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Literature Review on Fire Safety of Enclosed Vehicular Facilities for Battery Electric Buses

Report No.: A1-024790.02
Date: June 23, 2026
Authors: Nour Elsagan, Dana Duong, Islam Gomaa, Yoon Ko and Christopher Rabbitt

CONSTRUCTION
AUTOMOTIVE AND SURFACE TRANSPORTATION

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Literature Review on Fire Safety of Enclosed Vehicular Facilities for Battery Electric Buses

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List of Acronyms

AST	Adiabatic Surface Temperature
ASTM	American Society for Testing and Materials
BEB	Battery Electric Bus
BMS	Battery Management System
CFD	Computational Fluid Dynamics
CFM	Cubic feet per minute
CO	Carbon Monoxide
CO_2	Carbon dioxide
EC50	half-maximal effective concentration
EV	Electric Vehicle
EVF	Enclosed Vehicular Facilities
FED	Fractional Effective Dosage index
FIC	Fractional Irritant Concentration index
HRR	Heat Release Rate
ICEB	Internal Combustion Engine Bus
ICEV	Internal Combustion Engine Vehicle
IDLH	Immediately Dangerous to Life or Health
ISC	Internal short circuit
kWh	Kilowatt-hour
LC50	Lethal Concentration 50
LCO	Lithium Cobalt Oxide battery chemistry
LFL	Lower Flammability Limit
LFP	Lithium Iron Phosphate battery chemistry
LIB	Lithium-ion Battery
LNO/LMO	Lithium-Nickel Oxide/Lithium-Magnesium Oxide battery chemistry
MW	Megawatt
NCA	Lithium Nickel Cobalt Aluminum Oxide battery chemistry
NCM	Nickel-Cobalt-Manganese
NFPA	The National Fire Protection Association
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
PAC	Protective Action Criteria
PHRR	Peak Heat Release Rate
ro-ro	Roll-on/Roll-off ships
SEI	The solid-electrolyte interphase
SFPE	Society of Fire Protection Engineers
SOC	State of Charge
THR	Total Heat Release
TR	Thermal Runaway
UL	Underwriters Laboratories
VOCs	Volatile Organic Compounds
WM	Water Mist

Executive Summary

This report summarizes the literature review examining the fire safety of enclosed vehicular facilities (EVF) for battery electric buses (BEBs), focusing on key aspects such as BEB fire size, potential for reignition and explosion, toxic emissions and environmental impacts and challenging suppression. The report also discusses the fire protection systems for EVFs, in particular: fire detection, suppression, ventilation and smoke control, separation distances and fire barriers, quarantine zones and first responders' challenges. Due to the limited research on BEB fire safety, previous studies involving passenger electric vehicles (EVs), internal combustion engine vehicles (ICEVs), and conventional internal combustion engine buses (ICEBs) are also reviewed to draw insights and establish background knowledge.

This review identifies significant knowledge gaps regarding BEB fire safety. Full-scale fire test data for BEBs are scarce, limiting the understanding of peak heat release rates (PHRR) and associated hazards unique to BEBs, since BEBs are larger than passenger EVs. While some modeling research extrapolates similar behaviors observed in passenger EVs and ICEVs to BEBs, scalability assumptions lack experimental validation, particularly for high-performance EVs (>100 kWh) and heavy-duty EVs (up to 1000 kWh).

Early battery fault and thermal runaway detection systems, including the role of battery management systems (BMS) and advanced techniques such as electrochemical impedance spectroscopy and machine learning, are discussed, but building-level fire detection and suppression systems remain relatively underexplored.

This review examines the effectiveness of various fire suppressants and suppression systems in addressing the fire protection challenges in EVF, highlighting critical gaps in research and practice. Water remains the most practical and widely used suppressant for EV fires, with enhanced flow rate density requirements for parking structures now reflected in the updated NFPA 13 [1] provisions for modern vehicles. Other suppressants, including gaseous agents (e.g., $C_6F_{12}O$, HFC-227ea) and solid agents (e.g., ABC powder), show limited efficacy in preventing reignition or thermal runaway, often requiring confined spaces and careful consideration due to potential chemical by-products like hydrogen fluoride (HF). The review finds that further research is needed to explore innovative suppressants and effective suppression systems since the conventional ceiling-mounted sprinkler systems are reported to be inefficient at suppressing deep-seated battery fires in EVs without continuously providing a high volume of water.

In response to evolving risks, new active and passive fire protection requirements from the NFPA and local jurisdictions (e.g., San Francisco Fire Department) mandate higher water spray rates and extended spray durations, as well as separation barriers for areas with EV charging stations (either sprinklered or not); however, many questions remain regarding the heightened fire hazards associated with BEBs in parking structures and EVFs. In this regard, active research is ongoing in various research institutions around the world including SFPE, NFPA and UL. Gaining a deeper understanding of the hazards and developing improved mitigation technologies are essential for developing robust safety standards, enhancing fire mitigation strategies and facilitating the broader adoption of BEBs in various operational settings.

Advancing research in these areas will improve understanding of the unique fire safety challenges associated with BEBs and support the development of effective mitigation strategies, thereby promoting the safer deployment and integration of electric buses.

1 Introduction

The use of electric vehicles (EVs) has risen rapidly over the last decade worldwide [2] as a route to reducing greenhouse gas emissions. Passenger EVs and battery-electric buses (BEBs) are key components in Canada's net-zero emissions plan [3] to achieve a 45-50% reduction of greenhouse gas emissions by 2035 below 2005 levels [4].

Canada is rapidly advancing in public transit electrification, with multiple cities and provinces making significant strides. Nonetheless, a recent report by Canadian Urban Transit Association (CUTA) reported a short-term decline in the procurement of BEBs by Canadian transit agencies. BEB procurement dropped from 66% to 42% (0–3 years) and from 88% to 66% (4–6 years) between 2024 and 2025 [5]. This is mirrored in cities worldwide, as part of efforts to reduce greenhouse gas emissions and improve local air quality, as they are increasingly considered a viable alternative to conventional internal-combustion engine buses for these reasons [6]. This has resulted in a rapid increase in BEBs in operation globally, with corresponding visibility on some of the associated implementation challenges [6].

As of April 2026, Toronto Transit Commission (TTC) has 328 BEBs delivered and 180–200 BEBs in daily revenue service. TTC is aiming for a zero-emission bus fleet by 2040 [7]. York Region Transit (YRT) plans to add 180 zero-emission buses by the end of 2028 to an existing fleet of 14 [8]. TransLink (Metro Vancouver) will scale up from 19 existing BEBs to 178 by 2030, in addition to trials of a 60-foot electric trolley bus with in-motion charging [9]. In 2019, Edmonton Transit Service (ETS) ordered 40 BEBs which was considered the largest Canadian purchase at the time. Service began in 2020 using overhead charging infrastructure [10]. Saskatoon Transit received its first two BEBs in May 2024. These buses entered service in July 2024. Saskatoon Transit's goal is to achieve a 100% electric fleet by 2030 [10]. Currently, OC Transpo in Ottawa operates 30 BEBs, with a plan approved in 2021 for C$350 million federal funding for 350 BEBs and charging infrastructure to target fully zero-emission transit by 2036 [11]. Calgary Transit purchased 120, 40-foot BEBs to replace end-of-life diesel buses. Deliveries begin in 2027, with all 120 BEBs expected to be in service by the end of 2028 [12]. In Montréal, Société de transport de Montréal (STM) operates 42 BEBs and 147 new BEBs will be received by 2027 [10]. The first 10 BEBs in BC Transit [13] began arriving in Victoria and additional 125 BEBs are on order, with about 80 expected to be in service by the end of 2026. In May 2025, Halifax Transit launched its 60 new electric transit buses into service [14]. Fredericton Transit currently operates four hybrid diesel-electric buses and added 6 new hybrid buses as of May 2025 [15].

The deployment of BEBs impacts the transit infrastructure and requires either the construction of new depots or upgrading the existing ones to accommodate the need for large-scale charging systems, requiring new layouts and electrical equipment. Moreover, transit agencies must often negotiate new power connections or substation upgrades with local utilities and regulators [16]. The agencies have also to ensure sufficient grid capacity; especially for overnight depot charging of large fleets. Facilities must be able to handle the added load from charging stations at peak demand [17].

A recent study by McMaster University [18] assessed the electrification of transits in Canada. The study evaluated fleet requirements, infrastructure needs, electricity demand, and the cost-effectiveness of greenhouse gas (GHG) reductions under a fully electrified bus transit system. Results indicated that full electrification of transit would require a 17% increase in fleet size and an additional 1.255 TWh (terawatt-hour) of electricity annually, equivalent to 0.20% of Canada's total generation. This additional demand remains well within existing generation capacity, given that Canada maintains average annual net electricity exports of approximately 27.6 TWh. These findings suggest that fleet electrification is technically feasible from an energy supply perspective. Furthermore, the study concluded that the rise in electricity demand would be modest across provinces, with minimal system-level impacts on provincial grids.

Depot chargers convert AC grid power to DC power for the battery using offboard power electronics, enabling higher power transfer than onboard converters alone [19]. Charging systems can be plug-in or pantograph

(overhead) chargers. In plug-in chargers, a physical cable connects the charger to the bus charging port. These chargers can operate at medium to high power levels suitable for overnight or extended stop charging (e.g., 40–150 kW typical for depot plug-in systems). The charging session is often manually initiated and completed by maintenance staff or drivers [20,21]. Pantograph charging is an automated conductive charging method where an overhead connector either mounted on the charging infrastructure (pantograph down) or on the bus roof (pantograph up) makes contact with vehicle interfaces to deliver power [20,21].

From a fire safety perspective, charging systems introduce localized high-current connections, which can become potential ignition sources if faults occur (e.g., loose connections, insulation degradation, or arc faults). Electrical rooms housing rectifiers and transformers require compliance with electrical fire protection codes and appropriate suppression systems. Proper grounding, isolation systems, and emergency shutoff mechanisms are critical to prevent electrical hazards during fire events or firefighting operations.

More importantly, BEBs pose a different set of fire safety challenges in the bus depots than conventional internal combustion engine vehicles (ICEVs) [22] which is attributed to the lithium-ion battery (LIB). Several BEB and BEB garage fires have been reported, which are summarized in APPENDIX A. The mitigation of fire risk associated with BEBs and their effect on EVF is discussed in detail in a later section.

