety benefits of early warning systems and enhanced evacuation protocols [23]. Controlled experiments and post-fire analyses confirmed that high-capacity ventilation systems significantly reduced smoke density and improved both the survivability and evacuation success rates. These findings highlight the necessity of integrating adaptive infrastructure, advanced fire modeling techniques, and routine safety assessments into tunnel fire prevention strategies. Initiative-taking tunnel fire management, aligned with global disaster resilience frameworks, such as the Sendai Framework, is essential for ensuring urban safety and sustainable transportation infrastructure.

Several catastrophic railway tunnel fires, including the Summit Tunnel fire (UK, 1984) [24], Great Belt Tunnel TBM fire (Denmark, 1994) [3], Mont Blanc Tunnel fire (France and Italy, 1999) [25], Daegu Metro fire (South Korea, 2009) [26], and Kaprun Funicular Tunnel fire (Austria, 2000) [27], have exposed critical deficiencies in emergency response, fire-resistant materials, ventilation efficiency, and evacuation procedures, prompting international advancements in risk assessment methodologies [28, 29], stricter fire safety regulations, and the integration of computational fire modeling techniques to enhance tunnel fire prediction and mitigation.

Fire modeling has evolved significantly since the 1900s [30, 31], progressing from basic fire curves to advanced computational simulations. In the 1950s, Thomas & Heselden [32], Kawagoe [33], and Kawagoe & Sekine [34] developed equations relating fire temperature to ventilation conditions during compartment fires. By the 1970s, parametric fire temperature-time curves were introduced, incorporating the effects of conductive materials such as bricks, wood, and plaster on fire behavior. In the 1990s, fire models were expanded to simulate large enclosed spaces such as parking garages and hangars [35, 36]. Since the 2000s, advancements in computational techniques have enabled the simulation of localized fire spread through the integration of Computational Fluid Dynamics (CFD) and Finite Element Method (FEM), thereby significantly improving fire prediction and safety strategies. Modern fire simulation tools, such as computational fluid dynamics (CFD) and fire dynamics simulators (FDS), play a crucial role in optimizing tunnel fire safety. These advanced modeling techniques enable engineers to predict fire spread and smoke behavior in enclosed environments, optimize ventilation systems to control heat and gas dispersion, and assess structural responses to high-temperature exposure. By integrating these tools into tunnel design and fire safety planning, engineers can develop more effective mitigation strategies and enhance overall tunnel resilience. Advanced studies have demonstrated the importance of integrating CFD with thermal simulations to enhance the fire safety in tunnels. For instance, Lumet [37] applied Large-Eddy Simulation (LES) to analyze pollutant dispersion and smoke propagation, while Beausoleil-Morrison [38] highlighted the benefits of adaptive controls for improving real-time fire modeling accuracy. These advancements have led to the development of more efficient evacuation protocols, advanced ventilation and suppression strategies, and stronger tunnel infrastructure capable of withstanding fire-induced loads, ultimately enhancing tunnel fire resilience and emergency response effectiveness.

Extensive research on tunnel fires has provided critical insights into fire dynamics, smoke behavior, and risk mitigation strategies. Full-scale fire experiments and CFD simulations have been instrumental in analyzing smoke generation, dispersion, and ventilation efficiency [39, 40]. Thomas [41] and Oka and Atkinson [42] explored buoyant fluid movement and smoke control, while Ingason & Lönnermark [43] examined time-dependent heat and temperature developments in tunnel fires. Further studies by Li & Ingason [44] investigated the role of ventilation in fire spread with and without suppression systems. Nakahori et al. [45] assessed ventilation strategies for bidirectional tunnels, particularly focusing on zero-flow conditions. Additionally, Kodur and Naser [46] examined fire hazards in critical transportation infrastructure and proposed effective risk reduction measures, whereas Tarada & King [3] evaluated fire protection techniques, including spray-applied fireproofing, cementitious coatings, and polypropylene fibers, as well as the effectiveness of fixed fire suppression systems. Further advancements in numerical modeling and computational simulations have significantly improved tunnel fire safety assessments. CFD-based fire simulations are widely employed to calculate heat transfer, smoke density, toxic gas distribution, and ventilation performance [47]. FDS [17, 48] provides fire growth predictions, heat transfer modeling, and suppression system activation times [34, 35, 49]. Additionally, visualization tools such as Smokeview (SMW) and Consolidated Fire and Smoke Transport (CFAST) [50, 51] enable three-dimensional (3D) simulations of smoke propagation and fire evolution, thereby assisting emergency planning and evacuation strategies. Despite these advancements, tunnel fires remain highly complex events with multiple unknown variables, including combustion materials, ignition methods, and fire-spread rates. Data from landmark studies, such as the Memorial Tunnel Fire Test [52] and Runehamar Fire Test [53], have been instrumental in validating fire behavior models and establishing key parameters for fire growth, decay rates, and ignition points. These findings provide safety measures to ensure that emergency exits, ventilation openings, and suppression systems are designed to facilitate safe and efficient passenger evacuation in the event of a tunnel fire.

The Gaziantep Suburban Project (Gaziray) Rail System Line is a joint venture between the Republic of Türkiye State Railways (TCDD) and the Gaziantep Metropolitan Municipality, serving as an environmentally friendly mass-transit system in Gaziantep, Türkiye. Providing suburban transportation services between Gaziantep City Center and Nizip District, approximately 25 km away, the project aimed to facilitate urban transportation and reduce traffic congestion. With a total length of 25.532 km (25,532 m), the line features 16 stations, two of which are underground, and commenced operations on November 5, 2022 (see Table 1). Following İZBAN-İzmir (formerly known as Egeray), Marmaray-İstanbul, and Başkentray-Ankara, it is the fourth suburban train system in Türkiye [54]. All vehicles on the line operate using electricity and emit no gases harmful to the environment. The operation of a line incorporates smart systems to ensure its energy efficiency. Similar to modern security systems, all stations feature closed-circuit television (CCTV) cameras, fire detection and suppression systems, emergency announcements, and emergency exits. Furthermore, each wagon is equipped with a door and window alarm system to enhance line security. The Gaziray Rail System Line features a single-rectangular tube box section and a four-track tunnel design, as depicted in Figure 1, and is detailed in

Tables 2 and 3. The total length of the Gaziray Rail System Line is 3.634,336 m, incorporating two underground stations with cut-and-cover sections: Adliye and Topraklık. In addition to these underground stations, the remaining stations were designed as railway-level-crossing stations. This study specifically examined the impact and evaluation of potential train fires on tunnel structures between 11+995 km (beginning at Selimiye Station) and 16+622 km (ending at Mücahitler Station). This study focuses on cut-and-cover sections and underground stations in Adliye and Topraklık. The analysis aimed to assess the structural integrity and safety measures in place to mitigate the effects of fire incidents within these critical sections of the rail line.

Table 1. Station information of the Gaziray Rail System Line [54]

No.	Stations	District	Type	Distance to first station [km]
1	Başpınar	Şehitkamil	Railway-Level Crossing	Beginning
2	OSB-3			1+965
3	OSB-4			2+975
4	Dülük			5+345
5	Stadyum			8+615
6	Beylerbeyi			9+525
7	Fıstıklık			10+455
8	Selimiye			12+095
9	Adliye		Underground	13+961
10	Topraklık			15+685
11	Mücahitler		Railway-Level Crossing	16+521
12	Gaziantep Garı			17+591
13	Göllüce			19+611
14	Seyrantepe			21+741
15	Mustafa Yavuz			22+531
16	Taşlıca			24+811

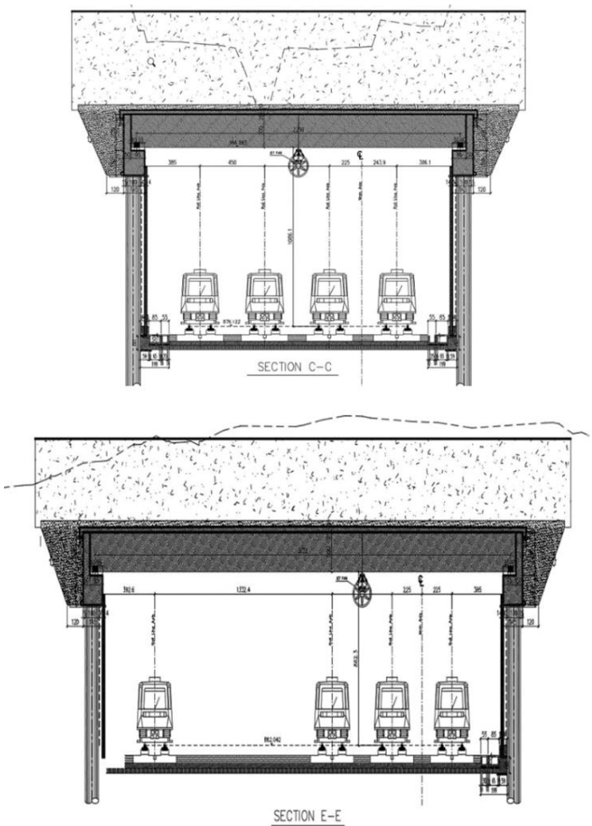

Figure 1. Typical cross-sections of the single-rectangular tube box section and four-track tunnel in the Gaziray Rail System Line (unit of measurement used for elevations is [m], and for dimensions, it is [cm]) (Adopted from Gaziray Rail System Line [54]).

