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Literature Review on Parking of Electric Vehicles

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Table of Contents

List of Tables

Executive Summary

Transportation using internal combustion engine vehicles (ICEV) is considered as one of the major contributors to greenhouse gases that are responsible for climate change and rising temperatures. Electric vehicles (EV) present a greener solution to ICEV, however they pose a different fire hazard due to their propulsion system (the lithium ion battery). In this report, the potential hazard and recent incidences of EVs in parking areas are reviewed. In addition, fire codes, guidelines and standards of parking structures are discussed to assess their effectiveness against the potential hazard imposed by EVs in parking structures. Finally, the knowledge gaps and research opportunities to improve the fire safety of EVs in parking structures are presented and discussed.

1. Overview

In 2015, 196 parties, including Canada, signed the Paris agreement to set a framework to limit the global temperature rise to 1.5°C compared to the pre-industrial era. Global warming is attributed to the greenhouse gases, mainly carbon dioxide, resulting from anthropogenic activities. In Canada, transportation is responsible for 27% of the greenhouse gas emissions [1], which is due to the combustion of fossil fuels in internal combustion engines (ICE).

Several greener alternative fuel vehicles exist to replace ICE vehicles, like Hydrogen vehicles and Electric vehicles (EVs), where the latter are more widely prevalent. In 2020, just in Canada, 2.5% of the newly registered cars were EVs [2]. In addition, the city council of Ottawa approved the plan proposed by OC Transpo to purchase only zero-emission buses, by selecting battery-electric buses with in-garage charging as the suitable technology for the years from 2022 to 2027. The aim is to have a fully electric bus fleet by 2036 [3].

Electric vehicles and their power source (Lithium-ion batteries) present an emerging technology with a different fire hazard from conventional internal combustion engine vehicles (ICEV). However, most of the current fire safety regulations and standards for parking structures have been developed based on ICEVs. Moreover, there are still questions regarding the fire safety of EVs which present potential research opportunities.

2. Objectives

In this report, a literature review was conducted in order to

(1) Review the potential hazard and recent incidences of EVs in parking areas;
(2) Review relevant fire codes, guidelines and standards and discuss their effectiveness against the potential hazard imposed by EVs in parking structures;
(3) Highlight the knowledge gaps and research opportunities to improve the fire safety of EVs in parking structures.

3. Electric Vehicles

The power source in EVs is Lithium-ion battery (LIB) which offer high energy density, long life and reliability that suits the use in EVs, thanks to its advanced chemistry comprising a carbon anode, a metal oxide cathode and an organic liquid electrolyte. However, this composition raises the concern of potential fire hazard of LIBs since they already contain the fuel (organic electrolyte) and oxygen (metal oxide cathode) that can react together and release heat leading to thermal runaway. Risks pertaining to thermal runaway extends from thermal failure, mechanical failure, internal/external short circuiting, or electrochemical degradation. Moreover, as manufacturers pursue greater driving ranges for EVs, more LIBs are used which leads to increasing the potential heat released in case of fire.

The LIB consists of four primary components; cathode, anode, electrolyte and separator. The Lithium ions are stored at the anode during charging and the Lithium ions migrate to the cathode during discharging to generate the electric charges. Several cathode materials are commercially available, which are mainly transition metal oxides (e.g. LiCoO2 (LCO), LiMn2O4 (LMO), Li(NixCoyAlz)O2 (NCA) and Li(NixCoyMnz)O2 (NCM) and LiFePO4 (LFP)). The Li-ions deintercalate from the cathode to the anode and vice versa through the electrolyte. The electrolyte should allow the rapid transmission of Li-ions, be compatible with the electrodes and also inert. The most common electrolytes available in commercial LIB are ethylene carbonate (EC), diethyl carbonate (DEC), propylene carbonate (PC), ethyl methyl carbonate (EMC) and dimethyl carbonate (DMC), in addition to salts dissolved in the solvents (e.g., Lithium hexafluorophosphate (LiPF6), Lithium hexafluoroarsenate monohydrate (LiAsF6), Lithium perchlorate (LiClO4), and Lithium tetrafluoroborate (LiBF4). Finally, the separator separates the anode and cathode to avoid internal short circuits while allowing the flow of Lithium ions. The separator should be chemically and thermally stable, good wettability and fine permeability with electrolyte. The most common membranes in the commercial LIB are polyolefin membranes made from polyethylene (PE) or polypropylene (PP).

Both ICEV and EV pose fire hazard due to the flammable materials including flammable plastic components and power source (fossil fuel or LIB). Generally, the heat released from EV fire is less than or equal to the heat released from ICEV fire. Lecocq et al. [4] tested two pairs of EVs and ICEVs. The first pair had same weight of 1100 kg while the weights of the ICEV and EV in the second pair were 1400 kg and 1500 kg, respectively. They concluded that the heat released from the first pair was similar (peak heat release rate (HRR) and rate of growth) while the peak HRR and rate of growth was higher for the ICEV in the second pair. Lam et al. [5] conducted a test series of similar ICEVs and EVs, and they concluded that the measured peak HRR and heat flux in the ICEVs tests were due to the burning of a full tank of gasoline which was higher than those measured in the EVs tests.

In general, our knowledge and practice with the fire safety of ICEV is much better developed compared to EVs. Heat released during LIB fires depends on the battery chemistry (i.e., cathode material), packing, capacity and state of charge and is accompanied by release of toxic gases. Moreover, EV fires can be due to self-ignition resulting from LIB thermal runaway, which can occur during charging, parking or driving [6]. Another challenge in EV fires is suppression, especially when the onboard battery is involved in the fire because it is inaccessible by the fire suppressant, and it has a high potential to reignite if not sufficiently cooled.

