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Analysis of Electric Vehicle Fire Risks in Car Parks

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Abstract

The increasing use of Electric Vehicles (EVs) is leading to a higher proportion of EVs in car parks. In this study, a comprehensive analysis of EV fire risks is conducted, and the adequacy of the existing building regulations for car parks in the UK is evaluated in light of EV fire risks.

A thorough literature review is undertaken to explore the fire risks associated with EVs. An assessment of the likelihood of fire ignition in EVs and conventional vehicles is performed in this work, which reveals that the likelihood of fire ignition is higher for an EV. A radiation analysis is conducted for both vehicle types, indicating that the distance between EVs in car parks should be increased. A novel approach to predict and compare the total energy release (THR) from fires of both vehicle types is implemented in this work. This analysis shows that the THR from an EV fire could be up to 40% higher than an equivalent Internal Combustion Engine Vehicle (ICEV) variant. The fire spread analysis of both vehicle types is conducted utilising the existing fire test results and employing the point source fire model, which unveils that the fire spread occurs much faster for an EV. The combination of faster fire spread and a higher energy release per vehicle would have a greater impact on the car park structure and pose a greater threat to firefighters.

The analysis undertaken in this study suggests that the existing building regulations for car parks pertaining to structural fire resistance, ventilation, and suppression systems should be revised to address the risks associated with EV fires. Further assessment is required to evaluate the adequacy of current regulations pertaining to the charging of EVs in car parks to mitigate the heightened fire risk during charging.

Abstract (Malayalam)

ഇലക്ട്രിക് വാഹനങ്ങളുടെ ഉപയോഗം വർദ്ധിക്കുന്നത് കാർ പാർക്കുകളിൽ ഇലക്ട്രിക് വാഹനങ്ങളുടെ അനുപാതം വർദ്ധിക്കാൻ കാരണമാകുന്നു. ഈ പഠനത്തിൽ, ഇലക്ട്രിക് വാഹനങ്ങളുള്ള കാർ പാർക്കുകളിൽ മതിയായ അഗ്നി സുരക്ഷ ഉറപ്പാക്കുന്നതിന് യുകെയിൽ നിലവിലുള്ള കെട്ടിട നിയന്ത്രണങ്ങളുടെ പര്യാപ്തതയുടെ ഒരു പരിശോധന നടത്തുന്നു.

ഇലക്ട്രിക് വാഹനങ്ങളുമായി ബന്ധപ്പെട്ട തീ അപകടസാധ്യതകൾ കണ്ടെത്താൻ ഈ പഠനത്തിൽ സമഗ്രമായ സാഹിത്യ അവലോകനം നടത്തുന്നു. ഇലക്ട്രിക് വാഹനങ്ങളിലും പരമ്പരാഗത വാഹനങ്ങളിലും തീപിടിക്കാനുള്ള സാധ്യതയെക്കുറിച്ചുള്ള ഒരു വിലയിരുത്തൽ ഈ പഠനത്തിൽ നടത്തുന്നു, ഇതു് ഒരു ഇലക്ട്രിക് വാഹനത്തിനു് തീപിടിക്കാനുള്ള സാധ്യത കൂടുതലാണെന്നു് വെളിപ്പെടുത്തുന്നു. ഈ പഠനത്തിൽ, കാർ പാർക്കുകളിൽ ഇലക്ട്രിക് വാഹനങ്ങൾ തമ്മിലുള്ള ദൂരം വർദ്ധിപ്പിക്കണമെന്ന് ഒരു റേഡിയേഷൻ വിശകലനം സൂചിപ്പിക്കുന്നു. ഇലക്ട്രിക് വാഹനങ്ങളുടെയും പരമ്പരാഗത വാഹനങ്ങളുടെയും തീപിടുത്തത്തിൽ നിന്നുള്ള മൊത്തം ഊർജ്ജം പുറത്തുവിടുന്നത് മുൻകൂട്ടി കാണാനും താരതമ്യം ചെയ്യാനുമുള്ള ഒരു നൂതന സമീപനം ഈ പഠനത്തിൽ നടപ്പിലാക്കുന്നു. ഈ വിശകലനം കാണിക്കുന്നത് ഒരു ഇലക്ട്രിക് വാഹന തീയിൽ നിന്നുള്ള മൊത്തം ഊർജ്ജം പുറത്തുവിടുന്നത് ഒരു പരമ്പരാഗത വാഹനത്തേക്കാൾ 40% വരെ ഉയർന്നതാകാം. ഇലക്ട്രിക് വാഹനങ്ങൾക്ക് തീ പടരുന്നത് വളരെ വേഗത്തിലാണെന്ന് ഈ പഠനം വെളിപ്പെടുത്തുന്നു. അതിവേഗം തീ പടരുന്നതും ഇലക്ട്രിക് വാഹനത്തിൽ നിന്ന് ഉയർന്ന ഊർജ്ജം പുറത്തുവിടുന്നതും കാർ പാർക്കു് കെട്ടിടത്തിൽ കൂടുതൽ അപകടസാധ്യത സൃഷ്ടിക്കുകയും അഗ്നിശമന സേനാംഗങ്ങൾക്കു് കൂടുതൽ ഭീഷണി ഉയർത്തുകയും ചെയ്യും.

ഇലക്ട്രിക് വാഹനങ്ങളുമായി ബന്ധപ്പെട്ട അപകടങ്ങൾ കുറയ്ക്കുന്നതിന് കാർ പാർക്കുകൾക്ക് നിലവിലുള്ള കെട്ടിടനിർമ്മാണ നിയന്ത്രണങ്ങൾ പരിഷ്കരിക്കണമെന്ന് ഈ പഠനം നിർദ്ദേശിക്കുന്നു. കാർ പാർക്കുകളിൽ ഇലക്ട്രിക് വാഹനങ്ങൾ ചാർജ് ചെയ്യുന്നതുമായി ബന്ധപ്പെട്ട നിലവിലെ നിയന്ത്രണങ്ങളുടെ പര്യാപ്തത വിലയിരുത്തുന്നതിന് കൂടുതൽ വിലയിരുത്തൽ ആവശ്യമാണ്.

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Nomenclature

Acronyms

BEV	Battery Electric vehicle
BMS	Battery Management system
DMC	Dimethyl Carbonate
EV	Electric Vehicle
EMC	Ethyl Methyl Carbonate
HRR	Heat Release Rate
ICEV	Internal Combustion Engine Vehicle
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
NMC	Lithium Nickel Manganese Cobalt
LIB	Lithium-Ion Battery
PHEV	Plug-in Hybrid Electric Vehicle
PHRR	Peak Heat Release Rate
REEV	Range Extended Electric Vehicle
SOC	State of Charge
SOH	State of Health
TR	Thermal Runaway
THR	Total Heat Release
VCE	Vapour Cloud Explosion

Chapter 1 Introduction

Car parks, a fundamental infrastructural component of the transportation industry, are vital in modern society, promoting accessibility and enhancing economic growth. With the increase in the use of passenger vehicles, there is a corresponding growth in the construction of car parks to meet the growing parking requirements.

Fire safety is substantial in car parks as it is essential to ensure the life safety of people and the protection of vehicles. A fire incident in a car park is considered a rare event. However, there have been several car park fire incidents in the UK. There have been 790 fire incidents in enclosed car parks in England from 2010 to 2020. Even though people stay in a car park for a short period, fire incidents in car parks have caused casualties. Twenty non-fatal casualties and one fatal casualty due to fires in car parks in England were reported from 2010 to 2020 [1]. In the US, on average, 4000 fire incidents occur in a car park annually [2]. Car park fires are more dangerous to firefighters involved in fire control operations. There have been incidents like the fire in the Gretzenbach car park in Switzerland that have caused the death of seven firefighters due to the collapse of the roof [3].

The increasing popularity of EVs is leading to a higher number of EVs being parked and charged in car parks. The burning behaviour and the risks of EVs differ from that of Internal Combustion Engine vehicles (ICEVs). The fire risks associated with ICEVs are known through past fire incidents and vast fire experiments. However, the fire risk of EV fires is not entirely understood yet. Significant technological advancements have led to new varieties of LIBs being used in EVs for enhanced performance, exacerbating the unfamiliarity of EV risks.

