Simulation-Based Performance Analysis of Ventilation and Fire Protection Strategies in Road Tunnel Fires: Review

[a]Rohan Jaiswal, [b]Nakul Mahalle, [a]Aayush Dubey, [a]Ravi Shankar Kumar, [a]Anuj Goswami, [a]Nirmalya Shukla, [a]Piyush Chaudhary

[a]Undergraduate Student, Department of Fire Engineering, National Fire Service College, Nagpur, India
[b]Assistant Professor, Department of Fire Engineering, National Fire Service College, Nagpur, India

Abstract

Tunnel fires pose severe risks due to confined geometry, limited evacuation options, and rapid smoke propagation. This literature review compiles insights from recent studies on smoke movement, ventilation control, fire suppression, and evacuation behaviour in tunnel environments. It also highlights the growing use of simulation tools like PyroSim and Pathfinder to analyse fire dynamics and human response. Key findings across studies include the significance of critical ventilation velocity, the risks of smoke back- layering, and the throttling effect in high-heat-release fires. While systems like water mist and deluge sprinklers improve tenability, their effectiveness depends on placement, droplet behaviour, and airflow interaction. Evacuation outcomes are shown to rely heavily on visibility, exit spacing, and guidance systems. The review underscores that tunnel safety requires a coordinated approach, where fire suppression, ventilation, and evacuation systems work in synergy. This paper aims to provide a more consolidated foundation for designing a more resilient tunnel fire safety system by thoroughly examining the tested strategies and simulation based evaluations.

Keywords:

Tunnel Fire, Fire Dynamics, Ventilation, Fire Suppression, Evacuation, PyroSim

1. Introduction

Underground tunnels are a critical part of transport infrastructure, offering faster, safer routes through dense urban areas, mountainous regions, and under waterways. However, they also introduce some of the most complex fire safety challenges. Tunnels unlike buildings, possess an enclosed geometry having limited ventilation, limited accessibility for firefighters, and constrained evacuation routes- all of which makes the fire much difficult to contain and manage; consequences being tunnel fires are much severe, not only due to the flame propagation but primarily because of intense smoke propogation, loss of visibility and toxic gas exposure in a short timeframe.

Notable incidents such as the Mont Blanc Tunnel fire (1999) and Gotthard Tunnel fire (2001) highlighted that most fatalities in such events are due to smoke inhalation and CO poisoning, not direct flame contact.
[1] These tragedies shifted international attention toward fire safety in tunnels, prompting new technical investigations, full-scale fire tests, and regulatory changes. The European Parliament, through studies like that by Alan N. Beard, has called for a stronger, standardised, and risk-based approach to tunnel safety.

Table 1: Major Tunnel Fire Incidents and Lessons Learned

Incident	Year	Country	Causes	Casulaties	Key lesson learned
Mont Blanc Tunnel	1999	France - Italy	Truck carrying flour & margarine caught fire	39 deaths	Importance of smoke control & emergency exits
Gotthard Tunnel	2001	Switzerland	Collision of heavy goods vehicles	11 deaths	Need for longitudinal ventilation & quick response
Burnley Tunnel	2007	Australia	Multi-vehicle accident, HGV fire	3 deaths	Fire load underestimated; HRR exceeded 100 MW
RunehamarTests	2003-2016	Norway	Full-scale HGV fire experiments	Experimental	Validated deluge & mist systems, airflow interaction

Their findings focus on the urgency of integrating data-driven decision-making, emergency response planning, and ongoing system monitoring, especially for heavy goods vehicle (HGV)-related incidents.[2]

The report emphasises that traditional prescriptive safety codes, while still useful, are often insufficient for modern, long, or complex tunnels. As tunnels grow in size and traffic volume, there is a growing shift toward performance-based fire safety design, supported by simulation tools, intelligent detection systems, and real-time adaptive ventilation. This shift is resonated in regulatory frameworks like NFPA 502 and PIARC, which now cautiously support the inclusion of active fire suppression technologies and evacuation modelling in tunnel fire strategies.[3]

Tunnel fire safety today requires a unified approach—balancing prescriptive norms with performance based measures like advanced modelling, and ensuring that fire detection, smoke control, suppression, and evacuation planning are not treated in isolation but as components of a coordinated system.

2. Evolution of Tunnel Fire Research

2.1 Early Understanding: Passive Design and Fire load misjudgement

Tunnel fire research initially relied on passive protection strategies, with conservative assumptions about fire size. Design fire loads were generally assumed to peak around 20 MW, intensity which was considered by longitudinal ventilation and structural resistance. However, the Burnley Tunnel fire of 2007, alongside research from the University of Edinburgh, demonstrated that heat release rates (HRRs) could exceed 120 MW [4], especially in fires involving heavy goods vehicles (HGVs). This work fundamentally challenged prior design assumptions, introducing the critical concept of supercritical fires and highlighting throttling effects, where large fires resist longitudinal airflow and require increasing fan capacity to maintain tenability despite stable critical ventilation velocities.