Although fires in parking structures are rare, they cause very large economic losses. For example, the fire at Liverpool's Echo Arena (UK) destroyed 1400 vehicles [7]. The fire at Stavanger Airport (Norway) destroyed 300 vehicles and presented a unique opportunity to investigate the involvement of electric vehicles in fires on large scale [8].

Fire spread between cars in parking structures is critical in determining the extent of the fire and the ability of the fire department to successfully control and extinguish it. However, there is limited test data on this spread between newer cars. Some testing of multiple modern vehicles has shown very rapid fire spread between vehicles in a parking garage configuration, on the order of 10-20 minutes [9].

Most of the current design guidelines and standards for parking structures were developed based on vehicle fire tests performed many decades ago. These standards assume that there will be limited fire spread between vehicles before suppression. However, new modern vehicles are larger with increased use of polymers and other combustible materials which ignite easier and burn more intensely. In addition, the increasing number of alternative fuel vehicles like plug-in hybrid electric vehicles (PHEVs), EVs and hydrogen fuel cell vehicles present a fire hazard different from conventional ICEVs.

In this report, we investigate the applicability of the current guidelines and standards for parking structures to fire safety of EVs. We highlight the research gaps and provide high-level recommendations for a research road map as well as specific guidelines for parking EVs.

EVs involved in collision and fire incidents may present unique hazards associated with the high voltage system (including the battery system). These hazards can be grouped into three distinct categories: chemical, electrical, and thermal.

4. Parking structures

Parking structures can be stand-alone or attached to other occupancies. They can be also classified into closed or open. According to the international building code (IBC), a parking structure is considered open if natural ventilation can be achieved by (1) uniformly-distributed openings on two or more sides (2) openings not less than 20% of the perimeter wall area of each tier (3) openings not less than 40% of the perimeter length of each tier.

Different materials are used for the construction of parking structures, concrete assemblies, combination of steel and concrete or mass timber.

The design of parking structures has been changing to accommodate more vehicles and save space. They are very often built underground and many of them are typically built in multilevel design. Therefore, energy density is high in car parks. In addition, some of the recent parking structures use car stacking mechanisms, where hydraulic systems lift two or more cars above each other, which consequently increase the parking density and the risk of rapid fire spread. Moreover, new vehicles tend to be heavier and larger [10] and the increasing use of plastics and alternative fuels (i.e., EV and hydrogen cells) in vehicles increase the energy content during a fire both in intensity and duration. Some of the parking structures also have charging stations for EV which pose another fire hazard since electric vehicles are active during charging.

Fire protection in parking structure should account for the type of construction, parking density, location of the garage (i.e., above or below grade, open or closed configuration) and proximity to other occupancies. Parking garage fires are generally limited to a single vehicle. Only about 8 percent of incidents extend to the area beyond the footprint of the vehicle, where the fire has originally started [11].

Generally, fire spread between vehicles, especially from the initial to the second and third vehicles determines the extent of the fire and the ability to successfully control and extinguish [9,12]. Joyeux et al. showed that there is no structural collapse if the fire doesn't spread beyond 3-4 vehicles [13]. Therefore, early detection and suppression are crucial for fire protection of parking structures with modern vehicles.

However, many fire codes still categorize parking structures as ordinary hazard group 1. This has changed in the latest version of NFPA 13 (2022) where parking structures are currently considered as Extra hazard group 2. The national building code (NBC) of Canada eases the active fire protection requirements (i.e., sprinklers) for open parking structures assuming natural ventilation is sufficient and the easy accessibility of the firefighters to the parking. Although LIB fires require huge amounts of water to extinguish, the use of sprinklers will at least prevent the spread of fire to other vehicles. The fire protection in garages gets more challenging with the presence of charging stations for the EVs. It is note worthy to mention that NFPA 70 developed standards to address the growth in EV charging stations.

5. Recent incidents of EV fires in parking structures

Vehicle fires in parking structures developing into large, out of control events are fairly rare, and civilian injuries in these types of incidents are few. However, fires in parking structures can lead to very large economic losses, as evidenced by recent fires at Liverpool's Echo Arena (UK) and at the Stavanger Airport (Norway), interestingly both were open parking structures where fire protection is mainly achieved by natural ventilation. It should be noted that recent changes in codes and standards (as will be discussed in the next section) require the addition of sprinklers in open garages.

- Liverpool's Echo Arena

One of the larger recent events occurred in Liverpool, England in December of 2017 in an open, 8-level concrete parking garage with 1,600 car capacity. A fire believed to have started in a 2002 model Land Rover that had been "converted to a different fuel arrangement" and spread throughout the parking structure, resulting in damage to over 1,400 vehicles, and severe structural damage that the building was demolished [7]. The local fire chief claims that if the parking garage had been equipped with sprinklers, it would have made it easier to contain and suppress the fire, by putting more water on the fire [14]. The fire chief also points out that when dealing with a "running fuel fire" foam is required, which the local fire department did not have access to. Once the fire fully developed, fire crews reported additional vehicles becoming involved every 30 seconds.