The current building regulations for car parks have been developed considering the fire risks associated with conventional ICEVs. There needs to be more certainty about the adequacy of the current building regulations to ensure a sufficient level of safety in the event of EV fires in existing car parks built based on these regulations. To bridge this knowledge gap, a comprehensive investigation of the fire risks associated with EVs should be conducted for comparison with fire risks associated with conventional cars.

1.1 The Rise of EVs

For the purpose of this study, the term “electric vehicle” (EV) will refer to any type of electric car, including Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicle (PHEVs), and Range Extended Electric Vehicles (REEVs). This study does not consider other types of EVs, such as bikes, scooters, vans, buses, and heavy goods vehicles.

There has been a rise in the production and sale of EVs over recent years. This rise can be attributed to increased efficiency, lower pollution, and lower oil import compared to the ICEVs. The usage of EVs over conventional vehicles contributes to the reduction of greenhouse gases. The efficiency in driving range for EVs has improved over recent years, which has also contributed to the rise in its sales. The highest driving range for EVs is 405 miles [4]. In addition, various government regulations and incentives for EVs have been implemented.

On the other hand, there is a significant decline in the production of ICEVs. As part of the net zero 2050 strategy, the UK government has banned the production of ICEVs from the year 2030. All new vehicles sold will be fully zero emission from 2035 in the UK [5].

Every year, EV sales have been increasing in the global market. The global sales of EVs were 16.5 million in 2021. This is approximately three times the number of EVs in 2018 [6]. The rise in the global sale of EVs is illustrated in Figure 1.

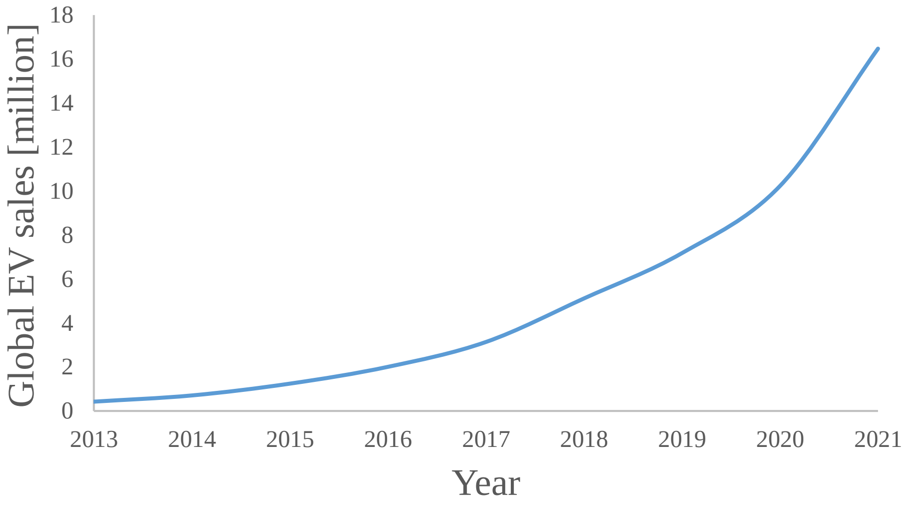

Figure 1: Global sales of EVs [6]

There has been a spike in EV sales after the pandemic in 2020. In the US, the EV sales in 2021 were double that of 2020 [7].

In the UK as well, EV sales have been rising. The UK is the fifth largest consumer of EVs as of 2023 [8]. Vehicle statistics for 2021 show that the number of BEVs, PHEVs, and HEVs has increased by 76%, 70%, and 57%, respectively, when compared to the sales in 2020 [9].

The proportion of EVs and ICEVs in the UK from 2014 to 2027, projected data obtained from Statista [8], is displayed in Figure 2.

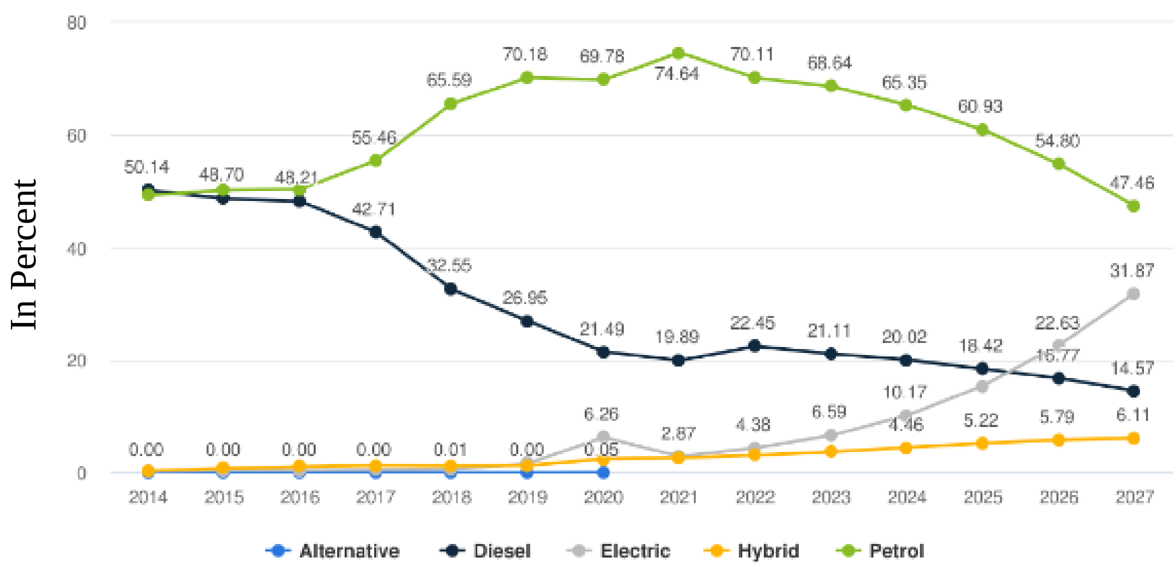

Figure 2: Forecasted sales of EVs and ICEVs [8]

From the above statistics, currently (as of 2023), ICEV's yearly unit passenger cars sales in the UK is 90%. By 2027, the yearly unit sales of ICEVs would reduce to 62%. EV unit sales in 2027 are projected to be 40% of the total passenger car sales.

1.2 Lithium-Ion Battery

1.2.1 LIB in EVs

Lithium-ion batteries (LIBs) are widely used in EVs. These batteries have very high energy storing capacity and energy density when compared to other types of batteries. LIBs have a very long service life. An average Tesla battery can last up to 1500 charging/discharging cycles, i.e., more than 20 years for an average person [10].

The energy capacity of LIBs in EVs ranges from 28.9 kWh to approximately 200 kWh for a GMC hummer EV [11]. A LIB of higher energy capacity poses a higher fire risk. BEVs are equipped with higher capacity LIBs when compared to PHEVs.

A battery cell works based on the electrochemical potential. There are different types of battery cells, including prismatic, coin type, pouch cell, and cylindrical cells. Tesla uses cylindrical type cells (18650) for its battery pack [12]. A battery module consists of many such cells. A battery pack consists of several such modules. The battery pack of a Tesla Model S is depicted in Figure 3. The battery pack is located on the underside of the vehicle floor. Standard battery pack designs include,

- Floor design: Square/rectangle-shaped battery pack located in between the two wheelbases
- T-shaped design
- Rear design: The battery pack is located near the rear wheelbase of the vehicle. Rear-design battery packs are typically seen in PHEVs [13].

The battery pack designs used in an EV are illustrated in Figure 4.