Table 2. Detailed station and section data for the Gaziray Rail System Line from 11+995 km to 16+622 km

Stations		Sections	Distance to first station [km]	Slope [%]
Selimiye	Start		11+995	-1.600
	Middle		12+095	-1.600
		A-A	12+170	-1.600
	End		12+195	-1.600
		B-B	12+640	-1.600
		C-C	12+890	-1.600
		D-D	13+350	-1.600
		E-E	13+770	-1.600
Adliye	Start		13+861	-1.600
	Middle		13+961	-1.600
	End		14+061	-1.600
		F-F	14+110	-1.600
		G-G	14+410	-0.600
		H-H	14+570	-0.600
		I-I	14+730	-0.600
		J-J	15+110	-1.425
		K-K	15+390	-1.425
Topraklık	Start		15+585	-1.425
		L-L	15+590	-1.425
	Middle		15+685	-1.425
	End		15+785	-1.425
		M-M	15+870	-1.425
		N-N	15+930	-1.425
		O-O	15+990	-1.425
		P-P	16+170	-1.425
		R-R	16+310	+0.900
		S-S	16+370	+0.900
Mücahitler	Start		16+422	+0.900
	Middle		16+522	+0.900
	End		16+622	+0.900

Table 3. Single-rectangular tube box section and four-track tunnel cross-section details

Sections	Height [m]	Width [m]	Cross-sectional area [m^2]
C-C	10.86	21.40	232.40
D-D	9.80	21.40	209.72
E-E	8.82	30.10	265.48
F-F	8.04	25.75	207.03
G-G	8.19	21.30	174.45
H-H	9.15	21.30	194.90
I-I	10.08	21.30	214.70
J-J	7.63	21.30	162.52
K-K	7.58	25.61	194.12
L-L	7.58	29.94	226.95
M-M	7.58	26.05	197.46
N-N	7.58	21.58	163.58
O-O	7.58	21.20	160.70
P-P	7.53	21.20	159.64
R-R	7.52	22.23	167.17
S-S	7.53	34.01	256.10

Table 2 provides a detailed breakdown of the Gaziray Rail System Line, focusing specifically on the sections between 11+995 km and 16+622 km. The table lists all stations and sections within this range, along with their corresponding distances from the starting point at Selimiye Station. In addition, the table includes the slope percentages for each segment, indicating the gradient changes throughout the line. These comprehensive data are crucial for understanding the structural and operational characteristics of rail systems, particularly for evaluating the impact of potential train fires on tunnel structures. The tunnel structure was designed in an open-cut manner, with open portals at both ends. The open-cut tunnel structure comprises 14 ventilation openings, each measuring 4.8 m² (1.2 m x 4 m). In addition, there were nine emergency exit staircases within the tunnel. It is assumed that all passengers can be evacuated from the platform within 4 min and reach a safe point within 6 min in compliance with the rules of the National Fire Protection Association (NFPA) 130 [55]. The previous version, NFPA 130, 2020, also provides essential guidelines for the design and operation of fixed-guideway transit and passenger rail systems. The NFPA 130 standard, which governs the safety requirements for fixed-guideway transit and passenger rail systems, specifies a minimum walkway width of 760 mm. This standard is crucial for ensuring safe evacuation during emergencies and providing a clear path for maintenance and inspection personnel. However, the study adopted a more conservative approach by setting the minimum walkway width to 1000 mm. This increased width exceeded NFPA 130 requirements, providing additional safety and comfort for passengers and workers. The objective of this study is to assess the potential impact of a train fire on the tunnel structure of the Gaziray Rail System Line. To assist with the provision of the necessary ventilation strategy and capacity, the critical speed (the minimum airspeed needed to avoid the stratification of smoke and harmful combustion products in the desired direction during a fire) was determined. This is aimed at ensuring the operational functionality of environmental control systems and achieving a critical airspeed in the opposite direction to that of human evacuation, without compromising structural integrity.

This study employs Subway Environmental Simulation (SES v4.1) software, sourced from the Subway Environmental Design Handbook [56] to model fire dynamics and assess tunnel ventilation strategies. SES v4.1 defines track characteristics, train properties, and fire scenarios, providing time-dependent temperature distributions and estimating fire exposure thresholds for critical tunnel components. The study evaluates ventilation system efficiency, particularly tunnel ventilation fans and jet fans, by extracting boundary values from SES v4.1 outputs and integrating them into CFD simulations. To ensure a comprehensive evaluation of tunnel fire safety, SES v4.1 is utilized as a one-dimensional (1D) CFD model, focuses on longitudinal airflow dynamics and smoke movement along the tunnel. This approach offers computational efficiency, making it a cost-effective alternative to full-scale fire testing and high-performance 3D computational fluid dynamics (CFD) simulations. Unlike 3D CFD models, which account for transverse and vertical variations, SES v4.1 provides rapid analysis suited for long, narrow tunnel structures. However, for complex station areas, 3D CFD modeling is required with SES v4.1 outputs serving as a boundary condition for detailed airflow assessments. By integrating SES v4.1 with 3D CFD tools, this study optimizes ventilation system performance, suppresses smoke stratification, and ensures compliance with NFPA 130 [55] safety standards. The methodology (illustrated in Figure 2) refines tunnel fire safety protocols for the Gaziray Rail System Line, particularly in cut-and-cover sections, underground stations (Adliye and Topraklık), and the tunnel segment between Selimiye and Mücahitler stations (see Tables 2 and 3). The integration of advanced computational models enhances fire safety planning, and ensures structural integrity, effective smoke control, and safe evacuation conditions.

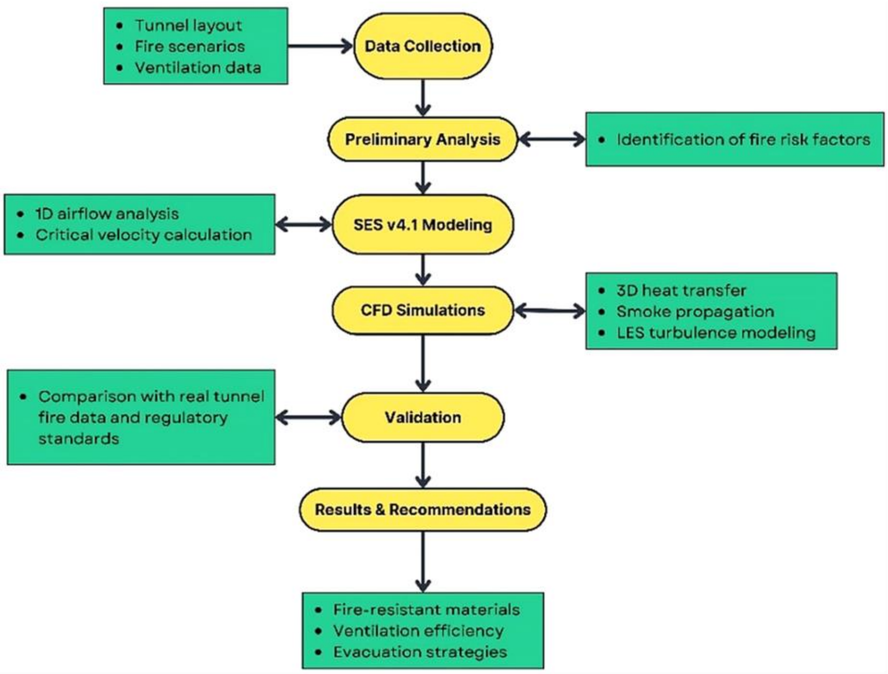

Figure 2. Workflow of the tunnel fire safety analysis methodology

This study was systematically designed to evaluate tunnel fire safety within the Gaziray Rail System Line. Section 2 details the fire modeling techniques used to simulate various fire scenarios, providing the foundation for subsequent analyses. Section 3 presents an in-depth examination of SES v4.1 model, including temperature distributions, air velocity criteria, fire scenarios, and ventilation fan deployment strategies. Section 4 discusses the findings of the study, derived from numerical simulations and empirical validation, and offers critical insights into the fire behavior and ventilation efficiency. Finally, Section 5 concludes the study with key insights and recommendations, emphasizing the importance of robust fire safety measures for railway tunnels.

The research methodology illustrated in Figure 2 outlines the step-by-step process of data collection, computational modeling, scenario analysis, and validation. The integrated approach combines SES v4.1 1D fire simulations with CFD-based 3D fire behavior assessments, enabling a comprehensive evaluation of the ventilation system performance and overall fire safety in the Gaziray Rail System tunnels. This study applies fundamental fire dynamics principles to distinguish between the pre-flashover and post-flashover fire stages, emphasizing their implications for evacuation planning, ventilation system efficiency, and structural resilience. The interaction between fire-induced heat and tunnel structures was examined to assess the effectiveness of jet fans, smoke extraction systems, and ventilation pathways in maintaining the critical airflow and visibility conditions during fire emergencies.

