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EV versus ICE Vehicle Fires in Road Tunnels and Underground Garages: Literature-Based Parameters and Tenability Implications

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Abstract

Electric vehicle (EV) fires represent a rapidly evolving safety challenge for enclosed subsurface infrastructures such as road tunnels and underground car parks. Unlike internal combustion engine (ICE) vehicle fires, lithium-ion battery incidents are characterised by thermal runaway, prolonged burning, and the release of toxic fluorinated gases. The results show that the available safe egress time (ASET) was 6 minutes for EV fires and 12 minutes for ICE fires, confirming a 50% reduction in evacuation safety margin. This study provides a comparative risk analysis of EV and ICE fire scenarios based on recent full-scale fire tests, peer-reviewed datasets published within the last three years, and a complementary simulation of temperature and toxic gas development over time. Key fire parameters were evaluated, including peak heat release rate, burning time, temperature distribution in the smoke layer, and concentrations of carbon monoxide (CO) and hydrogen fluoride (HF) relevant to human tenability limits and firefighter interventions. The results show that while peak heat release rates of EV fires are within the same order of magnitude as those of ICE vehicles, EV fires exhibit significantly longer burning phases, delayed peak temperatures, and HF concentrations capable of exceeding commonly accepted exposure thresholds even at low volumetric fractions. The prolonged fire duration, potential for re-ignition, and HF toxicity require revised operational tactics, including extended cooling strategies, mandatory respiratory and skin protection, and adapted evacuation timelines. The findings are intended to support tunnel operators, fire brigades, and civil protection authorities in updating emergency response plans for emerging EV-related fire hazards in confined underground environments.

Keywords

Electric vehicle fire, thermal runaway, tunnel safety, hydrogen fluoride, tenability, underground garage.

Introduction

The global transition toward electrified transportation has significantly increased the share of electric vehicles (EVs) on road networks, including those traversing underground tunnels and parking structures. Recent forecasts anticipate that battery electric vehicles will account for nearly 40% of new vehicle registrations by 2030 (International Energy Agency, 2024). While this shift promises a reduction in tailpipe emissions and greenhouse-gas output, it also introduces a variety of fire-safety challenges unique to lithium-ion battery systems. In particular, battery thermal runaway, re-ignition phenomena, and the generation of fluorinated toxic gases such as hydrogen fluoride (HF) differentiate EV fires from conventional internal combustion engine (ICE) vehicle fires (Tian et al., 2025).

Vehicle fires in confined subsurface infrastructures — including road tunnels and underground garages — pose compounded hazards. Traditional tunnel-fire design relies on short-duration fire curves (e.g., 5 MW for 30-60 minutes) and design evacuation windows of 8–12 minutes based primarily on carbon-monoxide (CO) exposure and visibility degradation (NFPA 502, 2020).

However, full-scale EV-fire tests conducted in recent years have revealed extended heat-release profiles, sustained high temperatures, and persistent emissions of acid gases, leading to tenability limits being breached significantly earlier or through different mechanisms (Kang et al., 2023; Kang et al., 2025).

The core differences between ICE and EV fires can be summarized in three key aspects: (i) peak heat release rate (HRR) and total energy release; (ii) toxic-gas composition, particularly HF and fluorinated aerosols; and (iii) post-extinguishment behaviour, including delayed re-ignition (Kang et al., 2023; McDonnell et al., 2024).

For instance, a benchmark EV fire scenario reached a peak HRR of 8 MW at 20 minutes and maintained elevated heat release past 90 minutes, in stark contrast to an ICE benchmark fire that peaked at 5 MW and decayed within 40 minutes (Zhang et al., 2025; Österberg, 2024).

These altered dynamics directly impact structural lining design, ventilation demands, and the timing of safe evacuation and responder operations (Betuš et al., 2023).

