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A Review of Battery Fires in Electric Vehicles

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Abstract: Over the last decade, the electric vehicle (EV) has significantly changed the car industry globally, driven by the fast development of Li-ion battery technology. However, the fire risk and hazard associated with this type of high-energy battery has become a major safety concern for EVs. This review focuses on the latest fire-safety issues of EVs related to thermal runaway and fire in Li-ion batteries. Thermal runaway or fire can occur as a result of extreme abuse conditions that may be the result of the faulty operation or traffic accidents. Failure of the battery may then be accompanied by the release of toxic gas, fire, jet flames, and explosion. This paper is devoted to reviewing the battery fire in battery EVs, hybrid EVs, and electric buses to provide a qualitative understanding of the fire risk and hazards associated with battery powered EVs. In addition, important battery fire characteristics involved in various EV fire scenarios, obtained through testing, are analysed. The tested peak heat release rate (PHHR in **kW**) varies with the energy capacity of LIBs (E_B in **Wh**) crossing different scales as $\boldsymbol{PHRR = 2E_B^{0.6}}$. For the full-scale EV fire test, limited data have revealed that the heat release and hazard of an EV fire are comparable to that of a fossil-fuelled vehicle fire. Once the onboard battery involved in fire, there is a greater difficulty in suppressing EV fires, because the burning battery pack inside is inaccessible to externally applied suppressant and can re-ignite without sufficient cooling. As a result, an excessive amount of suppression agent is needed to cool the battery, extinguish the fire, and prevent reignition. By addressing these concerns, this review aims to aid researchers and industries working with batteries, EVs and fire safety engineering, to encourage active research collaborations, and attract future research and development on improving the overall safety of future EVs. Only then will society achieve the same comfort level for EVs as they have for conventional vehicles.

Keywords: Li-ion battery; Electric vehicle; Fire incidents; Fire tests; Heat release rate; Fire suppression

1. Introduction

The electric vehicle (EV) uses an electric motor and relies on electric power for propulsion. The term EV usually refers to road vehicles, but more generally it may also include rail vehicles, surface and underwater vessels, and aerospace applications. In this review, this term is restricted the road EVs that are fully or partially powered by a Li-ion battery (LIB). Battery electric vehicles (BEVs) rely solely on electric energy whereas plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs) can also be powered by an internal combustion engine.

The EV was invented in the 1800s as a consequence of a series of breakthroughs concerning the battery and the electric motor [1]. In the 1900s, there was a brief period in which EVs were in demand due to fuel shortages and environmental crises [2]. However, the interest for EVs dropped after the 1930s, when oil and gasoline became cheap and easily available, enabling petrol-driven vehicles to travel faster and further [3]. Today, billions of internal combustion engine vehicles (ICEVs) vehicles are being driven, consuming about 87% of

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petroleum or about 33% of our global energy [4]. However, limited natural energy resources, the increasing world population, and global warming exacerbate people's perception of energy vulnerability and the need for more sustainable transport solutions.

Along with the rapid development of the LIB since the 1990s, EVs returned to the global stage in the 21st century. Today, EVs are not only a symbol of green transportation, but they also present extraordinary driving performance [1,2]. However, compared to the ICEVs which has seen continuous use and development over the last century, EVs are still far from mature, especially when it comes to their perceived fire safety. This safety concern stands in the way of the EV becoming the dominating transportation system [5,6].

The introduction of EVs and fire incidents involving them have attracted considerable media attention. **Table 1** lists a selection of EV fire incidents that happened in 2018, and **Figure 1** shows some photos of such incidents. In general, most of the EV fire accidents are caused by the thermal runaway of LIB. The common causes of EV fires include the self-ignition (or spontaneous/auto ignition) in parked vehicles due to arson or sustained abuse, for example, fire during the charging process, self-ignition while in driving, and fire after the traffic accident such as the high-speed collision [7]. Therefore, the propensity of self-ignition during the normal charging, parking and driving conditions, due to the thermal runaway of LIB, makes the EV fire unique and very different from fires in ICEVs.

***Table 1*.** The list of selective EV fire accidents occurred in 2018

Date	Location	Vehicle	Incident	Comments
Jan [8]	Chongqing, China	Tesla, BEV	Fire in the parked vehicle	Spontaneous ignition
15 Mar [9]	Bangkok, Thailand	Porsche Panamera, PHEV	Fire while being charged	Car's charging cable plugged to socket in the living room without built-in safety systems, and fire spread to the house
18 Mar [10]	Catalonia, Spain	BMW i3 REx, PHEV	Fire in the parked vehicle	Spontaneous ignition
23 Mar [7]	California, USA	Tesla Model X, BEV	Post-crash fire	Fire extinguished on the scene but reignited twice at tow yard 5 days later
May [11]	Anhui, China	Other, BEV	Fire while being charged	
May [11]	Unknown	Yiema, BEV	Fire while being charged	
8 May [12]	Florida, USA	Tesla Model S, BEV	Post-crash fire	Fire initially extinguished quickly but reignited during loading on tow truck and once again at the tow yard.
15 May [13]	Ticino, Switzerland	Tesla, BEV	Post-crash fire	Vehicle hit a barrier, turned over and burst into flames.
20 May [11]	Hangzhou, China	Jiangling, BEV	Fire while being charged	
21 May [11]	Hubei, China	Zhong Tai, BEV	Fire while being driven	Self-ignited without traffic accident
28 May [11]	Shenzhen, China	Other, BEV	Fire while being charged	
4 Jun [11]	Shandong, China	Other, BEV	Fire while being driven	Self-ignited without traffic accident
5 Jun [11]	Beijing, China	Other, BEV	Fire while being charged	
15 Jun [14]	California, USA	Tesla Model S, BEV	Fire while being driven	Fire extinguished on the scene without reignition
12 Dec [15]	Gelderland, Netherlands	Jaguar I-Pace, BEV	Fire in the parked vehicle	The vehicle front was burned but no involvement of the battery pack.
18 Dec [16]	California, USA	Tesla Model S	Fire in the parked vehicle	Fire started at workshop parking lot, and the fire reignited twice.

The battery is not only the fuel to power the EV but also the major fuel to feed the EV fire, similar to gasoline or diesel being the major fuel to feed ICEV fires. The mechanisms of battery thermal runaway, as well as, the battery fire phenomena, risks, and hazards have been reviewed in [17–20]. These reviews emphasized the safety characteristics of battery material and chemistry and summarized recent scientific understandings of battery fire dynamics. However, the overall fire risk and hazards of EV are still poorly understood. Fire tests on large-scale EV battery packs and full-scale EVs are expensive and rarely published. With the expansion of the EV market, EV ownership is constantly increasing. Meanwhile, the energy density of LIBs continues to increase [21], despite unsolved fire-safety issues. As a result, the probability of EVs fire accidents will increase. This paper reviews these fire risks as well as accidents involving EVs, that are powered by the battery, especially the LIB. The limited large-scale fire tests of EV and the corresponding fire-protection strategies are also reviewed in detail.

Figure 1. Typical EV fire accidents in recent years: (a) a Renault-Samsung electric vehicle model 'SM3.Z.E' caught fire while driving on 15 January 2016 in Korea [22]; (b) a pure battery electric bus caught fire in a charging station on 26 April 2015, Shenzhen, China, and this electric bus was not in charging when it caught on fire [23]; (c) a Tesla Model S released smokes while being driven on 15 June 2018 in California, USA, and the fire was extinguished by injecting 1135-L water and foam [14]; and (d) the EV fire accident happened in a parking lot on 20 May 2018, Hangzhou, China [24].

1.1. The Growing Demand for Electric Vehicles

According to McKinsey's Electric Vehicle Index, EV sales have been growing dramatically every year since 2010 (**Figure 2**) [25]. The market scale of EVs has also expanded from negligible before 2010 to 1.3% of all newly sold vehicles in 2017. Today the volume of new EVs sold surpasses one million units. BEVs make up 66% of this total. The growth rate of BEV sales has mostly been faster than that for PHEVs. Therefore, BEVs are more likely to further strengthen their position of being the dominant EV in the future [26]. Note however that other trends may occur in markets other than that for road EVs.

The EV market has excellent performance in many countries and regions around the world. In 2018, China led the market with a 48% market share followed by the European Union with 26% [27]. Although consumers tend to be resistant to new technologies ("social" barriers) [28] and EVs are still less mature and reliable ("technical" barriers) in terms of their lifespan, range, availability of charging stations, than petrol-driven vehicles. Government subsidies, however, prove to be a great propellant in the EV market. In fact, government policy plays an important role in EV sales and its trajectory in every major market. In addition, the continuous reduction in the cost of the battery, as well as increasing battery performance and growing production volumes, further promotes the EV market. As a result, EV battery pack costs are expected to decrease to US$ 150 per kWh within 2020-2023 [29].

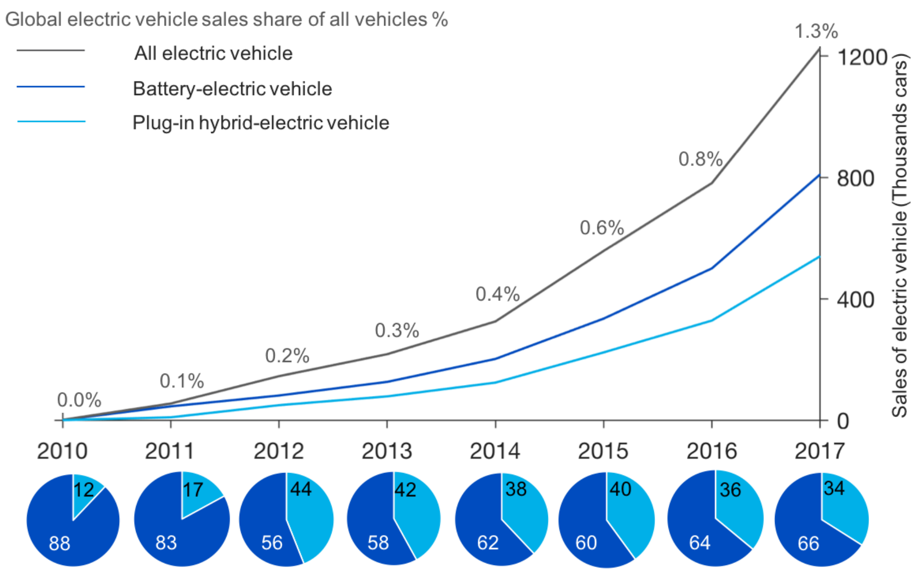

Figure 2. Sales percentage of EV in the global vehicle market, and a worldwide number for two types of battery electric vehicles from 2012 to 2017 by McKinsey [25].

With the stimulation of positive government policies, Europe Union leads the way in promoting the EV market. In Norway, EVs count for 34.7% market share of new car sales in 2017 and 52% if hybrid vehicles are included [30]. The incentives offered by Norway's government include (1) BEVs are exempted from vehicle registration tax; (2) BEVs are exempted from value-added tax; and (3) BEVs pay the lowest rate of the vehicle license fee. Finally, BEVs have access to bus lanes and are exempted from road tolls [31]. France is second behind Norway in the European continent in the registration of hybrid and electric passenger vehicles [32]. Based on an Electric Car Index prepared by OSV Ltd, France managed to overtake Norway, the leader position in Europe EVs market. The government projected a €400-million R&D program for EVs. In 2017, 11,987 EV charging points had been installed, and EVs sale accounts for 1.5% of the French personal vehicle market. Germany has set itself the goal of becoming the lead market and provider for electric mobility by 2020 as part of its long-term zero-emission mobility vision [33]. The German government launched several plans for EV research and development (R&D). For example, $240M will be used on the batteries that power electric cars, making domestic production a priority and ensure that German experts are trained in the technology.

In the USA, the domestic scale of EVs increases from 9,750 in 2011 to 762,000 in 2017 [29]. This improvement is partly due to state policies and the decreasing battery cost [34]. The U.S. federal government has initiated a tax credit for PEVs purchased since 2010. The tax credit ranges from $2,500 to $7,500 for each vehicle based on its battery capacity and gross vehicle weight rating. Apart from financial incentives, other priority, like high occupancy vehicle (HOV) lane exemptions and expedited license plate acquisitions, has been offered. Extending electric vehicle policy incentives through 2020 enables sustained market growth [35].

In China, the government has been providing generous subsidies for EV purchasing since 2009 [36]. These subsidies, which are part of the Electric Vehicle Subsidy Scheme of China, were updated in 2013 to scale with the EV's electric driving range rather than its battery capacity to promote both the quality and safety of EVs. The target of China's subsidy program is to boost the popularity of EVs and build national champions and e-mobility ecosystems for the coming decades. It is predicted that China will have 200 million EVs on the road by 2040 and cover 60% market share of total local passenger vehicle sales [29].

Japan had a long history with EVs due to its limited natural resources. The first Japan-manufactured EV, the Nissan Tama, hit the road as early as 1947 [37]. Japan has been investing heavily in battery research and was among the first countries to introduce PHEVs to the global market [38]. As a result, several of the most popular EVs that are available today, such as the Nissan LEAF and Toyota Prius, are Japanese. Apart from those above, many other countries around the globe provide substantial tax rebates for EV purchasing and ownership. Examples of these are Singapore, the Netherlands, and Ireland [29].