2.2 Shift Toward Active Fire Safety Measures

Upon recognising the limitations related to passive systems, researchers turned to active fire protection method such as water deluge and water mist systems. The Runehamar fire tests (2016) were a landmark in this shift. These tests compared TN-25 and TN-17 nozzles, revealing that larger droplets from TN-25 offered superior flame suppression and fire spread control. However, suppression performance was strongly influenced by several factors like airflow direction, nozzle distance, and activation timing— indicating that such systems must be carefully integrated into overall tunnel design.[5]

2.3 Regulatory Recognition and Risk-Based Approaches

Following catastrophic fires like Mont Blanc and Gotthard, regulatory agencies began revamping tunnel fire safety standards. A pivotal study by the European Parliament, led by Alan N. Beard,[2] emphasized upon risk-based approaches, proposing that prescriptive rules be supplemented by quantitative models and performance-based designs. The report urged for the integration of active systems, improved ventilation coordination, and real-time system validation. In response, authorities such as NFPA and PIARC revised their frameworks to cautiously support active suppression, stressing the importance of large-scale testing and multi-system synergy.[1]

Table 2: Evolution of Tunnel Fire Safety Approaches

Era	**Focus**	**Typical fire size assumed**	**Strategy**	**Limitation**
Early Stage (pre-2000)	Passive protection (structural resistance, fire load limits)	20 MW	Longitudinal ventilation + fire-resistant lining	Underestimated real HRR of HGV fires (>100 MW)
Transition (2000–2010)	Active protection (deluge, mist, detection systems)	50-100 MW	Large-scale fire tests (Runehamar)	Suppression–ventilation interactions not fully understood
Current (2010–present)	Performance-based, risk-informed design	100-200 MW	Simulation tools (FDS, PyroSim, Pathfinder)	Limited integration of ventilation, suppression & evacuation

3. Smoke Movement and Ventilation Control

3.1 Behaviour of Smoke in Confined Tunnel Geometry

Smoke propagation in tunnels differs significantly from open environments due to confined geometry, ventilation influence, and buoyancy effects. In tunnel fires, hot gases form a dense smoke layer near the ceiling, rapidly deteriorating visibility and breathable air. It was observed during a study that a lower longitudinal ventilation velocity (e.g., 0.5 m/s) led to higher peak temperatures directly above the fire, while higher velocities (e.g., 1.9 m/s) reduced local maxima by dispersing heat more widely. These findings justifies that ventilation is not merely a tool for smoke removal but also a determinant of thermal stratification and smoke layering, which are critical for structural resilience and safe evacuation.[6]

3.2 Ventilation Timing and Direction: A Critical Decision

Ventilation activation timing and airflow direction are pivotal in determining the outcome of a tunnel fire scenario. Premature activation of fans can push smoke into occupied regions, the exposure hazard, while delayed activation can lead to thermal buildup and smoke backlayering. Various studies shows that an airflow velocity between 1 - 1.5 m/s to be maintained during evacuation. Both insufficient and excessive velocities were shown to contribute to either flame propagation or ineffective smoke displacement, respectively.[7]

3.3 Longitudinal Ventilation Systems and Smoke Flow Patterns

Longitudinal ventilation systems are widely adopted due to their simplicity and cost-efficiency, yet they present considerable complexity under fire conditions. In the study, it was revealed that such systems can intensify fire growth, particularly for heavy goods vehicle (HGV) fires. At a ventilation speed of 3 m/s, the fire intensity was observed to increase by 4–5 times; at 10 m/s, the fire could become 10 times more severe due to the enhanced oxygen supply. While low ventilation speeds may limit fire escalation and aid in localised smoke control, higher velocities pose threats to downstream evacuees by accelerating smoke spread.[7][8]

Table 3: Effect of Ventilation Velocity on Tunnel Fire Behaviour

Ventilation Velocity (m/s	**Observed Effect on Fire/Smoke**	**Risk to Occupants**
0.5 m/s (low)	High ceiling temperature, localized smoke	Poor tenability near fire zone
1–1.5 m/s (moderate)	Optimal for evacuation; prevents back layering	Recommended range for safe egress
3 m/s (high)	Fire intensity increased 4–5x due to oxygen supply	Smoke spread downstream faster
10 m/s (very high)	Fire intensity 10x higher; suppression less effective	Extremely hazardous

3.4 Understanding and Predicting Smoke Backlayering

Smoke backlayering—where hot gases move against the airflow—remains a persistent hazard in tunnel fires. The limitations of the cube-root relationship in predicting critical ventilation velocity (CVV), especially for fires exceeding 100 MW or occurring in non-standard tunnel geometries. In order to produce more precise CVV estimates, the researchers suggest updated modelling techniques that take into account obstruction effects, tunnel cross-section, and flame geometry. These improvements aid in designing ventilation systems that are responsive to realistic fire scenarios.[9]