The LIBs are the main propulsion system currently used in EVs. LIBs can exhibit thermal runaway (TR) if damaged (thermally or mechanically), overheated, or improperly managed [22]. TR is the rapid rise in temperature that cannot be dissipated to the environment, resulting in an exponential increase in temperature. During this increase in temperature, side reactions within the battery can trigger gas release as well as the combustion of components within a cell (e.g., the battery electrolyte) potentially resulting in a fire or explosion, should proper conditions exist. The heat transfer to the neighboring cells may result in TR propagation within the module [23] which can increase fire intensity. The gas venting during TR is generally similar to a jet with a relatively high initial velocity, and thus if ignited, jet flames may form at an early stage of a fire [24]. Moreover, LIB fires have a large heat release rate, a rapid temperature rise and a prolonged period of elevated temperatures [25,26], requiring larger amounts of water [27–29] or special fire suppression methods [30,31]. LIBs also have a tendency to reignite due to residual energy in cells that have not undergone TR, hours or even days after the initial fire is extinguished. For these reasons, a particular example of EV firefighting tactics involves submerging the vehicle in a large water reservoir to ensure no reignition. The sequence of events in case of a thermal runaway is illustrated in Figure 1.

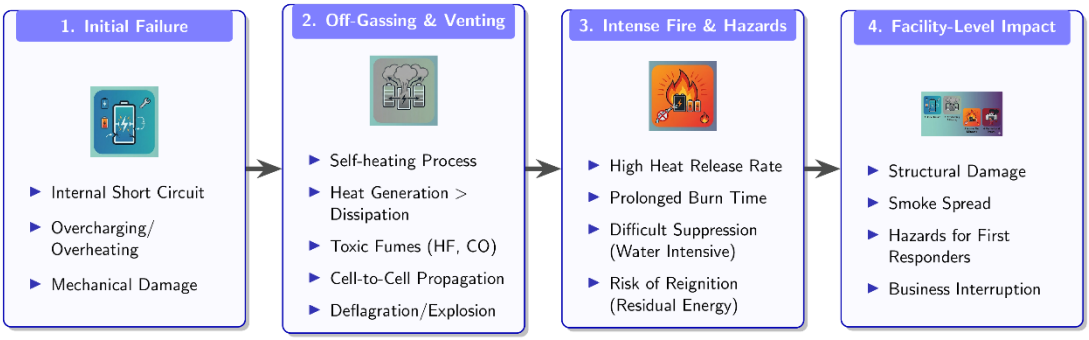

Figure 1. Sequence of key fire hazards in BEBs

Although EV fires are reported to occur less frequently than those in ICEVs [32], it is important to note that ongoing data collection is needed to fully understand EV fire causes including battery aging and variation among rapidly evolving EV technologies. EV fires are harder to extinguish due to the nature of LIB fires [22,33]. Moreover, they produce toxic gases different from ICEV fires, including HF (depending on the battery chemistry and electrolyte), which can pose significant risks to first responders and bystanders. These different fire hazards

and the increased use of EVs point to an emerging need for research, especially for larger capacity EVs such as BEBs.

While the fuel tank capacity in ICEVs is measured in litres or gallons, the battery capacity in EVs is measured in kilowatt-hours (kWh). The battery capacity of commercially available BEBs ranges from 60 to 660 kWh (900 kWh for articulated BEBs) with the most typical capacity levels in the 200–300 kWh range [34], while that of EVs ranges from 10 (microcars) to 200 (SUVs and vans) kWh [35]. This higher battery capacity of BEBs proportionally increases the potential total heat release in case of fire and subsequent emissions. Moreover, the high battery capacity has a higher impact on peak heat release rate [22] and potential explosion energy [24]; both of which will be thoroughly discussed in the following sections.

To summarize, BEB fires need to be studied because they pose different challenges compared to fires in ICEVs. BEB fires are different from internal combustion engine bus (ICEB) fires due to the nature of the LIBs, which can experience thermal runaway. These fires are harder to extinguish, often requiring specialized firefighting methods and emergency plans, and pose a risk of reignition hours or even days later if the battery was left in a state where further temperature rise was still possible due to stranded energy. As the deployment of BEBs in transit systems increases across Canada and globally, the need for dedicated study of their fire hazards is paramount. While broader research on EV fire safety informs the field, a focused study on BEBs improve safety for passengers, first responders, and infrastructure.

2 Scope of review

The scope of this literature review is the fire safety of Enclosed Vehicular Facilities (EVF) housing battery electric buses (BEBs). In particular, this literature review covers previous work examining the major fire hazards resulting from the presence of the lithium-ion battery in the BEBs:

- The fire size or design fire size, and in particular the peak heat release rate (PHRR) and growth rate of burning BEBs,
- The potential for reignition and explosion,
- The toxic emissions and environmental impacts of BEB fires,
- The challenges of suppressing BEB fires.

However, due to the limited research on BEBs, studies on passenger electric vehicles (EVs), passenger internal combustion engine vehicles (ICEVs) and internal combustion engine buses (ICEBs) are also included. The conclusions from those studies form background knowledge and points of comparison for BEB studies.

Furthermore, this review also examines studies on the fire protection of EVFs housing BEBs, examining fire protection systems such as fire detection, fire suppression, ventilation and smoke control, separation distances and fire barriers, quarantine zones and firefighting response. Again, due to limited research on BEBs, fire safety studies on other fuel-type vehicles are examined to draw insights into BEB EVF research. Finally, the review concludes by outlining gaps that need to be addressed in BEB fire safety research.

The literature search was conducted using mixed methods, including a database search on Scopus, ScienceDirect and IEEE Xplore, as well as citation chaining and keyword searching on Google Scholar.

3 Potential Fire Hazard and Challenges of BEB in EVF

The unique hazards and the different set of fire safety problems posed by BEBs when compared to conventional ICEVs are primarily attributed to the LIB system which critically influences the fire characteristics of BEBs. In the following sections, we first discuss the different possible ignition scenarios that might lead to BEB fire followed by presenting the potential fire hazards associated with BEB in EVFs particularly due to the LIB.

3.1 Ignition

Ignition of a BEB could result in a flaming event with visible flames resulting from gaseous fuel combustion, or non-flaming event with a lot of associated off-gassing/smoke. Flaming ignition might result in jet flames and consequent ignition of other parts of the BEB or another nearby object (e.g., another BEB) which increases the fire intensity. Once ignition occurs within a battery enclosure, fire spread can produce sustained combustion and release flammable gases, contributing to fire growth, with the large-format batteries used in BEBs presenting additional challenges due to their higher energy capacity and bulk. [36]

Ignition of a BEB while parked or being charged in an EVF could be caused by:

3.1.1 Thermal runaway

Studies have shown that battery malfunction is a leading cause of BEB fires, typically in the form of internal failures within the battery pack that lead to TR.TR is the critical failure mode of LIB leading to LIB fires and explosions, specifically deflagrations [37,38]. It is characterised by a mechanism of chain reactions, during which the materials of the battery components undergo exothermic decomposition, whereby the released heat cannot be adequately released causing further decomposition and heat released, leading to a rapid and uncontrollable temperature increase. This self-heating process triggers a chain of highly energetic chemical reactions. The typical sequence of reactions as temperature rises includes [39,40]:

- Breakdown of SEI Layer: The solid-electrolyte interphase (SEI) layer on the anode decomposes (90-120°C), releasing CO_2 and making the anode vulnerable.
- Reaction between Anode and Electrolyte: The exposed anode reacts with the electrolyte, generating heat and flammable hydrocarbons (e.g., C_2H_4, C_3H_6, C_2H_6).
- Separator Collapse and Internal Short Circuit Formation: Polyolefin separators melt (polyethylene at 135°C, polypropylene at 166°C), causing shrinkage and eventual collapse, leading to direct contact between electrodes and widespread ISC. Ceramic-coated separators can maintain structural integrity to higher temperatures (200-260°C).
- Decomposition of Cathode and Reaction with Electrolyte: Cathode materials decompose at higher temperatures, some releasing oxygen. Thermal stability varies significantly between materials. Higher nickel-content NCMs have higher capacity but lower thermal stability.
- Decomposition of Electrolyte: Organic solvents in the electrolyte decompose exothermically (above 200°C), releasing CO_2, fluoride gases, and hydrocarbons.

Thermal runaway could occur as a result of:

- Thermal Abuse: Overheating and fire exposure can result in components' exothermic decomposition and initiation of a thermal runaway.
- Overcharge: Overcharging can lead to lithium dendrite growth at the anode or collapse of the cathode structure, with oxygen release, and violent reactions between the cathode and electrolyte.
- Over-discharge [41,42]: While potentially underestimated, over-discharging can lead to abnormal heat generation, SEI decomposition, and dissolution of the copper current collector. Dissolved copper can migrate and form dendrites, ultimately causing internal short circuits (ISC).
- External Short Circuit: External short circuits can lead to rapid discharge and significant ohmic heat generation, leading to rapid cell swelling and temperature rise.
- Mechanical Deformation: Deformation of the battery pack can tear separators, leading to ISC and leakage of flammable electrolyte.
- Penetration: Direct penetration by sharp objects can create instantaneous internal short circuits, generating significant heat and initiating TR.

Pack design can influence the course of these processes; for example the integration of phase change materials into cell linings have been studied for their potential to slow or prevent TR initiation and propagation. [43]

3.1.2 Charging

Several reported BEB fires occurred while charging (refer to APPENDIX A). Ignition of BEB could occur while charging due to failure of the onboard charger as a result of electrical fault (overcurrent/overvoltage), overheating or arcing within the charger compartment. It could be due to the failure of the battery management system (BMS) to regulate charging current or cell balancing, resulting in overcharging of a battery module and subsequent overheating. Moreover, ignition could happen due to a fault in the charging connector or cable which might also result in localized heating. BEB garages employing high-voltage DC charging systems pose a higher fire risk since fast charging significantly stresses LIBs and increase the likelihood of thermal runaway [44].

3.1.3 Electrical system ignition (non-battery)

Other electrical equipment on board the BEB (e.g. HVAC systems, inverters, converters, or DC-DC units) could also fail and result in overheating and subsequent ignition. Ignition could also happen due to loose connections or clogged cooling passages, or a short circuit in low-voltage wiring.

3.1.4 Mechanical or thermal causes

BEB ignition could also happen due to the overheating of the different mechanical components within the BEB like the drivetrain (motor or gearbox) components or the brakes. The overheating of the brakes could ignite accumulated grease, debris, or rubber residues and easily start a fire. In addition, fuel-fired Heaters are also a known high risk ignition source.