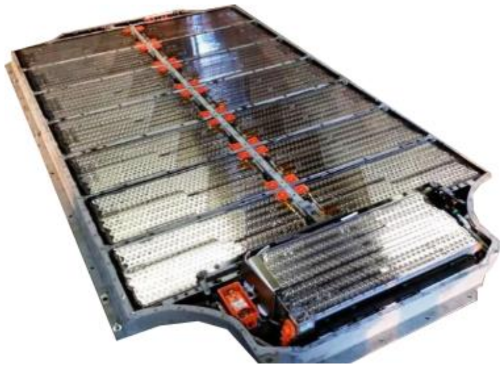

Figure 3: Tesla Model S battery pack [14]

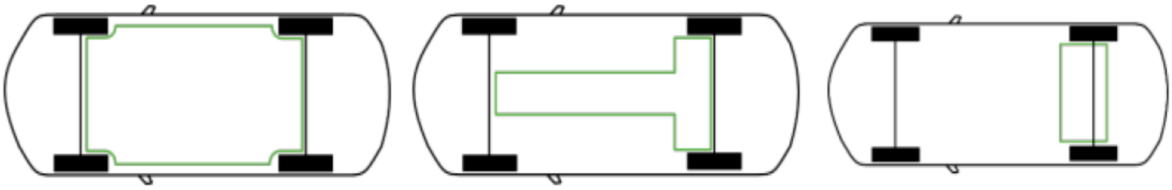

Figure 4: Battery pack design used in EV [15]

1.2.2 Working Principle of a LIB

A LIB works based on the movement of lithium ions between the anode and cathode through an electrolyte. When a LIB is charged, the lithium ions are transferred from the cathode, which is made of lithium metal oxide, to the anode, which is made of graphite. The reverse process occurs when the battery discharges [11]. The separator prevents the movement of electrons through the electrolyte. The solid electrolyte interface (SEI) layer plays a critical role in the protection of the electrolyte against degradation by the electrons. The internal structure of a LIB is shown in Figure 5.

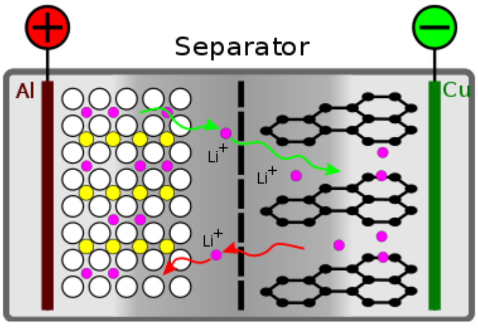

Figure 5: Structure of a LIB [16]

Commonly used metal oxides for the cathode of a LIB are the LCO (Lithium Cobalt Oxide), LMO (Lithium Manganese Oxide), LFP (Lithium Iron Phosphate), NMC (Lithium Nickel Manganese Cobalt) oxides. In terms of thermal stability, LFP-based LIB is superior to other LIBs [11]. In addition, the LFP batteries are found to last longer, i.e., they reach their end of life at an extended period when compared to other batteries. LFP batteries are also considered safer than other types of LIBs. The surface temperature and the gases produced after Thermal runaway (TR) are lower for an LFP-based battery [17]. However, LFP batteries are heavier than other batteries [18].

Separators are generally made of polyethylene, polypropylene, or polyolefin. The electrolyte used in a LIB is an organic solvent containing lithium salts such as Lithium hexafluorophosphate ($LiFP_6$) [19].

1.2.3 Thermal Runaway

TR is a phenomenon that could occur in a LIB, which can eventually result in the release of toxic and flammable gases, fire, or explosion. A TR is initiated when the normal operating temperature of the battery is exceeded. The initiating causes for temperature rise include

- Overcharging of the battery due to the failure of the Battery Management System (BMS) to cut off the electric supply.
- Battery exposed to extreme environmental conditions, such as extreme temperatures
- External short circuit in the wiring of the battery
- Internal short circuit: this could be due to a manufacturing defect, water entering the battery, fast charging, etc.
- Mechanical damage to the battery
- Manufacturing defects: These include poor sealing of battery cells causing electrolyte leakage, non-uniform electrode thickness, and contamination of battery components [15]

When the temperature of the battery exceeds the normal operating temperature, certain chemical reactions occur in the battery, which is exothermic in nature. This will again cause the internal temperature of the battery to increase. Some of the heat is lost through the battery pack surface. The SEI layer starts to decompose at around 80°C [20]. At this stage, gases such as H_2 and CH_4 are released. As the temperature increases, the lithium at the anode starts to react with the electrolyte, and this results in the release of hydrocarbon gases. When the temperature exceeds 130°C, the separator between the two electrodes starts to melt. This will result in a short circuit between the two electrodes and a subsequent temperature rise. When the temperature exceeds 150-200°C, the heat generation exceeds the heat loss, and the exothermic reactions become self-sustaining [20]. At 180°C, the cathode starts to degrade, which is a highly exothermic reaction. This process also results in the production of oxygen [11]. Finally, the electrolyte begins to burn.

TR occurring in a cell in the battery pack will transfer the heat to the adjacent cells, which will result in a rise in temperature and the subsequent TR of the neighbouring cells. The TR will propagate through the battery module unless the heat transfer is interrupted.

The abuse conditions leading to TR are summarised in Table 1.

Table 1: Battery abuse conditions [11,20]

Thermal	**Mechanical**	**Electrical**
Exposure to high/low air temperature	Car collision/ debris damaging the battery	Overcharging/over-discharging
External fire/heat source	vibration	Short circuit- external and internal
Poor ventilation	Water immersion	Failure of BMS

1.3 Causes and Likelihood of an EV Fire

Statistical data suggests that EV fires are not as common as conventional automobile fires. However, the fact that there are fewer EVs than ICEVs should be considered when comparing the probability of ignition in these vehicles.

An EV can ignite in different circumstances. Based on past EV fire incidents, it is known that an EV can ignite when it is being charged, when it is involved in a road accident/collision, or when the battery is exposed to extreme weather conditions [21]. Furthermore, arson and external fire could also lead to an EV fire. Due to the lack of sufficient statistical data, it is difficult to determine the most likely cause of an EV ignition.

Based on an analysis of the global BEV fire incidents that occurred from 2010 to 2022, it was found that there has been a total of 337 verified BEV battery fire incidents [22]. Apart from this, there have been 82 additional BEV battery fire incidents, about which precise data is not available. The yearly statistics are illustrated in Figure 6. There is a significant increase in the number of fire incidents in 2021 and 2022, which could be due to the rapid rise in the sale of BEVs after the pandemic in 2020.

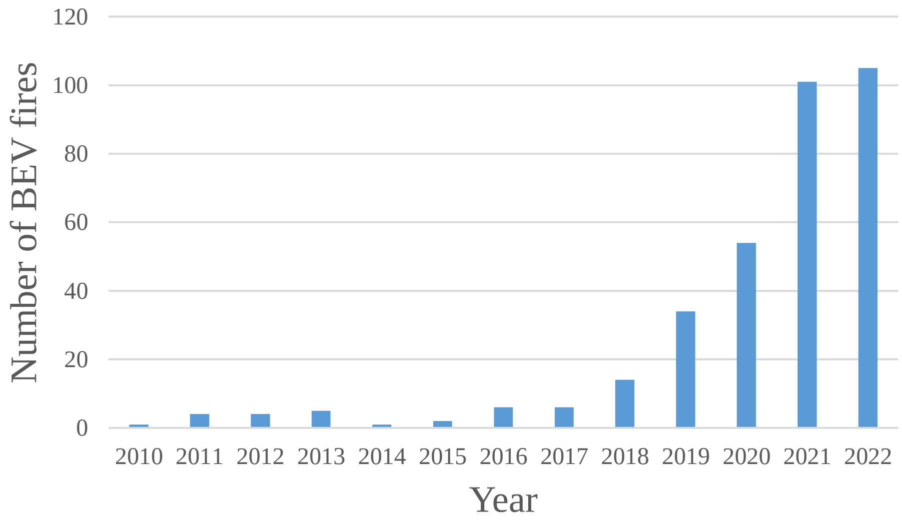

Figure 6: BEV fire incidents from 2010 to 2022 [22]

The common causes for short circuits in batteries include- collision, charging, debris damaging the battery, manufacturing defect in the battery, overheating, repair, water submersion (flood), external fire, and arson.

From the analysis of fire incidents [22], 17% of all EV fire incidents, which originated from the battery, occurred during or shortly after the charging process. This data indicates that charging has a substantial potential to induce a short circuit in the battery, but the reason for this still needs to be fully understood. A large percentage of these instances were also caused by a vehicle collision or road debris damaging the battery.

The preceding statistics include solely the BEV fires involving the battery. However, fire can occur in other parts of the BEV as well. Moreover, PHEVs are not included in this data.

