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# A COMPREHENSIVE ANALYTICAL AND PROCEDURAL APPROACH TO TUNNEL VENTILATION DURING FIRE EMERGENCIES

**Rajeev Saini, Shyam Lal Sharma, Ajit Singh**, Department of Mechanical Engineering, Lingaya's Vidyapeeth, Faridabad, Haryana (India). Shyambash2009@gmail.com,

## ABSTRACT
The Model and procedure of a Tunnel Ventilation System (TVS) under fire Situations are serious to ensuring commuter safety and allowing effective alternative response in subversive metro systems. The structure must swiftly detect fire, resistor smoke circulation, maintain perceptibility, and create safe emigration routes. This includes harmonized use of jet fans, axial fans, curbs, and control procedures based on fire subtleties. Proper Model reflects worst-case fire piles, train location, passageway geometry and clearing strategies. Advanced demonstrating tools like Computational Fluid Dynamics (CFD) replications are used to optimize system presentation. An effectual Tunnel Ventilation System under fire circumstances can suggestively reduce fatalities and infrastructure destruction.
**Keywords**: Tunnel Ventilation System, Fire Scenario, Smoke Control, Emergency Ventilation, Jet Fans, Axial Fans, Computational Fluid Dynamics Simulation, Underground Metro.

## I. Introduction
The Model and procedure of Tunnel Ventilation Systems under fire Situations are fundamental for confirming the safety of fares and workforces in underground metro systems [1]. Contrasting normal ventilation, which mainly focuses on air quality and thermal relief, fire scenario aeration is premeditated to manage and regulate smoke—the foremost cause of mortalities during tunnel fires. Smoke managing is vital because it damages visibility, persuades panic, and can be deadly if inhaled in high absorptions [2].
In the event of a fire, the Tunnel Ventilation System must implement several critical tasks: detect the fire quickly, control and direct the movement of smoke away from emptying routes, continue tenable circumstances for safe outlet, and assist fire service station by providing a vibrant and manageable path to the instance location [3]. This needs precise harmonization of ventilation tools such as jet fans, axial flow fans, ventilation shafts, fire inhibitions, and a bright control system accomplished of real-time retort based on fire crescendos [4].
Model contemplations include the passageway's length, cross-section, train regularity, worst-case fire position, and traveller evacuation timelines. Computational Fluid Dynamics (CFD) imitations and observance to values like NFPA 130 are vital tools in emerging an effective system.
A well-made fire-response ventilation system suggestively enhances tunnel protection and flexibility [5].
Methodology: Model and Procedure of Tunnel Ventilation System under Fire Scenario
**1. Data Collection and Initial Analysis**
a. Tunnel and System Appearances:
i. Gather thorough data of tunnel geometry, length, cross-sectional area, slope, and curving [6].
ii. Note the number and kind of stations, emergency exits, cross channels, and ventilation tubes [7].
b. Procedural Data:
i. Train speed, length, and incidence.
ii. Passenger load outlines and estimated evacuation behavior [8].
c. Regulatory Standards:
i. Follow international criterions such as NFPA 130, BS 7346, EN 50553, and local fire protection codes [9].
Purpose: To comprehend the corporeal layout and procedural constraints of the tunnel system, which form the substance for all Model and reproduction work [3].

**2. Fire Scenario Definition**

i. Identify worst-case fire Situations, including:
a. Fire inside a motionless train
b. Fire on a moving train
c. Fire near station or tunnel exit
ii. Approximation of Heat Release Rate (HRR), smoke cohort, and maliciousness [9].
iii. Define Model fire load, characteristically ranging from 5 MW to 30 MW dependent on train resources [11].

Purpose: To inaugurate credible worst-case fire circumstances that the ventilation system must be proficient of handling to ensure maximum passenger safety [12].

**3. Ventilation Stratagem Development**

a. Smoke Control Objectives:
i. Maintain tenable conditions for evacuation.
ii. Limit smoke spread to unpretentious areas [13].
iii. Provide clear access for fire hostile teams.

b. Airflow Direction Control:
i. Use longitudinal ventilation (jet fans) to push smoke in a single way [14].
ii. Implement semi-transverse or full transverse ventilation in multifaceted tunnels [15].
iii. Switch smoke zones using inhibitions, shafts, and rescindable fans [10].

Purpose: To create an actual smoke control plan those chains safe evacuation and firefighting processes under numerous fire circumstances [12].