1.2. EV Batteries and their Fire Risk

Fire incidents are one of the risks that surround vehicles. With the number of EVs increasing, they have started to become more visible in EVs. For most of the BEV and PHEV fire accidents, especially for self-ignition, the fire starts in the battery power system (**Figure 1**). In terms of propulsion, the battery capacity can be analogized to the gasoline capacity in an ICEV's fuel tank. Therefore, the EV fire is connected with the fire risk and hazard associated with the battery cell and power system, as well as, the size and capacity of the battery pack. In general, the greater the number of batteries and the greater the amount of energy they may contain, the greater the fire risk for EV [18,39,40].

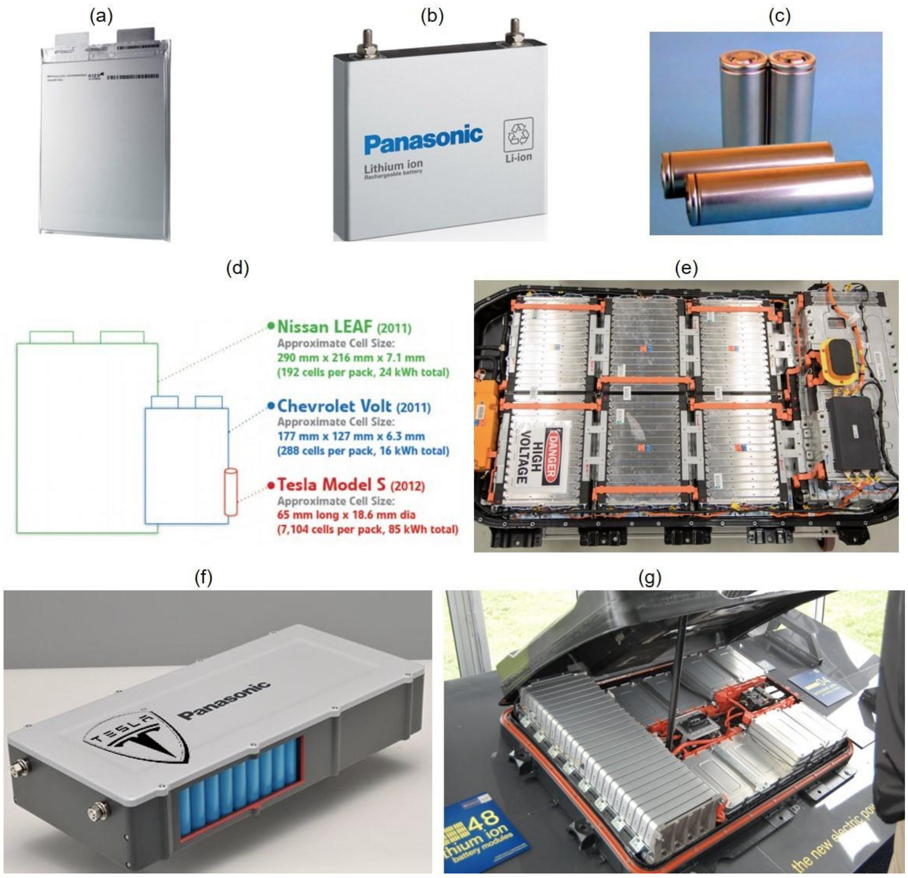

Figure 3. Typical EV battery cells: (a) the pouch cell; (b) the prismatic cell; (c) the cylindrical cell; (d) approximate battery cell size of popular EVs (e) the 60 kWh battery pack is fully assembled by LG Chem in Korea, which employs 288 prismatic pouch cell; (f) Tesla's battery module, which consists of hundreds of cylindrical cells; (g) Nissan LEAF battery pack [41–45].

The number of batteries employed by EVs may be very large. This is necessary as the power consumed by a regular EV is thousands of times greater and faster than that of an ordinary smartphone. EV batteries must offer a lot of power (up to a hundred kW) and high energy capacity (up to tens of kWh). Simultaneously, they meet significant challenges related to space limitations and weight restrictions while maintaining an affordable price [46]. Generally, EV batteries are composed of cells, modules and a pack [47]. Battery cells, the basic unit of a LIB, are connected in series or parallel to form a battery module. A frame is used to fix the cells together and protect them from external shocks, heat, and vibration. The battery pack is the assembly that integrates the modules within the pack infrastructure. This infrastructure includes structural components, wiring, cooling loops, and power electronics [48]. Furthermore, several modules are installed with systems that manage power, charging/discharging, and temperature [49]. These are typically referred to as the Battery Management System (BMS). This condensed assembly enables the EV to store a lot of energy. However, this also makes it challenging to manage temperatures inside the pack [50].

The properties of individual battery cells determine the driving performance of an EV. Conventional battery technologies, such as the lead-acid, nickel-cadmium (NiCd), and nickel-metal hydride (NiMH) have all been used in EVs. Despite posing a lower fire risk than LIBs, their energy density and capacity, as well as the rate of charging and discharging, are much more limited. This makes them unsuitable for modern EVs. Since Dr Goodenough invented the LIB in 1980, and Sony commercialized it in 1991, the LIB has been widely used in all kinds of electrical devices, including EVs. Today, the LIB dominates the EV market and is expected to do so in the next few decades [21,29]. The popularity of LIBs is primarily due to their high energy density and long cycle lives compared with conventional battery technologies [51]. Additionally, a lower weight makes the LIB most suitable for vehicles as it can promote transportation efficiency.

Based on the configuration and manufacturing process, there are three types: cylindrical cells, prismatic cells, and pouch cells, as illustrated in **Figure 3**. All these three types of cells are used in real vehicles, and **Table 2** lists the basic parameters of three common battery cells. Typically, the capacity of LIB cells used in EVs can vary from 3 to 300 Ah for different types and manufacturers. On the vehicle level, the typical energy density is above 100 Wh/kg, as shown in **Table 3**. This energy is related to the chemistry and construction of the LIB cell. For example, Tesla uses NCA (nickel, cobalt, and aluminium oxide) in the cylindrical 18650 cell that delivers impressive specific energy of 3.4 Ah per cell or 248 Wh/kg. The highest energy capacity found in passenger EVs is the Tesla Model S, which provides about 100 kWh. This energy capacity can offer a driving range above 380 km on a single charge [52]. However, the hazard of an EV fire also increases with the greater number and capacity of batteries (or fuel), as the potential fuel load also increases [18,39,53].

Table 2. Basic parameters of three typical battery cells [54].

Manufacturer	Configuration	Geometry [mm]	Voltage [V]	Capacity [Ah]	Specific Power [W/kg]	Weight [g]
Panasonic	Cylindrical	∅18.5×65.3	3.6	3.2	120	48.5
Hitachi	Prismatic	148×91×26.5	3.6	28	2300	720
Kokam	Pouch	462×327×15.8	3.6	240	360	4780

Table 3. Battery pack information for selected BEV with a specific model and range test [26]

Brand	Capacity [kWh]	Cell density [Wh/kg]	Cell type	Range [km]
Nissan Leaf S (2017) [55]	40	229	Pouch	243 (EPA)
Renault Zoe 40 (2017) [56]	41	228	Pouch	400 (NEDC)
BMW i3(2016) [57]	42.2	230	Prismatic	246 (EPA)
Tesla Model S (2017) [58]	90	~250	Cylindrical 18650	509 (NEDC)

Since the Li-ion battery became the dominant power source for EVs a decade ago, the fire risk and LIB has become a significant safety issue. This is related to the increasing scale of deployment and energy density of the battery pack. The word Lithium (as a chemical element) itself has questions of safety tagged to it [18,59,60]. When a Li-ion battery is exposed to an external impact and experienced extreme operating conditions, it can break, eject sparks, flammable gases and toxic smokes which can be further ignited and lead to steady combustion, jet flames or a gas explosion [21,61,62].

Although a regular battery system has a low probability of self-ignition [63,64], it is vulnerable to external thermal, mechanical, and electrical impacts that may materialize during extreme operating conditions or incidents. Comparatively, electrical impacts and extreme operating conditions are rare for most portable electronic devices, such as the laptop and smartphone, but they are considered as the normal operating conditions. In contrast, the operation condition is more severe for an EV battery considering the frequent acceleration and deceleration in complex road and traffic conditions. Moreover, the battery capacity (or fuel load) of EV is thousands of times greater than that of portable electronic devices, which means a more severe fire hazard in the case of thermal runaway and ignition. On the other hand, however, the safety measures that are included in the EV and battery pack design are more advanced, reducing the likeliness of (spontaneous) failure. Therefore, it is inappropriate to assess the battery fire risk in EVs, based on the impression of battery fire risk in portable electronic devices.

Thermal Impact: Users expect to be able to operate their EV just like a convention internal-combustion vehicle, i.e., even in extreme cold and hot environments. For example, EVs are expected to be useable in California, where summer temperatures above 45°C may occur, or in the street of Norway and Canada with a daily winter temperature below -5°C and occasionally below -15°C. Like humans, the battery performs best at room temperatures (20~30°C). Extreme hot and cold temperatures are negative for the battery's performance and will shorten their lifespan (**Figure 4**). In high-temperature conditions, some unwanted chemical reactions can occur and result in overheated batteries [18,60]. With a poor thermal dispassion ability, it is then possible to trigger a thermal runaway[18,63], which can lead to an EV fire in the end. In cold temperatures, the battery's internal resistance increases. This resistance can promote the growth of metallic dendrites [1] and also cause additional heating effects to take place within the battery, which increases the chance for a battery fire to be triggered [18,50,65].

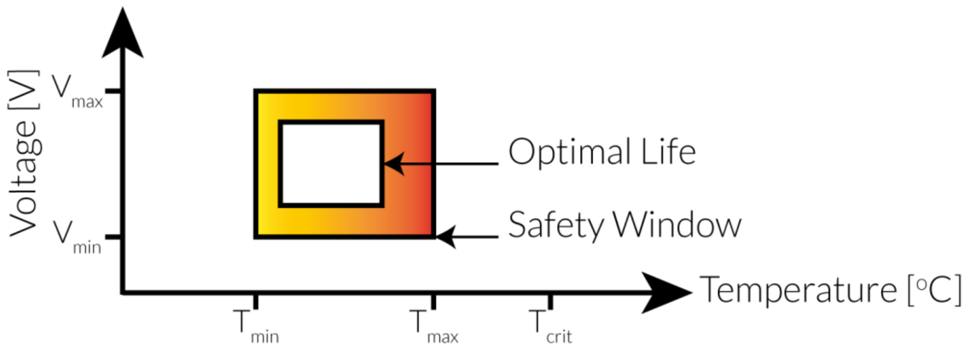

Figure 4. LIBs should operate within a limited temperature and charge range to warrant optimal life and safety [5]. Reprinted with permission.

Mechanical Impact: Most commercial LIB cells are relatively fragile without the protection of an EV structure and/or battery module and pack enclosure. Like any other conventional vehicle, the traffic accident is an occurrence that may happen in the lifetime of an EV. Nevertheless, with the modern design of LIBs and EV, the large majority of crashes will not cause harm to the battery [66,67]. LIB packs are usually integrated into highly reinforced areas of the vehicle (see **Figure 5**), with the aim of eliminating the risk of being penetrated during crash conditions. At high speeds, however, which some EVs are capable of reaching in a very short time [52], even the highest level of protection is not enough to consistently prevent fire (see **Table 1**).

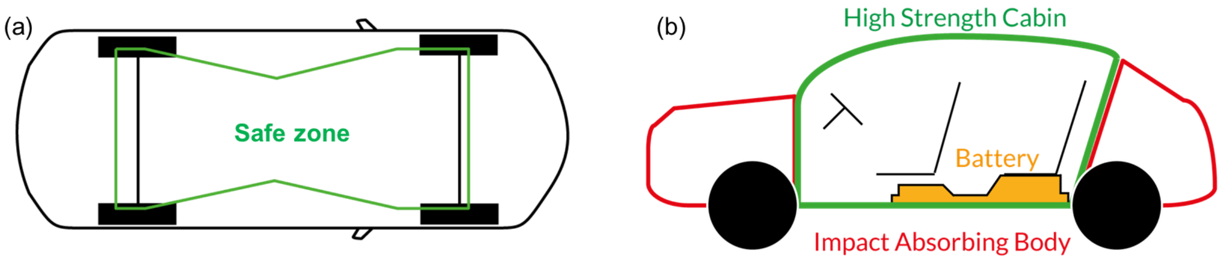

Figure 5. (a) LIBs are typically located inside the 'safe-zone' [66], and (b) battery layout for a Nissan Leaf [68].