The likelihood of fire in an EV can be compared to that of an ICEV to evaluate the fire risk. Comparing the likelihood of fire occurrence in EVs and ICEVs is not straightforward due to the substantial disparity in the number of vehicles of each type.

Some evidence reveals that the likelihood of fire ignition of EVs is substantially lower than that of ICEVs. According to Willstrand et al. [23], the EV fire likelihood is 5 and 20 times lower than ICEV fires based on statistics in Norway and Sweden, respectively. However, most of the analysis does not consider the disparity in the number of vehicles of each type. In this work, the likelihood of EV and ICEV is compared with consideration of this disparity.

1.4 EV Fire Risks

The vehicle components and working of an EV and ICEV are different. The different components of a BEV and ICEV are depicted in Figure 7 & Figure 8. The main difference is the power source, which is the battery in an EV. Whereas in an ICEV, it is petrol/diesel. EVs are equipped with additional components such as motors, charging systems, converters, and additional electronic boards [23].

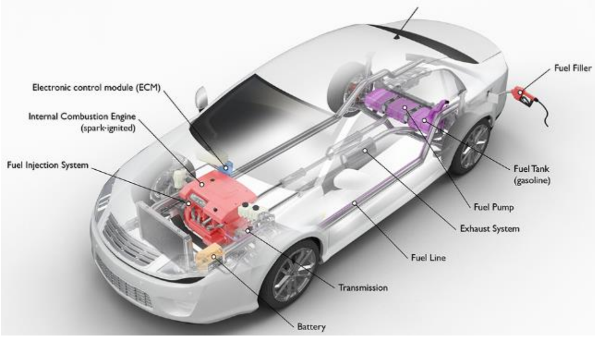

Figure 7: Components of an ICEV [24]

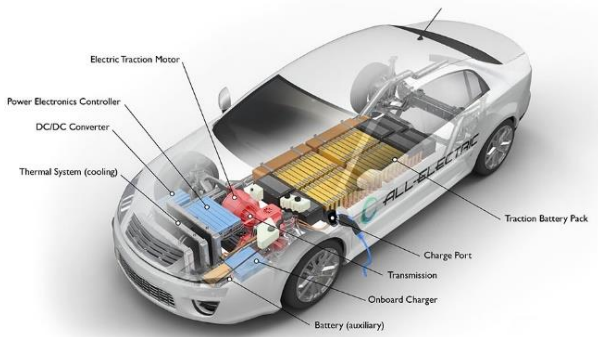

Figure 8: Components of BEV [23]

The risk risks imposed by these two types of vehicles are different due to the significant difference in the fuel system.

1.4.1 Battery Jet Fire

The ignition of battery vent gases, which are flammable and toxic, emitted from the battery pack can lead to a jet fire. The ignition of the vent gases could either be due to an external ignition source, friction between the vent gases and the opening, or arcing (which typically occurs at SOC levels above 50%) [25]. The jet fire emanating from the battery pack is the main cause of the fire spreading to the body of the EV. Jet fire from the battery will also result in rapid **fire spread to adjacent vehicles**. The fire spread from an ICEV is well known [26]; however, for an EV, it is not the case. In this work, the fire spread analysis of EVs and ICEVs is performed based on the available fire test results. The jet fire emerging from the sides of the EV during the fire test conducted as part of the BRAFA project [27] is depicted in Figure 9.

Figure 9: Battery jet fire emerging from the sides of an EV [27]

Jet Flame Location

The jet fire could emerge either from the vehicle's sides or rear side. The location of the jet fire depends on the location of the safety valve. Safety valves on the battery packs are located either on the top side or on the sides of the battery. If the safety valve is provided on the top of the battery pack, the jet fire will emerge from both sides of the vehicle after a deflection from the vehicle's body. Most of the EV battery packs have safety valves located on the sides [12]. This will result in a longer jet fire emerging from one of the sides of the vehicle. In addition to the safety valve, there are additional openings on the battery for electrical connections. These electrical connectors/cables would melt due to the TR or the battery fire, which would result in the release of vent gases and jet fire emanating from these openings. In the EV fire experiment conducted by Cui et al. [28], jet fires were observed from the vehicle's sides and rear. The rear side flame was from the opening on the battery pack due to the melting of the electrical interphase.

Jet Fire Length

Flame lengths measured from batteries were found to be significantly longer when compared to the battery dimension. The flame from an NMC battery during the nail penetration experiment was nine times longer than the module [25].

Based on experiment results, the length of flame from the battery pack was found to be between 2 to 2.8 m [29]. The battery jet fire length typically varies from 2-3 m in length depending on the capacity of the battery pack [30].

The Temperature of the Jet Fire

Huang et al. [31] conducted experiments on large-scale LIB cells of 50 Ah capacity. Based on several experiments, it was found that the flame temperature from a LIB cell can be expected to be in the range of 700-900℃. Similar temperatures were also measured near the battery pack in the PHEV fire experiment [13].

1.4.2 Radiation from an EV Fire

In the case of an EV fire, the burning of the body of the EV and the jet fire origination from the battery pack will contribute to heat radiation, which is not the case for an ICEV fire.

In the experiment conducted by Lam et al. [32], a sudden intense flame was observed from the battery; at this moment, there was a sudden peak in the Heat Release rate (HRR) and in the heat flux measured on the side of the vehicle. In the fire test conducted by Watanabe et al., the peak heat flux measured on the sides of the vehicle coincided with the battery release and jet fire [33]. This indicates that the jet fire from the battery has a significant contribution to the heat radiated from the EV fire.

Radiation from a burning vehicle will pose a hazard to the neighbouring vehicles, firefighters approaching the vehicles, and the people nearby. By the analysis of the radiation from a burning vehicle, it is possible to estimate,

- The safe distance for evacuation of occupants from the car park
- The safe distance for the firefighting operation
- The safe distance for parking adjacent vehicles- parallel and lateral directions

The heat radiation from an EV will be higher than a similar ICEV due to the additional jet fire radiation. The extent of additional radiation from an EV can be estimated based on radiation calculations. Hu et al. [34] conducted experiments on the burning of ICEV minivans and estimated the radiation based on the assumption of flame shapes. The calculated safe distances are presented in Table 2.

Table 2: Safe distances for ICEV based on radiation calculation [34]

Scenario	Safe distance (m)
People (based on a threshold of 1.4 kW/m^2)	7.3
Firefighters- with full protection gear (based on a threshold of 7 kW/m^2)	2.7
Adjacent vehicles (10 kW/m^2)	2.1

Such radiation calculations are not performed for an EV fire. By considering the radiation from the battery jet fire and the vehicle body fire, the heat radiation from an EV and the safe distances can be estimated, which is carried out in this work.

1.4.3 Peak Heat Release Rate and Total Heat Release for an EV Fire

HRR is one of the main parameters used for the assessment of fire hazards [35]. By comparison of the Peak HRR (PHRR) and the THR of the ICEV and EVs, the severity of each type of vehicle fire can be assessed. The fire experimental data pertaining to EVs is limited.

Based on available fire test results of EVs and ICEVs, some literature sources concluded that the PHRR and THR of an ICEV and EV are similar [32,33,36,37]. In the study conducted by Willstrand et al. [36], it was found that the PHRR of an EV is 5.7 ± 1 MW, whereas, for an ICEV, it is 6.2 ± 2.5 MW. The THR for an EV was found to be 6.1 ± 1.5 GJ, and for an ICEV, it is 5.9 ± 2.5 GJ. However, the comparison is not made considering the size and fuel capacity of the vehicles.

The PHRR of an EV and ICEV depends on several factors and is highly dependent on the ignition source. A justified comparison of fire risk in terms of the PHRR of an EV and ICEV of similar class can only be performed when the ignition and test conditions of both vehicles are identical. The variability of PHRR is discussed in detail in this work.

Due to wide variability in the fire test, the fire risk of an EV and ICEV cannot be judged only based on the measured PHRR. A comparison of the THR of these vehicles is required to understand the severity of these fires.

In this study, a novel approach is adopted to compare the THR of the ICEV and EV of different classes (small, medium, and large) by a detailed analysis of the available test results considering the contribution of the vehicle body and the fuel separately.