SES v4.1 simulations determine the critical velocity thresholds needed to suppress smoke backlayering, ensuring an effective ventilation strategy for fire control. These results serve as key inputs for advanced 3D CFD modeling to improve the accuracy of fire safety assessments. Conversely, CFD modeling provides a high-resolution, three-dimensional analysis of the heat transfer, smoke dispersion, and pollutant transport. The incorporation of large-eddy simulation (LES) techniques allows for a precise representation of microscale variability and atmospheric conditions, thereby enhancing the predictive accuracy of fire behavior in enclosed tunnel environments. By simulating different fire scenarios, CFD models facilitate the optimization of ventilation control measures, emergency smoke extraction strategies, and evacuation protocols, ensuring compliance with NFPA 130 [55] and other international safety standards.

This integrated approach bridges gaps in existing research by leveraging the complementary strengths of SES v4.1 and CFD modeling, delivering both theoretical advancements and practical guidelines for railway tunnel fire safety. The Gaziray Rail System Line serves as a case study, validating this methodology and providing real-world insights into the design and implementation of resilient tunnel fire-protection strategies. The findings of this study contribute to tunnel fire safety planning by offering actionable recommendations for improving fire-suppression systems, emergency evacuation measures, and ventilation system optimization. The proposed framework supports the development of tunnel infrastructure that adheres to global fire safety regulations, ensuring enhanced passenger safety, reduced fire risks, and improved structural resilience.

2. Modeling

In fire simulations conducted to determine tunnel ventilation system capacities, it is assumed that passenger and freight trains remain stationary in designated tunnel, turnout, or layover areas to enable the simulations. This study focused on scenarios involving stationary trains within a tunnel or station, which are considered critical for emergency response planning. This approach enabled a detailed examination of the effectiveness of the ventilation system in managing smoke and ensuring safe evacuation. The simulations conducted in this study assumed a complete halt in train operations during an emergency, thereby excluding any potential effects of additional trains moving inside or outside the tunnel. Consequently, the piston effect, which is caused by the movement of trains and is known to significantly influence airflow and smoke propagation, was not factored into the emergency scenario analysis. Typically, the piston effect is relevant in non-emergency scenarios, where it affects factors such as the air pressure, velocity at stations, and heat dissipation from regular train operations.

This study aims to provide a comprehensive understanding of the capabilities of ventilation systems in handling emergency situations with stationary trains. The trains, modeled in one dimension, were considered as time-dependent heat sources in these areas. The characteristics of the trains used in the simulations are listed in Table 4, and a front view of the vehicle is shown in Figure 3. The gauge of a railway track is defined as the minimum perpendicular distance between the inner faces of two rails. The standard gauge width was 1435 mm, and a gauge of 1435 mm was used for the Gaziray Rail System Line (see Figure 3).

Table 4. Properties of passenger and freight trains

Property	Value
Passenger train fire load	12 Mw
Freight train fire load	100 Mw
Convective heat coefficient	0.8
Convective heat transfer (passenger train)	9.6 Mw
Convective heat transfer (freight train)	80 Mw
Train cross-sectional area	10.7 m^2
Train length (freight train)	460 m
Train length (passenger train)	180 m
Train perimeter	-
Train superficial friction coefficient (passenger train)	0.023
Train superficial friction coefficient (freight train)	0.1
Drag coefficient (passenger train)	0.55
Drag coefficient (freight train)	0.56

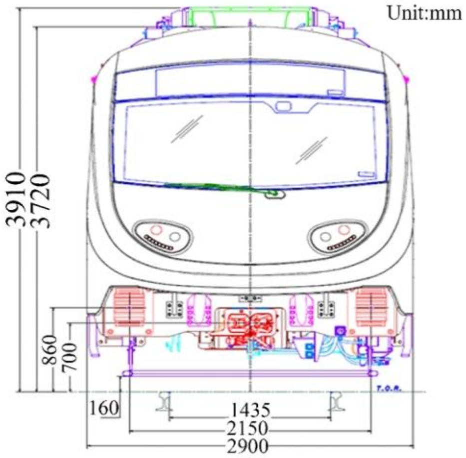

Figure 3. Front view of the vehicle

The study utilized the SES v4.1 program, a tool specifically designed for 1D analysis, well-suited for metro and underground transportation networks. This program operates under the assumption that key variables, such as air velocity and temperature, remain constant across the cross-section of the tunnel (y- and z-directions), but vary longitudinally along the tunnel length (x-direction). This 1D approach simplifies the computational process by focusing on the dynamics crucial for smoke control system design, namely, smoke propagation and ventilation flows. By assuming that the tunnel's width and height are much less significant than its length, SES v4.1 effectively manages the computational challenges of modeling extensive tunnel systems, allowing for a streamlined analysis. This simplification not only reduces the computational load but also enables the program to analyze an entire tunnel system in a single computational effort, which is much more time-efficient than more complex 3D models. The capability of SES v4.1 to deliver accurate and actionable results for tunnel-specific scenarios without the prohibitive time and computational costs associated with 3D simulations makes it an invaluable tool in this study. This provides detailed insights into the effectiveness of various smoke control strategies under simulated fire conditions.

3. Design of the Tunnel Ventilation System

3.1. Subway Environmental Simulation (SES) Model

During the simulation model development stage, the architectural designs of the tunnel and station were simplified and represented as 1D elements to be used in SES v4.1 program. The primary reasons for limiting rail top-level values within certain boundaries of railway tracks are ensuring passenger comfort and safe operation. The EN 13848-Track Geometric Quality Standard [57] provides recommendations for limiting the changes in the rail profile over a certain track length. Variations in the track profile led to the formation of different forces on the track, depending on the train speed, magnitude of the change, and length of the section where the change occurred. Restricting these variations aims to reduce vibrations that affect passenger comfort and ensure operational safety. Table 3 details the cross-sectional dimensions of the single-rectangular tube box section of the Gaziray Rail System Line and the four-track tunnel cross sections. The data obtained from the cross-sectional plans provided approximate measurements of height, width, and cross-sectional area of each section. The sections, labeled sequentially (e.g., C-C and D-D), reflect the dimensions along different points of the tunnel. The creation of this table is particularly important because of the variability in cross-sectional areas observed across different sections. Owing to the presence of various cross-sections along the line, and to avoid excessive use of space with numerous cross-sectional views, only typical sections, specifically C-C and E-E, are illustrated in Figure 1. The tunnel cross-sections and rail top-level values for each section are listed in Table 5.

Table 5. Tunnel sections and railhead elevation and values

Sections	Railhead elevation [m]
C-C	1.086,10
D-D	979,60
E-E	882,30
F-F	803,60
G-G	819,00
H-H	915,00
I-I	1.008,10
J-J	763,10
K-K	757,60
L-L	757,60
M-M	757,60
N-N	757,60
O-O	757,60
P-P	753,40
R-R	752,30
S-S	752,80

The values in Table 5 are elevation values relative to the average sea level, considering the altitude of the central province of Gaziantep, which was approximately 850 m. When creating the scenario, the tunnel was considered to range from position 15+828 km to 15+920 km towards the Mücahitler station of the line, considering the M-M and N-N sections. The line ventilation system of the Gaziray rail system consists of a jet and axial fans designed to accommodate both normal operational needs and emergency situations. In an incident scenario, such as a fire, 18 jet fans are deployed to manage smoke, operating in a push-pull configuration to effectively control smoke movement. This setup is crucial for maintaining clear evacuation paths and ensuring safety because the system directs ventilation against buoyancy forces, although this may require increased fan power. This approach prioritizes passenger safety by adhering to international safety standards that emphasize rapid smoke removal from occupied spaces and potential evacuation routes. Jet fans are specifically intended for emergency use, but are also capable of addressing comfort requirements, such as managing excessive heat or humidity when necessary. This dual functionality allows for operational flexibility, although the primary design purpose is emergency scenarios. Axial fans, on the other hand, are installed to provide fresh air during regular operations and maintenance phases. They are strategically placed along the tunnel to maintain comfortable conditions but are not involved in emergency smoke management and are thus not the focus of this study. In Figure 4, the 3D visualization of the tunnel system serves as a representative illustration of critical scenarios, specifically highlighting the conceptual design rather than depicting all detailed ventilation elements. The figure primarily shows the ventilation direction against buoyancy forces, underscoring the system's design emphasis on safety over energy efficiency during emergencies. This visualization helps convey the capacity of the system to manage critical incidents, ensuring that smoke and toxic gases are effectively managed to protect human lives during evacuation.