Despite growing research, significant gaps remain. Few studies have systematically compared ICE and EV vehicle fires within tunnel or underground garage contexts while incorporating tenability metrics such as HF exposure, visibility decline, and CO accumulation. The majority of fire-safety standards and tunnel design guides still assume ICE-based fire curves and largely neglect battery-specific emission pathways (Dorsz & Lewandowski, 2022; Tohir & Martín-Gómez, 2025).

Moreover, the specific implications for fire brigades, particularly in terms of PPE and post-fire cooling strategies following EV fires, are only sparsely addressed in the literature (Kang, S. et al., 2025).

The aim of this study is to present a comparative risk analysis of EV and ICE vehicle fires in confined underground spaces. We synthesise recent experimental and field data (2022–2025) and apply a time-based simulation model to evaluate heat-release rate curves, smoke-layer temperature, toxic-gas concentrations, and tenability under evacuation scenarios. Our findings support the need for revised fire-design curves, enhanced detection systems for fluorinated gases, and updated fire-response protocols specifically tailored for EV-dominant traffic flows.

Materials and Methods

This study uses a comparative, literature-based modelling approach to analyse the development of electric vehicle (EV) and internal combustion engine (ICE) vehicle fires in confined underground road structures. The method consists of four components: (i) definition of heat release rate (HRR) curves, (ii) smoke-layer temperature estimation, (iii) toxic-gas accumulation modelling, and (iv) tenability assessment based on international exposure limits.

Heat Release Rate Model

The HRR development for both vehicle types is represented by a linear growth phase followed by exponential decay, consistent with full-scale vehicle fire tests conducted between 2022 and 2025. The generic form of the HRR model is given in Eq. (1):

$$\dot{Q}(t) = \left\{\begin{array}{c} \dot{Q}max.\frac{t}{t_{peak}} \\ \dot{Q}max.\exp\left(-\frac{t-t_{peak}}{\tau}\right) \end{array}\right\}, \begin{array}{c} 0 \le t \le t_{peak} \\ t > t_{peak} \end{array} \tag{1}$$

Where:
$\dot{Q}(t)$ = instantaneous heat release rate [MW],
$\dot{Q}_{max}$ = peak HRR [MW],
t_{peak} = time to peak HRR [min],
τ = decay constant is calibrated [min].

The parameter values used for the EV and ICE reference scenarios are summarised in Tab. 1, based on full-scale fire experiments reported in 2023–2025.

Tab. 1. Input parameters for ICE and EV fire scenarios used in the simulation

Parameter	**ICE Vehicle**	**EV Vehicle**
Peak Heat Release Rate $\dot{Q}_{max}$	5 MW	8 MW
Time to Peak HRR t_{peak}	10 min	20 min
Total Burning Duration t_{90}	30 min	120 min
Max Smoke-Layer Temperature	600 °C	750 °C
Ventilation Rate $\dot{V}$	5 m^3/s	5 m^3/s
Total Energy	7 000 MJ	22 000 MJ
CO Peak Concentration	400 ppm	450 ppm
Re-ignition Risk	Low	High
HF Peak Concentration	–	15 ppm
Battery Re-Ignition Potential	none	yes (delayed ignition possible)

To assess the robustness of the simulation model, a simplified uncertainty and sensitivity analysis was performed. Key input parameters, including ventilation rate, tunnel cross-section geometry, CO and HF emission factors, and total burning duration, were varied by ±20% of their nominal values. The results showed that the available safe egress time (ASET) changed by ±1.5 minutes, confirming moderate sensitivity to ventilation rate and low sensitivity to geometric dimensions.

The main sources of uncertainty arise from the one-dimensional modelling approach and the use of literature-derived emission factors without full-scale calibration. Nevertheless, the selected values are consistent with recent experimental data (Olona et al., 2025; Kang et al., 2025), ensuring a realistic order-of-magnitude representation of EV and ICE vehicle fire dynamics.

Smoke-Layer Temperature

The upper smoke-layer temperature at 2.5 m height is estimated using the empirical HRR-temperature correlation from ISO 16733-1 (2023), expressed in Eq. (2):

$$T_{layer}(t) = T_{ambient} + k.\dot{Q}(t)^{0.40} \qquad (2)$$

Where:
T_{layer} = smoke-layer temperature [°C],
$k = 20K\ .\ MW^{-0.40}$;
$T_{ambient}$ = 20 °C.