1.4.4 Toxicity

TR of the battery cells will result in the release of toxic and flammable gases once the pressure inside the battery exceeds the safety venting pressure. Gas venting occurs in two stages. The first venting occurs at an internal battery temperature of 120℃, and the second venting occurs at around 160℃ [38]. This results in the formation of a vapour cloud outside the battery. This is seen as a white vapour ejected from the battery and is an early warning of the occurrence of TR in a battery [25]. Most of the gases released are toxic, and some of the gases released at the initial stages after TR are heavier than air, such as SO_2 [39].

The amount type of gases released depends on cell chemistry, energy capacity [40], and the State of Charge (SOC) of the battery.

Gases found to be released from LIB include HF, CO_2, CO, H_2, HCN, C_2H_4 [41], SO_2 [25], components of Ethyl Methyl Carbonate (EMC) and Dimethyl Carbonate (DMC) [42]. In addition, some traces of alkanes, alkenes, and metals were also observed. The presence of HCN was also found in the clothing of firefighters involved in the control of the explosion incident that occurred in the lithium-ion battery energy storage system [41].

When emissions from EVs and ICEVs are compared, certain gases are emitted from both vehicles. However, the concentration of HF released from an EV fire is significantly higher. HF from an EV is from the sources of fluorine present in the battery, such as Electrolyte ($LiPF_6$) and the material used as a binder in electrodes (PVDF).

Based on the toxicity analysis of a LIB fire in an enclosed space, it was found that the concentration of HF and SO_2 were more critical and had more impact than CO on the toxicity [19].

In the fire test conducted by Lecocoq et al. [37], HF was detected in both ICEV and EV fires. A similar peak was observed in both cases since the battery venting did not occur. The released HF was from the burning of coolants used in the air conditioning system. A rise in HF is observed in EV fires when the battery is involved in the fire. The total amount of HF from an EV fire is significantly higher (1.8 to 2.5 times) when compared to ICEV fires.

In the experiment conducted by Sturm et al. [40], it was found that the HF content released from EV fires was 60-80% higher than from ICEV fires. From the LIB fire experiment, it was found that Cobalt, Li, and Mn (metal particles) were also released. Moreover, it was also found that HF, Phosphine, and F-aerosols were also released. All these gases can create a toxic environment in an enclosed space such as a car park.

Willstrand et al. [36] found that the HF released from batteries varies with the battery capacity. The HF emission from the LIB experiment conducted by Sturm et al. [40] also follows this trend. From these experiments, it is found that, on average, the rate of emission of HF was 300 mg/Wh. The concentration of HF during the EV fire, measured at the height of 1.6 m, was found to exceed the IDLH 30 limit (immediate danger to life and health, 30-minute exposure duration).

1.4.5 Explosion risk

In the absence of immediate ignition of the vent gases released from the battery, a vapour cloud could be formed in the area surrounding the EV. This vapour cloud formed could result in a potential vapour cloud explosion (VCE) if there is a delayed ignition. Chances of VCE will be higher in enclosed spaces such as a car park than in open areas, where the vapour cloud will be dispersed due to wind. Such an explosion can result in rapid fire spread to adjacent parked cars and poses a risk to people nearby and firefighters.

An analysis of all global EV battery fire incidents revealed that the VCE occurred only in 5% of the incidents [22]. The rest 95% of the incidents led to quick ignition of the battery vent gases, resulting in jet fires.

The occurrence of a VCE is also dependent on the SOC of the battery, as discussed in Section 1.5.1. The chance of VCE is higher when the SOC of the battery is lower. At higher SOC levels, the proportion of asphyxiating gases in the vent gas is higher. At lower SOC levels (below 50%), the larger composition of vent gases was found to be flammable. In addition, the chances of arcing, which rapidly ignites vent gases before the formation of a vapour cloud, are lower when the SOC level is lower [25]. VCE will occur if there is a delayed ignition.

The degree of confinement also influences the possibility of a VCE. VCEs are less likely to occur in a battery venting occurring in an open environment. Based on statistical data on EV battery fire incidents, 70% of all VCE incidents occurred in enclosed spaces.

In most of the fire tests conducted on EVs, VCEs were not observed. Most of these experiments were carried out in open environments where confinement of battery emissions does not occur, and chances of VCE would be lower. The possibility of VCE is also dependent on the method of ignition used in these experiments. If the ignition source is a burner fire, then the gasses venting from the battery will ignite spontaneously due to the readily available ignition source.

Similar is the case when the vehicle body/compartment is ignited. The VCE would occur only if there is a delayed ignition, which is not the case in many of the experiments. In most of the experiments, the SOC of the EV battery was higher than 80%, which would result in higher emissions of asphyxiating gases.

In the experiment conducted to study the characteristics of PHEV fire [13], a vapour cloud was formed and resulted in a VCE. The experiment was performed in an open space. The VCE occurred after a long duration (50-60 min). The long-time delay for the explosion could be due to lack of confinement, lower chances of arcing in a low-capacity battery (13 kWh), and the battery abuse method adopted (external short circuit).

In the experiment conducted by Cui et al. [28], TR was induced in an EV battery pack. The EV was covered in a baffle. The vent gases from the battery accumulated under the baffle and resulted in an explosion within 7 seconds of the gas release. Here the rapid explosion was caused due to the confinement of the gases under the baffle. The ignition source for the vapour cloud accumulated under the baffle was readily available since the battery TR was induced with an electrical furnace.

There have been several EV battery VCE incidents across the world. Based on an analysis of EV battery fire incidents, it was found that 14 such incidents have occurred globally from 2010 to 2021 [43]. Some of these incidents occurred while the EV was being charged [44], while some occurred in EVs parked in garages without being charged [45]. One incident occurred after an EV collided with a tow truck [46]. The blast pressure from such an explosion can blow the car parts away, and, in some incidents, even the garage structure could be damaged [45].

The flammability limit of the battery vent gases depends on the cell chemistry and the type of gases emitted. For an LFP-based battery, the lower and upper flammability limits are 6% and 50% [17].

Several flammable gases are emitted from a battery. H_2 is one of the gases. The percentage of H_2 in the vent gases could be as high as 30% (by volume) [47]. The blast pressure from a 100-kWh battery at a 20m to 50m distance could be 14-20 kPa (considering the effect of H_2 only). Such levels of overpressure can cause serious structural damage, serious injuries, and even death [48].

The VCE is a notable additional risk of EVs when compared to ICEVs. In car parks, a vapour cloud could be formed after the TR of an EV battery. Vapour clouds formed in car parks, due to the low ceiling height, could reach the lower flammability limit much faster and could result in a VCE. Such an explosion would result in rapid fire spread, could damage the car park structure, and would also endanger the safety of people and firefighters.

1.5 Charging of EVs and the Associated Fire Risks

With the increase in the use of EVs, car parks in the future can be expected to have a higher number of EVs. Charging systems are currently provided in car parks. An EV would normally take about 8 hours to completely charge a 60-kWh battery using a 7-kW charger [49]. Rapid charging methods are frequently employed, greatly reducing charging time. A slow charger is rated 3.7 kW, a fast charger is rated 7 kW or 22 kW, whereas rapid chargers are rated 43-50 kW. In addition, there also exists ultra-rapid chargers, which are rated 150 kW, incorporating three-phase DC charging.

Given the present trend in the use of EVs, providing charging points in parking lots is unavoidable. There have been some policy updates in providing charging facilities in car parks. A charging facility is to be provided for one in five car parking spaces in London [50]. However, it is also critical to consider the added fire risk associated with charging an EV.

Recent guidelines published by the FPA [30] for the charging of EVs emphasise that an EV is at a very high risk when it is being charged. According to Xie et al.

[51], 80% of all EV fires occur when the vehicle is charging. However, there is no statistical data to substantiate this statement.

