FIRES IN ROAD TUNNELS

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ABSTRACT

Road tunnel fires are among the most critical safety challenges in modern transport systems due to space constraints, extreme heat, and difficult evacuation. This paper analyses key risk factors and technical solutions for fire prevention and suppression in tunnel infrastructure. The study examines fire development phases, the role of intelligent detection systems (such as linear heat detectors), and the importance of integrated management via control centres. A particular emphasis is placed on a modern safety challenge: the presence of electric vehicles in tunnel traffic. In conclusion, it is highlighted that tunnel safety depends on the synergy of advanced infrastructure, precisely defined firefighting protocols, and the continuous training of operational forces.

Keywords: fire protection, road tunnels, electric vehicles, lithium-ion batteries, detection systems, firefighting tactics

INTRODUCTION

While tunnels are vital components of modern transportation networks, they present significant safety risks, with fires posing the most critical threat due to confined spaces and limited evacuation options. This paper examines the specific characteristics of tunnel fires, the essential safety and detection infrastructure, and the pivotal role of control centres in effective incident management. By analysing standardised firefighting procedures and reflecting on the catastrophic 1999 Mont Blanc tunnel fire, this study highlights the necessity of integrating advanced technological systems with strategic operational planning to minimise risk and enhance safety.

TUNNEL FIRE CHARACTERISTICS

A fire in a tunnel has specific characteristics that make it extremely dangerous compared to fires in open spaces. The enclosed space, limited ventilation, high concentration of flammable materials, and restricted access for emergency services make a tunnel fire one of the most complex safety challenges.

Fire Development and Spread

Since the distance between the tunnel ceiling and the burning material is relatively small, flames in the centre of the fire quickly reach the ceiling. Thermal energy then transfers to the structure or is transported via smoke gases in the airflow direction. The energy transferred to the ceiling and the energy of hot gases emit thermal radiation back towards the burning material, which accelerates heating of the condensed phase and contributes to faster fire development. Fire development in an enclosed space can be divided into the following phases: ignition phase, growth phase, flashover, fully developed phase, and decay/extinguishment phase.
The temperature of a tunnel fire can exceed 1,000°C, while smoke spreads at speeds greater than 10 m/s, significantly complicating evacuation and intervention (Ingason et al., 2015).

Causes of Fire

The most common causes of fires in road tunnels include traffic accidents and vehicle collisions, engine or electrical installation failures, overheating and ignition of tires or brakes, improper transport of flammable materials, and human negligence and violation of regulations. Analysis of European Union data shows that over 60% of tunnel fires occur as a result of traffic accidents involving heavy goods vehicles or buses (Evans, 2016).

Electric Vehicles as Special Fire Causes

Electric vehicles (EVs) introduce a new risk dimension due to lithium-ion batteries which can enter thermal runaway – exponential temperature increase leading to self-sustaining combustion that does not require oxygen, making standard suppression methods ineffective.

In the specific environment of tunnels, EV fires present critical dangers due to two key factors: emission of toxic gases (combustion of electrolyte releases high concentrations of hydrogen fluoride, hydrocyanic acid, and other toxic compounds) and extreme temperatures with re-ignition risk exceeding 1000°C (Sturk et al., 2019;

Doughty & Roth, 2012).

Consequences of Fire

The consequences of a tunnel fire are multiple – from human casualties and material damage to prolonged tunnel closures and traffic disruption. Smoke and heat waves represent the greatest threat to life, as the majority of tunnel fatalities are caused by asphyxiation before being reached by flames. High temperatures can damage concrete linings and safety installations, leading to costly and lengthy repairs (Gaggero & Salvo, 2015).

SAFETY ELEMENTS IN TUNNELS

Tunnel Lighting

Tunnel lighting must cover normal operation, power failure and emergency evacuation scenarios. Backup power provides autonomous supply for up to two hours. Traffic signals at both entrances must switch to red immediately upon detector activation (Pravilnik o sustavima za dojavu požara, 1999).