- Stavanger Airport (Norway)

Another fire with very extensive impact occurred on January 8th, 2020 in an open parking garage at Stavanger airport in Sola, Norway [8]. The fire is reported to have started in a 2006 diesel car (Opel Zafira). The Norway fire destroyed 200-300 vehicles inside the building, with a further 1,300 vehicles trapped with some degree of heat and smoke damage, and part of the five-story structure collapsed. The owner of the originating vehicle stated that he attempted to start it, saw smoke coming from the engine compartment, and soon after flames. News articles about the incident report that it still took the fire department approximately 19 minutes from ignition until first units arrived, and that the first fire fighters claimed to have seen as many as 10 vehicles burning on arrival, though this has not been confirmed. As the airport firefighters are not able to respond to non-aircraft fires while the airport is operating, the closest responding fire fighters had a travel time of up to 13 minutes.

As of the time of writing the report, there has been no large fire in a parking structure that was initiated by EV fire. Generally, Fires in EVs could be caused by (1) spontaneous self-ignition, like the destruction of a brand-new electric bus in a spontaneous fire in Hong Kong on 14 December 2015 [15] (2) while charging, like the destruction of a Tesla Model S in Norway on 1 January 2016 and a Porsche Panamera in Bangkok on 16 March 2018 (3) reignition following a thermal or mechanical abuse, like the Tesla Model S that crashed in Florida, USA, by impacting a wall at 140 km/h. The impact led to the vehicle being engulfed in flames. After the fire had been subdued and the vehicle was removed from the scene, it reignited. When the destroyed vehicle finally arrived at the tow yard, it reignited once more. Another recent example is the crash and fire of a Tesla and another vehicle on the highway in Sacramento- California in March 2023 where the Tesla was completely engulfed in fire.

Several incidents were reported for EVs catching fire while parking. Some examples are the fire accident of Tesla Model S occurred during fast charging in Norway in 2016 and the fire accident of a parking BYD Qin Pro EV in 2020.

In Canada, since there’s no national database on fires and most provinces don’t track whether vehicle fires involve EVs, the numbers of fires of EVs can’t be reported. Most of the reported fires in garages are in parking structures attached to apartment buildings. For example, In January 2018, 2 fire incidents took place, the first was in parking garage in a building in Mississauga and resulted in destruction of all the vehicles in the garage. The other one was in a parking structure in the Victoria Park and Eglinton avenues area in Toronto and resulted in the damage of a number of cars. The reason of the later was attributed to careless smoking [16]. In December 2018, a fire broke up in a car in the garage of an apartment building in Stoney creek in Hamilton.

Fires in house garages are also common. For example, one person was sent to hospital in life-threatening condition after a fire fully engulfed a garage in Scarborough, Toronto in May 2022.

Other examples of fires in parked EVs in Canada;

(1) A multi-vehicle fire broke out in Eaton Centre parking garage on 22 September 2022 [17]. Fire fighters were able to clear the smoke and evacuate the mall and no injuries were reported. Five vehicles were scorched before the fire was successfully extinguished. It was reported that the fire was due to accidental mechanical issue [18].

(2) A fire broke out in the upper level of the Fallsview Casino parking garage in Niagara, GTA in July 2018 and led to the brief evacuation of the Avalon Ballroom theatre and Grand Buffet [19].

(3) A parked EV in a residential garage in Montreal started fire which triggered an explosion that projected the garage door across the street and caused damage to the attached structure in July 2019.

(4) In February 2014, A Tesla Model S vehicle started fire while parked in a garage in Toronto.

(5) In August 2022, the residents of 300 apartments in Quebec City were forced to evacuate after an electric vehicle caught fire in the building's underground garage. The car was completely damaged and towed away and no injuries were reported. [20]

EV fires present a new challenge for fire fighters since they require large amounts of water (~ 10 m^3) to suppress in addition to the electrocution risk due to the stranded energy in their batteries. Moreover, the accessibility of the batteries can present an issue as they are contained in watertight, fireproof box, therefore firefighters usually tilt the car using jacks to reach the battery compartment at the bottom. Fire engines generally carry about 2 m^3 of water, EV fires that happen away from municipal water supplies (hydrants) can drain resources quickly. Recently, firefighters reported the use of 22.7 m^3 of water to suppress the fire of a Tesla model S car on the highway in sacramento- California in January 2023. They also had to tilt the car up with jacks, spraying water directly into the bottom battery compartment.

Another issue associated with fires of EVs is the probability of reignition which occurs when individual battery cells catch fire at different times. Once a battery cell has gone into thermal runaway, caught fire & has been suppressed, that cell typically does not catch fire again. However, other nearby cells or cells in other modules that were damaged in the initial incident, may then go into thermal runaway & ignite. In some cases, reignition happens several days after the first event. Some of the most common practices to avoid reignition are to allow the traction battery to completely burn out, while protecting exposures or monitor the battery for a period of time with a thermal imaging camera and listening for audible signs of thermal runaway (e.g., popping or hissing noises) prior to releasing the vehicle for towing.

6. Current codes and standards

Standards and codes typically define minimum requirements to achieve 3 different levels of protection; life safety, asset protection, and safety of fire services. The basic requirements for parking structures provide (1) fire resistance, which is specified as a time to failure under a standardized fire test, and (2) requirements for sprinkler protection. The current codes and standards for parking structures are old and slowly changing to accommodate the new challenges and fire hazards posed by new vehicles. For example, most regulatory bodies considered open parking garages to have a low fire risk and that their fire risk would be largely mitigated if smoke is allowed to escape. It was also assumed that sprinklers and detection systems were not required in open parking garages if they were constructed with non-combustible or limited combustible materials. In addition, past regulations generally assumed that fire spread from one vehicle to another would not occur, and if it did the fire department would arrive in time to control it. However, many of these legacy assumptions, especially vehicle-to-vehicle fire spread, were contradicted by the recent incidents in Liverpool’s Echo arena and the Stavanger Airport, among others.