Electrical Abuse: The pursuit of fast charging and discharging combined with the high driving performance for EVs have a negative effect on their fire risk [69,70]. LIBs are made to receive and store a pre-defined amount of energy in a set amount of time. Exceeding these limits, which can be the result of charging too quickly or overcharging, may degrade their performance, or result in premature failure. Usually, electrical abuse is accompanied by Joule heating and internal chemical reactions. The former generates heat whereas the latter may, in time, lead to an internal short circuit. Some EV fires may result from inappropriate operating conditions and internal faults, such as the short circuit in the high voltage circuit, overcharging and overheating environment, as shown in **Table 1**. However, for many EVs, most types of electrical abuse are not possible if their BMS is designed properly and functions correctly [71]. Besides the failure of the battery cell, it is likely that a large portion of the cases where "self-ignition" or "spontaneous ignition" incidents that have occurred are related to poor manufacturing and design procedures and/or inadequate electronic control systems, BMS, and power transmission control systems.

1.3. Hazards of EV fires

Concerns associated with EV fires are mostly related to the utilization of a LIB. As EV manufacturers pursue greater electric driving ranges and implement more LIBs, they also increase the potential heat released from an EV when a fire occurs. This increase in fire risk is proportional to the increase in the mass and capacity of the battery (or the fuel). During the burning of LIBs, the generation of flammable/explosive gases and toxic smokes, such as hydrogen (H_2), methane (CH_4), carbon monoxide (CO), and hydrogen fluoride (HF), can pose a threat to those involved [72,73]. The fire-safety problems relating to EVs are complicated and complex, which need a comprehensive consideration. Nevertheless, a better understanding of these key fire parameters helps provide a systematic evaluation of EV fire.

Thermal Runaway and Battery Fire: EV fires can be caused by battery failure, and the most common failure of LIB is the thermal runaway. Thermal runaway is a widely observed phenomenon in chimerical and combustion processes, referring to an overheating event in which exothermic chain reactions take place and overcome the cooling [53,74,75]. For the LIB, thermal runaway usually means a dramatically increasing battery temperature (greater than 10°C/min [76]) or the activation of safety vent, which indicates that exothermic thermochemical and electrochemical reactions have been triggered. The battery thermal runaway is usually accompanied by the ejection of a large amount of dark smoke, hot sparks, and powerful jet-flames [72]. As this process takes place within the individual cells, its risk potential increases when allowed the propagation of thermal runaway or fire throughout a battery [18,77].

After thermal runaway has initiated, smoke is released from the safety valve or through cracks in the battery shell. This smoke consists of a mixture of flammable and toxic gases. The flammable gases could be ignited by nearby ignition sources such as fire, sparks, and electrical arcs or may even be self-ignited due to a poor cooling condition. The resulting flame may then further heat the battery. If the gas-release rate out of the battery shell is lower than the internal gas-generation rate, the battery cell may also burst. The safety valve can release some of the accumulated gas that are typically generated during the pre-ignition thermal runaway process, but it may not be able to prevent the cell from external heating, such as flame radiation or a burning battery nearby. In addition, if the released gas is allowed to accumulate in an enclosed area and mix with surrounding oxygen, a gas explosion may occur once a pilot source like a spark and flame is present [18,53].

Energy release from EV battery fire: Both ICEV and EV contain a large quantity of flammable materials, including the power system or fuel (liquid petroleum fuel or battery) and flammable plastic components [78,79]. For modern vehicles, the mass of plastics used in vehicle ranges from 100 to 200 kg [78], which is larger than that of gasoline (less than 50 kg) [80]. As the heat of combustion for common plastics without fire retardants (e.g. 38.4 MJ/kg for polyethylene and 27 MJ/kg for PS) is not very different from the gasoline (47 MJ/kg), the total heat release from burning plastic components may have a major contribution to the vehicle fire, especially if the gasoline tank is not full. Nevertheless, there is no major difference between ICEV and EV in terms of plastic components, so that the major difference is their power system and the fuel (gasoline vs. battery).

As LIB includes many different combustible components, its heat of combustion depends on the chemistry, packing, capacity, and state of charge (SOC). For example, for a 2.9 Ah (11 Wh) commercial pouch-type LIB, the heat of combustion is found to be about 4 MJ/kg [81], while it is about 2 MJ/kg for a 18650 cylindrical battery [18,39,40]. In general, the heat of combustion for LIB is one order of magnitude smaller than gasoline. Nevertheless, because of the small (chemical or electrical) energy density of the battery, the weight of the EV battery pack is at least one order of magnitude larger than gasoline for ICEV. Based on limited data of the commercial LIBs of different scales, the ratio of energy (E_B in Wh) to weight (M_B in g) may be fit to $E_B = 0.14M_B$, as summarized in **Figure 6**(a).

Compared to the electrical energy stored in the battery, the thermochemical energy released from the battery fire, including both the thermal runaway heat inside the battery (i.e., the internal heat) and flame sustained by the flammable gases injected from the battery (i.e., the flame heat), is much higher [18,39,40]. As summarized in **Figure 6**(b), the battery fire can release 5~10 times more energy of the stored electrical energy (or the kinetic energy), depending on SOC.

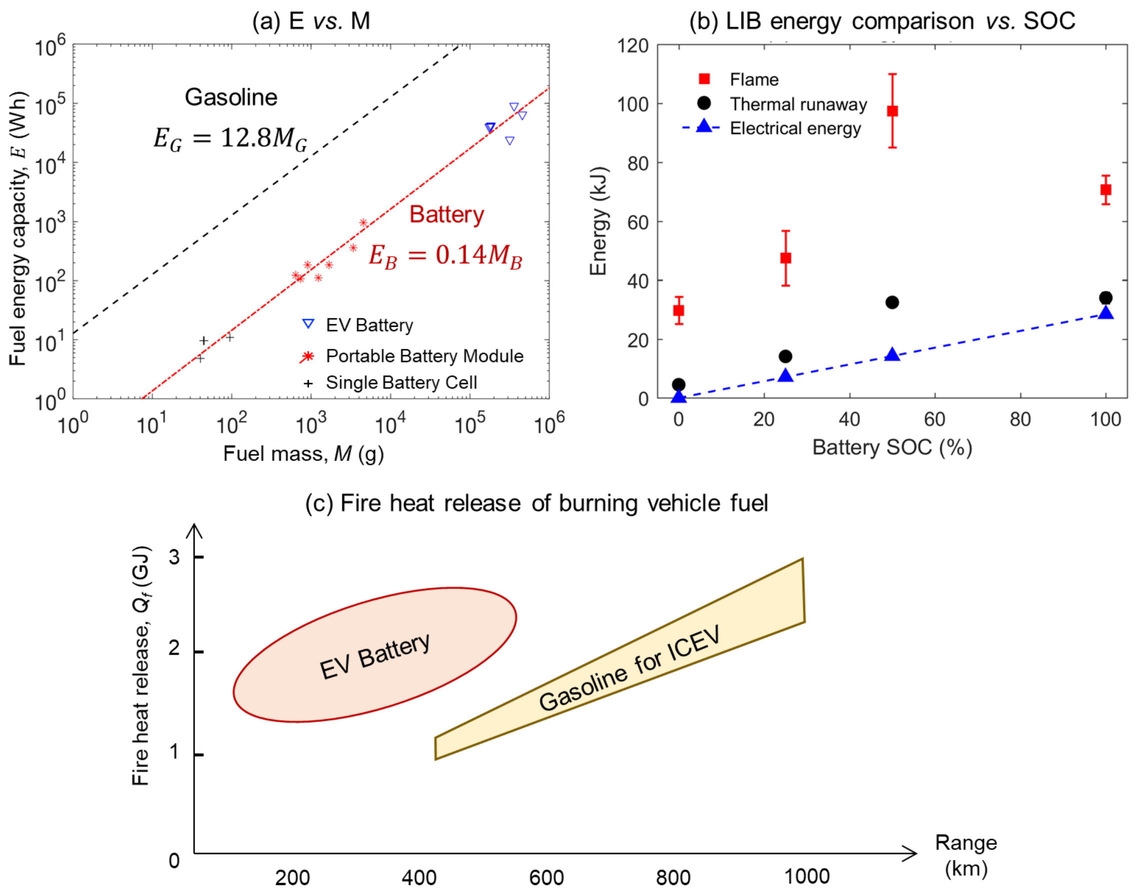

Figure 6. (a) Stored energy and mass of common commercial LIBs of different scales, compared with gasoline, where detailed data and references are listed in **Table 4**, (b) the comparison of flame heat from battery fire, internal heat of thermal runaway, and the stored electrical energy of a 18650 NMC battery vs. SOC [40], and (c) fire heat release of burning vehicle fuel vs. range.

According to US Department of Energy data for 2018 model vehicles [82], the light EV ranges from 100 to 550 km with a median of about 200 km, while the light gasoline ICEV has a minimum range of 400 km and a median range of about 700 km, as shown in ***Figure 6***(c). Assuming the heat of flaming combustion is seven times its stored electrical energy, the total heat release from burning an EV battery pack of 90 kWh is

$$Q_{LIB} = 90\text{ kWh} \times 7 = 2.3\text{ GJ} \quad (1a)$$

The battery pack of 90 kWh may support a driving range of 400 km for a light EV.

For a better comparison, we choose a typical gasoline vehicle with a fuel economy of 7.3 L/100 km [80]. Then, with the same range of 400 km, the volume of gasoline is about 30 L, and the total heat release of burning the gasoline can be estimated is

$$Q_G = 400\text{ km} \times 7.3\text{ L}/100\text{ km} \times 47\text{ MJ/kg} \times 0.75\text{ kg/L} = 1\text{ GJ} \quad (1b)$$

which is about half of the EV battery pack. In other words, under the same range, the fuel load or the fire heat release of the LIB pack is about twice that of a gasoline tank, indicating a larger fire hazard and requiring more stringent risk-mitigating efforts.

It is worth noting that a gasoline vehicle can have a larger range (e.g. above 800 km) with a typical fuel tank size of 45-65 L (i.e., 35-50 kg gasoline), while the amount of gasoline decreases with the driving distance. In contrast, the total mass of EV fuel (LIBs) does not decrease along with the driving of EV, and the potential heat release of burning LIB does not vary significantly in the SOC range of 20~100% (see **Figure 6**a-b) [39,40]. Moreover, compared to the total heat release, the heat release rate (HRR) of fire is a better indicator of the intensity and hazard of fire.

Table 4 The energy capacity, PHRR, and mass for batteries of different scales and applications.

Battery & Fire	Energy, E_b [Wh]	*PHRR* [kW]	Mass [g]	Configuration
Single Battery Cell	11	20.9 [81]	95 [81]	pouch
	10	9.1 [83]		cylinder
	10	-	45 [84]	Cylinder 18650
	8	1.9 [85]		cylinder
	10	5.6 [86]	44.3 [86]	Cylinder 18650
	5	8.3 [86]	40.2 [86]	Cylinder 18650
Portable Battery Module	112	54.8 [87]	1,228 [87]	pouch
	124	-	639 [87]	-
	107	-	734.8 [87]	-
	92	28.5 [87]	-	pouch
	124	57 [87]	-	pouch
	185	49.4 [88]	1,675 [88]	prismatic
	26	21[89]	-	pouch
	259	145 [89]	-	pouch
	800	70 [85]	-	cylinder
	288	39 [85]	-	cylinder
	72	14.3 [85]	-	cylinder
	32	6.6 [85]	-	cylinder
	16	3 [85]	-	cylinder
	962	442.6 [84]	4,560 [84]	cylinder

	185	37.8 [90]	900 [90]	prismatic
EV Battery	16,000	300 [65]	-	prismatic
	12,000	1,515 [91]	-	-
	18,000	1,651[91]	-	-
	40,000	-	174,672 [55]	-
	41,000	-	179,825 [56]	-
	42,200	-	183,478 [57]	-
	90,000	-	360,000 [57]	-
	24,200	-	318,000 [92]	-
	64,000	-	457,200 [93]	-
EV Fire (battery + plastics)	24,000	6,300 [94]	-	-
	16,500	4,200 [94]	-	-
	23,500	4,700 [95]	-	-
battery power station fire	500,000	2,555 [96]	-	-
	1,000,000	5,070 [96]	-	-
	2,000,000	10,150 [96]	-	-
	3,000,000	15,220 [96]	-	-
	4,000,000	20,290 [96]	-	-
	5,000,000	25,370 [96]	-	-

Heat Release Rate (HRR): The HRR (or the power of fire) is the most important parameter to characterize a fire[†] [53]. Compared to the heat of combustion or the total heat release from fire, HRR is a better indicator of fire intensity and hazard. HRR may be expressed as

$$HRR\ [MW] = \dot{m}\Delta H_e = A_f \dot{m}''\eta\Delta H_c \tag{2}$$

where $\dot{m}$ is the burning rate [kg/s] that could be measured by the mass-loss rate during the experiment [95]; ΔH_e is the effective heat of combustion [MJ/kg]; A_f is the floor/surface area of fuel or fire [m^2] which is the floor of EV; $\dot{m}''$ is the burning flux [kg/m^2-s]; η is the combustion efficiency which depends on the oxygen supply; and ΔH_c is the heat of combustion for EV batteries which varies with the type and SOC of LIB.