Penetration or deformation of the battery as a result of vehicle collision, improper mounting, or penetration by foreign objects can also result in battery failure, internal short circuits, and rapid temperature rise [45,46]. This risk can be influenced by the design of the enclosure, and battery pack mounting location on the bus [47].

3.1.5 External factors

BEBs could catch fire from another burning object; like another adjacent parked bus (BEB or ICEB) or electrical infrastructure (distribution boards, transformers, or ceiling-mounted cable trays). This substantially increases the fire size. In such scenarios, fire spreads within the depot and becomes uncontrollable resulting in huge losses. Refer to Hanover and Stuttgart bus depot fires and Philadelphia bus storage yard fire in APPENDIX A. Other ignition sources could result from improper maintenance, such as improper reassembly of components or leaving a heater or welding tool on a bus during repair work.

3.2 Fire size and design fires

It is well established that the key factor in determining the danger and potency of a fire is determined by the peak heat release rate (PHRR) and the heat release rate (HRR) curve of a burning object. The PHRR is one of the key parameters to measure when performing full-scale fire tests, while the initial fire growth rate and the entire HRR curve characterized by the burning duration and the fire decay phase should also be carefully examined to fully understand the fire behaviour. Design fires are a key part of the engineering analysis for fire protection system designs and sizing for fire detection, fire suppression, smoke control, and structural fire resistance. Thus, the design fire should be developed to properly capture the fire characteristics so that the requirements of the anticipated fire protection systems and operational measures could be sufficiently defined.

Previous literature has established that the PHRR and HRR curves in full-scale fire tests with passenger battery EVs (BEVs) is comparable to those of passenger internal combustion engine vehicles (ICEVs) [48–54], depending on the ignition method. However, recent work by Sturm et al. [31] has found that if the LIB pack ignites quickly (by injecting saline solution into the battery during their fire test), its contribution would be significant, resulting in the measured PHRR from an EV being almost twice as that of an ICEV for the same vehicle. A comprehensive review was conducted on battery electric fires in EVs in [22], while an overview of full-scale fire testing of ICEVs and EVs is reported in [55]. The authors reported that the PHRRs of passenger vehicles, both

EVs and ICEVs, range between 4 – 10 MW while the growth rate varies between medium-slow (5-10 min to reach 1 MW) and medium-fast growth rates (150-300 s to reach 1 MW).

Although heat release rate data is available for passenger EVs, full-scale fire test data for BEBs are very limited. Currently, the only publicly available full BEB fire data is the test conducted by Peng et al. [56]. The authors conducted a full-scale fire test on an 8.5 m BEB equipped with lithium iron phosphate (LFP) batteries by simulating thermal runaway through overcharging the battery packs. The results showed a rapid fire propagation where the flame from LIB ignition caused the breaking of the upper window glass after 3 min then ignited the passenger cabin. The BEB was fully engulfed in fire within the subsequent 10 min. In addition, the temperatures and heat fluxes measured at 1 m from the BEB were too high and posed significant risks of fire spread to adjacent buses. Moreover, the maximum ceiling-level temperatures in the garage reached as high as 1000°C–1200°C for about 5 min which challenged the thermal resistance of the ceiling structure. It is worth pointing out that the reported temperatures in this experiment are similar to the temperature-time curves developed for tunnel fires (e.g., RWS curves and EUREKA curves [57]). These tunnel temperature-time curves exhibit a very rapid temperature rise, commonly exceeding 1000–1200°C within the first few minutes, and reach higher peak temperatures that may be sustained for extended periods. They represent a much more severe thermal exposure than the ISO standard curve (i.e., the ISO 834 fire curve represents a standard building fire with a relatively slow temperature increase, reaching approximately 900°C after about one hour). Unfortunately, no HRR was recorded in this test.

On the other hand, limited full-scale fire test data for ICEBs [58–61] are available. Reported PHRRs for non-articulated ICEBs reach around 35 MW in one study [61], while several other studies reported a PHRR of around 30 MW [58–60]. All of these studies also show that the growth rate of the fire for ICEBs is between that of a fast growth rate (150 s to reach 1 MW) and an ultra-fast growth rate (75 s to reach 1 MW).

For comparison, a single study conducted full-scale hybrid electric bus (HEB) fire tests [62], where thermal and gas analyses were performed, although no HRR measurements were taken. The diesel tank was about half full with diesel and the battery SOC was at 40–42%. A notable observation from the study was that the LIB pack contributed to the fire behaviour, although it was difficult to quantify this contribution to the increased fire severity. Furthermore, it was noted that a battery explosion would likely occur, followed by the intense fire, igniting nearby combustible and flammable materials in the vehicle. Additionally, one of the key goals of their study was to determine if the battery pack located in the bus ceiling area would fall down into the engine compartment or the passenger compartment, adding a new risk factor to the use of electric battery propulsion. After performing multiple tests, it was shown that the battery did not fall down into the compartment. However, it is important to note that the documented BEB fire that occurred in Paris in 2022 (See APPENDIX A) has shown different outcomes. In that case, the roof structure holding the battery packs collapsed approximately one minute after visible smoke emerged from the battery. However, the battery chemistry in that BEB consisted of lithium metal which reacts extremely fast compared to LIB.

Due to the limited data on full-scale BEB fires, some studies have assumed that like BEVs and ICEVs, BEBs would scale with ICEBs [63,64]. Although this scaling is supported by previous studies in small passenger ICEVs and BEVs, this assumption has yet to be experimentally investigated for high-capacity BEVs (>100 kWh) and heavy-duty BEVs, such as BEBs [22].

Several studies attempted to correlate the PHRR with the LIB capacity. In the recent review of available cross-scale battery fire data by Sun et al. [22], the authors proposed a scaling to quantify the additional contribution of the LIB pack to the PHRR of a burning EV based on data covering a capacity range from 5 Wh to 5 MWh;

$$PHRR = 2\,E_B^{0.6},$$

In another work, Willstrand et al. [54] derived the following equation based on data covering a capacity range from 10 Wh to 0.1 MWh;

$$PHRR = 1.56\ E_B^{0.67},$$

where E_B is the battery energy measured in Wh and the PHRR in kW, in both correlations.

Figure 2. PHRR as per correlations from Sun et al.[22] and Willstrand et al.[54] , and experimental data from Ditch and Zeng [65]

Figure 2 compares the PHRR as calculated using the two correlations and the experimental values measured by Ditch and Zeng [65] who conducted a series of small- to large-scale free-burn fire tests on Energy Storage Systems comprising either LFP or LNO/LMO batteries. The figure shows that the Sun et al. correlation is in better agreement with the experimental data compared to the Willstrand et al. correlation, for lower battery capacities. However, both correlations underestimated the PHRR for the 125 kWh battery. Therefore, the applicability of this correlation in estimating the PHRR for BEB batteries is questionable.

Nevertheless, the Sun et al. [22] correlation has been employed in the scaling of the additional PHRR due to the battery system in several numerical studies, and two numerical studies on BEBs [63,64] are reviewed in the present review.

In the first study [63], the fire hazard of an articulated BEB (60 ft in length) was numerically investigated in an enclosed repair garage and an open parking depot. The design fire was scaled to 52 MW, based on ICEB data and including the contribution of approximately 7 MW from an industry-standard 750 kWh battery pack. Particular goals of that study included modeling the effects of various passive and active protection measures, such as the separation distance between buses, the sprinkler system (i.e., based on requirements of NFPA 13 [1]), the smoke ventilation (i.e., based on requirements of the New York City Building Code); as well as the use of separation barriers and dropped fire curtains. Details of their findings on the effectiveness of these protection measures are discussed in later sections. The second study [64] focused on identifying any key fire and life safety issues associated with a BEB fire in an underground infrastructure. A design fire HRR curve for a BEB was developed and fire scenarios in a roadway tunnel were modeled with occupants egressing. The analysis accounted for the severity of the structural impact from the thermal exposure on the tunnel.

In a recent study, Hodges et al. [55] created models to estimate the time-resolved HRR curves for ICEVs and BEVs that could be scaled to larger vehicles, such as large SUVs. The HRR curve shape factor defining the PHRR and burning duration was found using empirical fits to many full-scale vehicle fire test data. The authors found that there was no significant difference in the HRRs between similarly sized BEVs and ICEVs. However, an important conclusion from this study is that the HRRs predicted from the model significantly exceed existing design fire sizes often considered in practice, pointing to the need for enhanced design considerations and reviews of codes and standards. It is important to also note that the model was not applied to heavy vehicles, such as ICEBs and BEBs [55].

Intuitively, one would expect that another important parameter that contributes to the fire size when dealing with LIB packs is the state of charge (SOC), which would be particularly important for safe management of LIB storages and transportation. However, studies on LIB cells have shown that the heat release does not vary significantly between 20–100 % charge [66,67]. On the vehicle level, full-scale EV fire tests by Lam et al. [50] showed that battery involvement in the fire may be earlier with increased SOC, resulting in a faster HRR climb. A recent study by Lee et al. [68] carried out full-scale fire tests to address the impact of SOC, and they reported that a lower SOC level resulted in a significant reduction in the fire intensity and PHRR of EVs, yet reignition hazards still remained.

For LIB battery fires, it is generally recognised within the fire engineering community that suppression systems primarily provide cooling and limit thermal runaway propagation rather than directly extinguishing the electrochemical reactions. Consequently, the HRR time profile, and hence the appropriate design fire, may not be significantly altered by sprinkler activation or other intervention, indicating that battery fires represent a class of fires where the design fire should be carefully developed, in conjunction with the fire protection strategy. Experimental fire testing reported by FM Global [69] for LIB energy storage systems (exploring LFP and LMO chemistries) shows that sprinkler activation results in only a modest reduction in peak heat-release rate and does not lead to extinguishment. These results indicate that water-based suppression influences the HRR time curve primarily through cooling and limited control of fire development, while leaving the overall fire severity of a battery thermal-runaway event largely unchanged.

3.3 Potential for explosion

EV fires resulting from thermal runaway release a substantial quantity of combustible gases in the initial stages (depending on SOC), which, upon reaching the ignition point or coming into contact with flames, can ignite violently, forming jet fires [70,71]. Gas cloud explosions might also occur during LIB fires. Basically, explosions are defined as a sudden and violent release of energy accompanied by a rapid pressure increase and can be classified according to the flame speed as deflagration (subsonic flame speed) or detonation (supersonic flame speed) [72] . There could also be a deflagration to detonation transition (DDT). Detonations are louder and often more destructive than deflagrations. It was found that these phenomena may occur during thermal runaway of LIBs under specific conditions [24,73]. DDT is closely related to the propagation speed of the flame front, which can be characterized by the laminar flame speed.