Some of the proposed changes are showing up in codes and standards, including:

- The recent 2023 edition of NFPA 88A, *Standard for Parking Structures*, (6.4.2) now includes a provision for all garages, open and enclosed, to have sprinkler protection.
- The 2021 edition of the International Building Code (406.5) requires open garages to be sprinklered, when specific area and height limitations are exceeded.
- Some national codes within the EU now require sprinkler protection in open garages above a certain floor area, height, or when located below a hotel or assembly occupancy.

The following subsections summarize some of the current codes for parking structures.

6.1 International Building Code (IBC) 2021

The IBC establishes minimum requirements for building systems using perspective and performance-related provisions. The code is intended to establish provisions that adequately protect public health, safety and welfare. Provisions for parking structures are stated in section 406 of the code under motor-vehicle-related occupancies.

Parking structures in the IBC are considered as type I, II or IV construction and follow their fire resistance rating requirements as stated in the code. For all parking structures, floor surface should be of concrete or similar non-combustible and non-absorbent materials. It should be also sloped to facilitate the movement of liquids to a drain or the main vehicle entry door. In open parking structures, Fire protection is provided by natural ventilation and the total length of the openings to provide natural ventilation shouldn't be less than 40% of the total perimeter. In addition, Interior walls shouldn't be less than 20% open. Sprinklers are only required in open garages when specific area and height limitations are exceeded. For enclosed parking structures, both mechanical ventilation and sprinklers systems are required to provide fire protection.

Section 406.2.7 recommends the installation of EV charging stations and systems according to NFPA 70 (American national electric code) with the equipment listed and labelled in accordance with UL 2202 (Standard for EV Charging System Equipment) and the EV supply equipment listed and labelled as per UL 2594.

6.2 NFPA 88A

In the United States, and some other jurisdictions, vehicle parking structures are governed by NFPA 88A, Standard for Parking Structures [NFPA, 2019]. The purpose of the standard is to provide minimum fire protection to parking structures. It covers the construction, fire protection and hazard control of parking structures. In NFPA 88A, the general structural fire resistance guidelines refer to requirements in NFPA 220, Standard on Types of Building Construction, where parking structures are categorized as type I or II. NFPA 13 [21] Standard for the Installation of Sprinkler Systems is used for sprinkler requirements.

In the most recent version (2023), NFPA 88A expanded its scope to include parking systems, in addition to open and enclosed parking structures, which might be fully-automated, mechanical or stacker. It also mandated the development of an emergency plan for the parking structures, ventilation of all enclosed parking structures by a mechanical system capable of providing a minimum of 300 L/min per m^2 of floor area during normal operating hours and the installation of an automatic sprinkler system in all types of parking structures.

The standard classifies the parking structures as enclosed, open or ramp type. The parking system is an either stand-alone equipment or incorporated into the building that parks vehicles by mechanical or automatic means, that also includes stacker parking systems.

According to the standard, only those parts of parking structures located within 3 m from another occupancy for any other purpose shall be separated by walls of fire resistance rating not less than 2 hrs according to ASTM E119 or UL 263. This rating can be reduced to 1 hr if the parking structure is protected throughout by sprinklers. Floors should be of non-combustible and sprinklers should be installed in all parking structures. The exterior sides in open parking structures should have uniformly distributed openings on 2 or more sides with total area 20% of the total perimeter wall area to provide natural ventilation.

Sections 7.1.6, 7.1.7 and 7.1.8 in the standard list some requirements for EVs charging stations. They should be listed and labeled according to UL 2202 (Standard for EV charging system equipment) and their equipment should be listed and labeled according to UL 2594 (Standard for EV supply equipment). The wireless power transfer equipment for transferring power to an EV should be listed and labelled according to UL 2750 (Outline of investigation for wireless power transfer equipment for EVs).

6.3 National Building Code of Canada (NBC)

According to the NBC of Canada, the basic design of parking structures is based on the requirements of CSA S413 and NFPA 88A is adopted for the fire protection requirements. The NBC states other requirements for parking structures like; areas requiring a barrier-free path of travel and wheelchairs accessibility, exterior barrier-free paths of travel to building entrances and exterior passenger-loading zones, load requirements for roof parking decks and fire department access.

The NBC classifies parking structures as open or closed. Where a roofed enclosure used for the storage or parking of motor vehicles has more than 60% of the total perimeter enclosed by walls, doors or windows, the enclosure shall be considered a garage. A building used as a storage garage with all storeys constructed as open-air storeys and having no other occupancy above it is permitted to have its floor, wall, ceiling and roof assemblies constructed without a fire-resistance rating provided it is a) of non-combustible construction, b) not more than 22 m high, measured between grade and the ceiling level of the top storey, c) not more than 10 000 m2 in building area, and d) designed so that every portion of each floor area is within 60 m of an exterior wall opening.

Although the scope of CSA S413, “Parking structures,” is limited to structural steel and reinforced concrete, the NBC allows the use of any type of material in the construction of storage garages and repair garages as long as they conform to the performance level outlined in the standard. Moreover, in the recent version of the code (2021), a parking garage on the first to fourth storeys can be constructed from encapsulated mass timber as long as it is sprinklered.