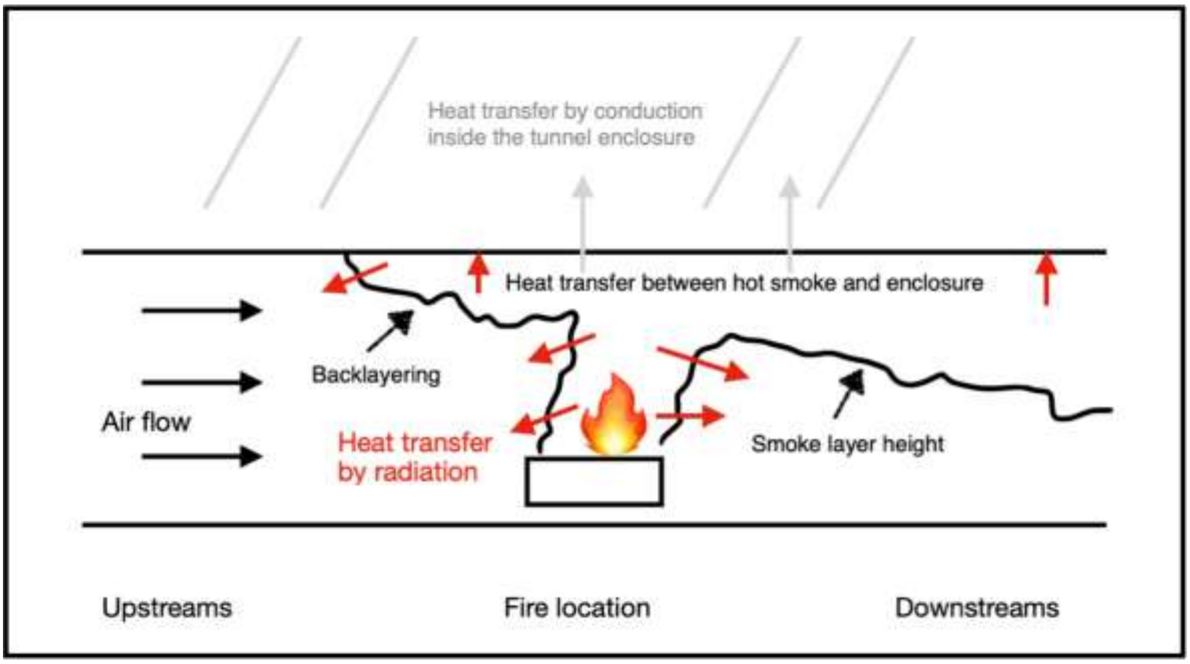

Figure 1: schematic diagram over a tunnel fire introducing several important terms.

3.5 The Throttling Effect: Resistance to Airflow in Growing Fires

An emergent concept in tunnel fire ventilation is the throttling effect, where fires resist incoming ventilation flows as their intensity increases. It was experienced in the experiment of throttling effect in Tunnel Fires, which used CFD simulations via the Fire Dynamics Simulator (FDS) to show that jet fans required for smoke control rise steeply with fire intensity. For fires ≤30 MW, 3–4 jet fans sufficed; however, for fires of 60–90 MW, 6–7 fans were needed, and even then, smoke control was not always successful due to disrupted flow patterns. The study highlights the inadequacy of relying solely on CVV and recommends scaling ventilation design based on both tunnel geometry and potential fire growth rates. [10]

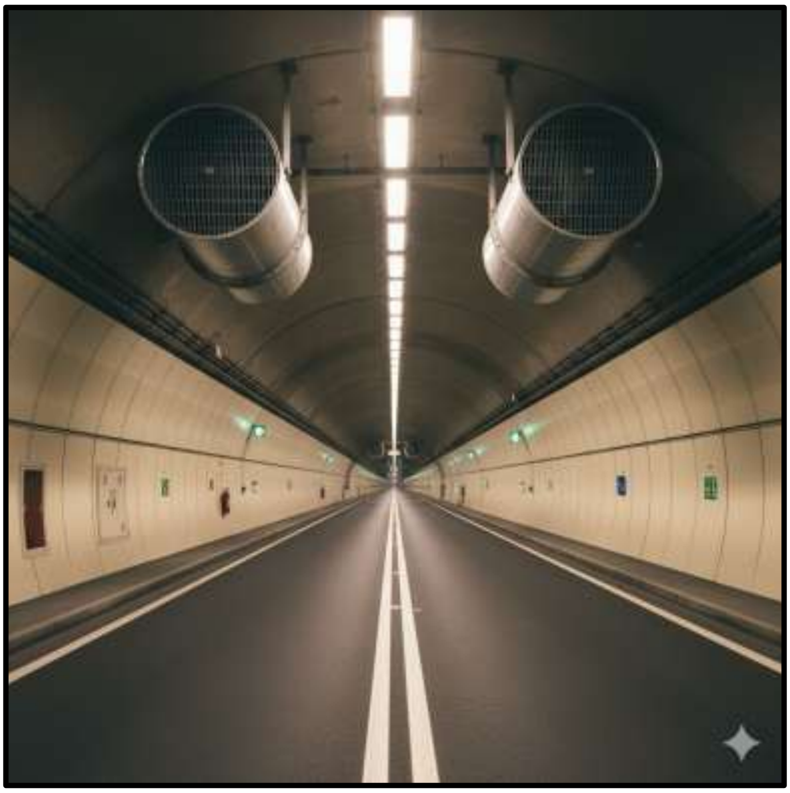

Figure 2: Interior view of a road tunnel showcasing prominent jet fans installed near the entrance for longitudinal ventilation.