Ventilation System

The ventilation system plays a key role in controlling the spread of smoke and heat waves. The control centre manages longitudinal and transverse ventilation, regulates airflow speed and direction to remove smoke from evacuation corridors, and creates smoke barriers to enable passenger evacuation and firefighter access.

Ventilation is mandatory in tunnels longer than 1 km with traffic exceeding 2,000 vehicles per lane per day, and consists of fire-resistant ceilings, axial-diagonal fans, motorised louvres every 75–100 m, and reversible fans for longer tunnels.

Water Supply and Hydrant Network

Every tunnel must have a sufficient water supply secured through hydrants. Hydrants must be placed near portals and along the tunnel at distances not exceeding 150 m. Pressure must be at least 6 bar and no more than 12 bar.

Video Surveillance

Video systems in tunnels must enable identification of stopped vehicles and smoke appearance. The monitoring system must allow the control centre to continuously monitor traffic throughout the entire tunnel. In the event of an emergency, the control centre screen automatically switches to the camera nearest the incident.

Fire Detection and Alarm Systems

Modern tunnel fire detection prioritises temperature sensors over optical smoke detection, as the latter is prone to errors from environmental contamination.

Linear Heat Detectors

These are the most reliable systems due to their resistance to false alarms and environmental interference. They consist of a sensor cable capable of early fire detection. The MHD 535 model is considered the industry leader, responding 50% faster than competitors even under high airflow. These systems are categorised as:

- **Integral:** React to temperature rise along the entire length.
- **Non-integral:** React to temperature rise at specific localised points.

Light Beam Detectors

These utilise a transmitter and receiver on opposite sides of the tunnel. Smoke interrupts the beam, triggering an alarm. They are particularly effective for high-heat fires that produce minimal smoke.

Additional Systems

Beyond automatic sensors, tunnels utilise manual alarm points for drivers and passengers. The complete fire alarm infrastructure integrates a central control unit, automatic/manual sensors, and alarm notification devices.

THE CONTROL CENTRE'S ROLE IN FIRE MANAGEMENT

The control centre is the hub for monitoring and managing all tunnel safety systems, including ventilation, lighting, fire detection, video surveillance, and communication.

Organisation and Functions

The operational room utilises monitoring systems (CCTV, SCADA, ITS) to communicate with emergency services, drivers, and staff. In the event of a fire, the centre detects the incident, activates safety protocols, coordinates evacuation, monitors the situation, and handles documentation.

Emergency Coordination

The SCADA system allows for real-time technical monitoring. Effective coordination with emergency services, supported by regular training, ensures compliance with NFPA 502 standards.

FIREFIGHTING IN TUNNELS

Extinguishment

Tunnels of certain length must have, alongside all preventive measures, a service with appropriate equipment: rapid vehicles with sufficient means (water, foam, powder), hydraulic tools, isolated air-line breathing apparatus, infrared cameras, and radio communication. Empirical data on time consumption in long tunnels: approach with breathing apparatus every 100 m – 5 minutes; laying C-hose every 100 m – 10 minutes; rescue of casualties every 100 m – 15 minutes.

Evacuation

Evacuation of endangered persons requires additional construction measures: construction of two tunnel tubes with one-way traffic, construction of a service tunnel alongside the main traffic tube, construction of vertical pedestrian exits to open space, and construction of vertical shafts. Requirements include: evacuation time 5–10 minutes, movement speed up to 1.5 m/s, maximum air temperature tolerable by an unprotected person 80°C for up to 15 minutes, and minimum visibility for evacuation of 7.0–15.0 metres.

Tactical Approach

In tunnel fire conditions, there is no established, accepted rule for tactical approach. Operations must not be undertaken with insufficient personnel, as they quickly become exhausted due to the mandatory use of breathing and heat protection equipment. The type of tactical operation is determined by the fire location in the tunnel – frontal approach is the only feasible option if it is possible to reach the fire source directly.