7. Research in fire safety of EVs

Most of the work in literature is conducted on batteries or modules since large fire tests on EVs are expensive and rarely published. Even though, the fire performance in LIB is different from EV which can be attributed to the different materials in EV (specially plastics) which contribute to the fire HRR and emissions and the inaccessibility of the battery compartment in EV.

Several full-scale fire tests were conducted on EVs and reported in literature. Lecocq et al. [4] tested the fire behaviour of 2 BEVs and their analogous ICEV. The vehicles were set into fire using a 6 kW propane burner. Fire development was the same for all vehicles tested. The fire propagation might be influenced by ventilation and ignition source which were the same in all tests. They reported relatively higher maximum HRR for ICEV. In addition, the effective heat of combustion was estimated 36-36.5 MJ/kg for ICEV and 30-31 MJ/kg for EV. Significant HF was released from both ICEV and EV, however it was higher for EV due to LIB. This study focused on the fire outbreak in the passenger cell. Other parameters such as fire scenario initiating event, the battery technology, its design and its position within the vehicle.

Watanabe et al. [22] conducted a real-scale fire test for a Nissan Leaf (EV) and a Honda fit (ICE). Both vehicles were ignited using 80 g of alcohol gel fuel at the left-rear soft bumper for the Nissan and the left-rear splash guard for the Honda. The heat release rate and the radiation heat flux were measured. The authors reported that there was no explosive burn in the LIB pack in the EV. The HRR and heat flux from the EV were higher than ICEV which might be attributed to the larger size of the EV (1520 kg vs 1275 kg).

Lam et al. [5] conducted a series of fire tests to compare the fire performance of EV, ICEV and PHEV. Seven vehicles were tested. Each vehicle was exposed for 30 minutes to controlled conditions simulating a gasoline pool fire. They concluded that the presence of a battery-powered propulsion system did not present a greater overall hazard than the conventional gasoline-based propulsion system. Moreover, the peak HRR and heat flux levels measured in the ICEV tests were higher than those measured in the comparison EV tests. They also occurred earlier than or around the same time as in the EV tests. The response of the EVs to the fire appeared to depend on the vehicle model, battery design and state of charge. For one model, the primary peak in HRR resulted from burning of the non-battery vehicle components, while a subsequent secondary peak, associated with high heat flux levels, occurred once the battery pack was fully compromised. For the other model, burning of the battery pack did not contribute to any significant increases in HRR or heat flux above the levels generated by the other vehicle components. The results from the PHEVs were consistent with those from the EVs and ICEVs.

Truchot at al. [23] tested 4 EVs in a facility simulating tunnel environment. Three cars were ignited using a 20 kW propane burner under the front left seat. The fourth was ignited by a 0.25 m^2 heptane pool fire located under cover, near the front right wheel. They measured the HRR and reported the peak HRR, time between ignition and peak HRR and total released energy. However, their main focus was measuring the emissions to evaluate their toxicity. Several toxic gases, mainly acids, were detected. Despite their quantities, they have low toxicity threshold which impose evaluating their toxic impact. They also found out that higher quantities of HF are produced during EV fires.

Willstrand et al. [24] tested three different vehicles, one ICE full-size van, model year 2011, a BEV full-size van with an 80 kWh battery and model year 2019 (BEV A), and a 2016 BEV family car with a 24 kWh battery (BEV-B). The vehicle size of the ICE-A car and the BEV-A were similar, but the max. HRR differed, peaking at 7 MW for the BEV and at around 6 MW for the ICEV. According to the test report, the effective heat of combustion in MJ/kg was almost equivalent for both full-size vans, whereas that of the BEV family car was considerably smaller. This is consistent with the findings for similar cars made by Lecocq et al. [4].The differences in burning characteristics are thus mainly due to the differences in fire development inside the car.

Sturm et al. [25] conducted full-scale fire tests of passenger cars in a road tunnel. They tested 5 vehicles; 3 BEVs and 2 ICEVs. They measured temperature and gas profiles in the tunnel. In addition, they measured the battery temperature and voltage during thermal runaway. They found that the internal cooling system of modern batteries is very efficient and will delay battery involvement in a vehicle fire – as long as the battery itself is not the source of the fire. They also concluded that the HRR from BEV is higher than that of ICEV and HF is the most critical emission from fire of BEV. In addition, they investigated different suppressants; water, fire blanket and fire lance. Their results showed that the usage of fire blankets was not successful. On the other hand, the usage of a fire lance to inject water directly into the battery casing proved to be very efficient. The battery fire could be extinguished within a very short time with a small amount of water. However, the application of such a fire lance requires the possibility of a direct approach to the vehicle and well-trained fire fighters.

Cui et al.[26] designed a full-scale fire experiment to explore the fire evolution process and characteristics of two parallel placed EVs a BEV, and a PHEV. This configuration of vehicles is representative of a typical scenario that BEVs and PHEVs are parked together. The initial ignition position is the battery pack of the BEV. The fire behaviors, hot plume spread process, and spatial distributions of temperature and heat radiation of the two-EV fire were analyzed in detail. The authors found that white smoke released from the vehicle chassis was a precursor to the BEV fire when the traction LIB pack encountered external heat sources. Flames appeared only after the white smoke accumulated and exploded. Buoyant diffusion flames dominated the BEV fire, and multiple appearances of jet fires from the thermal runaway (TR) battery pack made it more dangerous. The authors concluded that the peak temperatures of the external and internal flames of the BEV compartment are consistent with that of ICEVs. The flames of the two-EV fire spread faster than that of PHEV or ICEV fires.