To calculate the laminar flame speed of the gas mixture (10% CO_2, 37.1% CO, 42.8% H_2, 7.1% CH_4 and 3% C_2H_4) resulting from the LIB thermal runaway, Nilsson et al. [74] developed a kinetic combustion model. The calculated maximum laminar flame speed was 175 cm/s, while the maximum flame speeds of diesel and gasoline fuels used in conventional buses are 90 cm/s [75] and 50 cm/s [76], respectively. In other words, fires involving BEBs have a higher tendency to transition to detonations compared to ICEBs. The laminar flame speeds of gasoline, diesel and thermal runaway mixture for different equivalence ratios are shown in Figure 3.

In another work, Li [24] analytically calculated the potential explosion heat release from a BEB (with 320 kWh battery) and an equivalent conventional ICEB to be 4800 MJ and 3375 MJ, respectively. It is worth noting that the calculation assumed that all the electrolytes are vented and serve as fuels in case of an explosion. This assumption may tend to be too conservative as the probability of venting all the gases in an EV before ignition is low. The work concluded that the potential explosion energy of a battery is several times the energy stored in the battery, and it is even slightly higher than the explosion energy for an internal combustion engine that produces the same energy at the wheel. It should be noted that with a higher LIB capacity (>320 kWh), the potential explosion energy is expected to increase.

Figure 3. Laminar flame speed of gasoline [76], diesel [75] and thermal runaway mixture [74] for different equivalence ratios

3.4 Potential for reignition

Reignition is a known potential problem in EV fires that can occur hours, days or even weeks after the initial fire event. Reignition usually happens due to stranded energy or residual heat inside damaged or partially damaged cells in the battery, even after the fire has been suppressed. Movement, cooling, or firefighting water could also trigger the remaining unstable cells to heat up again. Moreover, thermal runaway in a LIB cell can occur days or even weeks after an initial incident (e.g., collision), leading to unexpected reignition of the pack. For example, a fire erupted in an EV parked in a wrecking yard in California after 3 weeks from a severe collision accident in June 2022 [77].

3.5 Toxic emissions and environmental impacts

Generally, combustion gases and particulate matter (smoke) are produced during fires. Toxic gases produced during LIB thermal runaway include but are not limited to benzene, carbon monoxide (CO), carbon dioxide (CO_2), hydrogen bromide (HBr), hydrogen chloride (HCl), hydrogen cyanide (HCN), hydrogen fluoride (HF), ammonia (NH_3), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2) [54]. HF is considered a characteristic emission for LIB and EV fires, which is toxic, reactive and highly soluble. Its deposition from the atmosphere onto surfaces is the dominant mechanism for removal of fluorine from air [78]. This means that the produced HF can find its way as hydrofluoric acid in water runoff or soil. In addition, the following metals can be emitted during thermal runaway into the air: lithium (Li), nickel (Ni), manganese (Mn), cobalt (Co), aluminum (Al), copper (Cu), chromium (Cr), and zinc (Zn) [54]. These metals deposit on the soot particles (particulate matter) produced during the fire and travel in the air.

The environmental impact of LIB fires is through two mechanisms; (1) Impacts via the deposition of soot particulates (with metals deposited on them) falling out of the plume. In this scenario, particulates can deposit onto either the surface soil or surface water. (2) Impacts via water runoff where contaminated water runoff due to firefighting operations can carry toxic compounds. Fire water runoff can enter the soil, groundwater, or nearby bodies of water, thus contaminating the environment. Examples of chemicals found in water runoff from LIB fires include metals, polycyclic aromatic hydrocarbons, hydrocarbons, fluorides and chlorides [79–81].

On the EV level, Truchot et al. [52] measured the gas emissions from burning three ICEVs and one EV, while Watanabe et al. [54] measured the gas emissions from burning two EVs and one ICEV. The authors reported significantly higher amounts of hydrogen fluoride (more than 27 times higher) and hydrogen bromide gas (more

than 5 times higher) from EVs compared to ICEVs [54]. Hydrogen fluoride is of particular concern as it can be absorbed through the skin posing a potential danger for firefighting first responders. However, Watanabe et al. [54] found that although significantly more hydrogen fluoride is generated, commonly used firefighting gear showed good performance against the gas. It should be noted that this conclusion is for passenger EVs, not for high capacity EVs such as BEBs. This requires further investigation for BEBs, as the increased battery size and capacity will likely produce more hydrogen fluoride and hydrogen bromide gases, potentially exceeding the protective capacity of firefighting gear. Furthermore, the authors found that the metal content, such as lithium, aluminum, cobalt, copper, manganese, nickel, and zinc, on the soot particles was significantly higher for the EVs; these metals are related to the composition of the LIB. Conversely, it was found that lead content on the soot particles was significantly higher in the ICEV.

The toxicity of smoke is analysed by combining the toxic potency of each chemical component in smoke. In particular, the analysis is based on the fractional effective dosage (FED) and fractional irritant concentration indeces (FIC) [82]. When the calculated value of FED or FIC exceeds a threshold value of 1, the tenability reaches its endpoint (for 50% of the population). Since individual susceptibility would vary depending on one's health condition, a threshold value lower than 1 is usually considered as a design value. A fire modelling simulation study [64] investigated the smoke dispersion and toxicity hazard from a burning non-articulated BEB (40 ft in length) in a tunnel. The design fire was obtained from NFPA 502 and superimposed with the contribution from the burning LIB, resulting in a PHRR of 35 MW. The combustion modelling of the BEB fire included production of toxic gases by computing yield data obtained from the BEV and ICEV fire tests [54]. Their results indicated that the FED and FIC were greater for the BEB fire (0.29 and 0.54) compared to the ICEB fire (0.17 and 0.41). Furthermore, both the FED and FIC from the BEB fire were near or exceeded the design limitation of 0.3, while only the FIC was exceeded for the ICEB fire.

Quant et al. [81] investigated the ecotoxicity of the water runoff from extinguishing BEV and ICEV fires. The results showed that the extinguishing water from both types of vehicles was highly toxic toward the tested aquatic species. Several metals and ions were found in concentrations above the corresponding surface water guideline values. Per- and polyfluoroalkyl substances were detected in concentrations ranging between 200 and 1400 ng/L. Extinguishing water from the BEV contained higher concentrations of nickel, cobalt, lithium, manganese, and fluoride compared with the water samples collected from the conventional vehicle. These concentrations will likely be higher in case of extinguishing a BEB fire.

In a recent study [83], a methodology was developed to assess health and environmental impacts from TR in large outdoor LIB Battery Energy Storage System units, linking exposure distances to wind speed, temperature, duration and type of burn (flaming vs non-flaming). The authors gathered TR emissions data and battery mass loss rates from literature based on battery characteristics (e.g., chemistry) and modelled the plume dispersion in Fire Dynamics Simulator (FDS) [84] for near-field exposure and AERMOD [85] for far-field exposure to determine the impact of the plume on public health and the environment. The health impacts were assessed using occupational and community exposure limits (IDLH, PAC), while the environmental impacts were based on LC50/EC50 thresholds and deposition calculations. The authors conducted several hypothetical scenarios and demonstrated how the methodology can be used by consulting engineers to conduct a site-specific hazard assessment.

A recent study [36] demonstrated that the quantity of toxic gas produced was correlated with the SOC, indicating that higher SOC conditions can contribute to the overall toxicity of the environment in the event of a thermal runaway.

3.6 Challenging suppression and persistent burning

The presence of the LIB in the BEB makes fire suppression challenging. Once the battery is involved in the BEB fire, there is a greater difficulty in fire suppression, due to the inaccessibility of the burning battery pack to

externally applied suppressants and the possibility of reignition without sufficient cooling. As a result, an excessive amount of suppression agent is needed to cool the battery, extinguish the fire, and prevent reignition [22]. It is well known that BEV fires require a large quantity of water to stop thermal runaway and prevent reignition [86]. Successful extinguishment of LIB fires can be achieved if the water reaches the inside of the battery [31]. However, the application of water streams to a burning EV in close proximity may result in a high-voltage shock due to the high voltage battery [80].

Another challenge is the type of fire extinguisher onboard the BEB. Generally, fire extinguishers are classified according to the type of fire they can extinguish into classes A, B, C, D and K corresponding to extinguishing fires from ordinary materials (e.g., plastics), flammable liquids (e.g., gasoline), electrical equipment, combustible metals (e.g., lithium) and kitchen fires; respectively. Class ABC extinguishers are used onboard ICEVs, and they work by releasing a dry chemical powder that smothers the fire by creating a barrier between the fuel and oxygen. However, this is not applicable to LIB since both the fuel and oxygen are contained in the battery.

3.7 Impact on structures

In the recent BEB fire test [56], the authors measured the temperature profiles at the ceiling-level in the garage and compared it against the ISO 834 temperature curve (a standard fire curve for testing the fire resistance of building materials). The results showed that the maximum temperatures at most locations were less than 1000°C. However, the temperatures at some locations reached as high as 1000°C –1200°C for about 5 min and exceeded the ISO 834 temperature curve. This was due to the high temperature flames erupting from the front and rear windshields. It is worth mentioning that the battery pack was located at the bottom rear of the BEB.

Raza and Li [64] modeled 2 fire scenarios of BEB and ICEB in a roadway tunnel using design fire HRR curves and estimated the adiabatic surface temperature (AST) at the tunnel ceiling and walls. When comparing the results, it was shown that the thermal exposure in terms of AST was higher for a BEB fire on the tunnel ceiling structure while a similar magnitude of AST was seen on the tunnel walls for both ICEB and BEB fires. Moreover, the temperatures to which the tunnel ceiling was exposed during the BEB fire were higher than those specified by the ASTM E119 (Standard Test Methods for Fire Tests of Building Construction and Materials), and ISO 834 standard fire curves for a period longer than 10 minutes. The analysis accounted for the severity of the structural impact from the thermal exposure on the tunnel. The results were compared with those from a conventional ICEB fire scenario.

Although the difference in the peak temperatures between ICEB and BEB fires is not significant, the extended burn time typical of EV fires—often several hours—can push structural elements past their fire-resistance rating even if peak temperatures are not extreme. Diesel fires are usually suppressible once the fuel source is removed or consumed. LIB fires can produce large flame jets and prolonged burning durations because damaged battery modules can reignite multiple times. The fire can continue even after the vehicle is fully engulfed, producing long-duration heating that significantly increases thermal exposure to structural members, potentially exceeding design fire resistance limits.