4. Fire Suppression Strategies

This section examines tunnel-specific fire suppression technologies, their configurations, effectiveness, and known limitations. Drawing from full-scale experiments, CFD simulations, and performance reviews detailed in the selected literature, each sub-section offers technical insights aligned with design, application, and integration of suppression systems in tunnel environments.

4.1 Fixed Fire Suppression Systems in Tunnels: Role and Relevance

Tunnel environments heavily depend on Fixed Fire Fighting Systems (FFFS) to delay fire growth and allow safe evacuation before emergency services intervene. Unlike in open structures, accessibility is limited, making deluge or mist systems critical.

Fixed Fire Protection Systems reduce heat release rates (HRR), prevent fire propagation, and enhance tenability by lowering temperatures and smoke density. However, their effectiveness depends on precise activation logic and integration with ventilation to avoid counterproductive outcomes like stratification breakdown or mist displacement.[3]

4.2 Deluge Systems: Nozzle Design and Droplet Behaviour

Deluge systems are often preferred in tunnels due to their straightforward mechanics and reliability. Performance hinges on droplet size, pressure, spray geometry, and nozzle type.

The Runehamar tunnel fire tests[3] compared multiple nozzles, including TN-17 and TN-25. TN-25 produced larger droplets, achieving better suppression by effectively cooling fuel surfaces and shielding downstream targets. In contrast, TN-17—producing finer droplets—was less effective under strong longitudinal airflow, with fire re-ignition observed after 45 minutes.
Thus, nozzle geometry and droplet mass significantly affect system performance in ventilated tunnels.[11]

4.3 Water Mist Systems: Advantages and Limitations

Water mist systems, valued for their lower water demand and infrastructure footprint, generate fine droplets that rapidly evaporate, cooling flames and reducing oxygen. Despite this, their performance deteriorates under strong airflow conditions.

Studies, including one from the University of Edinburgh,[4] indicate that fine mist droplets can be displaced hundreds of meters away by longitudinal ventilation before reaching the combustion zone, making mist systems less compatible with high-velocity airflow tunnels.
Mist systems perform best in tunnels with low ventilation velocities or confined geometries, where spray residence time remains high.[16]

4.4 Suppression Timing: Early vs. Delayed Activation

The timing of system activation greatly affects fire development and evacuation safety. The simulations using FDS and Pathfinder showed that early suppression helped delay flashover and maintain tenability. However, if triggered too soon—before proper ventilation is established—it could worsen conditions by condensing smoke and reducing visibility near exits.[12]
This indicates suppression systems should not rely solely on thermal triggers but should integrate dynamic smoke detection for intelligent activation.

4.5 Suppression and Ventilation Interaction: A Design Dilemma

One of the most critical challenges in tunnel fire safety is the interaction between ventilation and suppression. As observed in the Runehamar fire experiments[3] suppression without ventilation adjustment led to reduced system effectiveness due to droplet displacement and altered smoke buoyancy. Additionally, one study introduced the “throttling effect”, where intense fires resist airflow, altering how suppression and ventilation must be coordinated. Mist systems, in particular, become ineffective unless ventilation velocity is specifically controlled during discharge. Designers must coordinate fan speed, air direction, and suppression logic simultaneously.[4]

4.6 Limitations

While suppression systems reduce HRR and improve evacuation chances, they are not standalone solutions. Their effectiveness hinges on:

- Appropriate nozzle selection and spacing
- Integration with longitudinal ventilation systems

- Smart activation algorithms based on real-time smoke and heat feedback

Multiple papers have recommend using hybrid simulations (PyroSim + CFD tools) to predict system behaviour across various tunnel geometries and fire scales.[15]

Future work must focus on optimising suppression-ventilation coupling using probabilistic simulations, refining detection logic, and validating results with full-scale fire tests.

5. Human Behaviour and Evacuation in Tunnel Fires

Evacuation during tunnel fires is a high-risk process shaped by environmental and psychological factors. Key determinants such as visibility, heat, smoke spread, signage, and human decision-making under stress dictate evacuation speed and survival rates. The following sub-sections summarise findings from full-scale simulations and behavioural analyses presented in the literature.

5.1 Impact of Visibility and Smoke on Evacuation Time

A strong inverse relationship exists between smoke density (visibility) and evacuation speed. It was seen that when visibility drops below 10–15 meters due to smoke, evacuees exhibit delayed or halted movement. Additionally, hesitation increases when exit signage is obscured, or lighting fails.[13]

The same study quantified that evacuation time could increase by up to 60% in tunnels with poor ventilation or without illuminated exit signs—especially when CO concentrations also rise rapidly.

5.2 Exit Spacing and Evacuation Path Layout

One study evaluated side exits spaced at 300 m vs. 600 m intervals under different fire growth rates. It concluded that shorter exit intervals enhance survivability, particularly in cases of high HRR fires. Users typically head toward the first visible exit, emphasizing the need for visibility-optimized positioning of egress routes.[14]

Moreover, tunnel slope, pedestrian lighting systems (like flashing floor markers), and exit familiarity were noted to influence evacuee direction and speed.