Recently, Kang et al. [27] conducted a campaign for testing 2020 models of BEVs. They tested 2 BEVs, 1 ICEV and a hydrogen fuel cell electric vehicle. In addition, separated parts of LIB pack and BEV body were tested to allow the examination of individual contributions of the parts to the global BEV fire. The authors found that, the BEV fires continued up until 70 min. Their peak heat release rates were measured to be slightly lower than ICEVs but higher than the hydrogen fuel cell electric vehicle. In addition, the major contribution to the quantity of HRR in BEV fires was determined by the combustion of the conventional materials of the BEV body rather than the LIB pack. However, as a jet fire intensively discharged from the LIB pack, it accelerated flame spreading to adjacent combustible components, thereby leading to a rapid growth of whole car-fire. The findings discussed in this study could contribute mainly to the activities of first responders to BEV fire accidents where BEV fires originating from thermal runaway of LIB packs would be more hazardous than those derived from elsewhere, due to late human awareness of flames and their rapid development once ignited.

A summary of all the work conducted in literature for testing BEV fires is presented in Table 1.

Table 1. summary of full-scale fire tests of EVs from literature

Study	Vehicle	Ignition source	Ignition point	Measurement	Environment
Lecocq et al. [4], Truchot et al. [23]	ICEV, BEV	6 kW propane burner	Inside the passenger compartment	HRR, heat flux, mass loss, temp, gas flow, gas composition	Confined area (tunnel, 3.5 m high, 50 m long)
Lam et al. [5]	ICEV, BEV, PHEV	2 MW propane burner, 2.4 m x 1.2 m	Simulated pool fire underneath the vehicle	HRR, heat flux, temp, gas composition, voltage, mass loss	Free burn (full-scale test facility, burn hood 6 m x 6 m)
Watanabe et al. [22]	ICEV, BEV	80 g alcohol gel fuel	Behind rear wheel	Mass loss, mass loss rate, heat flux	Free burn (15 m x 15 m x 15 m fire test room)
Willstrand et al. [24]	ICEV, BEV	ICEV: a small diesel pool fire BEV: 30 kW gas burner	underneath fuel tank or battery pack	HRR, convective HRR, temp, gas and soot composition	Free burn (fire hall with a large calorimeter hood)
Sturm et al. [25]	ICEV, BEV	Saline solution for inducing short circuit in battery in one test and Propane burner for the other tests	The battery or seats inside the car	HRR, Temp, gas profiles, different suppressants	Tunnel 400 m long and 30 m^2 cross section
Cui et al. [26]	BEV, PHEV	2 electric furnaces (3 kW each)	Battery pack of the BEV	Heat flux, Temp	Open field
Kang et al. [27]	ICEV, BEV and hydrogen fuel cell electric vehicle	Propane burner or heating sheet or pan of heptane	Heating a LIB cell or the lower boundary of the pack	HRR, Temp, heat flux, weight	Open space

8. Knowledge gaps and Potential Research Opportunities

There are different levels of research in the lithium-ion battery and EV field and each level targets a different objective as shown in Table 2. Although, fires in EVs don't always start in the battery pack, ignition of the battery pack (either as starting point of fire or due to spread of fire from the vehicle body to the battery) results in rapid fire growth. In the study by Kang et al. [27] who tested battery packs, EVs and their bodies, it was found that most of the heat released from burning the EV was from the combustion of the body materials rather than the battery pack. However, as a jet fire intensively discharged from the LIB pack, it accelerated flame spreading to adjacent combustible components, thereby leading to a rapid-fire growth. Moreover, suppression of fires involving LIB is challenging and requires huge amounts of water. For example, Tesla company stated that at least 11000 litres of extinguishing water would be required for a fire in their cars. Another challenge is the water to reach inside the battery pack to cool it down.

Table 2. Research objectives corresponding to different levels of research from the fire safety viewpoint.[27]

Level	Type of specimen	Objectives
1	Component material	Thermochemical/electrochemical characteristics of the unit
2	Single cell	Thermal characteristics of the unit under thermal/ electrical/mechanical impact conditions, mechanism of gas venting and thermal runaway initiation, and quality/quantity of vent gas
3	Multiple cells/single module	Thermal characteristics of the unit under thermal/ electrical/mechanical impact conditions, and cell-to-cell thermal runaway/heat propagation
4	Multiple modules	Module-to-module thermal runaway/heat propagation in horizontal and vertical directions
5	Pack	Thermal characteristics of the unit under thermal/ electrical/mechanical impact conditions, and pack-to-vehicle body fire spread
6	BEV	Magnitude of BEV fire hazards, and BEV-to adjacent object fire spread

Over a third of all EV fires happen while connected to energized alternating current or direct current charging stations, or within 1 hour of being disconnected, indicating that there may be a greater risk of a fire during EV charging. To mitigate the impact of the fire of an EV and avoid its spread to adjacent cars, there are 4 crucial considerations; (1) ventilation (2) early detection (3) suppression (4) training fire fighters.

8.1 Ventilation

Open parking structures emerge as the main area of concern regarding fires in modern vehicles due to lack of any requirements for active protection systems in many fire codes. On the other hand, enclosed parkings with poor ventilation might result in accumulation of smoke and toxic emissions that hinders the evacuation or the accessibility of firefighters to the fire scene.

8.2 Early detection

Early detection of battery failure and subsequent early fire suppression would probably delay thermal propagation between battery cells as well as battery modules, which consequently would reduce the risk for a fire spreading from a battery pack to its surroundings.