4 Mitigating the fire risk of BEB and its impact on EVF

Several strategies may be applied to mitigate the fire risks posed by LIBs in BEBs within EVFs. The most suitable approach for selecting and designing mitigation systems starts with conducting a facility risk assessment and identifying facility specific design objectives. A fire risk assessment considers the different fire scenarios and their potential consequences. These fire scenarios are based on interactions among ignition sources (e.g., LIB), intervening combustibles (e.g., tires), available or code-recommended fire protection features, human factors (such as behavior and response during fire events) and facility characteristics. The design objectives for the fire safety of a parking facility generally are: life safety, property protection and operation continuity.

The potential consequences of a fire scenario may be evaluated using historical data, experimental evidence, analytical methods, or computational modeling. As part of this project, a fire dynamics simulation tool was developed to quantify the consequences of a fire related to LIBs in BEBs under different scenarios. The methodology, discussion and results are presented in another report.

This section discusses the different mitigation strategies available for EVFs housing BEBs. It should be noted that while LIBs are not the sole hazard in an EVF for BEBs, they are the primary focus of this report.

4.1 Detection

Early detection is key to reducing the severity of fire consequences. As fires in EVs are more difficult to extinguish than fires in ICEVs, early detection of the fire should be prioritized in order to minimize the fire size. Detection could be applied in the battery system to early detect thermal runaway of a single cell and avoid propagation to other cells. It could also be applied in the EVF to enable early firefighting and reduce the impact of the fire on the facility and other vehicles. Both are discussed in the following subsections.

4.1.1 EV level detection

The early detection of failures of the LIB is critical and is an active, ongoing field of research. Currently, several methods for the early detection of LIB failures include:

1. Temperature monitoring
2. Voltage monitoring
3. Current monitoring
4. Impedance and resistance monitoring
5. Gas detection
6. Machine learning and predictive analysis

A key component for the monitoring of the battery system is the Battery Management System (BMS). The BMS is an electronic system composed of several modules that monitor battery parameters such as voltage, temperature, current, power, State Of Charge (SOC) and State Of Health (SOH) [87]. Furthermore, the BMS is used to prevent overcharging and over-discharging, maintain cell voltage balance, and perform diagnostics and alerts [88]. As such, the BMS is the main mechanism for the early detection of failures via monitoring the parameters of the LIB system [45,89,90].

Thermal runaway of LIB cells can be caused by damage to the internal microstructure and a series of reactions resulting in a sharp rise in the internal temperature of the cell [91]. Earlier works have relied on predicting thermal runaway by monitoring the surface temperature of the battery; however, a time delay in the detection of the increased temperature occurs due to heat conduction. To address the time delay issue, electrochemical impedance spectrum (EIS) based prediction was proposed. EIS is a technique, whereby a small AC signal across a wide range of frequencies is applied to the battery and the response is measured. Previous work has shown that the impedance of the LIB cell decreases with increasing internal temperature. Srinivasan et al. [92] found that there is a change in phase shift at the early stages of thermal runaway, and the change is independent of cell capacity; thus, a warning method for thermal runaway was proposed by monitoring this phase shift. A method based on impedance characteristics for the estimation of the average internal cell temperature was developed [93]. This method was found to be robust, capable of predicting even when the battery's internal temperature is not uniform or even when the temperature undergoes fast changes. Furthermore, the SOC was found to influence the estimation of internal temperature at different frequencies.

On the LIB cell level, early stages of thermal runaway produce a large amount of gas. Golubkov et al. [94] and Lammer et al. [95] studied the gas composition, gas release amount, and total gas release rate of different types of cells when thermal runaway occurs at different SOCs. The authors determined that CO_2 is the main gas component during the first thermal runaway process of LIB cells [94,95]. This led to Cai et al. [96] developing a

method based on CO_2 concentration changes for the early detection of thermal runaway of the LIB pack. Their experiments resulted in a significantly earlier detection of the thermal runaway event, establishing a thermal runaway warning model based on CO_2 concentration detection.

Due to recent advancements in machine learning and AI, their applications to fire safety are becoming more common. For example, in a study by Hong et al. [97], they used a long short-term memory (LSTM) model to predict the voltage of a battery system in multiple steps, and the correlation coefficient method was used to judge the accuracy of voltage prediction by various factors. The method was validated against real data and showed promise when combined with an alarm or an alarm threshold. In another study by Ding et al. [98], the authors used a meta-learning approach for a classification task to estimate the thermal runaway risk at the battery cell level with promising results. More recently, machine learning has been adapted to perform early detection through the prediction of thermal runaway from temperature sensors [99].

In a BEB, the BMS must monitor up to thousands of cells and many modules in a single battery, the BMS becomes a large, complex hierarchy of hardware and software components, with multiple layers of protection, as well as multiple points of failure. Full or partial failure of the BMS due to a software/firmware bug, hardware failure, or design oversight can result in a major event for a battery. As a result, most BMSs are designed so that failure of an individual cell, module, BMS component, or loss of communication with any BMS subcomponent or subsystem will automatically and appropriately limit battery operation, or completely isolate the battery from the high-voltage circuit, while also reporting a corresponding alarm via the battery control system [87,88]. It is worth noting that the BMS in some BEBs only works when the vehicle is on [100].

In addition to the BMS, the following safety devices can be installed in LIBs [101]:

(1) **Enclosure protection (Ingress protection)** to protect batteries against harsh external conditions (i.e., dust, debris, moisture, rain, snow, car wash sprays, etc.)

(2) **Venting for temperature and pressure fluctuations**

During normal vehicle operations, the pressure can already fluctuate widely due to ambient temperature changes, heat generation in cells, and atmospheric pressure changes. These internal and external pressures need to be relieved in order to prevent the collapse of the protective shell of the battery. In addition, a thermal runaway can cause a significant pressure buildup due to the flammable gases released during this process. If these gases are not properly vented, it can result in potential overpressure. The enclosure protection venting system consists mostly of two stages: passive venting and active venting. The passive venting (i.e., stage one venting) is mainly designed to handle normal pressure fluctuations and to prevent contaminants from entering the enclosure. However, this type of venting is not designed to handle rapid pressure buildups in a thermal runaway event. For this event, stage two venting (active venting) is designed. When stage two venting is activated, the vent opens fully to rapidly release the flammable gases in a controlled manner, preventing further damage to the remaining cells and a possible uncontrolled overpressure event. Essentially, the vent prevents pressures from exceeding levels that would cause catastrophic failure during a thermal runaway event.

(3) **A positive temperature coefficient device (PTC)**

It protects the battery against a high current potentially caused by an external short circuit. This device ensures that a circuit is completed while operating within the safe temperature range. If this temperature is exceeded, or the cell temperature rises above this safe range due to external heating, the circuit is broken. [102]

(4) **A shutdown and ceramic-coated separator**

It stops the ion current flow in the battery when a higher temperature is reached. In addition, the ceramic-coated separators improve the separator's resistance to high temperatures and improves its resistance to collapse.

4.1.2 Building level detection

On the building level, quick detection of fire is an important first step for safe egress, fire suppression and firefighting initiation. This is crucial for the fast-developing BEB fire where the recent BEB fire test [56] showed that the entire BEB was engulfed in fire within 6 min. For reference, the fire growth rate for ICEBs is between 150 s (fast) and 75 s (ultrafast) to reach 1 MW [58–61] while the growth rate of ICEVs and EVs varies between medium-slow and medium-fast [55].

Generally, there are currently 5 types of fire detectors used in parking structures [101,103,104];

(1) Heat detectors

(2) Smoke detectors

(3) Combined heat and smoke detectors

(4) Air aspirated detectors

(5) Video Smoke Detection System

Other detectors that are specific to LIB fire detection are electrolyte vapor detectors, which can detect the vapors released from battery electrolytes during TR and hence enable early fire detection.

The transition of fleets from ICEBs to BEBs might require changing the detectors currently installed in the EVFs. A recent risk assessment for 2 bus centers in Montreal [105] recommended the use of an air-aspirated smoke detection system for all BEB fleets, while the detectors recommended for ICEB and hybrid buses are spot-type heat detection systems and fire and smoke video detection systems. Air-aspirated smoke detectors use tubes to deliver air or smoke to a central detector equipped with a sensor that can detect minute changes in the air's chemical composition or monitor smoke obscuration and can therefore detect the risk of fire at an early stage. Another type of detector that can be used in EVFs for BEBs is gas detectors adjacent to charging stations. It is worth noting that the use of smoke detectors in depots with ICEBs and BEBs could result in false positives due to smoke produced by poorly adjusted diesel auxiliary heaters.

Nevertheless, very few studies have examined the detection of EV fire on the building level. One white paper provided by Siemens [106] used their FDOOTC241 and FDOOT241 point detectors to examine the feasibility of using high pressure water mist, triggered by early detection. The test was conducted in a physically simulated garage space with a parked EV positioned between two ICEVs. The early detection from the point detectors and the activation of the high-pressure mist system were an effective suppression method, so much so that the adjacent ICEV showed almost no damage [106]. Alternative technologies such as machine learning have also been investigated for the detection of fire in EV charging stations and parking spaces [107]. The limited research on building-level detection of EV fires highlights a clear need for further study in this area.

Another approach for enhancing the fire safety of BEB depots is the use of integrated detection systems which combine multiple layers of detection, including on-vehicle BMS, charger monitoring (e.g., thermal sensors at charge points, overcurrent/overvoltage alarm), thermal cameras, gas sensors (especially for HF and VOCs) and smoke detection. These systems should be integrated into a centralized depot fire safety management platform that correlates alarms, triggers automated actions like ventilation or charger shutdown, and supports rapid response. By integrating diverse sensors with operational protocols and building controls, bus depots can achieve earlier fault detection, reduced fire-spread risk, and improved safety for personnel, assets, and the surrounding community. However, the use of such integrated systems in BEB depots is still limited.

4.2 Suppression

Currently, research is ongoing to identify effective fire suppressants and fire suppression technologies for EV fires. Water is the most practical suppressant for fighting EV fires, and it well known that EVs require much more

water than conventional ICEVs [22,108]. Extinguishing hybrid vehicles required 1–4 L/min of water and a quenching time of 15–56 min., while quenching EV fires required 4.4 to 10 L/min of water and a quenching time of 36–60 min. By comparison, an ICEV fire is normally extinguished within five minutes [105]. Furthermore, it is also known that even when the fire in an EV has been extinguished, there is a propensity for the LIB to reignite [22]. Additionally, it is difficult to use other suppressants to fight the EV fire [109]. Nonetheless, research into other suppressants has been conducted.