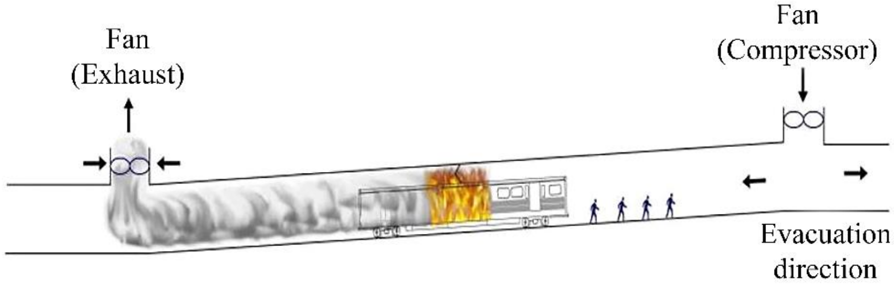

Figure 4. Representative 3D tunnel visualizations for critical scenarios

The decision to operate the fans against buoyancy forces, which means that the fans are set to blow in the opposite direction of the natural rise of hot air and smoke, is based on preparing for the worst-case scenario. This approach prioritizes safe evacuation routes, ensuring that smoke is effectively moved away from passenger escape paths. By counteracting the natural upward and forward movement of smoke, the system was designed to direct smoke towards exhaust points and maintain clear and safe evacuation routes. Ventilation systems are specifically engineered to perform optimally under the most challenging conditions, such as severe fires that generate significant heat and smoke. This ensures that even in less severe situations, where the buoyancy effect is less significant or the smoke load is lighter, the fans will still operate effectively. The design philosophy assumes that by planning for the worst-case scenario, the system will be robust enough to manage all other potential conditions, providing a reliable solution for smoke management during emergencies. This design ensures that the ventilation system can consistently protect passengers and staff, regardless of the severity of the situation. A network diagram of the simulation model is shown in Figure 5.

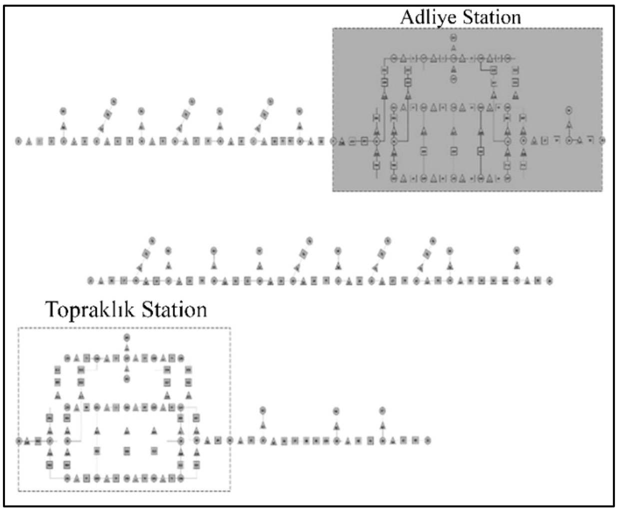

Figure 5. Network diagram of the SES v4.1 simulation model

3.2. Temperature Criteria

Given that NFPA 130 (Table B.2.1.1) [55] states that the maximum temperature in the tunnel evacuation direction should not exceed 60°C, people may be able to endure evacuation within a specific time frame, depending on the temperature they are exposed to in passenger areas and along the evacuation route. This study considered the ranges listed in Table 6 and assumed smoke-free temperature conditions. This table is crucial for the analysis presented here, as it helps establish safe exposure times under different thermal conditions within the tunnel during emergencies.

Table 6. Maximum duration of exposure during emergency evacuation concerning time (Adapted from NFPA 130, Table B.2.1.1 [55])

Exposure temperature [℃]	Exposure duration [min.]
80	3.8
75	4.7
70	6.0
65	7.7
60	10.1
55	13.6
50	18.8
45	26.9
40	40.2

3.2.1. Structural Temperature Criteria

Temperature-time-based graphs typically consist of two components: i) the temperature-time curve and ii) the material performance curve. They serve as tools to display the exposure time of the structure to heat during a fire and the performance exhibited by the structure against these temperature profile levels. This graph is widely used in fire engineering and structural design. These values are generally based on data obtained from fire tests that rely on heat propagation. The temperature-time-based performance of the structure determines the capacity of the materials to maintain the functionality of the structure during a fire.

3.3. Air Velocity Criteria

The Subway Environmental Design Handbook [58] provides a classified table from 0 to 12, which is the Beaufort scale used by the US Weather Bureau to determine wind force. The recommended maximum air velocity during emergencies on the Beaufort scale is 2500 fpm (12.700 m/s). Because the upper limit of normal conditions is considered to be 2200 fpm (11.176 m/s) and the lower limit is for emergency conditions, the maximum air velocity to which individuals are exposed during emergency conditions is taken as 11 m/s. Although the ventilation design throughout the evacuation time enables passenger evacuation, the ventilation system should protect the structure from the temperature reaching the tunnel wall and maintain its form for at least 1 h to ensure the functioning of the ventilation system. Although passenger safety is of paramount importance, the preservation of the safety of the structure has been considered to allow the facility to be operational shortly thereafter. The criteria for the air velocity discussed in this study are listed in Table 7.

Table 7. Fire condition air velocity criteria for station and tunnel areas

Location	Minimum	Average	Maximum
Platform (horizontal)	-	3.0 m/s	11 m/s
Stairs	-	1.8 m/s	11 m/s
Tunnels	0.75 m/s	-	11 m/s
Station entrance	-	-	11 m/s
Ventilation shafts	-	5.0 m/s	11 m/s
Sidewalk grilles	-	2.5 m/s	11 m/s
Grilles at 3 m and above from the sidewalk	-	5.0 m/s	11 m/s

3.4. Fire Scenarios

The emergency ventilation system for the Gaziray Rail System Line was meticulously designed to ensure the safe evacuation of passengers and provide a conducive environment for fire brigade and search and rescue teams during potential emergencies, such as fires in tunnels or stations. Maintaining the structural integrity at elevated temperatures is crucial for the effective functioning of these systems. Two primary scenarios are considered for the emergency ventilation system capacity: (i) scenarios involving trains inside tunnels, and (ii) scenarios involving trains inside stations. If a train remains operable in the event of a possible fire, the preferred action is to move it to the nearest station for passenger evacuation. However, if the train is stationary within the tunnel, passengers must walk towards the nearest station, tunnel portal, or emergency escape stairs, depending on the location of the fire and the affected car within the train. This study assumed that during a fire, the train in the tunnel is the only affected train, with other operational trains moving away from the fire zone or changing directions to avoid the incident area. The most critical scenarios occurred when the cross-sectional area, track gradient, and fire load were significant. Tunnel ventilation fans operate using the push-pull principle in these scenarios, directing smoke in a single direction to ensure that passengers and staff can evacuate without exposure to smoke. The specific direction of fans depends on the position of the fire within the train and the designated evacuation path. The fire scenarios were simulated using the $\alpha - t^2$ model, where α represents the fire growth rate, and t denotes time. For passenger trains with an assumed configuration of eight cars, the maximum fire size was set as 12 MW (see Table 4). The fire growth rate is moderate, represented by $\alpha = 12\ W/s^2$, with a convective heat fraction of 0.8. In this model, the total heat release rate (HRR) at a given time t, denoted as $Q(t)$, can be described by the equation $Q(t) = \alpha t^2$. The HRR increases quadratically over time until it reaches its peak value, assuming no suppression. For freight trains, a similar $\alpha - t^2$ model was employed with $\alpha = 12\ W/s^2$, corresponding to a maximum fire size of 100 MW (see Table 4). The time required to reach this maximum intensity, calculated using the model, was approximately 2900 s (48 min), which reflected a moderate fire growth rate under the given conditions.

The fire scenarios analyzed are listed in Table 8. In particular, the scenarios between SN-13 and SN-18 considered the situation where fans in the vicinity of the fire were disabled owing to high heat exposure. In such cases, the analysis focused on the air velocity supplied by other operational fans to ensure adequate smoke management and safe evacuation paths. The performance of these fans, correlated with the fire area, was thoroughly evaluated to understand the capacity of the ventilation system to manage the increased thermal load and to ensure passenger safety. Figure 6 illustrates the HRR curves over time for both the passenger and freight trains. The graph shows the growth of the fire to its maximum HRR, which is critical for planning and assessing required evacuation and response strategies. This detailed analysis provides a comprehensive understanding of the fire scenarios considered in this study, emphasizing that the system design effectively manages both passenger and freight train fires. The assumptions made regarding train configurations and the response of the ventilation system under different scenarios provide crucial insights for enhancing the safety protocols and system design.

Table 8. Fire scenarios.