The fire HRR depends significantly on the arrangement of fuel and the scale of fire [53]. For example, burning a 7.9 Wh (42 g) cylindrical LIB could produce a PHHR of 2 kW [40], while burning a small 11Wh (95 g) pouch-type LIB could produce a PHHR of 20 kW [81]. Although the energy and size of both LIBs are comparable, the difference in PHHR could be ten times. On the other hand, for a 16,000 Wh EV battery that is 10^3 times more powerful than portable cells, its fire PHRR could be only 300 kW, that is, only 10^1~10^2 times larger [65]. Thus, it is inappropriate to assume the HHR of burning a battery pack of 100 LIBs is 100 times that of burning one LIB, because it is unlikely that all available battery cells are ignited and burning simultaneously.

Based on the test data in the literature, the PHRRs of different LIBs crossing scales are summarized in ***Figure 7***, which approximately follows

$$\boldsymbol{PHRR = 2\ E_B^{0.6}} \tag{3}$$

where the units for PHRR and the battery energy (E_B) are [**kW**] and [**Wh**], respectively. For a battery fire, its HRR, total heat release, and toxic gases release are not only related to the chemical energy stored in the battery

[†] Other important parameters for fire hazard include toxicity, smoke production, risk of explosion, etc.

[97], i.e., SOC of battery and size of the pack, but they also strongly depends on the arrangement of LIB cells (fuel), the supply of air (oxygen), and (internal and external) cooling conditions.

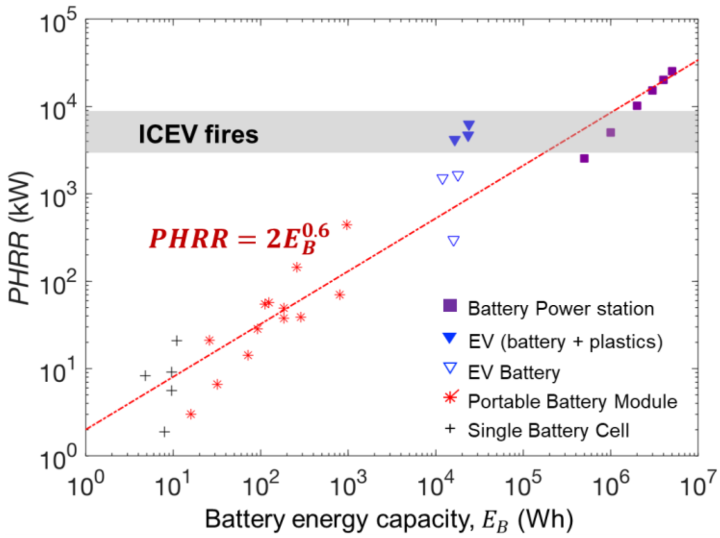

Figure 7. The peak heat release rate (PHHR) of burning Li-ion batteries of different scales, as well as, the comparison between full-scale EV and ICEV fires, where detailed data and references are listed in ***Table 4***.

For the full-scale EV fire tests, the PHRR for EVs will be reached, once the LIB also gets involved in the fire (i.e., ignition) [95,98], similar to other fire phenomena. Key fire characteristics related to burning ICEVs and EVs are summarized in ***Table 5***. These results can vary a lot depending on the amount of fuel in the fuel tank, capacity of the battery pack, and the amount of polymer material on-board. Generally, data suggests that EVs, which normally have battery packs of 20-40 kWh for BEVs and 1-20 kWh for PHEVs [5], will pose a fire threat comparable to that for conventional vehicles. The standard full-scale EV and ICEV fire tests and the time evolution of HRR are discussed more in **Section 3.1**. Nevertheless, whether this is true for high-performance EVs and heavy EVs, which may have a battery capacity of up to 100 kWh and 660 kWh, respectively, with respect to their ICEV counterparts, remains to be investigated.

Table 5. List of the heat release rate (HRR) of EV in recent full-scale fire tests, where tPHRR and THRR are the time to reach PHRR and total HRR, respectively.

Type	Vehicle	Weight before test [kg]	Battery or fuel capacity	PHRR [MW]	tPHRR [min.]	THRR[GJ]
BEV	2011 Nissan Leaf [94]	1520	24 kWh	6.3	40	6.4
	Unknown [95]	1122	16.5 kWh	4.2	~25	6.3
	Unknown [95]	1501	23.5 kWh	4.7	~20	8.5
	Vehicle 1A [91]	unknown	100% SOC	6	7	
	Vehicle 1B [91]	unknown	85% SOC	6	6	
	Vehicle 2 [91]	unknown	100% SOC	7	10	
	2014 Vehicle A [99]	1448	'Large' LIB 100 % SOC	6.0	7	
	2013 Vehicle A [99]	1475	'Large' LIB 80 % SOC	5.9	5.8	4.9
	2013 Vehicle B [99]	1659	'Large' LIB 100 % SOC	6.9	10.2	4.7
PHEV	Small PHEV [91]	unknown	unknown	6	~7	
	Large PHEV [91]	unknown	unknown	8	7.5	
	2013 Vehicle C [99]	1466	'Small' LIB 85% SOC & full tank of gasoline	6	7.5	4.6
	2014 Vehicle D [99]	1711	'Medium' LIB 100% SOC & full tank of gasoline	7.9	8.3	5.9

ICEV	Unknown [95]	1128	Full tank of Diesel	4.8	~20	6.9
	2003 Honda Fit [94]	1275	10 L of gasoline	2.1	35	4.3
	Unknown [95]	1404	Full tank of Diesel	6.1	~30	10
	2015 Vehicle A [99]	1096	Full tank of gasoline	7.1	6	3.3
	2013 Vehicle B [99]	1344	Full tank of gasoline	10.8	8	5.0
	Unknown [91]	unknown	40-50 L gasoline	7-9	~7	

Smoke and Toxicity: When the battery temperature exceeds about 150°C there is a large risk for thermal runaway. Once thermal runaway has been initiated, either the cell or its safety valve will burst and release toxic gas. As thermal runaway propagates, more battery cells will fail to generate more smoke and toxic gases. These toxic gases are, for example, hydrogen fluoride (HF), hydrogen cyanide (HCN), carbon monoxide (CO), etc [72,81]. Inhalation of these gasses can result in dizziness, headache, coma, loss of consciousness or even death [98]. The fluorine content inside the LIB cell may also form phosphorous oxyfluoride (POF_3), which may be more toxic than HF. The reaction formulas for HF and POF_3 production is demonstrated in the following equations:

$$LiPF_6 \rightarrow LiF + PF_5 \quad (4\text{-}1)$$

$$PF_5 + H_2O = POF_3 + 2HF \quad (4\text{-}2)$$

$$LiPF_6 + H_2O \rightarrow LiF + POF_3 + 2HF \quad (4\text{-}3)$$

Ribière *et al.* [81] found that for burning a 95-g pouch LIB, the maximum emissions of CO, NO, SO_2, HCl, and HF were 1.77 g, 195 mg, 220 mg, 25 mg, and 757 mg, respectively. These gas emissions differ among EV makers and types, where the chemistry and size of the LIB plays a role in potential gas emissions. Sturk et al. found the rate of gas emissions was slow and in low quantities for $LiFePO_4$ (LFP) cells [100]. The concentration of HF in the released species was however higher for LFP than for the NMC/LMO cells that emitted a larger gas volume in a shorter time, whereas the total amount of HF released was similar. This indicates the emission behavior of an electric bus, which employs LFP more frequently than passenger vehicles do, can be expected to be different from that of a burning passenger EV.

Information on the amount of toxic gasses released in both ICEV and EV fires is very limited. The tests performed by Lecocq *et al.* [61,95] give some insight into this matter, as shown in **Table 6**. The total amount of HF released by EVs is found to be roughly double that measured for the considered ICEVs [95]. The detected quantities of HF increase when the LIB starts to burn, which did not happen until 30 minutes after the fire was started in another part of the vehicle. If the fire did initiate in the LIB, this contribution might be spotted sooner. The risk of this emission, however, depends very much on the scenario of the incident. For outside scenarios, HF will likely rise and quickly dissipate, whereas in enclosed spaces this may be problematic if gasses are not evacuated. More full-scale tests are however needed to fully establish this. It is also recommended to apply a water spray jet for the removal of the toxic vapours and gases from EV fire. Acid gases such as HF, which are released in ICEV, EV, and LIB fires, can be reduced in their concentrations by spraying water on them to wash them out [1] [101,102]. Although the effectiveness of water spray has not been quantified, it is argued that this method is used already when mitigating the effects of chemical fires, and thus may provide firefighters with a useful tool to reduce the challenges of EV fire incidents in the field.

Table 6. List of toxic gas emissions from full-scale EV fire tests [95].

Vehicle	Weight	Battery or fuel capacity	Total CO (kg)	Total HF (kg)
Unknown BEV	1122	16.5 kWh	10.4	1.5
Unknown ICEV	1128	Full tank of Diesel	12.0	0.6
Unknown BEV	1501	23.5 kWh	11.7	1.5
Unknown ICEV	1404	Full tank of Diesel	15.7	0.8

Compared to the fire test on single battery cells and battery packs (e.g. [18,39,81,103]), there is still relatively little information on the actual behaviour of an EV in a fire. Full-scale fire tests are high in cost and often restricted by trade secrets. Nevertheless, with the scientific understanding of small-scale LIB tests and the accumulated database of EV fire accidents, reasonable forecasts could be made for their fire behaviour.

2. Lessons from past EV fire accidents involving battery

So far, EV fire accidents have been widely reported and subject to a large number of discussions throughout various media. Although the total number of EV fires is still much smaller than that ICEV fires [5,104], this could be mainly because the global market share of EV is still a few orders of magnitude smaller than ICEVs. Based on the statistics, almost half of the ICE vehicle fires are caused by arson, and many others are ignited by other existing fires [105]. In 2010, more than 26 cars were destroyed in an underground car park without a sprinkler system in Haarlem, Netherlands. In 2018, at least 1,400 vehicles in a multi-storey car park were destroyed in massive chain reaction fire at Liverpool, UK, which could be effectively stopped by a sprinkler system [106]. In other words, the fire-safety and flammability of vehicle is only part of the reason for fire accidents.

EV fire accidents are expected to follow a similar trend like those for ICEVs. Unfortunately, there is so far no clear statistics for the distribution of different causes for EVs accidents, e.g. arson, ignited by other existing fire, traffic accidents, and self-ignition. Note that there are a lot of self-ignited fire accidents for ICEVs, but the majority happen to the **aged vehicles**. For both ICEV and EV, most self-ignited fire accidents start in their power systems, that is, engine and battery, respectively. Because the majority of EVs in the world is still relatively new, and the number of EVs still rapidly grows, it is not statistically possible to make a fair comparison of fire risk between ICEV and EV.

When a fire event involves EVs, the battery is often referred to as the primary reason to start and prompt the EV fire. There are, however, many other factors that can lead to this, e.g. failure of the charging system, cable overload [107], ignition of other flammable materials, and arson [105]. These fire events that do occur in EVs are relatively new and often complex. They can, however, be divided into several categories:

I. The EV catches fire while stationary (often referred to as spontaneous or self-ignition). This may be related to extreme weather conditions, e.g. low/high temperatures or high humidity. It may even be related to 'spontaneous' internal cell failure. These failures can often be linked to abuse sustained by the LIB that exceeded its safety window at some point in its life.

II. The EV catches fire while being charged. This failure may be related to the failure of the LIB due to overcharging but is more commonly related to faulty or insecure charging stations and/or cables. This is also the major cause of LIB fire accidents of other electrical devices, e.g. hoverboards and smartphones, where battery management was found to be lacking.

III. The LIB of an EV is damaged as a result of a traffic accident, or other types of abuse. The damage done to the battery pack is so severe that the LIB ignites during or directly after the crash. The likeliness of an EV being involved in this kind of accidents will likely increase with the rising number of EVs in the street.

IV. The LIB of an EV has been subjected to thermal abuse and reignites after the initial fire had been dealt with.

V. The LIB and EV are ignited by external factors which may include, arson, wildland fires or a burning structure in the vicinity of the vehicle.

2.1. Typical Fire Accidents involving BEVs

Spontaneous Ignition: This fire accident occurred to a BEV (Lifan 650) in Guangzhou, China on 31 August 2018 [108], as shown in **Figure 8**. The EV ignited spontaneously and was a complete loss as the fire could not be extinguished in time. The Lifan 650 EV is a new model and, at the time of the incident, had only been on the market for two months. The fire initiated at the bottom of the car. This is also where the battery pack was located.

During the burning process, the fire was accompanied by a popping sound. This sound may have been resulting from bursting safety discs. In addition, there were several small explosions and the ejection of toxic black smoke.

Figure 8**.** The fire scene of a Lifan 650 EV, where the fire started at the battery pack installed in the vehicle chassis, and EV was completed destroyed by fire without effective fire suppression [108].