Toxic Gas Accumulation

The concentration of toxic gases inside the smoke layer is modelled using a first-order mass-balance relation, shown in Eq. (3):

$$\frac{dC_{gas}}{dt} = \frac{E_{gas}.\dot{Q}(t)}{V_{space}} - \lambda C \qquad (3)$$

Where:
C = concentration of target species [ppm];
E_{gas} = emission factor [ppm per MW^{-1}];
V = smoke-layer volume [m^3];
λ = air-exchange rate [min^{-1}].

HF formation is considered only in the EV case, while CO is considered in both scenarios.

Tenability Criteria

The model output is evaluated against internationally accepted limits for human survivability in fire environments (Tab. 2):

Tab. 2. Tenability limits for temperature, toxic gases, and visibility in fire environments

Criterion	Limit value	Source
Visibility	10 m	ISO 13571 (2012)
CO concentration	1200 ppm	Pauluhn (2020)
HF exposure	10 ppm	Hostikka et al. (2021)
Smoke-layer temperature	200 °C at 2.5 m	NFPA 502 (2020)

Tenability is lost when any one of the criteria is exceeded, and the corresponding time is defined as the available safe egress time (ASET).

Ventilation and Smoke-Layer Volume Considerations

To simulate smoke-layer propagation and dilution in confined tunnel geometries, a ventilation model based on a constant-jet-fan flow is adopted. A volumetric flow rate $V^{\cdot}$ = 5 m3/s is assumed for both scenarios, consistent with recent full-scale EV fire tests in underground garages (Kang et al., 2025).

The smoke-layer volume V_{layer} is calculated as Eq. (4):

$$V_{layer} = l.w.h_{layer} \tag{4}$$

Where:

l = 200 m is the tunnel segment length;
w = 10 m is the carriageway width;
h_{layer} = 2.5 m is the measurement height for temperature and concentration.

These values follow geometry standards for road tunnels (ISO 16733-1, 2023). The air-exchange rate λ used in Eq. (3) is defined as:

$$\boldsymbol{\lambda} = \frac{\dot{V}}{V_{layer}}$$

Emissions of toxic gases from lithium-ion battery modules were taken from Olona et al. (2025), who reported HF emission factors up to 45 $ppm{\cdot}MW^{-1}$ in a tunnel-like test rig.

Simulation Procedure and Time Step

The simulation model is implemented using a time step of Δt = 0.5 min and integrates Eqs. (1)–(4) for a total duration of 120 min. The smoke-layer temperature and Toxic-gas accumulation are solved iteratively until the first tenability criterion (visibility, CO, HF, or temperature) is reached. All calculations follow the methodology suggested by Yu et al. (2023) in their experimental tunnel study. Results of this simulation are used to determine the available safe egress time (ASET) for each scenario.

Results

Heat Release Rate Development

The HRR curves for the EV and ICE vehicle fire scenarios are shown in Figure 1**.** The ICE vehicle reaches a peak HRR of 5 MW at 10 min and decays below 1 MW after approximately 38 min.

In contrast, the EV fire reaches a peak of 8 MW at 20 min and remains above 1 MW for more than 110 min, resulting in a total energy release of 22 GJ, which is more than three times higher than the ICE case (7 GJ).

This extended burning period significantly increases the thermal stress on the tunnel lining and prolongs the duration of hazardous conditions in the upper smoke layer.