5.3 Human Behaviour Models and Limitations in Simulation

Although tools like Pathfinder and BuildingEXODUS provide quantitative simulation, they lack in replicating real-world behavioral unpredictability. It was noted that evacuees often exhibit non-optimal behaviours—e.g., returning to entry points, waiting for group members, collecting personal items, or ignoring alarm cues .[14]

These human tendencies introduce deviations between modelled and real evacuation patterns. The study suggested future models should include stochastic behaviour parameters, cultural differences, and delayed responses to better reflect real-world scenarios.

5.4 Integrated Safety Systems and Evacuation Aids

Evacuation success improves significantly when multi-layered safety systems are applied. Studies have suggested that the integrated use of audio-visual alarms, dynamic signage, and smoke extraction led to a 35–50% reduction in total evacuation time.[8]

By redirecting evacuees away from smoke-affected paths in real-time, the study confirmed that coupling suppression, detection, and intelligent evacuation guidance provides substantial safety gains—making a strong case for holistic system design.

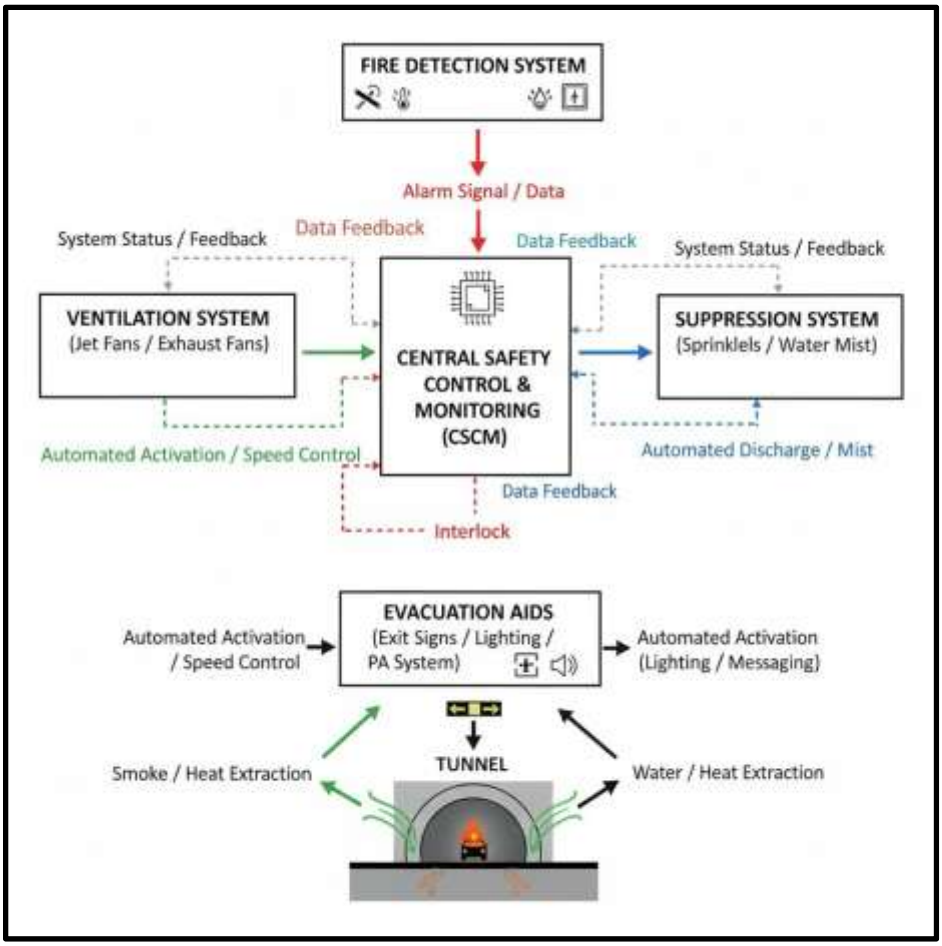

Figure 3: Conceptual diagram illustrating the integrated components of a comprehensive tunnel fire safety system for coordinated incident response.

6. Simulation Tools – PyroSim & Pathfinder

Simulation has become a cornerstone of modern tunnel fire safety engineering. Real-scale tunnel fire testing is costly, risky, and often impractical. Tools like PyroSim (for fire and smoke modelling) and Pathfinder (for evacuation analysis) allow engineers to recreate tunnel fire conditions with accuracy and flexibility. These tools support proactive safety design, system optimisation, and incident analysis, especially in complex tunnel geometries with constrained ventilation and evacuation options.

6.1 Importance of Simulation in Tunnel Fire Safety

Tunnel fire safety involves a complex interplay of geometry, ventilation, fire growth, and human response. Simulation models help engineers explore these variables without relying on full-scale testing.

The simulation in a study revealed that the location and activation timing of jet fans significantly affect smoke layering and temperature distribution. Delayed fan activation often led to thermal stratification collapse, which reduces visibility and accelerates untenable conditions.[7]

6.2 PyroSim for Fire and Smoke Modelling

PyroSim, which interfaces with the Fire Dynamics Simulator (FDS), is a CFD-based tool for modelling fire growth, HRR evolution, and smoke transport. It allows input of various tunnel parameters like geometry, fuel load, jet fan layout, and ventilation velocity.