4.2.1 Fire suppressants for LIB fires

A comprehensive review of the fire extinguishers of LIBs was conducted by Zhang et al. [25]. The authors concluded that the current fire extinguishing agents are not satisfactory due to poor cooling effect, electrical conductivity, large amounts required, generation of toxic gases and a tendency to reignition. It should be noted that in addition to the battery, class A materials (i.e., rubber and plastic) are present in the EV.

Fire suppressants can be divided into several types: gaseous, liquid and solid agents. Gaseous agents such as $C_6F_{12}O$, HFC-227ea, and liquid nitrogen (N_2) have been studied on the battery level, with relatively good results [110–112]. However, the use of gaseous agents should be limited to confined spaces, where they are most effective as total flooding systems designed for space protection, and to limit chemical exposure in occupied spaces. Furthermore, some agents such as $C_6F_{12}O$ and HFC-227ea also decompose into hydrogen fluoride (HF) gas [113,114], which is usually generated from EV fires; therefore, their use must be carefully considered. Finally, there is a propensity for the battery to reignite for some of the agents such as HFC-227ea and CO_2 after the suppression agent is applied, as these agents do not cool the battery sufficiently to prevent reignition [114].

Solid agents such as ABC powder, carbon dioxide and foam extinguishers have been studied and results indicate that those suppressants can extinguish LIB flames but its cooling capacity is fairly limited, resulting in failure to prevent reignition and TR propagation to neighboring cells [103,104,115–117]. As previously discussed, ABC powder fire extinguishers are currently used onboard transit buses.

Water is by far the most common liquid suppressant used. The most common methods of delivery are through sprinklers [118] and water mist systems [119,120]. Both methods have been shown to be effective for LIB fire suppression, provided a sufficient amount of water was continuously supplied to ensure no reignition. In addition, there is some experimental evidence for the utility of various water additives improving performance through reducing the volume of water required, extinguishing time, and suppressing the likelihood of reignition [45].

4.2.2 Enclosed vehicular facility fire suppression

At the building level, conventional water sprinkler systems remain the predominant fire suppression method in Canada. Although water mist (WM) systems are not yet as widely implemented as traditional sprinklers domestically, their global adoption is increasing due to their potential advantages in confined spaces and specialized applications [121]. Automatic sprinklers are considered essential for limiting fire spread between vehicles during an electric vehicle fire (EVF) [105], particularly in enclosed parking structures.

A full-scale experimental investigation by Jiang et al. [122] quantified fire hazards and evaluated sprinkler performance for both ICEVs and EVs in parking garages. The study comprised a free-burn calorimetry baseline test for an EV and two suppression tests using a sprinkler system designed according to Ordinary Hazard Group 2 (OH2) criteria, with a flow density of 0.20 gpm/ft² (0.008 m³/min/m²). Results indicated substantially earlier sprinkler activation in the ICEV test (3.5 min) compared to the EV test (28 min), reflecting differences in fire growth characteristics. While sprinklers effectively reduced gas temperatures immediately after activation, they did not prevent EV fire reignition associated with battery TR. Ceiling-level temperatures reached 806°C for the ICEV and 882°C for the EV. At 0.6 m from the vehicle, maximum temperatures were below 400°C for the ICEV but approached 900°C for the EV. Although suppression maintained relatively low temperatures near the battery for extended periods, localized temperatures exceeding 1000°C were recorded during thermal runaway events—

comparable to unsuppressed peak values. These findings highlight the limitations of conventional sprinklers in directly mitigating battery-driven combustion, despite their effectiveness in environmental cooling.

Raza et al. [63] conducted numerical simulations of fire suppression for an articulated 60-ft BEB in both enclosed repair garages and open parking depots. The model considered only the cooling effect of sprinklers and did not simulate full fire suppression, as comprehensive numerical suppression models are not yet available. Three spray densities corresponding to NFPA 13 [1] hazard classifications were examined: 0.008 m³/min/m² (Ordinary Hazard Group 2), 0.0122 m³/min/m² (Extra Hazard Group 1), and 0.016 m³/min/m² (Extra Hazard Group 2). Results suggested that 0.008 m³/min/m² was sufficient to reduce BEB temperatures to levels that inhibited fire spread to adjacent buses, while higher densities provided additional temperature reduction. Despite the absence of validation, the study emphasized that sprinklers are critical for preventing fire spread to neighboring vehicles, even when supplementary mitigation measures such as increased separation distances are implemented.

Beyond spray density, sprinkler design parameters such as spray coverage area and application duration significantly influence suppression performance. Increasing spray duration would also be needed due the persistent burning behaviour of battery; however, no experimental studies have identified the influence of spray duration specifically for EV fires. This represents a clear research gap.

Arvidson et al. [123] experimentally evaluated a deluge water spray system for ICEV and BEV fires under comparable test conditions simulating a roll-on/roll-off (ro-ro) space with a 5 m ceiling height. The system delivered 10 mm/min (372 L/min) via four hydraulically balanced nozzles spaced 3.05 m × 3.05 m, each covering 9.3 m² at 1.3 bar. Water application was manually initiated at a convective heat release rate (HRR) of 1 MW (approximately 1.5 MW total HRR). The deluge system effectively controlled fires for both vehicle types, as evidenced by reduced HRR during water application but renewed fire growth after water discharge ceased. These findings reinforce the role of sustained water application in maintaining fire control.

Water mist systems are increasingly investigated as an alternative or complementary approach. Water mist primarily provides indirect cooling by modifying the fire environment and limiting flame spread, rather than directly extinguishing the battery core. Li et al. [124] numerically assessed WM effectiveness in private garages, examining nozzle quantity and operating pressure. Their results indicated that spray density had a greater influence on fire growth control than operating pressure. However, WM enhanced mixing between air and smoke, reducing visibility in confined spaces. Temperature reductions were more pronounced closer to the fire source.

Lou et al. [125] evaluated fine water mist systems for EV fires in underground garages, focusing on cabin temperature and CO concentration control. Optimal parameters were identified as 16–18 L/min flow rate and 9–10 m/s velocity. The system effectively reduced cabin temperatures and limited thermal damage, while decreasing CO concentrations, thereby mitigating toxic gas hazards. Flow rate exerted a greater influence than velocity on CO reduction.

Chen et al. [126] experimentally investigated EV fire evolution in an underground garage with fine water mist suppression. Top-mounted mist reduced the temperatures of the front vehicle at human height by 52.2%, while a combined top-and-bottom spray configuration reduced temperatures at 1.7 m height from 306 °C to 69 °C (77.5% reduction). Thermal radiation was not effectively suppressed using top spray alone but was reduced by approximately 46.75% when both top and bottom sprays were employed. Additionally, fine water mist reduced O_2 consumption and suppressed the generation of CO_2, CO, and NO during battery combustion, though NO_2 production increased.

In 2023, Danfoss Fire Safety and Siemens [106] demonstrated the integration of rapid detection with high-pressure water mist systems for EV fires in parking garages. In full-scale tests, an EV battery fire was initiated between two adjacent ICE vehicles in a simulated garage constructed from steel containers. Although the EV sustained severe damage, the adjacent vehicles remained unaffected. The system maintained droplet stability even under relatively high wind conditions, demonstrating robustness in adverse environments.

Comparative investigations of portable suppression methods have also been reported. Funk et al. [127] conducted nine extinguishment tests in an open-sided enclosure, assessing direct methods (extinguishing lance, piercing device), indirect methods (water mist, fire blanket, water curtain), and combined approaches. Direct cooling methods proved most effective in controlling EV fires, while indirect methods limited fire spread to adjacent vehicles. Combined strategies were successful in all tests, highlighting the benefit of integrated suppression tactics. Zhao et al. [128] compared fire blankets, water spray, and compressed air foam for early-stage EV fires. They observed that fire intensity increased significantly upon passenger compartment involvement, suggesting that early intervention before compartment ignition can substantially reduce overall fire severity. Fire blankets effectively suppressed visible flames in early stages but did not halt battery thermal runaway, which is probably attributed to the fact that LIBs contain both fuel and oxygen which severely reduces the effectiveness of blankets and other techniques aiming to suffocate the flames. Fine water mist reduced temperature and HRR but did not extinguish passenger compartment fires or stop battery reactions. Compressed air foam also failed to suppress battery-driven combustion without prolonged cooling.

Overall, current literature indicates that conventional sprinkler systems are effective in reducing environmental temperatures and preventing fire spread between vehicles but are limited in suppressing battery thermal runaway. Water mist systems provide enhanced environmental cooling and gas control benefits, particularly in confined spaces, yet similarly face limitations in directly terminating battery reactions. A comprehensive review of applicable codes and standards related to BEB storage facility fire safety design was conducted separately and is presented in a companion report.

4.3 Ventilation and smoke control

As previously discussed, toxic gases are emitted during EV fires in addition to smoke. It is important to provide a proper ventilation system in the EVF to avoid the accumulation of toxic or flammable mixtures within the facility in normal operation which consequently reduces the risk of gas explosions [48]. In addition to the normal operation ventilation system, it might be recommended to install an emergency ventilation system that operates in the event of fire to control the smoke and support safe egress.

Gehandler et al. [129] numerically investigated the smoke toxicity from EV fires on ro-ro ships and calculated it as fractional effective concentration (FEC) and fractional effective dose (FED). They also investigated different normal operation ventilation strategies within ro-ro ships by simulating an open ro-ro space with an open end and openings in the side plating, as well as a closed ro-ro space with an open end or a closed ro-ro space with no openings. It should be noted that mechanical ventilation provided in ro-ro spaces with an open end or closed ro-ro space automatically shuts down once a fire is detected. The results demonstrated that natural ventilation provided in the open ro-ro space is crucial for maintaining tenable conditions during fires involving onboard vehicles (EVs and ICEVs). In addition, maximum FEC and FED values exceeded the acceptable threshold at all heights in the enclosed model while exceeding the same threshold only at the ceiling level in the open model.

Moreover, normal operation ventilation could impact the performance of the gas detector in the facility. Another numerical study by Qiao et al. [130] investigated the impact of different ventilation strategies on the evolution of EV fires in ships and concluded that ventilation enhances CO dispersion, leading to earlier detection by sensors and reducing maximum detection response times by over 25 s.