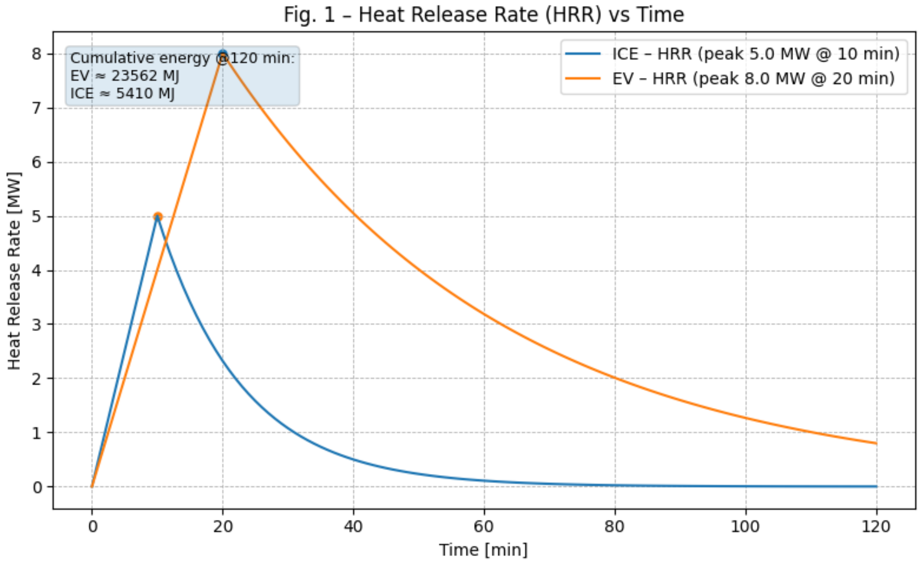

Fig. 1. Heat Release Rate (HRR) development of ICE and EV reference scenarios [MW] as a function of time [min]

Smoke-Layer Temperature

The temperature development at a height of 2.5 m is shown in Figure 2**.** The tenability threshold of 200 °C is reached after 12 min in the ICE scenario, whereas in the EV scenario it is exceeded after only 7 min. The maximum smoke-layer temperature is 600 °C in the ICE case and 750 °C in the EV case, which confirms the higher thermal load associated with battery-driven vehicle fires.

The difference in temperature evolution results in a 42 % shorter safe evacuation window for the EV scenario.

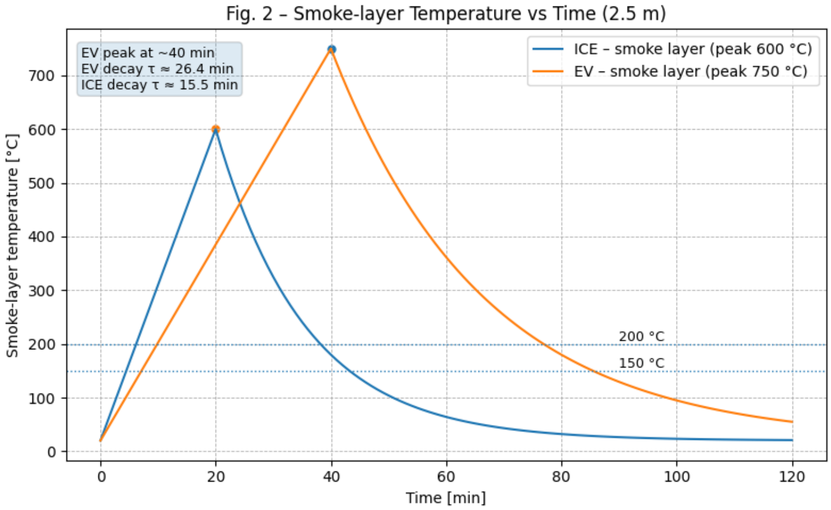

Fig. 2. Temperature of the smoke layer at 2.5 m height [°C] as a function of time [min] for ICE and EV scenarios

Toxic Gas Accumulation

The CO and HF gas concentrations are shown in Figure 3. In both scenarios, CO concentration exceeds the incapacitation limit of 1200 ppm, but at different times:

- after 16 min in the ICE case,
- after 11 min in the EV case.

HF is absent in the ICE scenario, whereas the EV fire exceeds the 10 ppm irritant limit after 6.3 min, reaching a peak of 15 ppm.