In a study, PyroSim was used to simulate a 200 m tunnel with different fan activation timings. It showed that early ventilation helped maintain visibility near exit routes for 3–4 minutes longer and delayed CO rise—thereby extending available safe egress time (ASET).[15]

It was also demonstrated that PyroSim can replicate heat distribution across the ceiling and predict critical back-layering conditions, validating its use in performance-based tunnel design.[9]

6.3 Pathfinder for Evacuation Simulation

Pathfinder simulates human movement during fire events using agent-based logic that factors in speed, visibility, CO levels, decision-making behaviour, and group dynamics. When combined with PyroSim data, it allows engineers to evaluate how evacuees behave in real-time tunnel emergencies.

From one of the Pathfinder simulations from a study demonstrated that increasing exit frequency and widening doors cut total evacuation time by up to 45%. Bottlenecks typically formed near poorly marked exits or under low-visibility zones, guiding improvements in layout and signage.

Pathfinder also showed that introducing dynamic signage and voice alarms redirected evacuees more efficiently away from blocked paths—reducing total evacuation time by over 30% in some scenarios.

6.4 Validation and Reliability of Simulation-Based Studies

The reliability of PyroSim and Pathfinder simulations has been confirmed through comparisons with large-scale tunnel fire experiments such as those at Runehamar and Memorial tunnels[5]. These tools comply with tunnel fire codes including NFPA 502 and PIARC, and their predictions align with known tenability thresholds and back-layering behaviour.

It was provided evidence from a study that FDS-based simulations closely matched real incident outcomes in terms of flame spread, CO concentration trends, and temperature profiles. Such validation underscores the reliability of using simulation tools for risk analysis, emergency planning, and tunnel safety system design.

7. Integration of Tunnel Fire Safety Systems: A Path Toward Comprehensive Protection

Modern tunnel systems—especially those serving urban interchanges, metro-rail hybrids, or multi-level vehicular corridors—are no longer linear infrastructures. They represent complex, confined, and high-risk environments with dynamic traffic profiles, flammable cargo exposure, and limited evacuation flexibility. Managing fire safety in such scenarios demands an integrated and adaptive approach—where ventilation, suppression, detection, simulation, and evacuation systems work together, not in isolation.

Although substantial advances have been made in individual safety domains—such as suppression nozzle optimization, jet fan control algorithms, and behaviour-based evacuation models—current literature reveals a critical lack of integration across these domains. The study of fire simulations accurately captured the effects of smoke layering, exit signage, and pre-movement delays using PyroSim and Pathfinder. However, these simulations typically analyse systems independently, without modelling their real-time interaction or feedback-based coordination.[15]

One study highlights that although individual elements like early suppression or longitudinal ventilation performance are well-validated, there is minimal research that synchronizes them into a systemic framework. As observed, even technically efficient systems—such as water mist suppression assisted by jet fans—underperform if airflow direction, occupancy patterns, or detection timing are not appropriately coordinated.[8][7]
In high-HRR fire events (e.g., >100 MW) the effectiveness of any single-point solution—like deluge systems or fixed

jet fans—depends on timing and interaction. Delayed fan activation, as simulated, resulted in smoke recirculation and reduced evacuation tenability despite suppression working correctly. [14]

These findings underscore the limitations of prescriptive, siloed designs. As tunnel infrastructure grows in scale and functional complexity, a shift toward performance-based design methodologies is essential. These must be supported by multi-system simulations, capable of testing fire detection, smoke movement, suppression reaction, and human behaviour simultaneously under varying conditions.

Despite strong evidence advocating integrated design, few studies have gone beyond component-level validation into true system integration modelling. This opens clear opportunities for further research in:

- Real-time coordination between detection and ventilation logic
- Feedback-based suppression control linked to HRR and smoke sensors
- Dynamic evacuation routing tied to environmental sensing Failure-mode testing under hybrid or cascading risk scenarios

By leveraging advanced simulation tools not just as diagnostic platforms—but as coordinated design engines—engineers can finally approach tunnel fire safety as a holistic, responsive system rather than a sum of isolated parts.

8. Research Gap

Although significant progress has been made in understanding tunnel fire dynamics, ventilation strategies, suppression technologies, and evacuation behaviour, a detailed review of the literature in this paper reveals several unresolved gaps that limit the development of a fully reliable, performance-based tunnel fire safety framework.

First, most studies focus on individual systems in isolation—such as ventilation control, deluge performance, water mist behaviour, or evacuation modelling—without examining how these components interact in real time during a tunnel fire. While tools like PyroSim and Pathfinder effectively model fire dynamics and human movement separately, integrated simulations combining smoke behaviour, suppression discharge, jet fan operation, and dynamic evacuation remain scarce. This gap restricts our ability to evaluate tunnel safety as a coordinated system.