EV charging is viewed as an additional fire hazard. The potential causes for fire during charging include,

1. Damaged charging system and charging cables. Stretching of the cable due to a shortage of cable length is one of the causes of cable damage.
2. Overcharging: Overcharged batteries pose a significantly increased danger of TR. Overcharging in batteries is prevented in normal operation by the BMS.
3. Fast charging: Charging a battery at a higher charging rate results in localised temperature rises inside a battery cell [52] near the current collecting tab. Internal hot spots could promote lithium dendrite growth and could cause an internal short circuit [53].
4. Failure of BMS: Failure of the battery's BMS can result in overcharging, failure of the cooling system, etc., which can result in potential thermal runways. In Belgium, a Tesla Model S caught fire due to a short circuit while being charged using a supercharger. The probable cause was suspected to be the fault in BMS, which then led Tesla to update the BMS system of this model [54].
5. Use of unapproved charging system/chargers/batteries: Some chargers would cause additional resistance and subsequent heat build-up. One such incident occurred in a Tesla Model S in California [55] while it was being charged. Even though the exact cause of the incident is not known, it was probably due to the heating of the chargers. Another similar incident occurred in Norway, where a short circuit in the charging system initiated the fire [56]. The use of unapproved and non-compliant chargers has also led to EV fire incidents [57].

6. Charging of a defective/old battery: if a battery is defective, then the conversion of electrical energy into chemical energy is affected. This would result in heat build-up in the battery.

When compared to a car park without a charging system, providing charging systems in car parks would result in most cars having a higher SOC of the batteries. Hence it is critical to analyse the effect of SOC on the TR, venting, and burning characteristics of a battery.

1.5.1 Effect of SOC

State of charge (SOC) represents the amount of energy remaining in the battery. It also describes the number of active lithium-ions at the anode. Higher the SOC, the higher the remaining driving range of the vehicle. A battery cell is fully charged when the SOC is 100%. The BMS of the battery prevents the battery from being charged above 100%. However, if the BMS fails to prevent overcharging, the battery could be charged above 100%.

SOC and TR

Golubkov et al. [58] conducted experiments on LIB to analyse the effect of SOC on TR. It was found that higher SOC batteries (LFP) were more prone to undergo TR. At 140°C, a 100% SOC battery underwent TR, whereas a 0% SOC battery did not undergo TR even at 250°C. Overcharged batteries are at a higher risk of undergoing TR. An overcharged NMC battery can undergo TR at a temperature as low as 65°C. The variation of critical temperature for TR with SOC levels is shown in Figure 10. SOC also has an effect on the severity of the TR. The higher the SOC, the higher the cell temperature attained during the TR, and the higher the chances of adjacent cells undergoing TR.

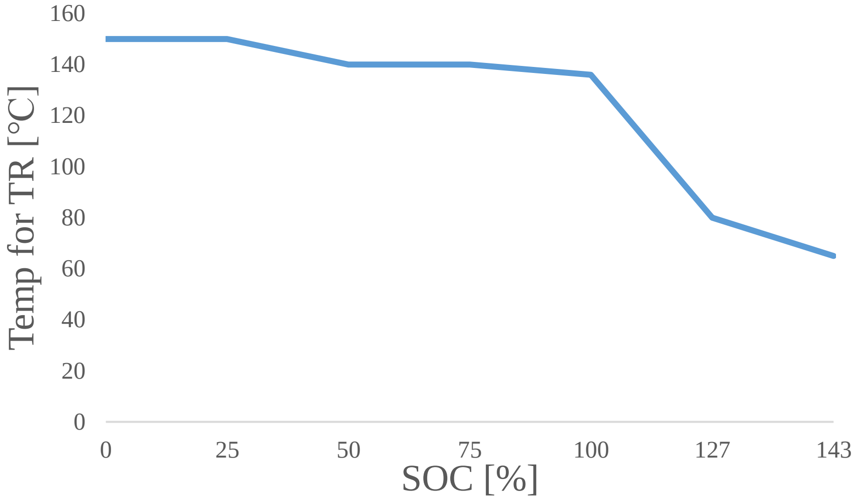

Figure 10: Variation of critical temperature for TR with SOC [58]

Doose et al. [42] conducted nail penetration experiments on LCO batteries of 5 Ah capacity to assess the effect of SOC and State of health (SOH) on TR. It was found that the cells with SOC lesser than 30% did not undergo TR during the nail penetration test. It was observed that the cell with higher SOC resulted in a higher surface temperature. The difference in the surface temperatures between a 50% SOC cell and a 100% SOC cell was as high as 125℃. Surface temperature after TR in a cell indicates the possibility of propagation of TR in a pack/module. This indicates that the chances of TR propagation through the pack will be higher for a higher SOC battery pack.

Keeping the SOC of the battery below 30% reduces the risk of TR significantly. The recommended SOC level for the transport of LIB is at or below 30% [59]. However, keeping the SOC level of an EV below 30% is not practical in car parks. The SOC of EVs parked in car parks with charging facilities can be expected to be on the higher end.

SOC and Vent gases

The amount of the gases released (CH_4, CO_2, CO, C_2H_6, and C_2H_4) were found to be higher for a battery of higher SOC [42,58]. With the higher production of reaction gases, the pressure inside the cell will be higher and will result in a quicker venting of these gases.

The quantity of HF released increases with a reduction of SOC of the battery [19]. A similar trend was also observed in the experiments conducted by Doose et al. [42], where in addition to the HF, the concentration of EMC and DMC were found to increase with the reduction of SOC of the battery. This is due to differences in chemical reactions occurring inside the battery due to the different reaction temperatures with varying SOC levels. At lower SOC, electrolyte evaporation occurs, and at higher SOC levels, electrolyte decomposition occurs.

It is observed that there is a change in the type of risk with varying SOC levels. TR occurring in a lower SOC battery will result in the release of gases with a potential for VCE. In contrast, TR occurring in a higher SOC battery will result in the release of more asphyxiating gases threatening the evacuation of occupants.

SOC and HRR

Larsson et al. [60] exposed LIB (LFP) cells to a propane burner fire and investigated the effect of SOC on TR. It was found that the higher the SOC, the higher the PHRR, which is depicted in Figure 11. This confirms that the higher charger battery will burn more severely.

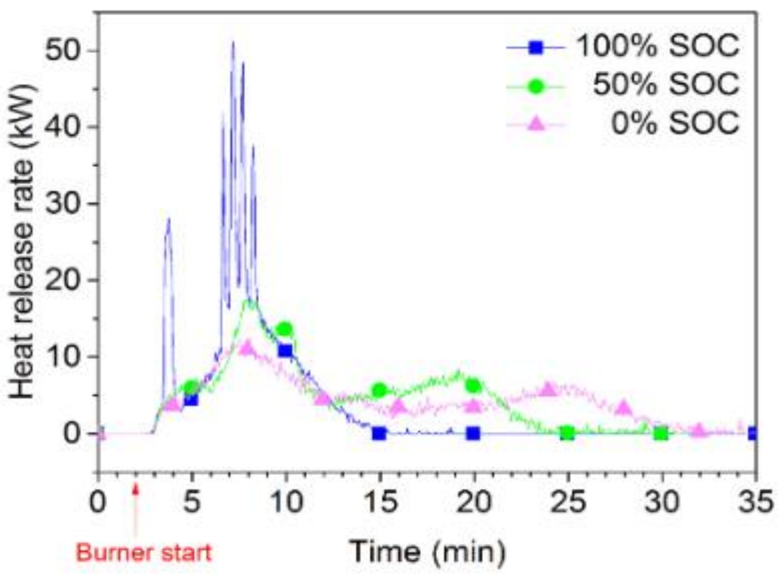

Figure 11: Effect of SOC on the HRR [60]

In some experiments, it was also observed that the heat released from higher SOC batteries is slightly lower. In the experiment conducted by Liu et al. [61], the total heat released from the flaming combustion of LIB cells during TR was measured in a cone calorimeter. It was found that at 100% SOC, the HRR was lower than 50% SOC battery. The jet fire from the 100% SOC battery was extinguished partially due to the high velocity of the gases released from the vent, resulting in unburned gases and a lower heat release. In the experiment conducted by Larsson et al. [60], this phenomenon was not observed. This could be due to the presence of an external burner in this experiment, which would result in the ignition of the vent gases released at high velocity at the higher SOC of the battery.

1.6 Firefighting Tactics for EV Fires in Car Parks

EV fires are extensively challenging to extinguish. The main reason behind this is the lack of an efficient extinguishment agent for the suppression of LIB fire. Additionally, the LIB in EVs is designed under the vehicle, which makes it even more difficult for firefighters to access the fire source. Moreover, when EVs are parked in car parks, the problem is even worse. The rapid spread of fire between these cars and the presence of a toxic environment makes the firefighting operation risky.