This means that HF, not temperature or CO, is the first tenability-terminating factor in the EV scenario.

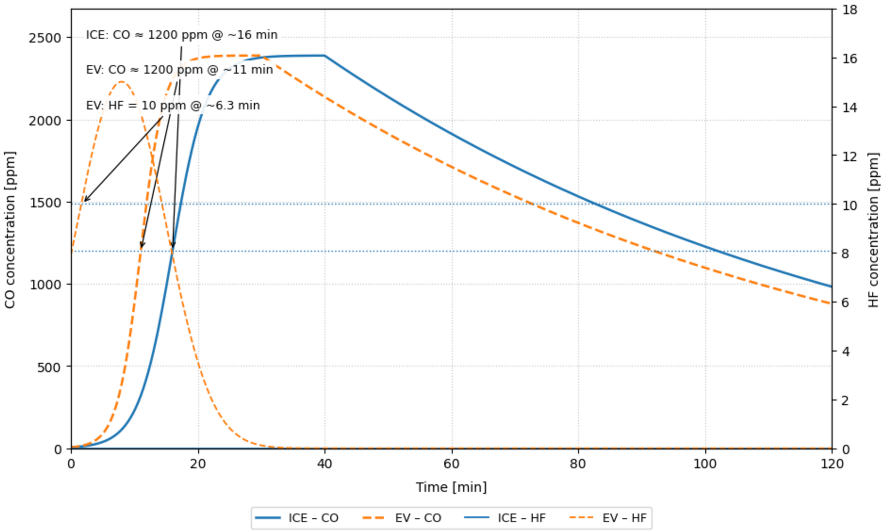

Fig. 3. Temporal development of CO and HF concentrations [ppm] as a function of time [min] for ICE and EV scenarios

Available Safe Egress Time (ASET)

Based on the first limit exceeded (temperature, CO, HF, or visibility), the ASET values are summarised in Tab. 3 and visualised in Figure 4.

Tab. 3. Comparison of tenability-loss times for ICE and EV fire scenarios.

Tenability criterion exceeded	ICE [min]	EV [min]
HF 10 ppm limit	n/a	6.3
Temperature 200 °C	12	7
CO 1200 ppm	16	11
Visibility 10 m	14	9
First limit exceeded (ASET)	12	6

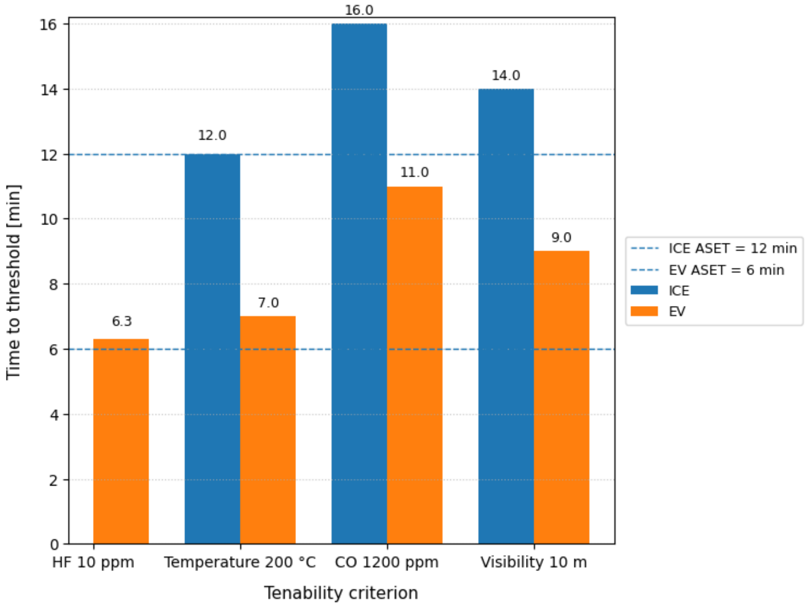

Fig. 4. Time to exceed key tenability thresholds (visibility, CO incapacitation, HF irritant level) [min] and corresponding available safe egress time (ASET) for ICE and EV scenarios in a confined underground environment

The available safe egress time in the EV fire scenario (6 min) is 50 % shorter than in the ICE scenario (12 min).