Scenarios	Train	Zone	Location [km]	Direction of evacuation
SN-01	Freight	Tunnel Portal-Adliye	13+900	Tunnel Portal
SN-02		Tunnel Portal-Adliye	13+453	Adliye
SN-03		Adliye-Topraklık	15+209	Adliye
SN-04		Adliye–Topraklık	14+775	Topraklık
SN-05		Topraklık-Tunnel Portal	15+708	Tunnel Portal
SN-06		Topraklık-Tunnel Portal	16+196	Topraklık
SN-07	Passenger	Tunnel Portal-Adliye	13+900	Tunnel Portal
SN-08		Tunnel Portal-Adliye	13+453	Adliye
SN-09		Adliye-Topraklık	15+209	Adliye
SN-10		Adliye-Topraklık	14+775	Topraklık
SN-11		Topraklık-Tunnel Portal	15+708	Tunnel Portal
SN-12		Topraklık-Tunnel Portal	16+196	Topraklık

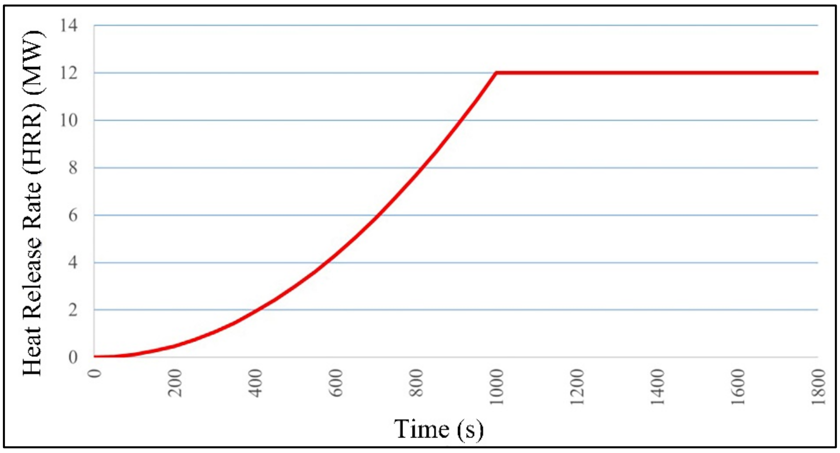

Figure 6. Heat release rate (HRR) curves for passenger and freight train fires in the Gaziray Rail System Line

3.5. Ventilation Fans

The tunnel ventilation system in the Gaziray Rail System Line is designed to operate in both directions (reversible), allowing smoke to be pushed in either direction, depending on the location of the fire and train within the tunnel. This reversibility ensures that the system can adapt to varying emergency scenarios and maintain safety by directing smoke away from the evacuation routes. The airflow capacity of fans must be consistent in both the suction and blowing directions to be effective. The system utilized both jet and axial fans equipped with advanced control mechanisms. These mechanisms consider various factors such as smoke detection, temperature gradients, and train positions. These factors are crucial in determining the appropriate direction and intensity of airflow during emergencies. The direction of the fan operation is determined by the control center operators, who are guided by real-time data from the smoke and temperature sensors. The primary goal is to direct the airflow opposite the evacuation route, ensuring that passengers can safely reach designated safe areas without encountering smoke. The system can reach its designed operational capacity within 30 s of activation in compliance with the NFPA 130 standards, which recommend that emergency ventilation fan motors achieve full operating speed within 30 s from a stopped position.

This quick response time is critical for minimizing the impact of smoke and heat during emergencies and for providing sufficient time for passenger evacuation. Jet fans, which are essential for emergency ventilation, are constructed to endure significant mechanical loads, including those caused by the piston effect of the train movement. This effect can generate substantial dynamic forces, potentially affecting fans' service lives. To mitigate these effects, fans are built using durable materials and are designed to minimize the impact of air pressure changes. In addition, mounting and housing structures are engineered to absorb vibrations and shocks, thereby reducing wear and tear. The system incorporates a dual ventilation strategy: during normal operations and maintenance phases, axial fans maintain sufficient air circulation by operating in a push-pull configuration. These fans are designed to handle normal temperature ranges, whereas jet fans are capable of withstanding temperatures of up to 250°C for one hour, ensuring that they function effectively even under extreme conditions. A rigorous maintenance regime is in place, including regular six-month inspections and real-time monitoring systems. These measures help detect and address any performance issues promptly, ensuring the longevity and reliability of the ventilation components. While the current study focuses on the general operation and maintenance of these systems, future research will delve into the specific impacts of the piston effect on jet fan durability and performance using finite element analysis (FEA) methods.

3.6. Critical Velocity

In the event of a train fire inside a tunnel, smoke and toxic gases can spread throughout the tunnel, endangering passengers. The primary role of a ventilation system is to direct these hazardous emissions in a single direction, thereby ensuring a safe evacuation route in the opposite direction. This was achieved by maintaining the critical velocity and the minimum airspeed required to prevent smoke backlayering. By maintaining the critical velocity, the system ensures that the smoke is kept away from the evacuation routes, providing a clear and safe path for passengers (as illustrated in Figure 7).

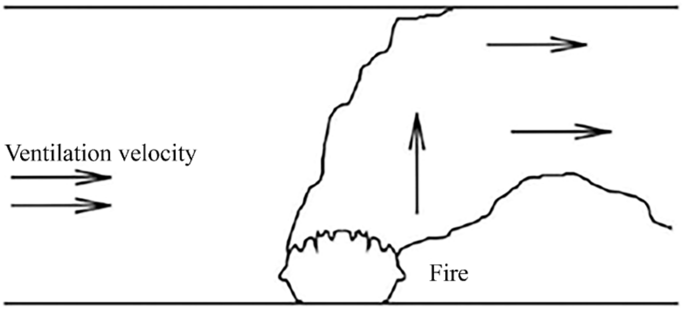

Figure 7. Dispersion of smoke and hot gases at critical velocity

Figure 7 shows the ventilation strategy, emphasizing the importance of directing the airflow against the buoyancy forces. Although this setup requires more fan power, it is crucial to maximize passenger safety by directing smoke away from the evacuation paths. The growth phase of a fire was considered in this evacuation strategy. If passengers attempt to evacuate from opposite directions around a centrally located fire, they may still face the risk of exposure to toxic gases during the evacuation. This situation can increase the likelihood of passengers being affected by harmful emissions even if they pass through a central fire area. To mitigate this risk, the evacuation plan assumes that passengers move towards the front or rear of the train away from the fire. This strategy was designed to ensure that passengers could be evacuated without exposure to critical levels of smoke or toxic gases before the fire reached its peak heat release rate. The critical velocity and ventilation setup of the system aims to prevent backlayering, ensuring that smoke does not flow back into the evacuation path, thereby maintaining a clear and safe route. The ventilation system was equipped with reversible fans capable of operating in both directions, depending on the location of the fire and the train within the tunnel. These fans use real-time data, such as smoke detection and temperature gradients, to determine the optimal direction and intensity of airflow. This capability allows the system to adapt quickly to changing conditions, ensuring that smoke is efficiently managed and directed away from passengers. The key risk addressed by this approach is ensuring that any fire originating from any part of the train does not reach a critical stage that threatens passengers during the evacuation process. An evacuation strategy was designed to maximize safety and minimize exposure to hazardous conditions by focusing on directing passengers to safe areas in front of or behind trains. Fan-forced ventilation plays a critical role in achieving and sustaining critical velocity, which prevents smoke backlayering. The fans were designed to quickly reach full operational capacity, ensuring effective smoke management, even under severe conditions. This comprehensive approach ensures that passengers can evacuate safely, thus minimizing their exposure to hazardous conditions during fire emergencies.

The critical velocity value (V_c) is dependent on various variables, such as the fire load (Q), ambient temperature (T), tunnel cross-sectional area (A), tunnel gradient (grade), tunnel height (H), and train cross-sectional area. The critical velocity value, given by Equation 1, was obtained by solving the equations for the critical velocity and smoke temperature in a fire zone.

$$V_c = K_1 \, K_g \left(\frac{g \, H \, Q}{\rho \, C_p \, A \, T_f}\right)^{1/3} \quad (1)$$

Here, K_1 is a dimensionless constant with a value of 0.606. K_g represents the gradient correction factor, C_p denotes the specific heat capacity of the constant-pressure air, and T_f denotes the smoke temperature in the fire zone. The formulae for T_f and K_g are given in Equations 2 and 3, respectively:

$$T_f = \frac{Q}{\rho \, C_p \, A \, V_c} + T \quad (2)$$

$$K_g = 1 + 0.0374(grade)^{0.8} \quad (3)$$

Here, ρ denotes the density of air, and grade represents the tunnel gradient as a percentage. If the ventilation direction is uphill or the tunnel slope is flat ($= 0\%$) around the fire, K_g is equal to 1. If the ventilation direction is downhill, then the value of K_g is greater than that obtained using Equation 3 for K_g. The reason for this is that the hot gases rise towards the ceiling of the tunnel, spreading more upward, particularly in sloping tunnels. Therefore, in the case of ventilation downhill, a higher ventilation speed is required to sweep the rising hot gases downward. This explains the calculation of higher critical velocity. Figure 8 shows a graph of the variation in the gradient correction factor with slope [59].