Generally, a critical ventilation rate is required to control the accumulation of flammable gases and prevent potential explosion when a cell failure occurs. It can be calculated using the following formula:

$$V_c = \frac{\dot{Q}}{Desired\ Concentration\ Factor \times LFL}$$

Where $\dot{Q}$ is the production rate of flammable gases, LFL is the lower flammability limit of the gas mixture and $Desired\ Concentration\ Factor$ is the fraction of LFL that is considered safe and usually considered as 25%.

Knowing $\dot{Q}$ is critical for determining the ventilation rate required for EVF explosion protection for BEBs. Bugryniec et al. [131] recently reviewed the gaseous emissions from the thermal runaway failure of LIBs and stated that as battery capacity increases so does the total amount of off-gas production. However, the authors could not find a correlation between the battery capacity (kWh) and the specific off-gas volume (l/kWh). Nonetheless, they categorized the gas production according to the battery chemistry and reported the following median specific off-gas volume based on battery chemistry: LCO: 394 l/kWh, 403 l/kWh; LFP: 126 l/kWh, 368 l/kWh; NCA: 169 l/kWh, 44 l/kWh; NMC: 519 l/kWh, 573 l/kWh – in air and inert atmospheres respectively. The authors stated that the LFLs for LFP and NMC batteries are 6.2% and 7.9% (in an inert atmosphere) respectively.

A recent risk assessment study [105] calculated the normal operation critical ventilation rate required for 2 transport centers in Montreal. The author assumed a gas production rate of 1 cubic feet per minute (CFM) per 1 ampere-hour (Ah) and a LFL of 10%. The calculated ventilation rate is 4 CFM for each ampere-hour of a LIB. With the expected maximum battery size of 525 kWh, this equates to approximately 5250 CFM (per 525 kWh battery) as the required normal ventilation rate. The author also recommended the integration of an emergency smoke exhaust system to ensure the removal of toxic products and control smoke in the event of fire. Currently, active research is ongoing on the use of mechanical ventilation during fire (emergency ventilation).

4.4 Separation distances and fire barriers

Fire and heat can spread from one bus to another through direct flame/plume contact and radiation. A longer distance between the parked vehicles decreases the probability for direct plume or flame contact. However, the current knowledge suggests that the required spacing may be so large that it would not be practical to implement. Moreover, the flame from a burning BEB might extend underneath the facility ceiling affecting several buses beyond the neighboring buses. Fire barriers can also be used to mitigate the fire spread between buses or zones within the EVF.

Raza et al. [63] numerically investigated the reduction in fire spread to adjacent buses from increased separation distances, a fire blanket, and a fire barrier of various heights. Results showed that although increasing the separation distance (from 3 ft to 8 ft) between buses reduces adjacent bus surface temperatures, the reduction was not significant enough to prevent fire spread. Furthermore, it was found that, except for a full wall-height fire barrier, neither the fire blanket nor the fire barrier provided sufficient protection to prevent TR initiation on the adjacent bus. Their research indicates the need to investigate the increased fire protection needs for BEBs, as well as the need for experimental data for BEBs to confirm these observations.

4.5 Quarantine zones

One of the major concerns associated with BEBs is the tendency to reignite or experience delayed ignition after a collision. Quarantine zones are used for damaged or alarming buses to prevent the risk of damaging other assets (e.g., buses or infrastructure) and avoid the environmental impact of a potential fire involving the suspected BEB [132]. Quarantine zones are usually outdoor areas separated from the bus depot and have a non-combustible floor. They can be equipped with firefighting systems. The suspected bus should be closely monitored in the quarantine area until it is removed or serviced, which could be for several days [44]. Examples of designs for quarantine areas can be found in [132].

Considering the battery itself, LIB fires tend to propagate quickly. To mitigate these fire conditions, containment of the fire by encapsulation of battery modules can be used. This encapsulation could be further enhanced with intumescent coatings or suppression systems, both of which are being developed by BEB manufacturers at the time of writing.

4.6 Emergency response and safety operation

EVFs for BEBs introduce new challenges to transit authorities. As part of their preparedness to adopt BEBs in their facilities, transit authorities are required to put in place emergency response documents for mitigating the hazard of BEBs. The Canadian Urban Transit Association's Zero Emission Bus committee has provided guidance on the preparation of these documents [133]. Emergency response documents from Toronto Transit Commission (TTC), Société de transport de Montréal (STM), and OC Transpo were obtained during this project. The documents from the three transit authorities reveal a unified safety philosophy regarding BEBs. The following summarises the similarities and differences across the three frameworks.

Similarities

- Immediate De-escalation: All sources mandate that a BEB must be taken out of service and passengers evacuated the moment a battery temperature warning is detected.
- Centralized Coordination: Every agency utilizes a central control hub—referred to as TOCC (Transit Operations Control Centre at OC Transpo), TCC (Transit Control Center at TTC), or COP (Centre Opérationnel Principal at STM)—to manage the incident, communicate with drivers, and alert emergency services.
- The Use of Quarantine Zones: All documents require the isolation of a suspect bus in a dedicated Quarantine Zone. These zones must be outdoors and located at a safe distance from buildings and flammable materials.
- Reliance on Telematics: Real-time data monitoring via platforms like ChargePoint (Viriciti) or Clever Device AVM is the standard for validating alarms and monitoring temperature trends without physically entering the vehicle.
- Post-Stabilization Procedures: Once a bus is in quarantine, all sources agree that it cannot be released until temperatures have stabilized and specialized personnel (engineering or OEM) provide authorization.

Different Technical Approaches and Thresholds

- The agencies employ different metrics to categorize the severity of a thermal event:
  - Stage-Based Model (TTC): These guidelines use a three-stage escalation model:
    - Stage 1: High Battery Temperature Warning (typically 35–47°C).
    - Stage 2: Critical High Battery Temperature (48–54°C), indicating a hardware issue rather than a cooling system failure.
    - Stage 3: Urgent Critical High Battery Temperature (55°C+), signaling a thermal event is likely underway.
  - Celsius-Trigger Model (STM & OC Transpo): These agencies use specific temperature milestones to dictate different tactical responses:
    - STM: Uses 40°C (yellow light/monitoring), 55°C (alarm/immediate evacuation), and 150°C (red light/confirmed fire).
    - OC Transpo: Uses 40°C (monitoring), 55°C (stop energy provision), 60°C (electrical disconnection/evacuate and call 911), and 137°C (fire detected).
- Maintenance Safety Standards: OC Transpo provides the most exhaustive detail on High Voltage (HV) PPE and maintenance protocols. They strictly enforce a "two-person rule" (Worker and Monitor) and require Category 2 (CAL 12) arc-flash gear, prohibiting any HV work if components are even slightly wet.
- Environmental Protection: The CUTA guidelines adopted by TTC uniquely emphasize post-incident environmental hazards. They are the only source to explicitly require air monitoring for hydrogen fluoride and water runoff containment to prevent heavy metals from entering the soil or groundwater after a fire.
- Quarantine Specifics:

  - TTC suggests a minimum clearance of 20 feet from buildings.
  - OC Transpo is significantly more stringent, requiring a 50-foot clearance from buildings and 100 feet of spacing between multiple quarantined buses to prevent fire propagation.
- OEM-Specific Dash Indicators: The TTC and OC Transpo documents highlight that driver displays vary by manufacturer. For instance, BYD buses may have no dashboard light for Stage 1 alerts, whereas Proterra buses use a "Turtle" de-rate icon for Stage 2.
- Location-Based Scenarios: STM is the only agency that provides separate, detailed protocols for whether the bus is "On the Road" versus "At the Transport Center," including specific rules for moving buses with a pickup truck if towing is not feasible.
- While all agencies coordinate with 911, the STM and OC Transpo documents include specific 911 communication protocols, instructing dispatchers to mention that the vehicle is electric and provide specific gate or parking lane numbers to first responders to ensure they arrive at the correct isolated location.
- Once appropriate emergency response planning has taken place, research has identified the importance of worker training to ensure that the emergency response plans can be quickly and accurately implemented [102].

4.7 Firefighting

The LIBs in BEBs present unique and complex challenges to firefighters. They can be summarized in the following points:

(1) The risk of electric shock posed by the high voltage and the stranded energy in the LIB. As a result, safety regulations require isolating the battery from the chassis of an EV in case of fire, however, that will not remove the energy from the battery itself [27]. In addition, [134] highlighted the potential of a damaged LIB to discharge electrical energy to the frame and body of the vehicle. Moreover, the application of water at close range to a burning BEB might result in high voltage shock [27]. Tests conducted by NFPA [135] demonstrated that the use of water or standard firefighting agents on burning electric passenger vehicles is generally not considered to present an electric hazard when there is no residual voltage or energized components

(2) Fire suppression of EVs requires huge amounts of water, and it is challenging to access the LIB to extinguish its fire. US National Transportation Safety Board (NTSB) [27] investigated 4 EV fire incidents and reported that, 300–1000 gallons of water were used to suppress the fire. Less water was applied when a rupture in the battery case happened during one of the investigated fires which enabled the water to access and cool the LIB. However, 20,000 gallons of water were applied in one of the investigated incidents because firefighters could not extinguish the fire until they elevated the vehicle and applied water directly to the battery on the underside. The amount of water required for suppression will increase with increasing the fire load in the BEB.

Sturm et al. [31] investigated the firefighting capabilities of fire blankets and a fire extinguishing lance for a passenger EV some time after ignition, emulating a real-life firefighting situation. When the fire blanket was applied, a strong initial reduction in the HRR was observed; however, when the battery started contributing to the fire, strong flames near the ground lifted the blanket, reducing its firefighting effectiveness. The issue of battery reignition was observed in the fire tests when using conventional firefighting methods; when the fire lance was used to pierce and inject water into the battery, full extinction of the fire was observed. Thus, in firefighting situations, water injection using a fire lance was shown to be effective in preventing reignition [31]. Yet, this is not proven for BEB fires, in particular for battery packs on the bus roof. Nonetheless, manufacturers claim that the fire lance is effective no matter where the battery is located and whether the vehicle is parked or in motion.
Guidance provided by EV manufacturers on where and how to access the LIB in case of fire can be crucial to ease firefighting of EVs and decrease the amount of water required to suppress the fire. It is

worth mentioning that Renault-France [136] worked with firefighters to design a firefighting access feature in all their EVs, which enables first responders to entirely extinguish a fire in the battery caused by external sources of flames. They mention that this feature allows firefighters to soak the battery and thereby extinguish the fire in under a minute. However, the viability of this solution is yet to be tested.

(3) Reignition of the LIB is another challenge in fighting EV fires. This is more probable in case of insufficient cooling of the battery. Moreover, there is no specific time frame for the battery reignition. It could happen after a few minutes from fire suppression [137] or a few weeks [77]. Thus, it is important to safely handle the EV for extended periods after a fire or a collision.