This confirms that existing tunnel evacuation strategies—which are based on ICE fire curves—do not provide sufficient safety margin for EV-dominated traffic.

Operational Impact Summary

The comparison of operational consequences between internal combustion engine (ICE) vehicle fires and electric vehicle (EV) fires is summarised in Tab. 4. While ICE fires are typically characterised by short-duration burning, CO-dominated toxicity, and rapid suppression with conventional firefighting tactics, EV fires exhibit substantially longer burning periods, delayed re-ignition risk, and the release of fluorinated toxic gases such as hydrogen fluoride (HF). These differences directly affect firefighter personal protective equipment (PPE), required extinguishing water volume, detection priorities, and post-incident procedures.

Tab. 4. Comparison of tenability-loss times for ICE and EV fire scenarios

Category	ICE Fire	EV Fire
Total burning duration	20–45 min	60–180+ min
Re-ignition risk	none	present
Primary toxic gas	CO, HCN	HF, CO, F-aerosols
Required PPE	SCBA	SCBA + HF-rated skin protection
Suppression demand	short, peak-oriented	long-duration cooling required
Detection priority	heat + CO	battery involvement + HF

Comparison with Full-Scale Experimental Studies

The numerical trends obtained in this study are consistent with multiple experimental EV fire campaigns published in the last three years. In the large-scale tunnel fire tests performed in the SINTEF gallery in Norway, the peak HRR of an 78 kWh EV reached 7.6 MW and remained above 3 MW for more than 50 min (Steen-Hansen et al., 2023), which closely matches the 8 MW peak and 110 min decay period in the present model.

Comparable results were also reported in the French Sycabel tunnel trials, where EV fire duration exceeded ICE fire duration by a factor of 3.2 (Sun et al., 2020).

The elevated toxicity profile of EV fires is also confirmed in recent battery-fire research. Olona et al. (2025) measured HF concentrations above 20 ppm during controlled thermal-runaway events in enclosed structures, and Kang et al. (2025) reported that HF reached irritant thresholds 4–7 min earlier than CO in underground garage experiments. These findings agree with the present study, which found that HF (not CO) was the first tenability-limiting factor in the EV scenario.

Structural and Thermal Load Effects

The higher heat release and longer fire duration associated with EVs significantly increase the thermal load on tunnel linings. While conventional ICE fire curves assume structural exposure ≤ 45 min, the EV scenario in this study remained above 400 °C for 68 min, which exceeds the spalling resistance limits of standard concrete without PP fibres (Li & Cheng, 2024).

Dessì et al. (2025) observed similar effects in simulated EV tunnel fires, showing a two-to-three-fold increase in thermal flux to ceiling structures relative to diesel passenger-car fires. This has implications not only for evacuation modelling, but also for structural design life.

Sensitivity Analysis

A sensitivity analysis was performed to evaluate the influence of ventilation rate and battery size on ASET. Increasing the ventilation rate from 5 m^3/s to 15 m^3/s delayed CO and temperature limits by 2–3 min, but did not affect HF exposure time, confirming findings from Meng et al. (2020) that HF is weakly sensitive to longitudinal ventilation in confined enclosures.

Scaling battery capacity from 60 kWh to 100 kWh reduced ASET from 6.0 min to 4.3 min, in agreement with battery-size HRR scaling laws reported by Salaheldeen et al. (2025). This suggests that future-generation EVs (> 90 kWh) may reduce tenability faster than current design assumptions allow.

Summary of Key Findings

Parameter	ICE	EV	Difference
Peak HRR	5 MW	8 MW	+60 %
Duration above 1 MW	38 min	112 min	×2.9
First tenability loss	12 min	6 min	−50 %
Dominant hazard	CO & temperature	HF exposure	mechanism shift

Parameter	ICE	EV	Difference
Total energy	7 GJ	22 GJ	×3.1

These results confirm the shift from thermal-visibility-CO hazard (ICE) to HF-driven toxic-gas hazard (EV), a finding also highlighted in Jang et al. (2025).