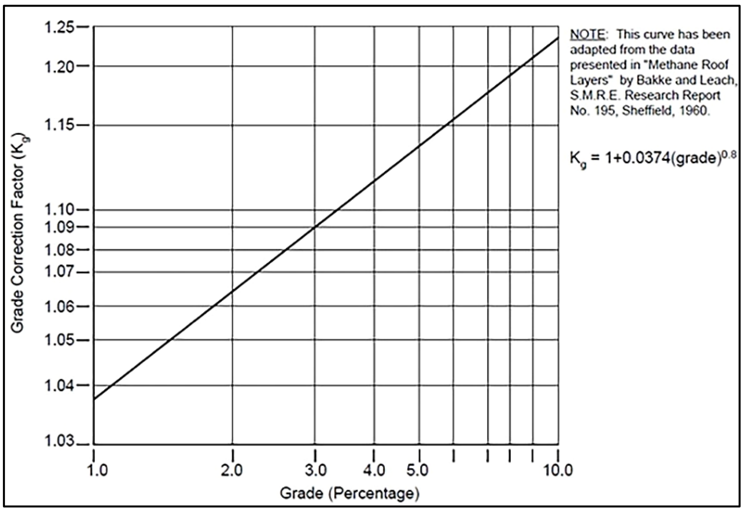

Figure 8. Graph showing the variation in gradient correction factor with slope [59]

3.7. SES v4.1 Simulation Outputs

To further analyze the impact of fire scenarios on tunnel thermal conditions, temperature distribution simulations were conducted using SES v4.1. The following contour plot illustrates the temperature variations along the tunnel length, highlighting the critical areas where heat accumulation occurred during a fire event. Figure 9 illustrates the temperature distribution along the Gaziray Rail System tunnel during the fire scenario simulated using SES v4.1. The analysis covered the tunnel segment from Selimiye Station (11,995 m) to Mücahitler Station (16,622 m) with a vertical height range of 0-10 m. The contour visualization highlights heat accumulation near the fire source (~14,300 m), where high-temperature zones (white/yellow) indicate intense thermal effects. In contrast, cooler zones (dark red/black) represent areas where the distance from the fire and ventilation measures reduced the heat buildup. The dashed cyan lines mark critical underground stations within the study area, including Adliye and Topraklık, and provide reference points for structural and safety evaluations

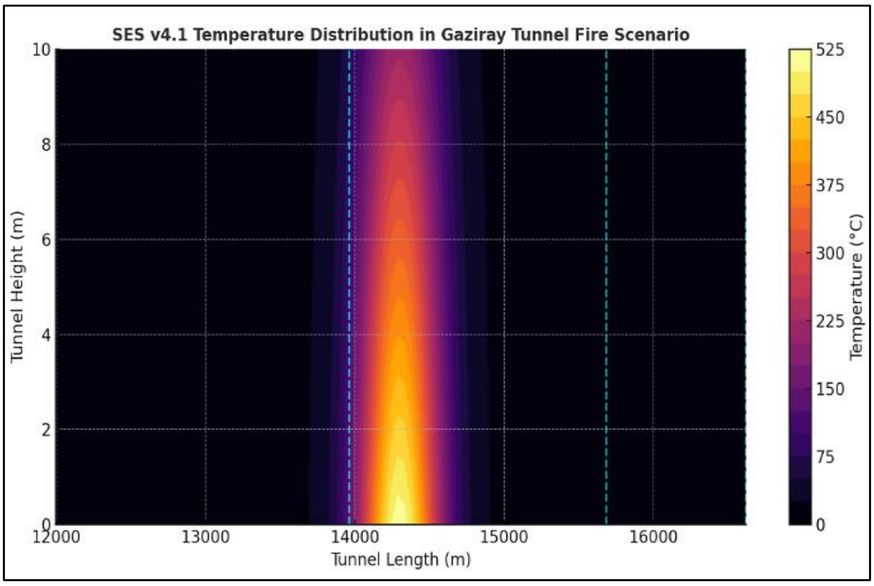

Figure 9. SES v4.1 temperature distribution along the Gaziray Rail System tunnel during a fire scenario

In this study, the fire HRR was set to a fixed value (approximately 100 MW) based on the expected fire load of a freight train, representing a high-severity scenario. The analysis assumes a stationary train, focusing on worst-case evacuation conditions. Future studies could explore varying fire intensities and train speeds to assess their impact on ventilation performance and smoke dispersion.

The airflow velocity within the tunnel must be effectively controlled to ensure fire safety and to maintain visibility during evacuation. The SES v4.1 model was used to evaluate the performance of the ventilation system in achieving the required critical velocity, which is essential for preventing smoke backlayering and stagnation. Figure 10 illustrates the SES v4.1 airflow velocity distribution along the Gaziray tunnel under fire-induced conditions, covering the segment from Selimiye Station (11,995 m) to Mücahitler Station (16,622 m), with a vertical height range of 0-10 m. The contour visualization highlights velocity variations, where lighter blue/white areas represent higher airflow speeds generated by jet fan ventilation systems, whereas darker blue areas indicate low-airflow regions. The dashed red lines mark the critical tunnel station locations (Adliye and Topraklık) as reference points for airflow assessments. The results demonstrate that airflow is optimized near ventilation zones, but gradually decreases along the tunnel length, emphasizing the importance of critical velocity maintenance in preventing smoke accumulation and ensuring safe evacuation conditions.

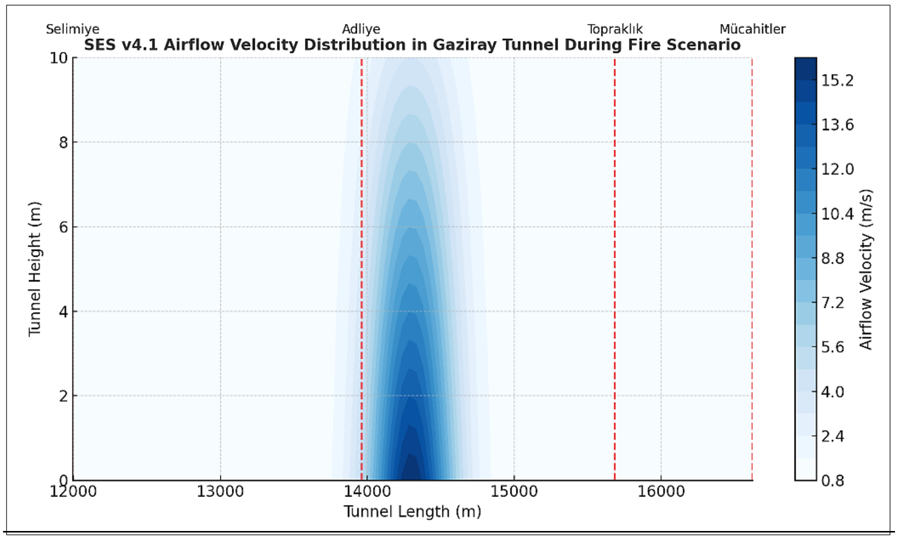

Figure 10. SES v4.1 airflow velocity distribution in the Gaziray Rail System tunnel under fire-induced conditions. The critical velocity regions demonstrate the performance of the ventilation systems in controlling smoke movement

In addition to airflow control, smoke propagation dynamics play a crucial role in ensuring a safe evacuation during tunnel fires. The SES v4.1 simulation results provide valuable insights into how smoke spreads within the tunnel under different ventilation configurations, thereby identifying critical zones where smoke accumulation poses a risk. Figure 11 illustrates the SES v4.1 smoke dispersion patterns along the Gaziray tunnel, covering the segment from Selimiye Station (11,995 m) to Mücahitler Station (16,622 m), with a vertical height range of 0-10 m. The contour visualization highlights smoke concentration levels, where darker areas (black/gray) indicate high smoke accumulation zones, particularly near the fire source (~14,300 m) and tunnel ceiling, whereas lighter areas (white/gray) represent regions where ventilation effectively reduces the smoke density. The dashed orange lines mark critical underground station locations (Adliye and Topraklık) as reference points for assessing the smoke clearance effectiveness. The results demonstrate that smoke is the densest near the fire, but gradually disperses owing to ventilation-assisted airflow, emphasizing the need to design evacuation routes that minimize exposure to high-smoking areas and ensure compliance with tunnel safety standards.