The following investigation revealed the possible reason of this EV fire. Investigation showed that the EV had soaked in water for more than 2 hours after a heavy rainstorm which caused water to leak into the battery pack. Afterward, when the owner drove the vehicle, this leakage may have caused short-circuit inside the battery pack and thus causing thermal runaway and fire. There have been several other recorded cases where EVs caught fire spontaneously without warning while being driven, after extreme weather or when parked (see **Table 1**). Unfortunately, follow-up reports stating the probable cause of these events are not published frequently.

On 14 December 2015, a brand-new electric bus was destroyed in a spontaneously ignited fire (***Figure 9***) [109]. It was Hong Kong's first locally designed electric bus which had a high energy efficiency of 0.78kWh/km and a long range of 380 km after four hours charging. This electric bus had just passed a road test and was ready for commercialization. The first witness notified to the police that thick black smoke was coming from the parking site where the new electric bus was parked. After half an hour, firefighters managed to extinguish the fire. The bus itself, however, was determined a complete loss. It was suspected that some technical support staff compromised the water sealing of the battery casings during performance tuning and inspection. Subsequent seepage of water into the compromised battery casings eventually led to short-circuiting and self-ignition.

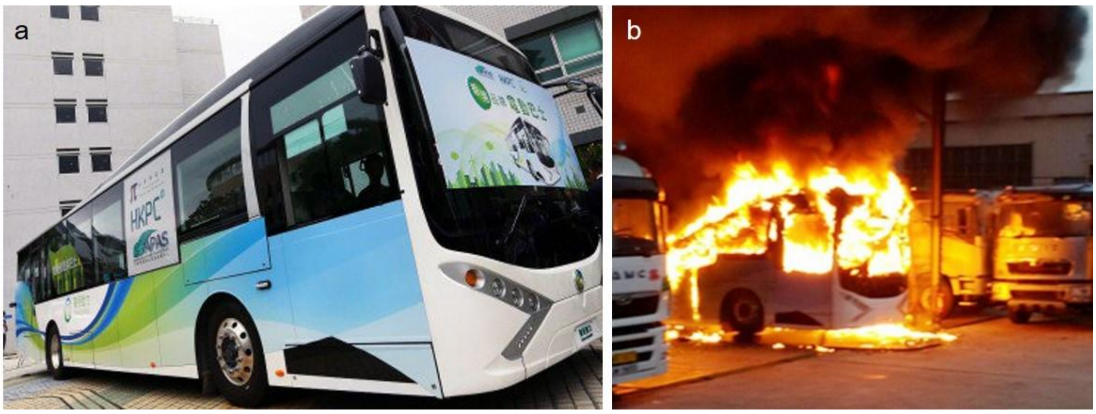

Figure 9. Photos of (a) Hong Kong's first locally designed electric bus, and (b) the fire scene of this electric bus on 14 December 2015 [109].

Charging: On 1 January 2016, a Tesla Model S caught fire during the charging process. The outcome of this event is shown in ***Figure 10***. According to news reports, the main cause of this incident was related to an error in the vehicle's onboard charging equipment. After the fire began in the charging equipment it then grew and spread to the rest of the car, including the battery pack [110]. Once the battery pack was ignited, however, it started to eject sparks and jet flames. Finally, any control of the fire was lost once breached into the passenger compartment. To limit the EV fire hazard, it is important to contain the battery fire if it does get involved or prevent it from being involved in any fire.

***Figure 10*.** The fire on a Tesla Model S while being charged at the supercharging station in Norway on 1 January 2016, where the fire also spread to the passenger compartment [110]**.**

High-Speed Collision: A Tesla Model S caught fire after colliding with road debris in the form of a large metallic object [111]. The object penetrated the battery pack from underneath and induced the fire shown in ***Figure 11***(a). Fortunately, the EV alert system discovered the problem and instructed the driver to pull over to a safe place. This gave the driver enough time to get out of the vehicle before the occurrence of fire. After this event, Tesla reinforced their EVs with ballistic shields and deflectors to prevent road debris from causing any damage to the contents of the battery pack.

Another Tesla Model S crashed on a concrete barrier at a high speed on the Arlberg Expressway, Austria on 18 October 2017, as shown in **Figure 11**(b). The fire was initiated in the battery at the front of the vehicle where it had hit the concrete wall [112]. The battery fire was reported to be extremely severe and produced a lot of toxic gases. In total, 35 firefighters were involved in the fire extinguishing activity and used large amounts of water to cool the battery down. The vehicle was then placed in quarantine for 48 hours to monitor it for reignition. Note that a battery fire is not necessarily the outcome of extreme crash conditions. In South Jordan, USA, an EV crashed into a heavy truck at 60 mph (97 km/h). There were no reports of fire despite the significant damage resulting from the frontal impact [113].

Figure 11. Fire in Tesla Model S (a) Tesla Model S caught fire after a collision near Seattle, USA [111]; and (b) Tesla Model S crashed on a concrete construction barrier in Austria at high speed and started a fire [112].

Reignition: Incidents involving EVs may also lead to secondary thermal events resulting from the overall amount of damage done to the LIB [12]. As mentioned earlier, the crash and fire in Austria were followed by a period in which the risk for this event was monitored. There are, namely cases in which reignition did occur once or multiple times. An example of this is a 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. Other cases where EVs reignited after a crash were presented in **Table 1**. This is of concern for post-crash handlers, who normally do not have the tools or training to handle such events safely.

External Factors: There are not many reported cases of EVs catching fire due to external factors. They do occur, however, as statistics provided by Tesla have shown. Their data estimates that approximately 15 % of Tesla's involved in fire incidents between 2012-2018, were caused by things unrelated to the vehicle, such as structure fires, arson, etc [104].

Figure 12. A firefighter was suppressing the fire of the faulted battery on the top of the electric bus [114].

In September 2016 at the USA, an improperly crimped wire on the roof of the bus resulted in a faulty electrical connection, which started to heat up nearby battery cells (***Figure 12***). Normally, the BMS would have shut-down the battery when this happens [114]. In this case, however, the temperature monitoring function of the BMS had already stopped working five days before the bus caught fire. Thus, it continued to heat the battery until it failed. The investigation concluded that this electric bus had a flaw in the fire-safety design and further suggested that there should be backup temperature sensors installed to supervise the battery conditions.

Figure 13. A chain fire on electric buses in Beijing, China in 2017, where firefighters used an extra amount of water to cool down buses to prevent the battery reignition, and piles of catkins was considered as the initial fire source [115].

On 1 May 2017, a severe chain fire disaster happened in the parking lot of Crab Island Resort, Beijing, China [116]. Nearly 80 electric buses and several private vehicles nearby were destroyed in this fire accident

(***Figure 13***). The following fire investigation revealed that fireworks used in a wedding celebration set fire to a catkin pile located next to the electric busses. In the parking lot, there were poplar and willow catkins (or seeds) pile up on the ground every spring without being properly disposed of. These catkins contain much bio-oil which makes them easy to ignite and generates enough fuel to cause severe chain fire.

The electric buses involved in the event above used LFP battery cells. These have a relativity low energy density, compared to other chemistries, and are often said to achieve a relatively higher fire safety [117]. Typically, the LFP battery cell needs an ignition temperature of 350~500 °C. That is much higher than ~200 °C for other LIBs [118]. However, such a high ignition temperature is still much lower than flame temperatures (>1200 °C) and fire plume temperatures (>600 °C). If an existing fire is burning near the vehicle, internal batteries could be heated up to the critical conditions of thermal runaway and start the chain fire considering the fire spread is fundamentally a continuous ignition process [119]. Alternatively, and perhaps more likely, it first ignited other combustible materials on the bus. The initial fire on catkin pile may have been easy to extinguish. However, once other combustible materials and the battery pack became involved in the situation further exacerbated, allowing the fire to become beyond control as it continued to spread.

2.2. Fire Incidents involving HEVs and PHEVs

Hybrid electric vehicles use a combination of electricity and gasoline as the power source. There are two types of hybrid vehicles. The original one could transfer the surplus chemical energy from fossil fuel via combustion engine into the electric energy and storage them into the battery pack [120]. The plug-in hybrid vehicle (PHEV) can also charge the electric power directly from the grid. Thus, consumers have the choice of using either as a charging source at any time, as long as there is gas in the tank or a charging station [121]. In other words, there are two types of the energy system and fuel in the hybrid vehicle, that is, the electric energy system with battery and conventional combustion engine with fossil fuel. The exhaust system of these vehicles may result in high temperatures, high enough to ignite the flammable fuels that are on-board.

Spontaneous Ignition: On June 7, 2008, a Toyota Prius was destroyed as a result of being driven on the freeway (***Figure 14***). This particular Toyota Prius was converted to a PHEV. Based on a report by fire investigators report, the main reason could be attributed to the improper assembly of bolted joints with electrical lugs inside the battery pack. The loose joints caused a high-resistance connection resulted in the overload which triggered the overheating and thermal runaway of the battery cell, and ultimately started the fire [122].

Figure 14. A Toyota Prius converted to a plug-in hybrid electric vehicle by the owner and was damaged by the battery fire. This fire accident resulted from the thermal runaway of the battery [122].

There was a hybrid electric bus fire accident on 16 March 2016 in Shenzhen, China (***Figure 15***). This public transport bus self-ignited during operating in the street. The fire started at the rear of the bus, and most of the bus was destroyed in the fire. Investigation showed that the self-ignition was initiated at the back of the carriage near the combustion engine [123]. The battery pack installed on both side of the bus was intact. Thus, the official report pointed out that the fire accident was not related to the battery or the battery management system. It is worth noting from this fire accident that for a hybrid vehicle, the battery system is not the only reason caused a fire. About 1% of all buses with internal combustion engines end up being involved in a fire. These fires most commonly originate in the engine compartment as this is where flammable fuels and hot surfaces are within close vicinity of each other. In warm climates, fires are also likely to occur in the wheel well area [3].

***Figure 15*.** The hybrid-electric bus fire accident on 16 March 2016 in Shenzhen, China, where the battery box is intact after fire [124].

A Kia 2013 Optima Hybrid caught fire while driving [125]. The driver successfully escaped from the car, despite the whole car being covered in flames 30 seconds after it started (***Figure 16***). Based on the inspection, Kia company said the car did not experience engine failure, and the causes may be electrical in nature. However, the exact cause of the fire could not be determined. Far from the isolated, as mentioned in the news article, many other Kia vehicles are reported spontaneously erupted in flames for an unknown reason [125].

***Figure 16*.** An HEV fire accident are January 2018:(a) the Kia2013 Optima Hybrid was covered by flames; (b) the ruined car after this fire incident [125].

Charging: A Porsche Panamera caught fire while its battery was being charged at home [126]. This fire accident happened on 16 March 2018 in Bangkok's Taling Chan district. The owner recalled she drove the car back home at around 10 pm, and she plugged the car in the home battery-recharging kit as per her routine. At 6 am an explosion shocked them. They found the car blazed. The fire damaged the owner's luxury home as well (***Figure 17***). The reason caused this fire is blamed to the improper installation and operation of the charging system. According to the authorized distributor of Porsche in Thailand, the damaged car had been purchased from an independent importer. Thus, the electrical cords, sockets and other equipment of the charging system of vehicles imported by independent firms may not have matched the safety requirements for use in Thailand.

Figure 17. The PHEV Porsche Panamera got on fire during charging on 16 March 2018 Thailand:(a) the fire was intense and damaged the owner's house; (b) firefighters tried to extinguish the fire using water [126].

3. Tests and Protection strategies for EV Fires

3.1. Standard Tests for EV Fires

LIBs are required to pass numerous compulsory test standards (e.g. ISO 12405-3, ISO 6469-1, UN 38.3, UN R100, SAE J2464, SAE J2929, IEC 62133, IEC 62660-2, IEC 62660-3, GB/T 31485) before they can be used for EVs. This is however related to different requirements in different countries [127,128]. Generally, EV battery tests can be categorized into the performance test and safety test [129]. The safety test provides insight into their failure response, either internal or external causations, which will be discussed in this section.