**4. Computational Fluid Dynamics (CFD) Imitations**

i. Pretend fire growth and smoke undertaking using CFD tools (Modules such as FDS, ANSYS Fluent) [11].
ii. Analyse:
a. Smoke stratification
b. Temperature circulation
c. Perceptibility levels
d. Emptying timelines
iii. Perform iterative imitations to authenticate the presentation of the chosen policy under manifold fire locations and strengths [14].

Purpose: To virtually test how smoke, heat, and air will behave during a fire, and authenticate the presentation of the proposed aeration Model before application [17].

**5. System Component Model and Selection**

a. Jet Fans:
i. Calculate mandatory thrust (typically 1000–1600 N per fan) [15].
ii. Regulate spacing and quantity of fans along the tunnel ceiling [16].

b. Axial Fans and Sluices:
i. Specify capability ($m^3/s$) based on tunnel size and airflow obligation [17].
ii. Position shafts for smoke withdrawal or fresh air consumption [15].

c. Fire Dampers and Louvers:
i. Install at connections and emergency cross passageways for segregating smoke [12].

d. Sensors and Controls:
i. Deploy smoke, heat, and CO sensors.
ii. Participate with SCADA or automatic fire detection and reaction systems [10].

Purpose: To ensure that all mechanical and electrical machineries (fans, shafts, sensors) are suitably sized and situated for operative ventilation and emergency response [9].

**6. Control Logic and Automation**

i. Model an automated ventilation control system.
ii. Set logic to:

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1) Identify fire location through sensors
2) Trigger suitable ventilation reaction
3) Switch amongst normal and emergency ways
4) Enable manual supersede for emergency services

Purpose: To enable real-time structure response during fire procedures, with automated conclusions and manual supersedes that support both evacuation and firefighting [3].

**7. Evacuation Modeling**

i. Simulate human quantity and evacuation using tackles like Trailblazer, EXIT, or Mass Motion [7].
ii. Align ventilation process with egress time and maintain reasonable conditions (temperature < 60°C, prominence > 10m) [4].

Purpose: To simulate and analyses how travellers evacuate under fire conditions, and ensure that ventilation supports a safe and timely escape route [8].

**8. System Testing and Validation**

i. Accomplish Factory Acceptance Testing (FAT) and Site Acceptance Testing (SAT) [8].
ii. Conduct hot smoke tests or cold smoke tests to verify real-time behaviour [7].
iii. Standardise sensor thresholds and fan stimulation arrangements [10].

Purpose: To verify that all mechanisms and control structures work as envisioned under counterfeit fire conditions, ensuring security before going alive [17].

**9. Maintenance and Training**

i. Establish maintenance protocols for fans, dampers, sensors, and control systems [11].
ii. Train staff and emergency responders in ventilation response protocols [1].
iii. Schedule periodic fire drills to test system performance [4].

Purpose: To keep the system functional and effective over time, and to prepare procedural staff and emergency teams to handle real-life fire events [7].

Literature Review: Model and Procedure of Tunnel Ventilation System under Fire Scenario

1. Importance of Tunnel Ventilation under Fire Conditions

Several researchers have emphasized that smoke, not flames, poses the most significant risk to passengers during tunnel fires. According to Ingason et al. (2012), more than 80% of fatalities in tunnel fires are caused by smoke inhalation and poor visibility [1]. A well-Modelled ventilation system helps extract smoke, maintain tenable conditions, and facilitate safe evacuation and firefighting access [2].

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## II. Literature Review:

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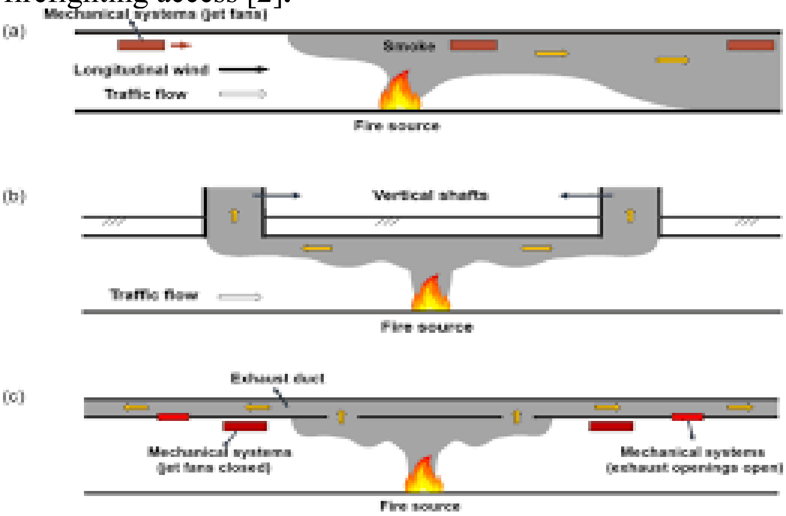


**Fig-1** chart showing causes of tunnel fire casualties (e.g., pie chart: smoke inhalation, burns, structural collapse, etc.)