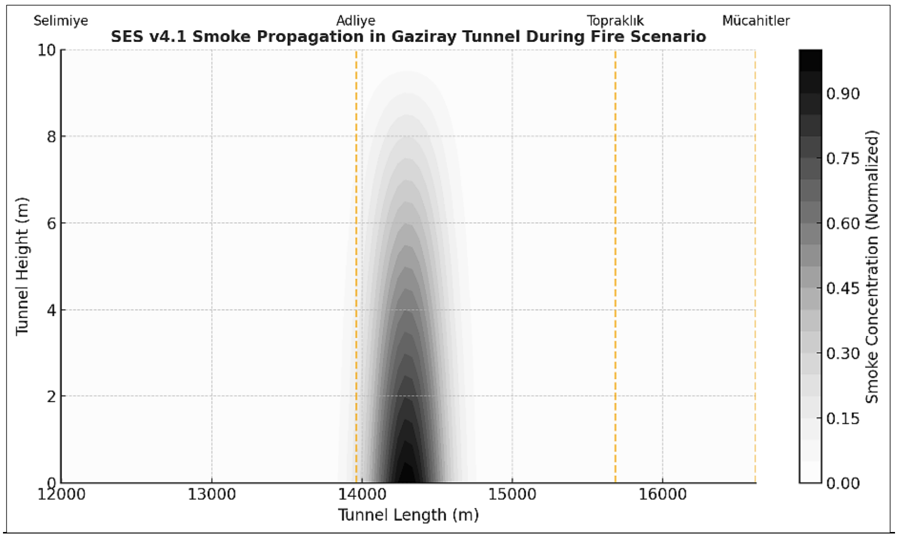

Figure 11. SES v4.1 smoke propagation contour plot for the Gaziray Rail System tunnel fire scenario, highlighting smoke dispersion patterns under different ventilation configurations

The SES v4.1 simulation (see Figures 9 to 11) results provided valuable insights into temperature buildup, airflow velocity, and smoke dispersion patterns within the Gaziray Railway System Line. The results highlight the importance of critical velocity thresholds, optimized ventilation strategies, and proper airflow management to ensure fire safety and effective evacuation measures. These findings were compared with international fire safety standards to assess compliance and to recommend improvements.

3.8. Validation of SES v4.1 and CFD Simulations

To ensure the reliability and accuracy of the SES v4.1 and CFD simulation results, a comprehensive validation strategy was applied, incorporating empirical verification, numerical sensitivity analysis, and compliance with international fire safety guidelines. The critical velocity thresholds derived from SES v4.1 were cross-checked against well-established empirical formulas, such as the Thomas Formula [60] and NFPA 502 guidelines [61]. The Thomas Formula, a widely used empirical approach for estimating the critical velocity in tunnel fires, was specifically applied to validate the airflow model. This ensured that the ventilation system performance was aligned with the theoretical predictions to prevent smoke backlayering.

The results were compared with the smoke control benchmarks outlined in the international tunnel fire safety standards. To further ensure the reliability of the SES v4.1 and CFD simulations, comparisons were made with well-documented large-scale tunnel fire tests, including the Memorial Tunnel Fire Test and Runehamar Fire Test. These experimental studies provide validated fire behavior data, and the key trends observed in our numerical simulations, such as heat accumulation zones, smoke movement patterns, and critical velocity requirements, demonstrate strong alignment with these real-world fire tests. To assess the numerical stability of the CFD models, a grid convergence study was conducted to verify that variations in mesh resolution did not significantly affect the simulation outcomes. Additionally, a sensitivity analysis was performed to assess the influence of key parameters, including fire HRR, jet fan positioning, and ventilation flow rates.

The results demonstrate converging trends across different mesh configurations, confirming the robustness and reliability of the simulation methodology. To enhance the accuracy and applicability of the SES v4.1 and CFD models for the Gaziray Rail System Line, the simulations were calibrated to reflect the tunnel geometry, ventilation infrastructure, and train fire load characteristics specific to both freight and passenger train operations. The placement and performance of 18 jet fans were optimized to align with real-world operational constraints, thereby enhancing the practical relevance of the findings. The study adhered to NFPA 130 [55], PIARC guidelines [62], and European safety directives for tunnel ventilation. The simulation results confirmed that the airflow velocities, smoke clearance rates, and temperature limits met or exceeded these regulatory benchmarks, further validating the methodology. In addition, the fire safety strategies for tunnel suppression and ventilation align with NFPA 502, which provides guidance on fire protection for road and rail tunnels, ensuring that the system design meets international safety requirements. These combined efforts ensure that the SES v4.1 and CFD simulation results are both theoretically and practically sound, enhancing their reliability for real-world tunnel fire safety assessments. Following the validation process, the SES v4.1 and CFD simulations were utilized to analyze fire-induced temperature distributions, airflow velocities, and smoke propagation patterns within the Gaziray Rail System tunnel.

4. Results and Discussion

4.1. Results

The final number and capacity of fans were determined based on the successful/valid scenario results, and the simulation outcomes are analyzed in this section. The results provided information on the air velocity and temperature for specific areas. The jet fan capacities were deemed sufficient when ensuring the critical ventilation velocity in the direction opposite to that of emergency escape. Consequently, the progression of smoke and hot gases in the evacuation direction was not possible. Additional pressurization is not required for emergency escape stairs in these areas, as there is no smoke direction towards these zones. Axial fans with a total capacity of 36 m^3/s were installed in the tunnel ventilation fan (TVF) shafts to discharge the polluted air and cold smoke that remained in the tunnels after firefighting, neutralizing tunnel temperatures during congested operation scenarios with high normal traffic circulation in the tunnels. These high-performance axial fans effectively controlled the air in the environment, creating an axial air balance by using the pressure difference when activated in the relevant area. Based on the analysis results obtained in this study, the positions of the ventilation equipment depending on the fire location and evacuation direction are presented in Table 9.

Table 9. Fire scenarios and ventilation strategies were developed

Fire location	Tunnel Portal–Adliye Station		Adliye Station–Topraklık Station		Topraklık Station–Tünel Portalı	
Passenger/Personnel evacuation direction	Tunnel Portal ←	Adliye Station →	Adliye Station ←	Topraklık Station →	Topraklık Station ←	Tunnel Portal →
Dampers at ventilation openings	Closed	Closed	Closed	Closed	Closed	Closed
Jet Fan-01-02-03	→	←	−	←	−	−
Jet Fan-04-05	→	←	−	←	−	−
Jet Fan-06	→	←	−	←	−	−
Jet Fan-07-08-09	→	←	→	←	−	←
Jet Fan-10-11-12	→	−	→	←	→	←
Jet Fan-13-14	→	−	→	−	→	←
Jet Fan-15	→	−	→	−	→	←
Jet Fan-16-17-18	→	−	→	−	→	←

This study thoroughly analyzed the critical velocities required to prevent smoke backlayering in the event of a fire, focusing on scenarios involving freight trains. The critical velocities determined using empirical formulae were validated through detailed simulations. The simulations assessed the fan capacities and airflow velocities necessary to ensure the ability of the system to effectively manage smoke during emergencies. Table 10 presents the critical velocities, simulated velocities, temperature data, and the impact of potential fan failures within the fire zone, providing a comprehensive overview of the performance of the system. In particular, the data include information from the initial scenario, SN-01, at the Tunnel Portal-Adliye Station, and the latest scenario, SN-18, at the Topraklık Station-Tunnel Portal (see Table 8).

These scenarios, highlighted in Table 10, show the range of conditions considered and robustness of the scientific analysis. The critical velocity values represent the minimum airflow required to prevent smoke backlayering and are calculated using specific fire scenarios and train characteristics. The simulated velocity column details the airflow velocities achieved through CFD simulations, reflecting the actual fan capacities and boundary conditions analyzed. The results indicate that the simulated velocities generally exceeded the critical velocities, thereby confirming the effectiveness of the system in preventing smoke from compromising evacuation routes. Notably, the simulations for scenarios SN-02 and SN-04 showed a significant margin above the critical thresholds, enhancing overall safety. The study also determined that 18 jet fans are required to maintain these conditions across the tunnel sections analyzed, as per the findings for scenarios from the Tunnel Portal to Adliye Station and Topraklık Station.

Moreover, the findings emphasize the need for additional precautions considering the potential exposure of the inner tunnel lining to high temperatures during fires. The results, particularly those from scenarios SN-01 and SN-18, underscore the importance of precise and well-calibrated simulations to ensure that a ventilation system can maintain safety under various emergency conditions. This comprehensive analysis, as shown in Table 10, demonstrates the effectiveness of ventilation design in managing emergency scenarios and highlights the critical role of simulations in predicting and preparing for real-world outcomes. The inclusion of both the initial and final scenario data provides a complete picture of the system's capabilities and areas for further optimization. The location and capacity information of the jet fans, which ensures the critical velocity required for safe evacuation in the tunnel, are provided in Table 11.

The maximum wall temperatures in the fire-affected section are listed in Table 12, according to the fire scenarios. These temperature values represent the condition one hour after the start of the fire for the freight train, which is associated with a high fire load of approximately 100 MW. Additionally, it was observed that smoke and stifling air from the fire were discharged from the station stair structures or tunnel portals. From the analysis results of the fire scenarios, it is evident from the temperature data in the staircase and platform areas that this situation jeopardizes the safety of passengers waiting for evacuation on station platforms. Consequently, as observed on the Marmaray line, the operation of freight trains with high fire loads during passenger train operating hours is crucial [63].