(4) The toxic chemicals emitted during an EV fire pose a health hazard to firefighters. While the use of SCBA (Self-Contained Breathing Apparatus) would protect their respiratory systems during firefighting, there is a risk of contaminating their personal protective equipment (PPE). [138] recently reviewed existing international standards for firefighters' PPE maintenance and handling after contamination and found that these standards do not specify sufficiently precise requirements, especially with regard to the effectiveness of cleaning firefighting clothing and the safety of its re-use. They also reported that cleaning firefighters' clothes using liquid carbon dioxide is more effective than traditional water cleaning. They also conducted a test where they exposed PPE to smoke from a burning EV battery, then inspected the contaminants deposited on them. The results showed that, the concentrations of polyaromatic hydrocarbons, formaldehyde and cobalt greatly exceeded the acceptable limits.

Recently, the Canadian Association of Fire Chiefs [139] assessed the information and training for fire service available for medium- and high-duty zero-emission vehicles. They highlighted that the lack of consistent empirical knowledge to drive and support evidence-based fire service training and strategy development is a major concern. In addition, they mentioned that the regulatory framework in Canada does not currently include requirements for clear external identification of alternative energy sources in vehicles. This is an ongoing problem for Canadian first responders that should be relatively easy to address at a minimal cost.

5 Knowledge Gaps

The fire safety of BEBs is an evolving area of research and regulation, with several knowledge gaps that need to be addressed to ensure safe deployment and operation. Full-scale fire test data of BEBs are scarce and currently, only one study [56] is publicly available. In addition, most thermal runaway research is based on lab-scale tests or passenger EVs. The studies on BEB fires currently available in the literature are mainly numerical investigations that extrapolate findings from ICEBs or passenger vehicles (EVs and ICEVs), though assumptions for scaling require further experimental validation. For passenger BEVs and ICEVs, research shows that HRR curve and PHRR data are comparable, however, that might not be scalable to BEBs versus ICEBs due to the larger battery capacity of the BEB. Although the THR is directly proportional to the battery capacity, that is not the case for the PHRR. This raises the question of the role of the battery in the hazard evolution during a BEB fire, whether the fire originates in the battery or in the bus combustibles. Data from full-scale BEB fire tests is needed to quantify the hazard in terms of HRR, PHRR and emissions. The presence of such test data is crucial to develop well-validated CFD models to further understand additional parameters, quantify the consequences of different fire scenarios and investigate different mitigation strategies in an EVF. Experiments are also needed to evaluate the toxic emissions released from a BEB during a fire to plan for ventilation and assess environmental impact.

In addition, BEBs have the potential to reignite and their fire suppression is challenging due to the inaccessibility of the battery to externally applied suppressants. Those hazards are not present in the case of ICEBs, which highlights a need to review fire protection systems design guides/standards of EVF to address the growing complexity of EV and BEB fires.

Early detection is crucial to limit the severity of BEB fires in EVF. LIBs are equipped with battery management systems (BMS) that monitor the temperature, voltage and general health of each cell within the battery pack and generate warnings in the event of a failure. Linking the BMS to the facility's fire detection system could provide

early alerts of abnormal behavior. At the building level, the transition from ICEBs to BEBs may necessitate modifications to existing detection systems, as fire development differs significantly. LIB fires are typically preceded by off-gassing during the early stages of thermal runaway and aspirating smoke detectors offer value in this context, as air circulation can transport early emissions into the sampling pipes, enabling earlier warning than conventional smoke detection methods. However, further studies should be conducted to evaluate the performance of different detectors for EV fires for early detection, less false positives and localization capabilities.

At present, no suppression agent or technology has proven fully effective at extinguishing EV fires. Water remains the most practical option, though EV fires demand significantly larger volumes compared to conventional ICEV fires. For BEBs, the substantially larger battery capacity increases both the complexity and the time and water required for suppression. A major challenge is the inaccessibility of the battery itself. One potential solution is the use of a fire lance to penetrate the battery casing and inject water directly, as demonstrated in one study [31]. Another approach could involve designing batteries with dedicated access points to allow water flooding in case of fire.

Currently, building codes and standards mandate sprinkler systems for the fire protection of parking structures, but they lack testing protocols or performance criteria tailored to the hazards posed by LIBs in BEB facilities. Ideally, suppression system performance would be measured by its ability to prevent fire spread from the bus of origin to adjacent vehicles. This requires further evaluation of water spray rates, design areas, discharge durations, and system activation methods. Additionally, the environmental impact of contaminated runoff water must be considered to establish proper disposal guidelines.

Another research gap related to suppression is onboard automatic fire suppression systems which are required for buses and coaches in engine compartments under UNECE Regulation No. 107 [140], however this regulation is not mandated in Canada. The application and effectiveness of these systems for BEBs remain uncertain and warrants further research [102].

Finally, the deployment of BEBs will require providing firefighters with adequate training and knowledge about the hazards of LIBs. It is important to notify the fire department nearest to the EVF with information about the locations and numbers of BEBs in the facility. Information about the LIB from the manufacturer will also be beneficial. Developing clear operating procedures for before, during, and after a fire will help improve the response of EVF in case of fire.

6 Conclusions

In this report, the potential hazards of BEBs in EVFs due to the presence of LIBs and corresponding risk mitigation strategies were presented. A literature review was conducted to gather the work related to the fire safety of BEBs in EVFs. Due to the scarcity of BEB data in literature, studies on passenger electric vehicles (EVs), passenger internal combustion engine vehicles (ICEVs) and internal combustion engine buses (ICEBs) are also included. The conclusions from those studies provide background knowledge and points of comparison for BEB studies.

Particularly, the major hazards of BEBs due to the LIB are:

(1) Complex and varying burning behaviour and fire size, in particular the peak heat release rate (PHRR) of burning BEBs,

(2) Potential for explosion

(3) Potential for reignition

(4) Toxic emissions and environmental impacts of BEB fires

(5) Challenges of suppressing BEB fires

(6) Impact on structures

In addition, the following mitigation strategies were discussed:

(1) Detection
(2) Suppression
(3) Ventilation and smoke control
(4) Separation distances and fire barriers
(5) Quarantine zones
(6) Emergency response and safety operation
(7) Firefighting

The report is concluded by discussing the knowledge gaps identified through the literature review. There is a clear lack of comprehensive full-scale fire tests for BEBs, limiting our understanding of heat release rates and other critical factors specific to these vehicles. While some parallels can be drawn from studies on smaller passenger EVs and ICEVs, with some studies extrapolating those findings to BEBs, assumptions about scalability have yet to be experimentally validated for high-performance EVs and larger vehicles such as BEBs. Furthermore, studies on fire detection and suppression at the building level remain sparse, and existing research primarily focuses on passenger EVs. This includes gaps in understanding the effectiveness of current suppression methods, the role of separation barriers, and the use of alternative suppressants for BEB-specific fire scenarios. Addressing these research gaps will contribute to more robust safety standards and improved fire mitigation strategies for the deployment of BEBs in various settings.

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APPENDIX A

Some reported major BEB incidents

Electric bus fires, while a concern, are statistically rare, especially compared to conventional diesel buses. Here, we report some of the major incidents caused by BEB fires that resulted in large damage or delayed the deployment of BEBs.

Where	When	What happened	cause	Consequences
Hanover-Germany	June, 2021	A fire at a bus depot in Hanover caused millions of euros in damage.	a potential technical defect, possibly related to the charging process	- 5 BEBs, 2 hybrids and 2 combustion engines were destroyed, as were also the building and the charging station.
Stuttgart-Germany	September, 2021	A large fire event in Stuttgarter Straßenbahnen (SBB)'s depot, in Gaisberg, that completely destroyed 25 buses of different models and kinds, including two with electric drives	electric bus during charging procedure	- 25 buses were destroyed - MVG Munich took out of service eight electric buses, of the same type until the cause of the fire was clarified.
Paris-France	April, 2022	Two BEBs from the same manufacturer got fire during the same month in Paris during operation.	intercell short-circuit caused by thermal runaway- the cause was in the battery manufacturing process.	- Loss of both buses without casualties - recall of batteries of the same type and vehicles fitted with them - 148 buses were withdrawn from the fleet and buses from the same manufacturer were grounded for 2 years
London- UK	May, 2022	A fire engulfed 6 buses, 2 electric and 4 diesel-powered, in Potters Bar bus depot.	BEB caught fire while charging	- Total loss of 6 buses - Recall of 90 BEBs
Connecticut-USA	July, 2022	A transit BEB began emitting smoke while	moisture in the high voltage	- Similar BEBs from the manufactures

		parked inside a maintenance facility. It had been placed out of service 2 days earlier due to an error in the bus charging system. The bus was pushed outdoor to an isolated parking area. Later, the bus was again emitting smoke, and fire was observed coming from the rear of the vehicle	lithium-ion battery system, which led to battery damage resulting in the fire	were removed from service while the incident was investigated.
Ahmedabad-India	June, 2024	3 BEBs caught fire while being charged. They were charred within 15 mins	faulty lithium-ion batteries during charging	- Total loss of 3 BEBs
Taichung-Taiwan	October, 2024	A fire occurred in a bus depot belonging to a now-defunct Electric Bus Company.	It is suspected that the cause may have been an electrical fault in a battery.	- Total loss of 9 BEBs
Massachusetts-USA	January, 2025	4 brand new school BEBs caught fire while being charged		- Total loss of the 4 buses
Huntsville-Canada	January, 2025	A school BEB caught fire during operation	The fire is not believed to have been caused by the large battery pack and probably attributed to mechanical issues.	- Delays or cancellations of planned electric bus purchases in some areas.
Mumbai- India	June, 2025	The incident occurred inside the workshop of the Ghansoli depot in Mumbai. The electric bus was stationed for repairs.The fire spread to three nearby diesel buses, which were under major repair .	A technical fault — insulation resistance (IR) failure — caused a short circuit in one of the four sealed battery packs in the BEB	- Total loss of 4 buses; 1 electric and 3 diesel - Minor damages to other 6 buses
Philadelphia-USA	June, 2025	A massive fire took place in an outdoor bus storage yard for decommissioned buses where they are stored for a year or less while making arrangements for their disposal. It should be noted that, before storing, the batteries were disconnected, the coolant was drained and	A battery on a BEB	- Damage of 40 decommissioned SEPTA buses (15 of which are BEB)

		the buses continued to be inspected in accordance with manufacturer recommendations.		