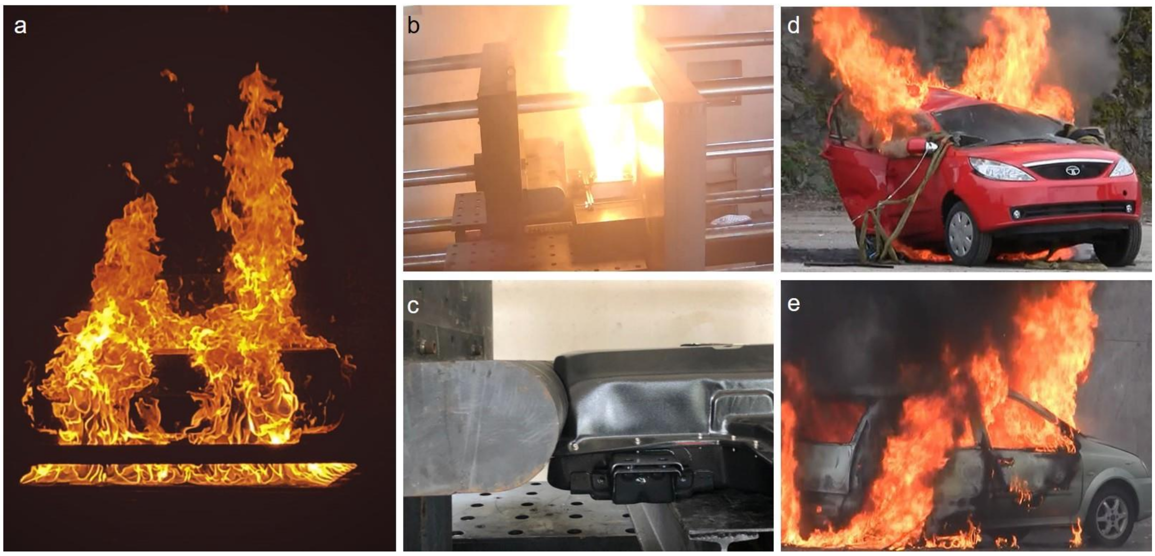

Figure 18. (a) Thermal abused test of an EV battery pack where the battery heated by the gasoline pool fire, and (b-c) mechanical abuse test (Crush test) of the battery pack with a battery cell capacity of 40 Ah, 16.8 V, and SOC=100% (unpublished tests by authors); and full-scale EV tests (d) drop test, and (e) ignited by an external fire source [130].

A complete body of abuse tests was defined in the abuse test manual for EV and HEV applications [131]. There are three typical incentives for triggering thermal runaway of battery, that is, mechanical, thermal, and electrical abuses. Thus, the abuse test manual, intended to simulate the actual use as well as these three abuse conditions are usually far beyond normal safe operating limits. **Figure 18** shows a group of typical abuse tests for EV battery packs and full-scale EVs. The test regulations cover four levels, that is, cell level, module level, pack lever, and vehicle level. Ruiz et al. [132] and Tidblad [128] provided a comprehensive review of various international standard and regulations and summarized the safety tests of Li-ion batteries in automotive applications under various abusive environments.

Mechanical abused tests include a series of test methods such as the drop test, the vibration test, the mechanical shock test, and the crush test. According to the international standards SAE J2464 [133] and SAE J2929 [134], the scale for the drop test is only at the pack level. While the test level is wider for some national regulations, such as UL 2580 [135], Freedom CAR [131] and QC/T 743 [131], which covers cell level, module level, and pack level. Recently, in collaboration with Skien Fire Department, Greenland Energy and the University College of Southeast Norway and RISE, a full-scale EV drop test was conducted, and a personal EV with a 26 kWh Li-ion battery pack was dropped from a height of 20 m. As illustrated in **Figure 18**(d), approximately 6 minutes after the impact, the temperature of the battery increased quickly and started to burn. After 9 minutes, the car was engulfed in the flames [130]. Vibration test is to verify the safety performance under a mechanical load due to vibration, which a battery system will likely experience during the normal operation of a vehicle. The vibration profile is given by the customer and verified to the vehicle application [136]. In the crush test, the crush bar which used to generate the crushing force has different requirements based on the test battery.

The thermal abuse test also consists of several test methods. For example, in SEA J2464 [137], the thermal abuse test includes high temperature hazard test for Pack module level and above, thermal stability test for cell level, cycling without thermal management for module and pack level and thermal shock cycling for cell level or above and passive propagation resistance test for module or pack level. The complete battery pack is exposed to an external fire in testing according to R100 Annex 8E [138]. Here the battery is exposed to external flames for 2 minutes and then observed until the test object's surface reaches ambient temperatures or has been decreasing for at least 3 hours. If there is no evidence of explosion during this time, the test is successful. This test is very similar to that normally performed on fuel tanks for conventional vehicles except for the long observation period. Note however that for EVs the decision can be made to perform the test in full-scale level (EV) or component level (LIB pack). Some published tests have shown that this test is not a major challenge when performed on EV level as it usually takes 25-40 minutes before the LIB pack starts to burn. If the LIB pack is considered by itself, this may drop to between 2-11 minutes [5].

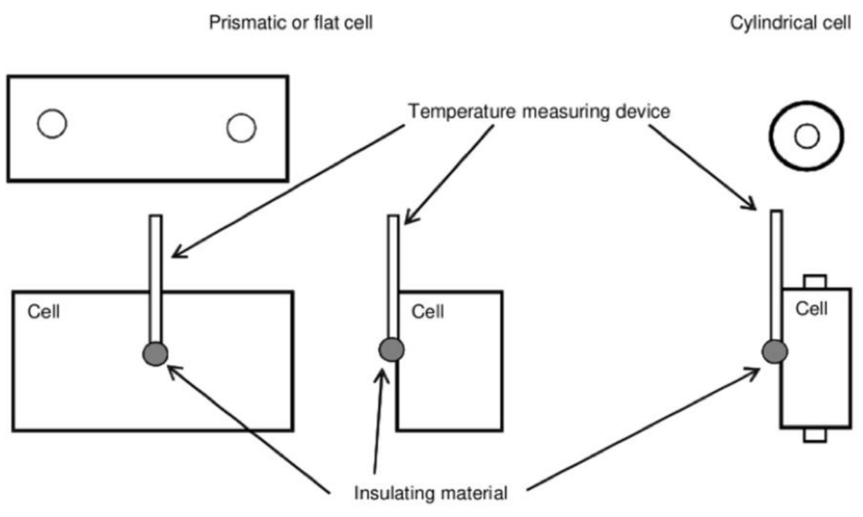

***Figure 19*.** Examples of temperature measurement plan for battery cells [136].

There are several main parameters that should be measured during tests. These are normally comprised of voltage, current, and temperature. According to IEC 62660-2 [136], the resistance of the voltmeters used shall be at least $1M\Omega/V$. The cell temperature shall be measured by use of the surface temperature measuring device. The temperature should be measured at a location which most closely reflects the cell temperature. The temperature may be measured at an additional appropriate location. ***Figure 19*** illustrates an example of temperature measurement for different battery cells.

The failure of battery may have several different outcomes, e.g. venting, fire or even explosion. These different hazards are classified by the European Council for Automotive Research and Development (EUCAR), see ***Table 7***. The responses of the battery to abusive conditions can be classified based on the hazard severity level. An explosion is classified as the most severe event.

Except for abuse tests, the evaluation of chemical hazards is also considered by some standards. The chemical-hazard test focuses on the emissions and flammability of toxic gases or smoke generated in the thermal runaway process. Some standards, such as SAE J2464:2009 [137], SAE J2929:2013 [139], and UL 2580:2013 [135], provide detailed information on quantifying and determining toxicity and flammability of Li-ion battery emissions. The measured emission composition should fall below certain degrees of concentrations.

Table 7. Hazard severity level and descriptions [137]

Hazard level	Description	Classification criteria and effect
0	No effect	No effect. No loss of functionality
1	Passive protection activated	No damage or hazard; reversible loss of function. Replacement or re-setting of the protection device is sufficient to restore normal functionality.
2	Defect/Damage	No hazard but damage to RESS (rechargeable energy storage system); irreversible loss of function. Replacement or repair.
3	Minor leakage/venting	Evidence of cell leakage or venting with RESS weight loss <50% of electrolyte weight.
4	Major leakage/venting	Evidence of cell leakage or venting with RESS weight loss >50% of electrolyte weight.
5	Rupture	Loss of mechanical integrity of the RESS container, resulting in the release of contents. The kinetic energy of released material is not sufficient to cause physical damage external to the RESS,
6	Fire or flame	Ignition and sustained combustion of flammable gas or liquid (approximately more than one second), excluding sparks.
7	Explosion	Very fast release of energy sufficient to cause pressure waves and/or projectiles that may cause considerable structural and/or bodily damage, depending on the size of the RESS. The kinetic energy of flying debris from the RESS may be sufficient to cause damage as well.

3.2. Fire Risk Assessment

The battery fire always initiates from the thermal runaway. So far, most fundamental research has studied the electrochemical reactions within batteries that are responsible for the thermal runaway [17,140,141]. Typically, these reactions represent the decomposition of the active material, the reaction between the anode material and electrolyte, the collapse of the separator, and the decomposition of the cathode. Much applied research from the industry and academia have investigated the thermal runaway of different batteries under different operational conditions and various external impacts [81,142,143]. Wang *et.al* [18] gave a detailed review of risk assessment of Lithium ion battery. Basically, these risks are assessed based on various battery abused tests.

Although these past studies [144–146] have provided some basic understanding on battery fire risk and supported the design of the thermal safety of Li-ion battery [147–150], there are still many unknowns about the fire dynamics of large-scale EV batteries and behaviours of full-scale EV fire. On the other hand, it is also easy to misinterpret the data of small-scale battery fire to evaluate the hazard of large-scale EV fire. For example, the weight of EV (e.g. 2,250 kg for the Tesla Model S) is five orders of magnitude greater than that of a battery cell (e.g. 45 g for a 18650 cell). Comparatively, the HRR of fire can only increase three orders of magnitude from several kW for a battery cell [39], to several hundred kW for a single EV battery pack [73], and several MWs for a full-scale EV fire [91]. So far, there is still a lack of research to scale up the risk and hazard of the small-scale battery fire to full-scale EV fire. More importantly, because of the rapid development in battery and EV, fire tests and R&D of fire-protection systems for EV still fall far behind.

As discussed above, the heat release rate (HRR) is the most important parameter to assess the fire hazard [53]. As seen from Eq. (3), the power of EV fire can be estimated by using the HRR of the battery pack, given the area of EV. According to the Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped with High Voltage Batteries offered by U.S. Department of Transportation [151], "*In the event of fire involving an electric vehicle (EV) or hybrid-electric vehicle (HEV), we always assume the high voltage (HV) battery and associated components are energized and fully charged*." In other words, the SOC should be assumed as 100%, which represents the worst fire scenario, for battery in risk assessment. Taking the EV powered by Lithium Titanate (LTO) batteries as an example, the average heat flux ($\dot{q}''$) of LTO is approximately 2.3 MW/m^2 in a fully charged stage [152]. This is comparable to 2~3 MW/m^2 for gasoline and other hydrocarbon liquid fuels of the same burning area [53]. Considering the floor area of a regular EV is $A_{EV} \approx 3$ m^2, the average fire HRR of this kind of EV can be estimated as

$$HRR = A_{EV}\dot{q}'' = 3 \text{ m}^2 \times 2.3 \text{ MW/m}^2 \approx 7 \text{ MW} \tag{5}$$

which generally agree with data summarized in ***Table 5***. Therefore, for the hybrid vehicle with an LTO battery, the HRR can be calculated in the same way, given the capacity of battery [152]. This calculated HRR could use to estimate the required volume of water or other fire-suppression agents to extinguish the EV fire.

Macneil [91] conducted several full-scale tests of BEVs and PHEVs to measure the HRR and temperature in EV fire. To start a fire, the EV was suspended above a propane gas burner, which had a fixed HRR of 2 MW. Then, the HRR of EV fire was computed based on O_2 consumption calorimeter with the correction for CO and soot production. **Figure 20**(a) shows the measured HRR for three EV fire tests: (1) Type-A EV with battery SOC of 100%, (2) Type-A EV with battery SOC of 85%, and (3) Type B EV with battery SOC of 100%. **Figure 20**(b) shows the measured HRR of a small and a large PHEV. For a better comparison, the HRRs of EVs are compared with baseline HRRs of internal combustion engine (ICE) vehicles that have different fuel tank capacities between 40 L and 50 L.

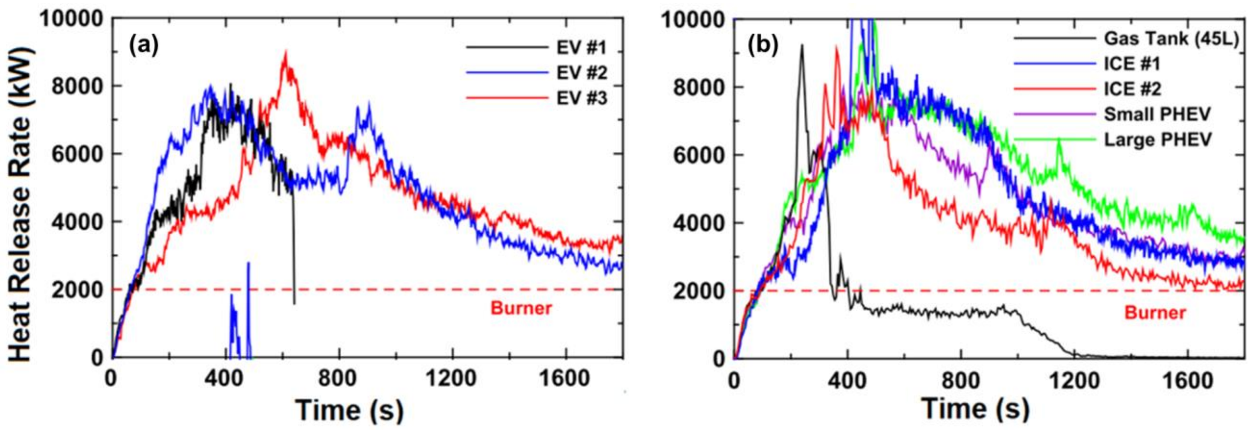

Figure 20. Evolution of HRR versus time for test vehicles which were suspended over a propane burner of 2 MW: (a) three different pure battery EVs, and (b) a small PHEV and a large PHEV compared with the gas tank and internal combustion engine (ICE) vehicles [91].