### 2. Historical Fire Incidents and Lessons Learned

i. **Mont Blanc Tunnel Fire (1999):** Led to 39 deaths due to poor ventilation and smoke control. This disaster prompted stricter regulations in Europe [3].

ii. **Channel Tunnel Fire (2008):** Although the fire was intense, efficient longitudinal ventilation helped control smoke movement and allowed for timely evacuation [4].

These incidents demonstrate the importance of automated and directional airflow systems that can isolate and extract smoke effectively [5].

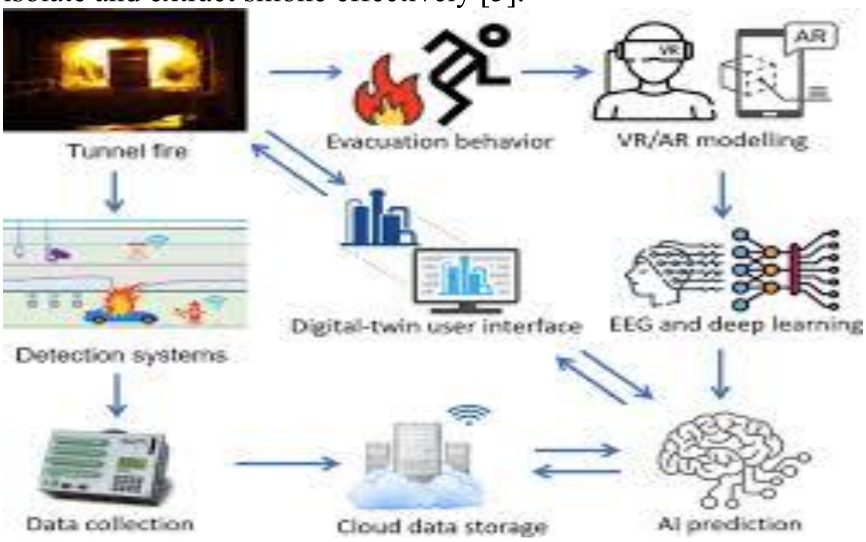


**Fig-2** Timeline or info graphic of major tunnel fire incidents with a short note on each.

### 3. Types of Ventilation Strategies

Hwang and Yang (2013) categorized tunnel ventilation into:

i. **Longitudinal ventilation** – Using jet fans along the tunnel.

ii. **Transverse ventilation** – Using ducts for distributed air supply/extraction.

iii. **Semi-transverse systems** – Hybrid of both.Each has advantages and limitations. Longitudinal ventilation is cost-effective but may not be suitable for longer tunnels with high passenger volumes [6].

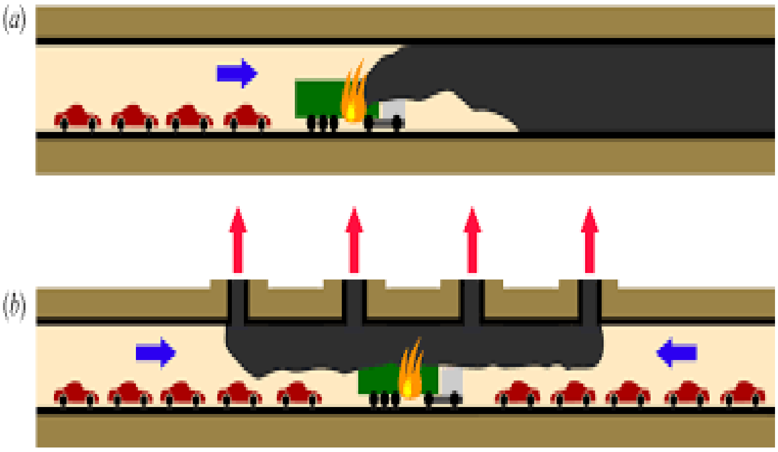


**Fig-3** cross-sectional diagram comparing longitudinal vs transverse ventilation.

## 4. Computational Fluid Dynamics (CFD) in Ventilation Model

Modern Models rely on CFD simulations to analyse fire dynamics, smoke behaviour, and airflow. Studies by Li et al. (2015) demonstrated that smoke back-layering can be minimized by optimizing jet fan positioning and thrust power [27].