Table 10. Fire scenarios and velocities provided for the simulations

Scenario No.	Critical velocity [m/s]	Simulated velocity [m/s]
SN-01	2.37	2.55
SN-02	2.32	2.61
SN-03	2.65	2.99
SN-04	2.34	3.37
SN-05	2.30	3.47
SN-06	2.47	2.89
SN-13	2.37	2.43
SN-14	2.32	2.45
SN-15	2.65	2.99
SN-16	2.34	2.53
SN-17	2.30	2.82
SN-18	2.47	2.81

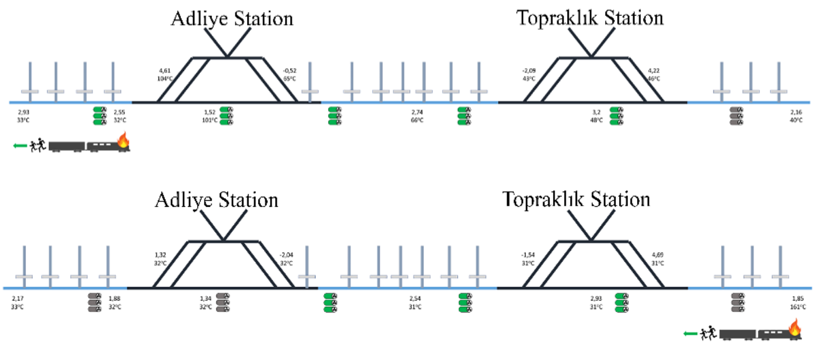

Table 11. Jet fan locations and capacities

Location	Number of fans	Outlet air velocity [m/s]	Outlet air flow rate [m³/s]	Thrust force [N]
13.670	3	35.7	40.4	1730
13.960	1	35.7	40.4	1730
13.960	2	35.7	40.4	1730
14.100	3	35.7	40.4	1730
15.480	3	35.7	40.4	1730
15.685	1	35.7	40.4	1730
15.685	2	35.7	40.4	1730
15.955	3	35.7	40.4	1730
13.670	3	35.7	40.4	1730
13.960	1	35.7	40.4	1730
13.960	2	35.7	40.4	1730
14.100	3	35.7	40.4	1730
15.480	3	35.7	40.4	1730

Table 12. The maximum wall temperatures were generated in the fire-affected areas.

Scenario No	Maximum wall temperatures [°C]
SN-01	774
SN-01	802
SN-02	894
SN-03	846
SN-04	776
SN-05	923
SN-06	774

The fire scenarios were selected based on a combination of a risk-based assessment, operational constraints, and previous tunnel fire case studies. The selection process aimed to encompass a range of potential fire incidents, including those originating from stationary and moving trains as well as fires occurring at critical tunnel sections such as stations and portals. Although this study covers a wide range of high-risk scenarios, it is acknowledged that rare or extreme events, such as cascading fire incidents or multitrain collisions, may require additional specialized evaluations. The results obtained from these scenarios provide a comprehensive understanding of fire behavior and ventilation efficiency under various conditions, aligned with established tunnel fire safety guidelines.

The findings obtained from the SES v4.1 simulations provide a comprehensive understanding of the thermal behavior, airflow dynamics, and smoke dispersion within the Gaziray Rail System tunnel under fire conditions. These results offer crucial insights into the optimization of tunnel fire safety measures.

- The results highlight significant heat accumulation near the fire source (~14,300 m), emphasizing the need for fire-resistant materials in high-temperature zones to protect structural integrity.
- Maintaining critical airflow velocity thresholds is essential to prevent smoke backlayering and ensure clear evacuation pathways. This study demonstrates the effectiveness of jet fan ventilation systems, particularly in high-risk zones, for maintaining controlled airflow.
- Smoke dispersion patterns revealed high-risk areas in which visibility and evacuation efficiency may be compromised. These findings underscore the importance of optimized ventilation configurations for improving smoke clearance and minimizing exposure to hazardous conditions.
- The simulation results align with international fire safety standards, including NFPA 130, validating the methodology and the proposed design strategies.

To further improve tunnel fire resilience and evacuation safety, the following measures are recommended:

- The periodic assessment of ventilation systems ensures that the airflow remains within the required safety threshold.
- Strategic placement of fire-resistant materials in high-temperature zones to enhance structural durability.
- The refined evacuation protocols based on the identified smoke dispersion patterns ensured clear and safe exit routes.

These findings provide valuable guidance for tunnel fire safety design and contribute to a more resilient and effective emergency response strategy for underground railway systems.

The results obtained in this study align with and expand previous research on fire safety and ventilation strategies in railway tunnels.

- The findings regarding heat accumulation near fire sources (~14,300 m) are consistent with those of Ingason et al. [6], who demonstrated similar temperature gradients under tunnel fire conditions. However, this study further refines these findings by incorporating SES v4.1 modeling to analyze the thermal effects on tunnel structural elements.
- The critical velocity thresholds identified in this study closely match those reported by Tarada & King [3]), who analyzed smoke movement control using jet fans in railway tunnels. However, the current study improves on these findings by evaluating the performance of 18 jet fans under various fire scenarios and confirming the compliance of the system with the NFPA 130 standards.
- The SES v4.1 smoke dispersion results are comparable to those of Kodur & Naser [46], who examined the ventilation effectiveness in tunnel fire scenarios. Nevertheless, this study advances the analysis by integrating tunnel-specific constraints and assessing the interaction between the ventilation efficiency and evacuation safety.

These comparative insights emphasize the novel contributions of this study, particularly in optimizing the ventilation design for the Gaziray Rail System and ensuring compliance with the international safety standards.

4.2. Discussion

The findings of this study contribute to the growing body of research on railway tunnel fire safety by integrating SES v4.1 simulations with ventilation performance assessments. The Gaziray Railway System Line in Gaziantep, Türkiye, serves as a critical infrastructure for public transportation, necessitating a thorough evaluation of the fire safety and emergency response strategies.

- The temperature distribution results highlighted significant heat accumulation near the fire source (~14,300 m), with peak temperatures ranging from 774 to 923°C one hour after fire ignition. These values indicate the potential for structural deterioration, emphasizing the necessity of fire-resistant materials in high-risk zones to mitigate post-fire damage and ensure rapid operational recovery.
- The results confirm that the existing 18 jet fans are sufficient to maintain critical ventilation speed (35.7 m/s), effectively preventing smoke backlayering and directing airflow away from evacuation paths. A TVF with a capacity of 36 m^3/s aids in temperature regulation and air quality control under normal and heavy traffic conditions.
- The results align with those of Ingason et al. [6] regarding temperature gradients, Tarada & King [3] regarding critical velocity thresholds, and Kodur & Naser [46] regarding smoke dispersion patterns. However, this study expands upon previous findings by integrating real-world tunnel constraints. SES v4.1 simulation outputs to provide a more practical application for railway tunnels and to confirm the system's compliance with NFPA 130 standards.

Several key measures have been proposed to enhance fire resilience and evacuation safety in underground railway systems based on the analysis of tunnel fire risks and evaluation of ventilation strategies.

- Tunnel linings should be strengthened with fire-resistant materials to minimize structural degradation.
- Optimizing ventilation configurations, including jet fan placement, to improve smoke extraction efficiency.
- Refining emergency evacuation protocols based on smoke dispersion patterns and evaluating the placement of emergency exits for accessibility.
- Ensuring continuous maintenance of fire detection and suppression systems to improve initial response capabilities.
- Provide fire safety training for personnel and raise awareness among passengers during emergency procedures.
- Regulating freight train operations to prevent scheduling overlaps with passenger services and to minimize exposure to fire risks.

5. Conclusion

Railway systems are an essential mode of public transportation that ensure fast, safe, and environmentally friendly mobility worldwide. The Gaziray Railway System Line is a major infrastructure project designed to improve the urban transit in Gaziantep and Türkiye. Although train fires are rare, they present significant risks that must be carefully managed to maintain the structural integrity and passenger safety. This study systematically assessed fire scenarios in underground tunnels of the Gaziray Rail System and evaluated the temperature distribution, airflow velocity, and smoke dispersion using SES v4.1 simulations. These findings indicate that high-temperature zones (~14,300 m) reach 774–923°C within an hour of a freight train fire, emphasizing the need for fire-resistant materials to mitigate structural damage. The ventilation system, comprising 18 jet fans, successfully maintained the critical airflow velocity (35.7 m/s), prevented smoke backlayering, and ensured a safe evacuation. The study confirms that transverse ventilation fans (TVF) operating at 36 m^3/s effectively regulate the tunnel air quality during both emergency and normal operation scenarios. No additional pressure is required for emergency escape stairs because the smoke is directed away from these areas. This study differs from previous research by integrating SES v4.1 and CFD simulations to develop customized ventilation strategies tailored to the Gaziray Railway System. These strategies ensure the effective operation of jet fans and axial ventilation systems during emergency events, demonstrating compliance with the NFPA 130 safety standards. By providing a comprehensive safety assessment, this study offers actionable insights for designers, operators, and decision-makers to ensure resilient and efficient fire management strategies for railway tunnel infrastructure.

6. Declarations

6.1. Data Availability Statement

The data presented in this study are available upon request from the corresponding author.

6.2. Funding

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6.3. Acknowledgements

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6.4. Conflicts of Interest

The author declares no conflict of interest.

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