These tests show the HRR of an average value of 5~6 MW and a peak value of 8~9 MW, which is close to the estimation of Eq. (3). In addition, the results also suggest that a fire in EV and PHEV has a similar HRR that of the ICE vehicle fire as well as the gasoline pool fire. This was also observed in tests by Lecocq *et al.*

[95]. In other words, the thermal hazard of EV fire is comparable to that of conventional vehicle fire accidents. Both electric and gasoline-powered vehicles have the same risk of fire after a severe crash [151]. In fact, the PHRR of EV is even lower than an ICE vehicle, which supports one opinion that pure BEV is safer than conventional vehicles or hybrid vehicles [117]. However, more full-scale tests with different types of BEV and PHEV are required to fully evaluate the EV fire hazards.

Another full-scale fire test was conducted on an electric-diesel hybrid bus by the SP Technical Research Institute of Sweden in November 2014 (***Figure 21***) [153]. The fire was set to start in the engine compartment and consumed the entire bus in the end. As the fire spread, the temperature increases of battery occurred 7 minutes after the temperature increase in the passenger compartment. Once the battery started to burn, the already intense fire becomes more disastrous. Finally, the burning of battery slows down but remains robust for a very long time, which is typical for a LFP battery fire.

Batteries typically need a certain period to accumulate enough energy to trigger the thermal runaway. This makes EVs different from the gasoline of conventional vehicle that more easily reaches the fuel flammability limit or flashpoint and can be ignited by a spark or flame. However, once the flame is attached to the battery or explosion occurs, it is difficult to extinguish the battery fire. In the case of battery failure, there may not be an apparent sign of the fire phenomenon at the beginning. The battery pack is namely enclosed and may be under the hood or inside the EV body. Hence the fire will likely not be noticed when it is in an early developed stage, while there is still plenty of time for occupants to leave the vehicle [154]. In order to offer more rescue time for occupants, it is imperative to have early detection of battery failure and suppress the fire as early as possible. Early detection and cooling may namely delay thermal propagation between battery cells as well as battery modules. If successful, this reduces the risk for a fire spreading from a battery pack to its surroundings. One sensible solution is to develop a reliable fire detection system for its powering system and an effective extinguishing system for EV fire.

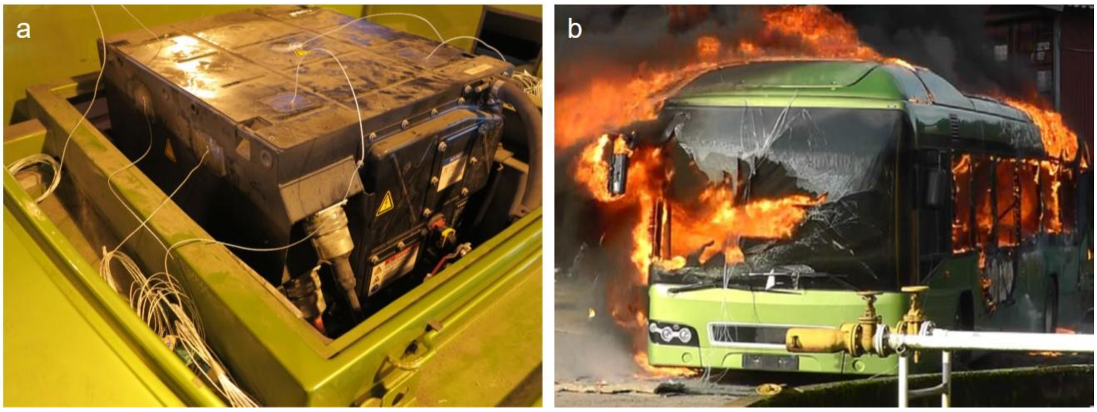

***Figure 21*.** A full-scale fire test of the electric-diesel hybrid bus (a) battery pack with thermocouples, and (b) bus in fire at 32.5 min [153].

With the dramatically increased number of EVs, concerns are also rising that relate to dealing with LIBs and EVs ready to be scrapped [155]. In Europe, only as few as 5% of Li-ion batteries are recycled [156]. The battery wastes could contaminate our ecology and thus need to be treated carefully. Additionally, there are no doubt potential fire risks during the collection, recycling, treatment and disposal of batteries and EVs. This risk is linked to the SOC and capacity of the considered LIB. Cumulated battery bulks and EVs have a lower self-ignition temperature or a higher self-ignition risk. Thus, the fire risk is likely to increase during the collection of batteries and the disposal of EVs [63,64].

Environmental concerns also relate to fire-water run-off. Analysis of dissolved species in fire-water run-off has been may contain elevated levels of fluoride and chloride [157]. These obtained values were found to be above the allowable limits in Germany. As a result, the considered fire-water run-off had to be sent for destruction at a wastewater treatment plant. One alternative is to lift the EV into a container before applying suppressant [158]. One of the benefits of this approach is that fire-water run-off and toxic media are contained in the enclosure, such that they do not spread to the surrounding environment and can more easily be sent for destruction.

3.3. Fire-Suppression and Firefighting Strategies for EVs

Compared to the abundant studies on the thermal runaway of battery and its protection strategies, there are much fewer studies on the suppression of battery fire and fire-extinguishing technologies. Despite this, they have identified that LIB fires are difficult to extinguish, requiring large quantities of suppressant, and may re-ignite [159]. These re-igniting fires are difficult to deal with as they can occur at random and even after a significant amount of time has passed since the primary thermal event. One way of ensuring there is no reignition is by letting the vehicle or LIB pack burn out completely. When all the active material in the LIB pack is consumed, the risk for reignition becomes much lower. In practice, however, this may not always be possible or the appropriate approach, and suppression or extinguishment is needed.

NFPA 10-2018 categorizes fires into five different classes [160]. An EV does not directly fall into any of these categories, yet its individual components do. They may be divided as follows:

A. Solid flammable materials in EV, e.g. seat foam and plastic interior decoration;
B. Flammable gases ejected from the battery after the thermal runaway, coolant, brake fluid, windshield washer fluid, transmission fluid and liquid fuels stored in hybrid EVs;
C. Electrical devices and BMS;
D. Li metal particles released from charged Li-ion batteries.

Therefore, if only carbon dioxide or other chemicals is used to suppress the battery fire, although the fire can be controlled, it cannot cool down the battery pack or prevent the re-ignition. On the other hand, if water spray is applied, it can both suppress the fire and cool down the EV, but it may trigger more electrical faults over time and react with Li to release hydrogen gas [161].

Relatively little is known about the extinction mechanism of LIB fires, and most of fire suppression tests in the literature focused on the small-scale portable LIB fires, as reviewed in [20].Hence the effectiveness of suppression agents and the reliability of existing fire suppression strategies for EV fire are often questioned. Carbon-dioxide or dry chemicals can extinguish the flames of a burning LIB. However, extinguishment of flames should be balanced against the possibility of a build-up of flammable gas and a delayed ignition leading to a gas explosion [162]. Cooling of the LIB, or inhibiting heat transfer between its cells, appears to be mostly positive. Water, which is a very common firefighting agent, offers excellent cooling capacity making it a good candidate for gaining control over LIB fires despite potential negative effects such as short circuits or toxic run-off water.

Colella [73] performed large-scale fire test on two different EV LIB packs (***Figure 22***). The parameters for the considered battery packs are listed in ***Table 8***. The fire tests considered both the LIB packs by themselves and while mounted inside the vehicle. The pack or vehicle was ignited by a 400-kW propane burner. For both battery packs, popping was heard, arcing and re-ignition was observed. Once it was clear the LIB pack was on fire, an attempt was made to suppress it.

Table 8. Fire suppression test for two Li-ion EV battery pack in a vehicle model where * means a battery with interior components [65,73].

Battery Pack	Type and configuration	Dimension [mm]	Weight [kg]	Energy [kWh]	Suppression time [min]	Water quantity [m^3]
A	Assembled from 288 3.6-V cells	822×968 ×378	151.1	-	2.2/3.5/9.8*	1.25/2.01/4.80*
B	T-shape with multiple linked modules	1650 (length)	198.1	16	14.0/21.4/9.3*	7.97/12.00/5.30*

For Battery A, re-ignition occurred 22 hours after the test had been terminated. The suppression effects included the use of water flow of 125 gallons per minute and four firefighters (two on hose line and two in support). ***Table 8*** also lists the suppression time and the quantity of fire-suppression water. The comparison showed that interior components of battery modules strongly contributed to the fire hazard and difficulties in suppressing Battery A, whereas the opposite trend was found for Battery B. These results showed although the LIB pack plays a role in EV fire, other flammable materials (mainly plastics) also have a significant effect, which is similar to conventional vehicles, as discussed in Section 1.3.

Figure 22. Full-scale fire-suppression test of EV battery packs inside a vehicle model: (a) Type A battery pack; (b)Type B battery pack with interior components; (c) fire behaviours of Battery A; and (d) fire suppression efforts [65,73].

More recently, RISE conducted a fire suppression test for several EV batteries with different extinguishing technologies, such as water spray and mist (Figure 23), and the locations of nozzles were varied [163]. The thermal runaway was initiated in one battery module by directly exposing it to a gas burner. Without the fire suppression, the continuous ignition of battery cells was observed with external visible flame. The test results showed that the water-based fire suppression system inside a battery pack has good potential to have a lasting cooling effect on the battery and to increase the chance of mitigating and preventing thermal runaway propagation. External activation had limited cooling effect or impact on the thermal runaway propagation, except for extinguishing flames outside the battery pack to prevent batter fire spread to the surroundings.

Many heavy-duty ICEVs today have a built-in fire suppression system. These systems are installed to protect the compartment spaces that have internal combustion engines and/or auxiliary heaters. These are namely often most the primary area in which a thermal event or fire arises. Systems such as these are either manually activated or automatically detect the fire before activating. Today, the use of said systems in busses is mandated in 63 countries [164] through UNECE Reg. No. 107 [164]. This regulation will come in force for coaches as well starting 2021. Insurance authorities have set their own standards for machines and heavy vehicles in SBF127 [165] and SBF128 [166], respectively. Both these standards, and regulations related to a test standard, SP Method 4912 [167], developed by RISE. This standard examines the system performance when exposed to low and high fire loads with or without ventilation, hidden fires, class-A fires as well as reigniting fires inside a mock-up of an internal combustion engine compartment space.

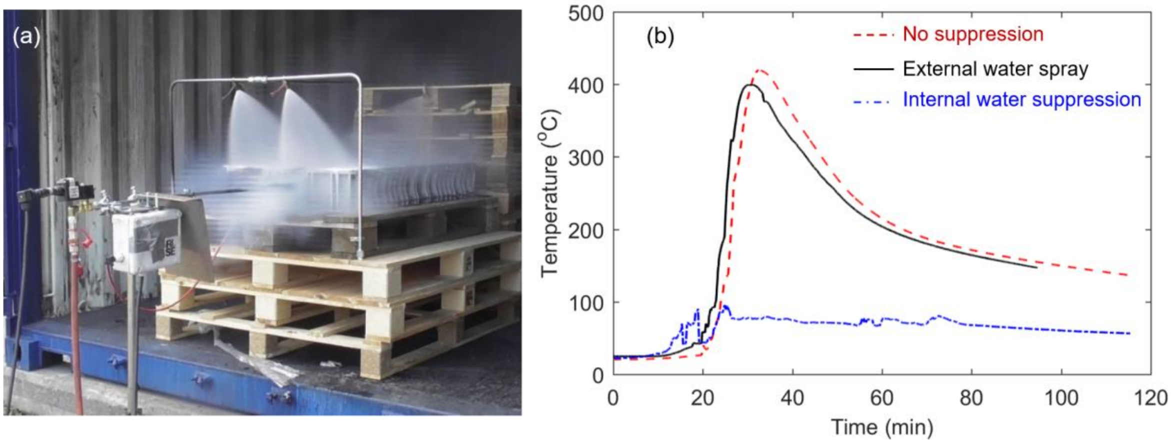

Figure 23. (a) A photo of the suppression test for EV battery fire, and (b) the temperature measurement of a battery near ignition location under different fire-suppression techniques [163].