EV Firefighting Tactics in Tunnel Environment

The firefighting tactics for electric vehicles in tunnels differ significantly from standard procedures due to the specifics of battery systems. The basic tactical goal is not only suppressing visible flames, but breaking the thermal runaway chain within the battery pack. The tactical approach is divided into three key phases:

(1) Offensive cooling with large quantities of water: Unlike conventional fires where foam or powder can be used, water is essential for EVs. Modern protocols recommend specialised nozzles (Fognails or Battery Extinguishing System Units) that penetrate the battery casing and inject water directly between cells.

(2) Smoke layer control and ventilation: Due to extreme smoke toxicity, tactics must be synchronised with the tunnel's longitudinal or transverse ventilation system to maintain 'critical velocity' and prevent backlayering.

(3) Safe removal and immersion: After localisation, the vehicle must be promptly removed from the tunnel, as re-ignition risk persists for up to 24 hours. The safest method uses specialised mobile water containers (RedBox systems) in which the vehicle is submerged (NFPA, 2020; Euro NCAP & CTIF, 2021).

CASE STUDY: MONT BLANC TUNNEL FIRE (1999)

The 1999 Mont Blanc tunnel fire is one of Europe's greatest traffic disasters, claiming 39 lives and serving as a critical turning point for tunnel safety standards.

The Incident

The fire began on 24 March 1999, when a cargo truck carrying flour and margarine caught fire. Despite attempts to extinguish it, the flames spread rapidly. Due to delayed traffic warnings, numerous vehicles were trapped inside. Poor communication between French and Italian rescue services caused the fire to burn for 53 hours, resulting in severe damage that closed the tunnel for three years and required nearly half a billion euros for repairs.

Incident Outcome

Following this tragedy and the subsequent Gotthard tunnel disaster (2001), the EU established mandatory safety standards through Directive 2004/54/EU to prevent similar catastrophes.

CONCLUSION

Fires in road tunnels represent one of the most critical safety challenges in the modern transport system. The specifics of the tunnel as an enclosed space, where temperatures can exceed 1,000°C and smoke spreads at speeds greater than 10 m/s, require flawless coordination between technical systems and human factors.

Linear temperature detectors enable rapid fire positioning with minimal false alarms. A growing challenge is posed by electric vehicles, requiring a tactical shift towards offensive battery cooling to prevent thermal runaway.

The analysis of the Mont Blanc tunnel case study serves as a reminder of the catastrophic consequences of inadequate integration and the importance of strict safety protocols. Achieving maximum safety in tunnels is not the result of a single measure, but the synergy of advanced infrastructure, specialised tunnel firefighting vehicles, and continuous personnel training. Implementation of international standards, with adaptation to local legislation, represents the only path towards minimising risks and efficient incident management in tunnel environments.

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POŽARI U CESTOVNIM TUNELIMA

SAŽETAK

Požari u tunelima predstavljaju ozbiljan sigurnosni izazov u modernim transportnim sistemima zbog ograničenog prostora, izuzetno visoke temperature i teške evakuacije. Ovaj rad analizira ključne faktore rizika i tehnička rješenja za prevenciju i gašenje požara u tunelima. Ispituju se faze razvoja požara, uloga inteligentnih sistema detekcije (poput linearnih sistema detekcije toplote) i značaj integrisanog upravljanja putem kontrolnih centara. Posebno se fokusira na savremeni sigurnosni izazov: prisustvo električnih vozila u tunelskom saobraćaju. Zaključuje se da sigurnost u tunelu zavisi od sinergije napredne infrastrukture, preciznih protokola gašenja požara i kontinuirane edukacije operativnih snaga.

Ključne riječi: zaštita od požara, cestovni tuneli, električna vozila, litij-ionske baterije, sistemi detekcije, vatrogasna taktika

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