There are 5 methods for detecting failure of LIB; (1) terminal voltage using the Battery Management System (BMS) (2) gaseous emissions (3) internal battery temperature (4) current variations as indication of short circuit; and (5) mechanical deformation using strain gauge sensors [28]. The most commonly used method is a combination of BMS and battery temperature. BMS can improve heat dissipation by thermal management, avoiding cell over-heating, and also locate a faulty cell within a battery pack. However, BMS measures the surface temperature and can’t detect the initial stages leading to thermal runaway. Internal temperatures measured via dedicated embedded sensors have a higher accuracy to predict thermal runaway, but they add a high cost as well as complexity to the pack. Gas sensors can be used to detect the initialization of thermal runaway. They are faster than voltage or temperature methods as the build-up of initial gases often precedes any significant changes in the voltage or temperature signals. However, it adds complexity and cost, and faults could trigger false alarms.

Currently, it is believed that detection of fires of EVs is similar to ICEVs. However, there are gaseous emissions specific to LIB (e.g., Heat flux and H_2) which can be used as early detectors of LIB fires. Nevertheless, their concentrations are low compared to other gases during EV fire and the applicability of their early detection is not investigated yet. Recently, Willstrand et al. [24] measured the emissions from burning two EVs and one ICEV and reported higher amounts of Heat Flux and hydrogen bromide gas (HBr) produced from EV fires. Moreover, they found that the metal content on soot particles was dramatically higher for the EVs, specially for metal elements typically found in LIB: nickel, cobalt, manganese, lithium, aluminum, and copper.

Generally, the main control systems in parking structures are smoke detection system, a sprinkler system and a programmed fire detection system [29]. However, the use of smoke and heat detectors may lead to false alarms or slow response [12]. Potential solutions are the use of infrared flame detectors and other visual systems, or smart detectors where multiple signals are interpreted by computer algorithms to distinguish false alarms from actual fires. Application of Artificial Intelligence (AI) methods can be also considered as a new technique to increase the accuracy of fire incidents detection in parking spaces, battery and charging systems. Furthermore, automatic early detection of heat, smoke, or other fingerprints of failure and anomalies in EVs and Parking spaces will be faster and easier with employing AI technique along other common fire detection and suppression systems.

8.3 Suppression

Currently, the most commonly used suppressant is water, however fire suppression of EVs requires huge amounts of water to cool down the battery and stop the electrochemical reactions. In a recent incident in Sacramento- California, firefighters reported the use of 6000 gallons (~23 m^3) of water to suppress the fire on an EV on the highway. Despite the challenges of fire suppression of EVs, only a few papers investigate LIB fire suppression, with those existing putting the emphasis on sprinkler protection of storage spaces, and without agreement on what extinguishing agents are effective in avoiding re-ignition. According to the authors' knowledge, only one paper [25] investigated different suppressants on EVs' fires.

The main challenge in suppression of EVs fires and LIBs fires in general is the water reaching inside the battery. External cooling of a burning but only slightly damaged battery is hardly effective. In a recent study by Sturm et al. [25], they investigated the use of a fire blanket and a fire lance to suppress the fire of EV and found that fire blankets were not successful once the battery was involved in the fire. In such a situation, the high fire dynamics, together with the self-supply of oxygen stored in the battery prevent the flames from suffocating. On the other hand, a fire lance extinguished the fire within a very short time and a small amount of water since it was able to inject water directly into the battery casing. In addition, the authors found that the internal cooling system of modern batteries is very efficient and will delay battery involvement in a vehicle fire – as long as the battery itself is not the source of the fire.

Moreover, the addition of additives to reduce the water's surface tension might facilitate the entrance of the water to deeper structures of the vehicle and thus better reach the inside the battery pack. This can be achieved by conventional foaming agents mixed to the water at a similarly low rate. However, more research is required to identify the most suitable agent and ratio. [30]

As discussed in section 6, fire protection in parking structures is provided by sprinklers; which might be unable to control fire in some situations [12]; for example:

- Cars parked at unusual angles or in corners
- Cars at the edge of the sprinkler spray area
- Fires starting, and spreading, inside or under vehicles
- Strong wind through garages blowing away hot gases, delaying activation.

- Electric vehicle battery fires with jet near floor
- Stacker systems with more than two levels
- Lower water application density in stacker systems

Another challenge to fire suppression in parking structures is the downwind drifting of hot gases during a fire event which might result in the inactivation or delayed activation of the sprinklers directly above the initiating vehicle and consequently, there would be less cooling effect on neighboring vehicles to limit the fire spread. It is important that the effects of wind on sprinkler activation and water dispersion is assessed and considered for these applications. A potential solution is to use an activation method not reliant on the temperature of sprinkler heads at a single location (usually at the ceiling), but a more complex system must be designed where sprinklers are tied to other fire detection methods. It should be noted that, false alarms are not a problem in parking structures.

8.4 Training of fire fighters

The current training and resources available for firefighters and emergency responders are inadequate to dealing with EV fires. Response guidelines are far different for EVs than for ICE vehicles, and proper training programs must be in place. Fire trucks and equipment also are insufficient for the task of extinguishing EVs.

Fires of EVs present a different challenge to firefighters due to the following characteristics [30]:

(1) high voltage

The voltage of the battery placed in ICEV is mostly 12~24V, while EVs are usually equipped with high voltage batteries of DC voltage of 100 ~ 360V or AC voltage of 650V. This poses a great risk of electric shock during suppression of EV fire, such as breaking down, cutting off electricity, putting out the fire and water related vehicles, so that first responders should strengthen insulation protection.