Fire-suppression systems may also be found in HEVs or even PHEVs, to protect their internal combustion engine and/or auxiliary heater compartment space. They are normally not considered for protecting LIBs (e.g. ***Figure 24***). Tests have namely shown that large quantities of suppressant are needed to sufficiently cool a burning LIB. These fixed-fire suppression systems may not be available to EV, because on a vehicle any system needs to remain mobile and efficient. Considering the limited capacity of fire extinguisher onboard and the difficulty in EV fire suppression, the premier purpose for the most present fire-protection system of EV is to alert the driver about the fire in the vehicle and proceed with immediate preventive action. Experiences on battery fire suggest that the primary effort of suppressing the EV fire is to cool down the temperature of the battery which is already in the thermal runaway state. The difficulty is the poor accessibility of batteries since most of the EV batteries are sealed off to prevent it from being penetrated by water and dust, and to ensure protection against external impact [168]. External application of water thus only affects visible flames, the external surface of the battery pack, and any materials surrounding it. Achieving this however still requires a large amount of water. Tests have shown that over 10,000 L (2,600 gallons) of water should be applied for EV fire depending on the size and location of the battery [169]. In addition, the suggested flow rate is very high at 200 L/min for extinguishing and cooling [101]. This may lead to large quantities of fire-water run-off. The larger quantity of suppressant will also dilute any toxic media, hence further analysis on the trade-off on using more, or less, suppressant is needed.

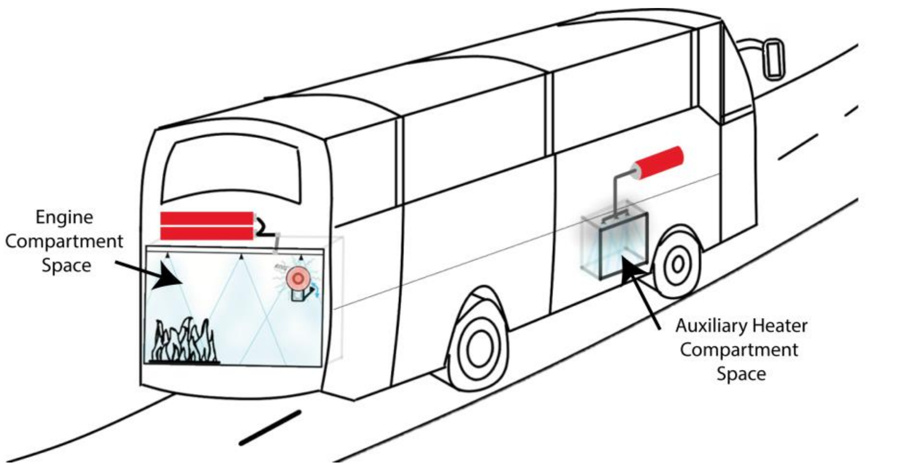

Figure 24. Typical fire-suppression system for a commercial bus with a combustion engine and auxiliary heater [170].

A large amount of suppressant needed is linked to the poor inaccessibility of the battery pack. This has been shown in tests performed by RISE [6]. Here they tested external and internal application of suppressant to a fire inside a LIB pack for heavy vehicles using limited quantities of suppressant. The commercially available systems tested comprised of 3-4 nozzles supplied by 13 L of water-based suppressant in total. They found that applying suppressant to the external surface of the burning LIB pack did not reduce internal temperatures or limit the risk for thermal propagation. However, applying suppressant directly into the pack gave positive results in terms of cooling and reducing the fire hazard. The risk for the module to module propagation and cell to cell propagation could be lowered using only a limited amount of suppressant. This shows the importance of direct access to the battery pack when there is a need to extinguish or cool it.

If an EV has been exposed to severe abuse, which may lead to a fire, it should be handled with special care. There is namely the risk that some of the energy which remains in damaged LIBs reacts exothermally and reignites a battery fire. Some guidelines are available which give information on how to handle when this risk exists. Examples of these are those developed by NFPA, SAE, and EDUCAM. After the fire is extinguished, or if there is a risk for fire, EVs that have been involved in accidents should be handled with care. These EVs should be parked in a restricted-access section of an open-air parking area a sufficient distance away from other vehicles, buildings, flammable objects and flammable surfaces [151]. It is never recommended to park an EVs with a damaged high-voltage system in an enclosed hall. Alternatively, the fire risk of an EV can be mitigated with the use of fire protection systems such as water sprinklers and/or fire detection systems. Battery packs of the damaged EV should not be directly exposed to the environment if there exists the possibility that water and moisture may seep into it. This can be mitigated by covering the EV with a weatherproof tarpaulin, for example, if needed. Last but not least, vehicles that pose a fire risk should be marked accordingly as to warn nearby personnel so that they can follow the appropriate routines and take any necessary precautions.

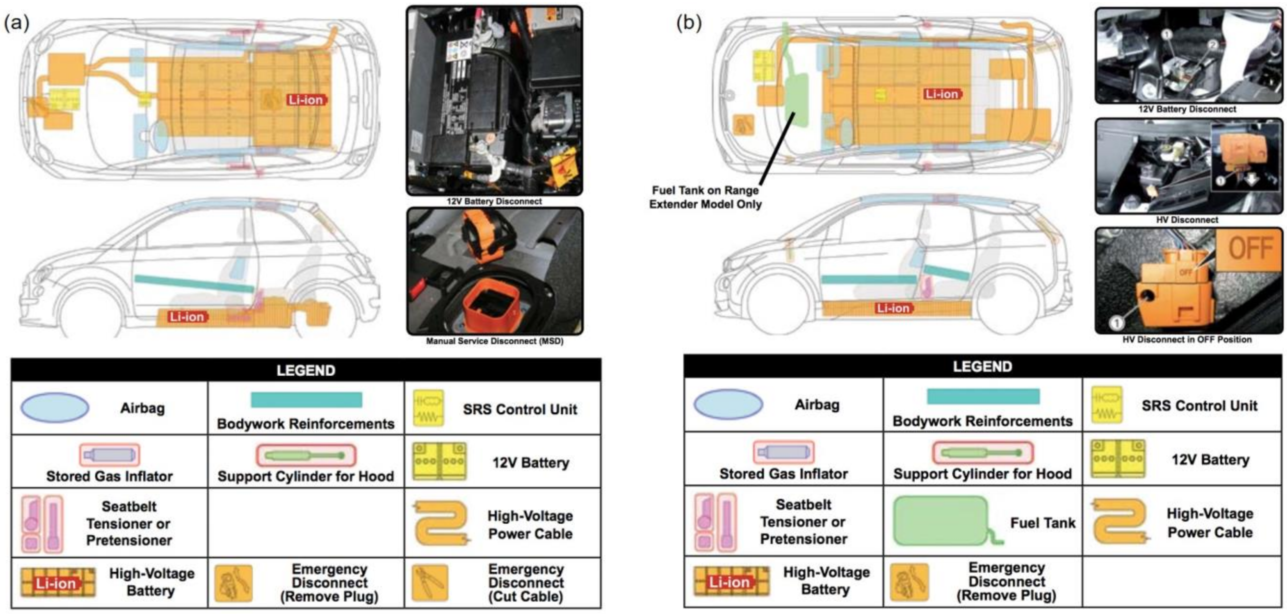

Figure 25. NFPA emergency field guide for (a) FIAT 500e BEV, and (b) BMWi3 hybrid EV [169].

Every EV manufacturer is supposed to inform their consumers the accidence guidance for specific models, including the fire emergency response. NFPA provides an emergency field guide to disable different batteries for different brand and model vehicles (***Figure 25***) [169]. The vehicle operators should be familiar with the guidance of safety information and practices. Manual service disconnects could disable the high-voltage battery without directly cut or touch components, but poor conduct could result in serious injury or death. When facing an EV fire accident, the emergency procedures are suggested as follows. As with any vehicle, if sparks, smoke, or flames coming from the vehicle are observed, customers should pull over, shut off the vehicle, exit the vehicle and move away from it before calling emergency services. In addition, customers should provide the emergency service with information on the type of vehicle the issue concerns, e.g. BEV or HEV. As with any vehicle fire, people should be informed not to inhale smoke, vapours, or gas, released by the burning vehicle as they may be hazardous. This could be best avoided by keeping a safe distance upwind, and uphill if possible, from the vehicle fire. Finally, customers should stay out of the roadway and stay out of the way of any oncoming traffic while awaiting the arrival of emergency responders.

The latest NFPA Electric vehicle emergency field guide [171] provides a more detailed instruction to handle vehicle fire accidents incidents involving mainstream hybrid and electric vehicles of different brands. The instruction is divided into two parts. The first part, the initial procedures, includes the methods to identify, immobilize and disable the vehicle. The second part is fire suppression strategy. Firefighting personnel should extinguish hybrid and electric vehicle fires using proper vehicle firefighting practices as recommended by the NFPA and in accordance with the department SOPs (standard operating procedures).

By summarizing different code of practices in different countries, the recommended EV firefighting process is described as follow

(1) Identify the vehicle. In some European countries, the fire rescue centres can request information based on a vehicle's license plates. This can help firefighters unequivocally identify the correct rescue datasheet;
(2) Determine the firefighting plan based on the situation;
(3) Protect the people first
(4) Control or extinguish the fire, and if the car is charging, switch off the charging infrastructure if possible.
(5) Vehicle should not be moved immediately, after the fire is extinguished;
(6) The final step is on-site cleaning. After fire accident, certain disposal procedures are also recommended, that is, the EV should be parked in an outdoor place after the accident because of the re-ignition ability of the battery.

As the total number of EVs increases every year, many public parking lots start to provide EV charging stations to attract EV drivers and demonstrate their sustainability commitment. There are some concerns associated with this, with several cities banning charging in parking lot structures. Parking lot structures have a large fire risk, considering the number and density of vehicles they may house (***Figure 26***). Their low ceilings contribute to the fire spread as they radiate heat down towards the fuel load whereas limited ventilation contributes to the accumulation of toxic gas. Parking lot structures are designed to be able to handle a few vehicles burning at the same time. As long as the fire is not allowed to spread beyond 3-4 vehicles, there will be no structural collapse [172]. The fire hazard may be further reduced by fire suppression systems, as it may help to prevent fire spread. Fire suppression systems such as conventional sprinklers may reduce the fire risk. The chemical hazard which burning vehicles, including EVs, may pose when parked inside buildings, should however be carefully considered.

***Figure 26*.** (a) Houston's Tranquility Park Garage with GRIDbot charging stations [173], and (b) hundreds of new EVs parked in a public area in Wuhan, China, showing a high fire risk [155].

NFPA 70 (National Electrical Code) has developed standards to address the growth in EV charging stations [174]. UL 2594 is one of the main standards and covers the different voltages available as well as safety and weather concerns. SAE J2293 and J1772 provide key design requirements to ensure interoperability with EVs [175]. Nevertheless, there is still a lack of data to prove the effectiveness or reliability of fire hydrant and sprinkler system for the parking lots with a large portion of EVs and many charging facilitates.

4. Concluding remarks

This paper reviews recent battery fires in electric vehicle (EV) as well as the related fire-safety issues and the fire-protection strategies. The fire risk and hazard of Li-ion battery (LIB) are particularly serious in EV, because of high demands in driving performance and charging speed, inevitable traffic accidents, and the increasing scale and energy density of battery packs. Several typical fire accidents in battery EVs, hybrid EVs, and electric buses are reviewed in order to provide a qualitative understanding of the risk and hazard of EV fire. An increased number of EV fire accidents will be expected as the market share of EV continuously increases in the next few decades. So far, there are a very limited number of full-scale EV fire tests because of the high cost and the restriction of trade secrets. Nevertheless, existing test results have revealed that the heat release rate of EV fire is comparable to that of the fossil-fuelled vehicle fire, while EV fire may release more toxic gasses like HF from burning Li-ion batteries. The tested peak heat release rate (PHHR in **kW**) varies with the energy capacity of LIBs (E_B in **Wh**) crossing different scales as $\boldsymbol{PHRR = 2E_B^{0.6}}$.

EV fire is harder to suppress because of the potential re-ignition of battery and the difficulty in cooling the battery pack inside. For the suppression of EV fire, water is still considered as most effective, and a significant amount of water is required to extinguish and cool the battery. However, less suppressant can be used if it is directly applied to the battery pack. Moreover, there is very little knowledge of the fire risk of the disposed EVs and wasted battery packs. In the future, fire-protection systems with a better design should also be required for buildings and parking spaces that contain a greater number of EVs and charging stations. This review aims to aid researchers and industries working with batteries, EVs and/or fire safety engineering, to encourage active research collaborations, and attract future research and development on improving the overall safety of future EVs. Only then will society achieve the same comfort level for EVs as they have for conventional vehicles.

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Nomenclature

Symbols		Abbreviations	
A_{EV}	EV floor area (m^2)	BEV	battery electric vehicle
A_f	area of fuel or fire (m^2)	EV	electric vehicle
ΔH_c	heat of combustion (MJ/kg)	HRR	heat release rate (W)
$\dot{m}$	burning rate (kg/s)	ICEV	internal combustion engine vehicle
$\dot{m}''$	burning flux (kg/m^2s)	LIB	Lithium-ion battery
$\dot{q}''$	heat flux (kW/m^2)	NCA	nickel, cobalt, and aluminium oxide
Q	heat release from fire (J)	NEDC	new European driving cycle
T	temperature (℃)	NMC	nickel, manganese, and cobalt
V	voltage (V)	PHRR	peak heat release rate (W)
η	combustion efficiency (%)	PHEV	plug-in hybrid electric vehicle
		SOC	state of charge (%)

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