In general, water is used to extinguish EV fires as a major portion of the fuel burning is the vehicle body parts, for which water is the most efficient agent. For extinguishment of the battery pack, extensive cooling is required. Based on the experiments, it is found that the external application of water is not efficient in stopping the propagation of TRs. Approximately 2600 gallons (approx.10000 L) of water is required to extinguish an EV battery fire [62]. A reliable source of water is critical for firefighting of EV fires. A sufficient number of fire hydrants would be required near car parks to tackle EV fires. From the fire extinguishing experiments conducted on EV battery packs, it was found that the external application of water would take up to 49 minutes [63].

EV fires in an open environment are often allowed to self-extinguish depending on the decision of the incident commander [62]. It would take approximately 90 minutes for the battery pack of an EV to self-extinguish. Another firefighting method for EV fires in open environments is to submerge the EV in a water container. This involves building a water-tight enclosure around the EV. This method, even though not effective in extinguishment, is effective in controlling the fire spread. Such firefighting tactics are not practical in the case of an EV fire inside a car park.

The application of water inside the battery pack, penetrating the battery pack, is one of the most efficient ways to suppress a battery fire. This method is not recommended by EV manufacturers. The direct application could be either through an e-lance [64] or BEST (Battery Extinguishing System Technology) apparatus [65]. The quantity of water required is significantly less with the direct water injection into the battery. In the individual battery pack fire experiment 80 kWh conducted by Sturm et al. [40], the firefighting lance was found to be highly efficient. The LIB fire was extinguished within 2 minutes of the application of water inside the pack, with 30 L of water. However, the application of e-lance for extinguishment of battery fire under EV is not a practical method. This method requires firefighters to work near the vehicle. It would not be possible to approach the vehicle due to the jet fire emerging from the battery. The space limitation between the cars inside the car park would make this firefighting method even more difficult. Moreover, the use of such devices requires a high level of training, as it could worsen the situation. The water injection is to be performed at the exact affected area of the battery pack.

Fire blankets suppress the fire by the smothering effect; it cuts off the oxygen supply to the fire. Fire blankets would be effective in controlling EV fire if the battery is not involved in combustion. If the battery is involved in the fire, fire blankets are not an effective control method. This is due to the presence of oxygen inside the battery, which keeps the fire burning. Moreover, jet fire from the battery emerging from the bottom of the EV renders the fire blanket inefficient [40]. RSA recommends the use of blankets to prevent the fire from spreading between vehicles [66]. However, given the close parking arrangement inside a car park, it would be practically difficult to cover the burning vehicle with a blanket.

1.7 Problem statement, Aims and Objectives

The use of LIBs in EVs introduces notable disparities in the risk imposed by EVs when compared to that of ICEVs. The widespread adoption of EVs, along with the increased risk during charging and difficulty in firefighting, makes EVs significantly more hazardous in car parks. This study endeavours to quantify the risks associated with EVs and ICEV by assessment of the likelihood of fire ignition, the radiation emitted, the total heat released, and fire spread.

This research aims to conduct a detailed investigation of the fire risks in these two types of vehicles based on the available literature, experimental data, and fire engineering calculations to analyse the adequacy of current building regulations and to propose updating if necessary.

The following objectives were established to accomplish the aim of this research work:

1. Conduct a comprehensive review of the existing literature and experimental fire test data to obtain insights into the differences in the fire risks of an EV and ICEV.

2. Evaluate the likelihood of the fire for an EV and ICEV based on the available fire incident statistics.

3. Perform radiation analysis of an EV fire to assess the contribution of jet fire to the radiation and to estimate the safe distance for firefighters and for parking adjacent vehicles.

4. Estimate and compare the THR of an EV and ICEV for different classes of vehicles.

5. Perform the fire spread analysis for both vehicle types based on existing experimental data and based on the Point Source Model to evaluate the fire spread risk and its impact on the fire safety of car parks.

6. Evaluate existing building regulations for car parks in relation to EV fires and assess the adequacy and provide recommendations for updating these regulations if necessary.

This thesis comprises of seven chapters. Chapter 1 provides an overview of EVs, LIBs, and EV fire risks. Chapter 2 compares the likelihood of fire ignition in EVs and ICEVs. The radiation calculations for both vehicle types are presented in Chapter 3. Chapter 4 includes the analysis of vehicle HRR and the calculation of vehicle THR. The fire spread analysis is presented in Chapter 5. Chapter 6 discusses the findings, implications, and limitations of this work. The recommendations for future research are also discussed in this chapter. Chapter 7 presents the summary and conclusions of this work.

Chapter 2 Likelihood of Fire Ignition

2.1 Methodology

To analyse the likelihood of fire ignition with consideration of the disparity in the number of vehicles of each type, two approaches are used in this work.

2.1.1 Likelihood-based on the Distance Travelled by the Vehicle

One approach is to compare the likelihood of fire occurrence in terms of the distance travelled. Likelihood per billion km travelled is given by,

$$Likelihood = \frac{n}{D} \times 10^9 \quad \textbf{(1)}$$

Where n is the number of fires reported for a specific type of vehicle, and D is the total distance travelled by each of these vehicles (km).

2.1.2 Likelihood-based on the Number of Vehicles of Each Type

Another reasonable approach is to compare the likelihood of fire occurrence per 100k vehicles of each type. Since the number of ICEVs and EVs are not similar, calculating the likelihood of fires per 100k vehicles of each type will enable a better comparison of likelihood. Likelihood per 100k vehicles is given by,

$$Likelihood = \frac{n}{N_v} \times 10^5 \quad \textbf{(2)}$$

Where N_v is the number of vehicles of each type (ICEV or EV).

2.2 Analysis and Results

2.2.1 Likelihood-Based on the Distance Travelled by the Vehicle

The likelihood of fire, normalised with respect to the distance travelled, for EVs and ICEV from various sources is listed in Table 3.

Table 3: Likelihood of fire based on distance travelled

SN	Type of Vehicle	Likelihood of Fire (per billion km travelled)	Source
1	EV	3.03	[67]
2	EV	3.12	[68]
3	ICEV	34.4	[68]
4	Average vehicle fire (US statistics)	32.7	[67]

When the likelihood of fire in terms of the distance travelled is compared, EVs are less likely to ignite than ICEVs, approximately 11 times lower than ICEV fires. Distance travelled is indirectly related to the likelihood of fire. The higher the distance travelled higher the chances of a collision. In addition, the higher the distance travelled, the higher the number of charging cycles, which is considered one of the causes of ignition in EVs. However, currently, EVs are less preferred for long-distance travelling. Moreover, the disparity in the number of vehicles still needs to be accounted for in this approach of normalising likelihood with respect to distance travelled.

2.2.2 Likelihood-Based on the Number of Vehicles of Each Type

Based on a study conducted on US vehicle fire statistics, the likelihood of fires in PHEVs, ICEVs, and BEVs was estimated [69]. The results of the study are listed in Table 4.

Table 4: Likelihood of fire based on 100k vehicles of ICEV, BEV and PHEV [69]

SN	Type of Vehicle	Fires[1]	Likelihood (per 100k vehicles)
1	ICEV	199533	1500
2	BEV	52	25
3	PHEV	16051	3474.5

Notes

1. The total number of vehicle fires in the US till 2022.

Based on the above statistics, the PHEVs are the most likely to ignite when compared to the other two types of vehicles. This could be because PHEVs have both an engine and battery system, and fire could occur in both of these systems. However, in this study, PHEVs are considered as a type of EV with a lower capacity battery. In terms of imposed risks, a BEV and PHEV are similar. Hence, based on the above results, the combined likelihood of EVs was calculated and is presented in Table 5.

Table 5: Likelihood of fire based on 100k vehicles of ICEV and EV

SN	Type of Vehicle	Number of fire incidents	Number of vehicles	Likelihood
1	ICEV	199533	13302200	1500
2	EV (Including BEV and PHEV)	16103	669966	2404

Based on the normalised results, the likelihood of fire in an EV is higher than that of an ICEV.