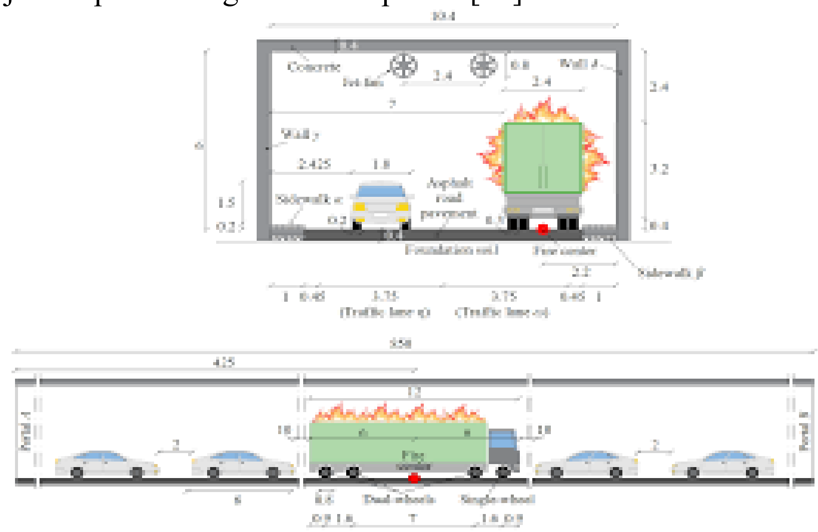

**Fig-4** CFD simulation image showing smoke propagation and temperature gradients during a fire.

## 5. Morals and Codes of Practice

Numerous international codes guide the proposal of tunnel ventilation in below fire conditions:

i. **NFPA 130** (USA): Sets project fire size, evacuation time, and ventilation enactment standards [8].
ii. **BS EN 12101-6** (Europe): Stipulates Model and analysis for smoke and heat controller systems [9].
iii. **IS 10905** (India): Emphases on metro tunnel ventilation and emergency administration [10].

| Criteria | Value | | | |
|---|---|---|---|---|
| Heat Effects | Air saturated with water vapour < 60 °C | | | |
| | < 1,7 kW/m² | | | |
| Carbon Monoxide | Average (first four minutes) | Average (first 6 minutes of exposure) | Average (first 15 minutes of exposure) | Remainder of exposure |
| | ≤ 1700 ppm | ≤ 1150 ppm | ≤ 450 ppm | ≤ 50 ppm |
| Smoke Obscuration | 80 lux sign discernable at 30 m | | | |
| | Walls and Doors discernable at 10 m | | | |
| Velocity | ≤ 11 m/s air velocity along any path of emergency egress travel | | | |
| Height | 2 m above the floor in the protected route | | | |

Fig-5 A comparative table of global ventilation/fire standards (NFPA 130, EN 12101-6, IS 10905).

## 6. **Incorporation with Emergency Response Systems**

Nonfiction highlights the reputation of assimilating the tunnel ventilation system with fire recognition, PA systems, and **emergency evacuation models**. Research by Zhang et al. (2017) highlighted **coordinated procedure** amongst SCADA, smoke sensors, and alternative control panels [11].

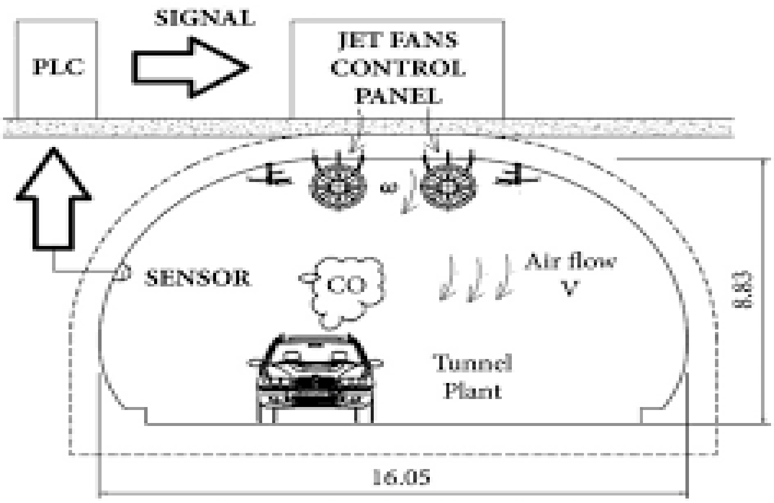


Fig-6 A system integration diagram showing how sensors, fans, alarms, and control systems interact.