Second, the interaction between longitudinal ventilation and suppression systems under high heat release rate (HRR) conditions (>100 MW) is not well established. Existing research highlights key issues—such as droplet displacement, increased HRR at high ventilation speeds, and the throttling effect—but there are no validated control strategies for optimizing fan speed, airflow direction, or suppression timing to ensure tenability during large-scale tunnel fires.

Third, evacuation studies generally assume static human behaviour, constant visibility, or fixed exit choices. However, real events show that evacuees respond to changing smoke layers, CO accumulation, and varying visibility. Dynamic, behaviour-driven evacuation models that incorporate real-time smoke movement, signage effectiveness, and ventilation shifts remain underdeveloped.

Fourth, although PyroSim and Pathfinder outputs align with selected full-scale tests, combined fire– evacuation models lack extensive real-world validation, especially for curved tunnels, multi-level infrastructures, or metro–road hybrid tunnels, which are increasingly common in urban settings. Most existing research focuses on straight, uniform tunnels, leaving complex geometries largely unexplored.

Finally, emerging technologies such as AI-based detection, adaptive ventilation algorithms, and intelligent evacuation guidance are identified in literature but remain at a conceptual stage with minimal experimental or simulation-backed validation for tunnel environments.

In summary, the literature shows clear gaps in:

1. integrated multi-system modelling of tunnel fire safety,
2. coordinated control of ventilation and suppression under high HRR conditions,

3. realistic, adaptive evacuation modelling,
4. large-scale validation of simulation tools in complex tunnel layouts, and
5. research on AI-driven, real-time safety management systems.

Addressing these gaps is essential for developing next-generation, performance-based tunnel fire safety designs suitable for modern and complex tunnel infrastructures.

9. Proposed Methodology Framework for Future Research

While existing literature has extensively discussed fire dynamics, smoke movement, ventilation strategies, and suppression interactions in tunnels, there remains a need for integrated, scenario-based performance evaluation using validated simulation tools. Building on the gaps identified in this review, the following methodology outlines the future research direction planned by the authors. This work intends to analyse tunnel fire behaviour under varying fire loads, ventilation strategies, and suppression configurations using PyroSim/FDS, enabling a performance-based approach to tunnel safety design.

9.1. Objective of the Future Study

The proposed research aims to conduct a simulation-based performance assessment of fire behaviour, smoke propagation, and tenability in a 200-m road tunnel under multiple design fire scenarios. The study will evaluate two system configurations:

1. **Natural Ventilation (Baseline Condition)**

2. **Integrated System:** Longitudinal mechanical ventilation + sprinkler suppression

The objective is to quantify the influence of these systems on temperature distribution, HRR evolution, visibility, back-layering, and evacuation tenability, addressing several gaps highlighted throughout the review.

9.2. Selected Design Fire Scenarios and HRR Basis

To ensure realistic and literature-aligned modelling, the study adopts three representative vehicle fire scenarios based on NFPA 502 and full-scale HGV fire experiments (Runehamar, Memorial Tunnel).

Table 4: Design Fire Scenarios for Future Simulation Work

Scenario	**Vehicle type**	**Peak HRR (MW)**	**Justification**
Scenario 1	Heavy goods vehicle (HGV)	100 MW	Represents severe HGV fires frequently exceeding 80–120 MW in full-scale tests; associated with worst tunnel disasters.
Scenario 2	Bus/ medium truck	25 MW	Aligns with typical HRR of buses and multi-compartment trucks; reflects moderate-severity events.
scenario 3	Passanger car	10 MW	Represents common tunnel incidents; matches peak HRR of single passenger vehicles.

9.3. System Configurations to be Evaluated

The study will compare tunnel response under two contrasting configurations:

Case 1 — Natural Ventilation Only

- Airflow driven purely by portal wind and buoyancy (≈0.5 m/s).
- No mechanical fans or suppression system.
- Represents *older tunnels* or *system-failure conditions* emphasized in historical studies.

Case 2 — Integrated Ventilation–Suppression System

- Longitudinal jet fans supplying 2 m/s airflow.
- Wet-pipe sprinkler system with 5 m spacing, activation at 93°C.
- Reflects *modern tunnel safety practice* and aligns with insights from Runehamar and PIARC recommendations.

This dual-case comparison mirrors the literature findings on:

- critical ventilation velocity,
- throttling effect,
- suppression–ventilation interaction,
- smoke back-layering control,

making the methodology consistent with global research directions.

9.4. Expected Performance Indicators

The following metrics will be analysed across scenarios:

1. Heat Release Rate (HRR) Evolution
- Influence of sprinkler activation on HRR reduction.
- Comparison across 10, 25, and 100 MW fires.
2. Temperature Distribution
- Ceiling jet temperature vs. evacuation height temperature.
- Identification of unsafe regions (> 60°C).
3. Smoke Propagation and Back-Layering Distance
4. CO Concentration Trends
- Tenability threshold: 1200 ppm.
5. Ventilation Effects
- Effectiveness of 2 m/s airflow in preventing upstream contamination.
6. Sprinkler Interaction
- Impact of water spray on plume behaviour and stratification collapse.