(2) toxic emissions during fire

EV fires produce larger amounts of toxic gases like HF, HBr, POF_3 and HCL compared to ICEV. Moreover, HF can be absorbed through the skin. This presents a health hazard to first responders. Li et al. [30] suggested personnel protective equipment (PPE) for firefighters during EV fire events which are listed in Table 3. Some of the suggested equipment are to protect from the high voltage and electric shock.

Although the work by Willstrand et al. [24] showed that the concentrations of toxic emissions produced during EV fires are less than the health exposure limits and that firefighting turnout gear materials showed good protection against HF, there might be a higher toxicity hazard in enclosed garages with low or no ventilation during fire events.

Table 3. suggested PPE for fire fighters during EV fire events

	head	Respiratory track	Body	Other parts
ICEV	Fire helmet	N95 face-mask	Fire fighting protective clothing	Fire gloves, exposure footwear for firemen, goggles
EV	Fire helmet	Fire positive-pressure breathing apparatus	Anti-fire and chemical protective suits	Insulating gloves, high voltage insulating boots, goggles

(3) probability of reignition

Lithium-ion batteries and packs have a high tendency to reignite after being involved in a fire or even a crash. In some cases, reignition might occur 22 hours after extinguishing the battery [31]. In some cases, EVs that were involved in a fire or a crash are isolated and the battery temperature is monitored for couple of hours to ensure that they won't reignite. In other cases, the battery is removed and transferred immediately, and plenty of water is used for cooling to prevent further combustion and reignition. The transfer/towing of the vehicle should be done with cautious to avoid the reignition. In case of parking structures, there can be a designated area for monitoring those vehicles.

(4) large amounts of water required for suppression

As previously mentioned, suppression of EV fires requires huge amounts of water (~22 m^3 as experienced in some incidents), nonetheless a fire truck can carry a maximum of 6 m^3. Although additives and fire foams might be effective in fire suppression and reduce the amount of water used, it is still unknown what is the most effective additive. Moreover, in some real incidents fire fighters had to turn around the burning vehicle to be able to reach the battery pack and suppress the fire.

(5) contamination and environmental pollution

Runoff water from suppressing EV fires might contain large concentrations of contaminants. In the study by Sturm et al. [25], considerable amounts of cobalt and nickel were found in the runoff water exceeding the acceptable threshold. This is not a problem for road tunnels and open

streets where the run-off water is collected in special basins and a waste water treatment is expected, but it might be in locations without such facilities. Some of the proposed solutions are the use leak proof pad to block the sewer to prevent sewage from flowing into sewers; Using a leak proof bag to plug the inside of the sewer, the sewer can be used as a temporary reservoir for centralized treatment of sewage after accident treatment; river channels or open ditches can be dammed to prevent the spread of sewage downstream; the surface sewage can be controlled by oil fence or sand embankment.[30]

9. Conclusions

This report presented a literature review of the potential hazard of electric vehicles and their recent incidences in parking areas in Canada and worldwide. The relevant fire codes, guidelines and standards were also reviewed and their effectiveness against the potential hazard imposed by EVs in parking structures was discussed.

The fire hazard of EVs is not higher than that of ICEVs. Nonetheless, it is different due to the presence of the LIB which already contains the fuel (organic electrolyte) and oxygen (metal oxide cathode) that can react together and release heat leading to thermal runaway. In addition, some of the new parking structures have charging stations for EVs and electric vehicles are active during charging which pose another hazard in garages. Although large vehicle fires in parking structures are not common, they might lead to large economic losses -if happen- as have been seen by recent fires at Liverpool's Echo Arena (UK) and at the Stavanger Airport (Norway).

The current codes and standards for parking structures are old and slowly changing to accommodate the new challenges and fire hazards posed by new vehicles. Mainly, most of them assumed that open parking garages have a low fire risk and there is no need to be protected by sprinklers and detection systems. Moreover, past regulations generally assumed that fire spread from one vehicle to another would not occur, and if it did the fire department would arrive in time to control it. However, many of these legacy assumptions – especially vehicle-to-vehicle fire spread - were debunked by the recent incidents in Liverpool's Echo arena and the Stavanger Airport, among others. Therefore, most of the recent changes in codes and standards include the protection of open garages with sprinklers.

Many research in literature was performed on the fire safety of LIBs or packs, only few involved EVs since such large tests are expensive. All studies agreed that the presence of a battery-powered propulsion system did not present a greater overall hazard than the conventional gasoline-based propulsion system, however there was a discrepancy on weather EV fires or ICEV fires have the higher HRR probably due to different sizes of vehicles, types of batteries and fire initiation location in those studies. Most of the studies reported the occurrence of jet flame from the battery pack which resulted in faster fire spread in case of EV fires. Fewer studies investigated suppression and one of the studies reported less amount of water was required when the water reaches the battery.

Early detection and suppression of EV fires are critical for mitigating their impact in parking structures and preventing the fire spread to adjacent vehicles. Several new technologies exist for early fire detection like infrared flame detectors and other visual systems, or smart detectors where multiple signals are interpreted by computer algorithms. In addition, detection of gases specific to LIB fires (HF and H_2) could be also used. The applicability of these new technologies in detection of EV fires in parking structures needs further investigation. Moreover, there are still research gaps on the best suppressant mixture and suppression strategy for EV fires. Firefighters also need updated resources and training for handling fires of EVs.

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