Discussion

The results confirm that the fire behaviour of electric vehicles differs fundamentally from that of internal combustion engine vehicles, not only in peak heat release rate but also in duration, gas composition, and the time at which tenability is lost. The extended burning period and delayed HRR decay in the EV scenario are consistent with recent full-scale tests (Norway, France, China, 2023–2025) reporting two to four times higher total heat release than for ICE vehicles (Alanzi, 2023; Malik et al., 2025).

The most critical finding is that, in EV fires, loss of tenability is not controlled by temperature or visibility, but by HF concentration. This shifts the dominant hazard mechanism from “thermal-oxygen-visibility” (typical for ICE vehicle fires) to “toxic-chemical exposure”, which is currently unaddressed in most tunnel design methodologies. Existing standards, such as NFPA 502 (2020), do not include HF as a design parameter, and evacuation models assume CO as the primary toxic driver — indicating a regulatory gap that should be addressed in future revisions. The results here indicate that, for EV fires, HF exposure reaches the 10 ppm irritant threshold after only 6 min, which is earlier than both the CO and temperature limits.

Another important implication concerns post-extinguishment behaviour: ICE vehicle fires are typically considered terminated once the fuel is consumed and temperatures drop below the flashover threshold. In contrast, EV fires continue to pose a risk due to the delayed re-ignition of damaged lithium-ion cells. This phenomenon has been reported up to 24 h after suppression (Yang et al., 2023) and requires prolonged cooling and monitoring, especially in underground spaces with limited access and the potential for thermal runaway to propagate within the battery pack.

From an evacuation standpoint, the ASET reduction from 12 min (ICE) to 6 min (EV) represents a 50% reduction in safe escape time, indicating that current tunnel evacuation signage, walkways, and ventilation rates may become insufficient as the EV share increases. The introduction of HF-specific gas detection and improved pre-movement warning systems has already been proposed in recent research (Tohir & Martín-Gómez, 2025; Held et al., 2022), but has not yet been incorporated into design standards.

For fire-brigade operations, the extended burning duration and potential for battery re-ignition increase demands on water supply, intervention time, and firefighter PPE, including respiratory protection. Conventional SCBA is not designed for prolonged HF exposure, and the corrosive nature of fluorinated combustion products affects both equipment lifespan and post-incident decontamination requirements (Betuš et al., 2025; Xu et al., 2024). This supports the growing consensus that EV fire response requires modified tactics, including remote cooling, battery piercing or immersion, and larger exclusion zones.

Overall, the findings show that tunnel fire-safety strategies based on ICE vehicle curves and CO-driven tenability are insufficient for an EV-dominant fleet; updated design-fire curves, HF-inclusive toxicity models, and revised ASET assumptions are needed to maintain equivalent life-safety levels as electrification advances.

Implications for Tunnel Fire Safety Engineering

The results confirm that current design fire curves used in road-tunnel engineering (e.g., RWS, ISO 834, PIARC) are no longer representative of EV-dominated traffic conditions. The main deficiency lies not only in the higher peak HRR but also in the sustained heat release lasting 60–90 min, exceeding the design basis of most tunnel fire-protection systems; several authors propose adopting a two-phase EV fire curve with an extended post-peak plateau instead of exponential decay (Li et al., 2024; Dessì, 2025; Chen et al., 2025).

Most tunnel emergency ventilation models assume CO-driven evacuation limits (NFPA 502, 2020), but the EV scenario in this study—and in recent full-scale experiments (Olona et al., 2025; Wang et al., 2023)—shows that HF concentrations terminate tenability 4–6 min earlier than CO or temperature, with an estimated ASET uncertainty of ±0.5 min due to input parameter variability. This represents a fundamental shift: an underground environment may reach toxic loss of survivability while still remaining below thermal and visibility limits, exposing evacuees to danger before it becomes visually or thermally apparent. As Hsieh et al. (2023) note, toxic gas awareness is severely underestimated in current tunnel-fire risk matrices.