These indicators are fully aligned with the gaps identified in Sections 3, 4, and 5 of the review (ventilation limits, suppression timing, human tenability).

9.5. Significance and Alignment with Review Findings

Integrating the above methodology into the review provides:

- A **clear bridge** between existing literature and your planned research.
- A **scenario-based, performance-driven** framework consistent with global tunnel fire research.
- A demonstration of how your work aims to fill the research gaps identified:

1. ventilation–suppression coupling,
2. HRR variability and design fire selection,
3. back-layering prediction limitations,
4. tenability mapping,
5. need for combined CFD and system analysis.

Conclusion

Tunnel fire safety has evolved from traditional prescriptive measures to complex, performance-based systems. The literature consistently shows that modern tunnel fires—especially those involving high fire loads and long evacuation paths—demand a comprehensive understanding of smoke dynamics, ventilation strategies, fire suppression technologies, and human evacuation behaviour. Early assumptions of manageable fire sizes have been challenged by real-world incidents and large-scale testing, emphasizing the need for adaptable systems capable of handling fires exceeding 100 MW. Studies highlight how ventilation timing, nozzle design, and exit placement can critically affect survivability, and how even minor oversights in system coordination can lead to cascading failures.

Simulation tools like PyroSim and Pathfinder have proven indispensable in bridging theory and real- world behaviour. These tools enable modelling of fire development, toxic gas spread, and crowd dynamics with high accuracy, validating their use in both design and forensic analysis. However, while significant advancements have been made in individual areas, the literature also reveals a notable gap in system-wide integration.

To contribute to this evolving field, our study will focus on analyzing smoke spread behavior under various tunnel ventilation conditions, performing simulation-based evaluations of evacuation processes during tunnel fires under forced ventilation, and examining the effectiveness of fire protection systems in enhancing tenability during road tunnel fire scenarios. This integrated approach aims to support more resilient and responsive tunnel fire safety designs.

References

1. Jonatan Gehandler. Road tunnel fire safety and risk: a review. Fire Science Reviews, Vol. 4, Art. No. 2, 2015.
2. A. N. Beard. Fire safety in tunnels. Fire Safety Journal, Vol. 44, pp. 276–278, 2009.
3. Jack R. Mawhinney. Fixed Fire Protection Systems in Tunnels: Issues and Directions. Fire Technology, Vol. 49, pp. 477–508, 2013.
4. Ricky Carvel. A review of Tunnel Fire Research from Edinburgh. Fire Safety Journal, Vol. 105, pp. 300-306, 2019.
5. Haukur Ingason, Ying Zhen Li. Large scale tunnel fire tests with different types of large droplet fixed firefighting systems. Fire Safety Journal, Vol. 107, pp. 29–43, 2019.
6. L.H. Hu, R. Huoa, W. Peng, W.K. Chow, R.X. Yang. On the maximum smoke temperature under the ceiling in tunnel fires. Tunnelling and Underground Space Technology, Vol.21, pp. 650–655, 2006.
7. P. Sturm, M. Beyer, M. Rafiei. On the problem of ventilation control in case of a tunnel fire event. Case Studies in Fire Safety, Vol. 7, pp. 36–43, 2017.
8. R.O. Carvel, A.N. Beard, P.W. Jowitt. The influence of longitudinal ventilation systems on fires in tunnels. Tunnelling and Underground Space Technology, Vol. 16, pp. 3-21, 2001.
9. Yasushi Oka, Graham T. Atkinson. Control of Smoke Flow in Tunnel Fires. Fire Safety Journal, Vol. 25, pp. 305-322, 1995.
10. Arnas Vaitkevicius, Ricky Carvel. Investigating the Throttling Effect in Tunnel Fires. Fire Technology, Vol. 52, pp. 1619-1628, 2016.
11. D. Van den Broecke, R. Emberley, T. Sietz, J. L. Torero, C. Maluk. Study on the effectiveness of fire suppression deluge systems in tunnels. Tunnelling and Underground Space Technology, Vol. 108, Art. No. 103764, 2021.

12. Z. Liu, X. Gu, and R. Hong. Fire Protection and Evacuation Analysis in Underground Interchange Tunnels by Integrating BIM and Numerical Simulation. MDPI Fire, Vol. 6, No. 4, pp. 139, 2023.
13. M. Fera, R. Macchiaroli. Use of analytic hierarchy process and fire dynamics simulator to assess the fire protection systems in a tunnel on fire. Int. J. Risk Assessment and Management, Vol. 14, No. 6, pp. 504, 2010.
14. Y. Cui and Z. Liu. Study on Fire Smoke Movement Characteristics and Their Impact on Personal Evacuation in Curved Highway Tunnels. Applied Sciences, Vol. 14, No. 12, Art. No. 6339, 2024.
15 A. Sarvari and S. M. Mazinani. A new tunnel fire detection and suppression system based on camera image processing and water mist jet fans. Heliyon, vol. 5, Issue 6, e0187, 2019.

Declaration:

Funding: The author(s) received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors for the completion of this research work.

Clinical Trial Number: Not applicable Ethics approval: Not Applicable Consent to participate: Not Applicable Consent for publication: Not Applicable