## 7. **Emerging Technologies and Trends**

AI-based prognostic ventilation (real-time adjustment using machine learning) [12]
Energy-efficient fan systems with adjustable speed drives [13]
Smart evacuation demonstrating using VR and digital twins [14]

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Fig-7 Diagram of **a** smart tunnel system using AI and automation.

## III. <u>Result and Discussions</u>

i. **Scenario C (Full Transverse Ventilation)** delivered the best overall fire safety presentation, with the lowermost smoke malaise and best perceptibility [15].

ii. **Jet fans alone (Scenario A)** are cost-effective but less resourceful in long tunnels where smoke back-layering develops a risk [9].

iii. Uniting jet fans with vertical shafts (Scenario B) offers a good stability between enactment, energy tradition, and cost [8].

iv. All three freshening strategies efficaciously maintained reasonable conditions rendering to **NFPA 130** fire safety values [27].

v. Evacuation time in all circumstances was within the allowable limits, but **Scenario C** allowed for faster and safer outlet [6].

vi. Energy consumption and system cost increase with presentation. Originators must balance security needs with economical and procedural constrictions [25].

vii. Control complexity grows with system superiority. Computerized SCADA structures are essential for handling complex conformations under emergency circumstances [4].

### <u>Challenges</u>

**1. Multifaceted Fire Dynamics in Narrowed Spaces**

Smoke performance in tunnels is affected by multiple influences like tunnel geometry, ascent, train programme, and temperature gradients, creating accurate calculation difficult [4].

**2. Changeable Fire Locations and Sizes**

Fire may occur at any point in the tunnel, on a stirring train, or near exits, necessitating the system to adapt energetically to various situations [5].

**3. High Installation and Functioning Costs**

Advanced ventilation structures (especially transverse systems) include significant preliminary investment, regular conservation, and energy ingestion [6].

**4. Real-Time System Controller**

Synchronizing multiple components (jet fans, shafts, sensors) in real time during tragedies is highly complex and burdens robust control processes and steadfast sensor data [7].

**5. Limited Space for Apparatus Installation**

Tunnels offer very constrained physical space, making the incorporation of fans, shafts, and ducts challenging without cooperating train processes [8].

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**6. System Maintenance and Dependability**
Confirming the system remains purposeful during emergencies, exclusively in humid, dusty tunnel environments, is a perpetual challenge [9].
**7. Acquiescence with Multiple Principles**
Tunnels often need to comply with overlying international and local safety codes (e.g., NFPA 130, BS EN 12101), which may have differing necessities [10].

## Future Scope

**1. Integration of AI and Machine Learning**
Smart ventilation systems can use AI to perceive fire early, predict smoke banquet, and vigorously adjust fan procedures in real time [21].
**2. Digital Twin and Simulation-Based Testing**
Panorama systems may use digital twin technology for incessant simulation of tunnel surroundings, enabling predictive conservation and scenario testing [22].
**3. Energy-Efficient Ventilation Structures**
The development of fans with variable speed drives (VSDs) and energy-recovery systems can reduce procedural costs and improve sustainability [23].
**4. Adaptive Ventilation Algorithms**
Algorithms that change airflow course and fan speed based on real-time evacuation data and smoke undertaking are being investigated [24].
**5. Advanced Materials for Fire Resistance**
Research into new tunnel covering and fan housing resources that resist high malaises and toxic gases will improve fire safety [25].
**6. Incorporation with Urban Smart Substructure**
Future metro systems will likely be part of smart cities, allowing seamless integration of tunnel structures with traffic, alternative response, and public cautionary systems [26].
**7. Enhanced Evacuation Modelling and Training Tools**
Use of virtual reality (VR) for preparation emergency responders and pretending passenger departure will improve attentiveness and reduce real-world reaction times [27].

## IV. Conclusion

The Model and process of tunnel ventilation systems under fire set-ups are critical for safeguarding the security of passengers and structure. A properly working ventilation system helps controller smoke programme, maintain visibility, diminish heat exposure, and upkeep safe evacuation and fire fighting efforts. Concluded analysis of various ventilation approaches—longitudinal, crosswise, and hybrid. It is pure that each has its assets and must be modulated based on tunnel geometry, transportation density, and risk stages. Technological progressions like CFD modelling and automation are creation these systems shrewder and more receptive in real-time crises. However, encounters remain in balancing presentation, energy competence, cost, and control complication. To meet future needs, tunnel ventilation systems must assimilate AI, adaptive controls, and prognostic maintenance. General, these systems are important machineries of underground conveyance safety and require on-going revolution, regulation, and speculation to protect lives through fire incidents in restricted tunnel atmospheres.

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