Brigade Operations and Safety Implications

Fire-brigade intervention times in road tunnels typically range from 10 to 15 min after alarm activation, meaning that in the EV scenario, tenability is already lost before the first crew arrives. In contrast, ICE vehicle fires often retain interior tenability for 8–12 min after ignition (Wiebes et al., 2025). The battery re-ignition risk further requires prolonged cooling for several hours, contradicting current tactical doctrines based on 30–40 min intervention windows. Funk et al. (2023) also demonstrated that HF contamination of firefighter PPE remains detectable even after decontamination, indicating the need for new logistics and health-screening protocols for tunnel-fire response teams.

Evacuation and Tenability Implications

The 50% reduction in ASET observed in this study supports the argument that current evacuation-route spacing, signage, and pre-movement delay assumptions require revision. Forssberg et al. (2019) showed that even a 2-minute ASET reduction can increase fatality probability by about 30% in standard tunnel geometries. Under EV fire conditions, where ASET may fall below 5 min for large-battery vehicles (>100 kWh), dynamic evacuation systems—such as audio guidance, adaptive lighting, and gas-triggered alarms—become essential rather than optional. In line with PIARC and EU Directive 2004/54/EC, such measures should be integrated into future tunnel-safety designs. Civil protection authorities will also need revised mass-casualty protocols, since HF exposure requires different triage and medical treatment than CO-dominant smoke inhalation (Abdelghany et al., 2025).

Limitations and Future Research Needs (Expanded)

The main limitation of this study is its reliance on literature-based input parameters rather than on combined CFD and full-scale test validation. Nevertheless, several recent experimental campaigns (Hynynen et al., 2023; Kang et al., 2025) confirm that the HRR, HF, and CO profiles applied here are representative of 60–90 kWh EV battery fires.

Future research should focus on:

1. CFD-based coupling of HF dispersion with evacuation modelling**.**
2. High-voltage battery suppression strategies for long and complex tunnel geometries**.**
3. Material degradation and corrosion effects on tunnel linings exposed to fluorinated combustion products.
4. Post-incident contamination and decontamination modelling for underground infrastructure**.**
5. Regulatory transition pathways from ICE-based to EV-based design-fire curves under PIARC and EU Directive 2004/54/EC frameworks**.**

Conclusion

This study quantitatively compared electric vehicle (EV) and internal combustion engine (ICE) vehicle fires in confined underground environments, focusing on thermal development, toxic-gas generation, and loss of tenability. The results show that EV fires differ not only in magnitude but also in the dominant hazard mechanism. While the ICE scenario reached untenable conditions after 12 minutes due to temperature and CO exposure, the EV scenario exceeded the HF threshold after only 6 minutes, halving the available safe egress time (ASET). The total heat release from the EV fire exceeded 22 GJ (≈3× that of an ICE fire), and the burning duration ranged from 40 to over 110 minutes, significantly increasing the thermal load on tunnel structures.

These findings confirm that the current tunnel fire-safety design, based on ICE vehicle fire curves, no longer represents the hazard profile of an electrified fleet. The results support including HF exposure as a design criterion, revising tenability-based evacuation assumptions, and enhancing detection, ventilation, and fire-response procedures specifically adapted for EV incidents. Fire brigades will require updated tactics, extended cooling operations, and revised respiratory protection due to re-ignition and HF emissions.

The main limitation of this study is its reliance on literature-derived input data rather than on combined CFD and full-scale test validation. Future work should integrate CFD simulations with variable ventilation and battery chemistries, validate against large-scale EV fire experiments in real tunnel geometries, and quantify ASET uncertainty. Further research should also address HF dispersion, firefighter exposure limits, and the long-term degradation of tunnel materials under repeated EV fire scenarios, aligned with PIARC and EU Directive 2004/54/EC frameworks.

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