There has been a sharp rise in EV fire incidents in the UK as well, particularly after 2020. From 2017 to 2022, in London, there have been 507 EV fire incidents, including electric cars, buses, e-scooters, and HGV fire incidents [70]. Out of the total number of fire incidents, 43% of the total incidents occurred in electric cars.

These statistics are from London alone, and this represents approximately 69% of total EV fire incidents in the UK.

Fleet News [71] gathered the vehicle fire statistics for the year 2019 in London, obtained by FOI request with London Fire Brigade. Based on this data and the information regarding the number of licensed EVs and ICEVs from 2009 to 2019 obtained from the Department for Transport [72], the normalised likelihood for each vehicle was calculated and is shown in Table 6.

Table 6: Likelihood of fire based on statistics in London [72]

SN	Type of Vehicle	Fires	Number of vehicles	Likelihood
1	ICEV	1898	2508165	75.7
2	EV	54	31930	169.1

Based on the above statistics in London, the normalised likelihood of fire ignition for an EV is more than double that of ICEVs. On the other hand, if the likelihood of fire in both vehicles is compared without considering the disparity in the number of vehicles, the likelihood of EV fire is much lower than ICEVs. A comparison of the normalised likelihood of fires reveals that the chances of EV fires are higher than that of ICEVs. According to EV Fire safe [22], one of the major causes of EV fires is due to collisions/accidents, which is not dependent on the type of vehicle and should be the same for an ICEV and EV. In addition, fire in an EV can also occur due to charging, debris damaging the battery, or manufacturing defects in the battery. These additional causes are not relevant and do not cause a fire in an ICEV.

In this approach, the distance travelled or the age of the vehicle is not considered. The distance travelled is assumed to be similar for both types of vehicles. The likelihood should be normalised with the number of vehicles and distance travelled by each type of vehicle. However, data pertaining to distance travelled is not readily available.

Most EVs in the UK currently being used are new, and the SOH of these batteries is good. These batteries will reach their end of life after the prescribed battery cycles. As the EVs age and the battery SOH is reduced, a significant number of TR and EV fire incidents can be expected in the future.

Chapter 3 Radiation Calculation

3.1 Methodology

In the case of an EV fire, the burning of the body of the EV and the jet fire origination from the battery pack will contribute to heat radiation. To calculate the total radiation from an EV, the flame shape of the battery jet fire and vehicle body is to be evaluated.

3.1.1 Flame Shape of the Battery Jet Fire

Flame Length

The jet fire emerging from the battery depends on the location of the vent or openings. If the vent is on the sides of the battery pack, the jet fire length and width can be determined from the horizontal jet fire correlation developed by Palacios et al. [73], which is depicted in Figure 12.

The horizontal flame length is given by,

$$\frac{X_f}{D_{or}} = 3.7 Q^{*0.35} \tag{3}$$

Where X_f is the horizontal flame length (m), D_{or} is the diameter of the orifice (m), and Q^* is the dimensionless HRR. The orifice diameter is taken as the vent opening on the battery pack, which is typically 50 mm [74].

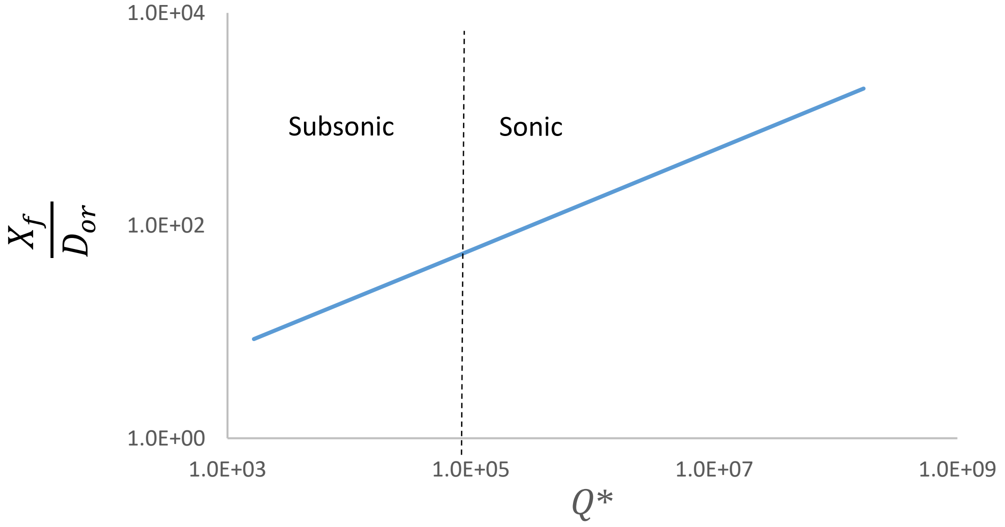

Figure 12: Dimensionless flame length based on experimental results [73]

The dimensionless HRR is given by,

$$Q^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D_{or}^2 \sqrt{g D_{or}}} \qquad \textbf{\textit{(4)}}$$

Where $\dot{Q}$ is the HRR (kW), g is the acceleration due to gravity, c_p is the specific heat, T_∞ is the ambient temperature, and ρ_∞ is the ambient density. The HRR is taken as the PHRR of the battery pack, which is calculated based on the battery capacity, equation ***(12)***.

The correlation is valid in subsonic ($Q^*<10^5$) and sonic flow regimes. In the subsonic flow regime, the jet fire is buoyancy dominated and would be tilted upwards. In the sonic regime, the jet fire is momentum dominated.

The jet fire length estimated based on this correlation gives a conservative estimate. In reality, the jet fire would get deflected by the vehicle's body.

The flame extension from the sides of the vehicle can be estimated based on the width of the vehicle and the width of the battery pack. The width of a typical battery pack is approximately 30 cm [75].

Flame Width

The width of the jet fire can be determined from the equivalent flame diameter correlation developed by Palacios et al. [73], which is graphically illustrated in Figure 13.

$$\frac{D_{eq}}{D_{or}} = 0.55 {Q^*}^{0.35} \qquad \textbf{\textit{(5)}}$$

Where D_{eq} is the equivalent flame diameter.

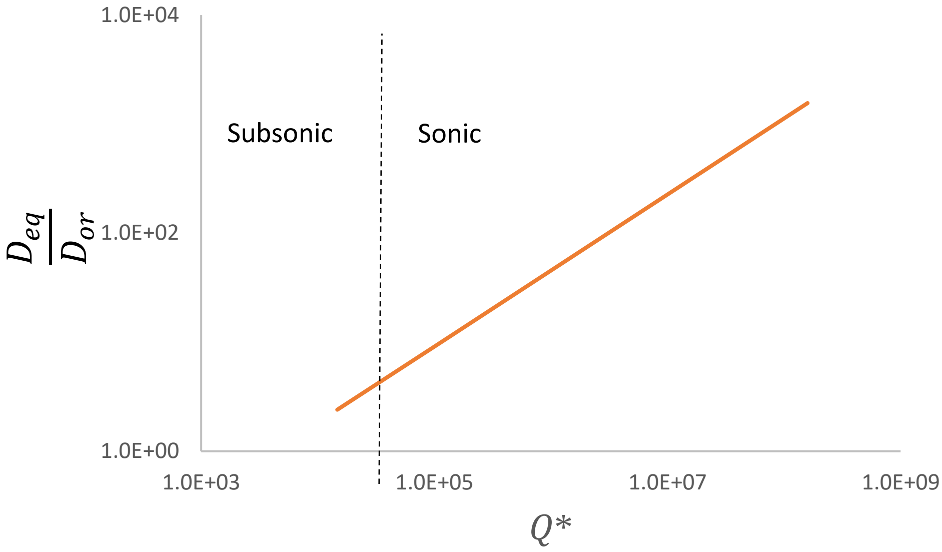

Figure 13: Dimensionless flame diameter based on experimental results [73]

3.1.2 Passenger Compartment and Spout Flame

Okamoto et al. [76] proposed a method to evaluate the flame radiation from passenger cars. Rectangular flame shapes were assumed for the passenger compartment and the spout flame, as shown in Figure 14. The dimensions of the spout flame were chosen based on temperature measurements and based on the assumption that lower-temperature regions do not contribute significantly to the radiative heat flux.

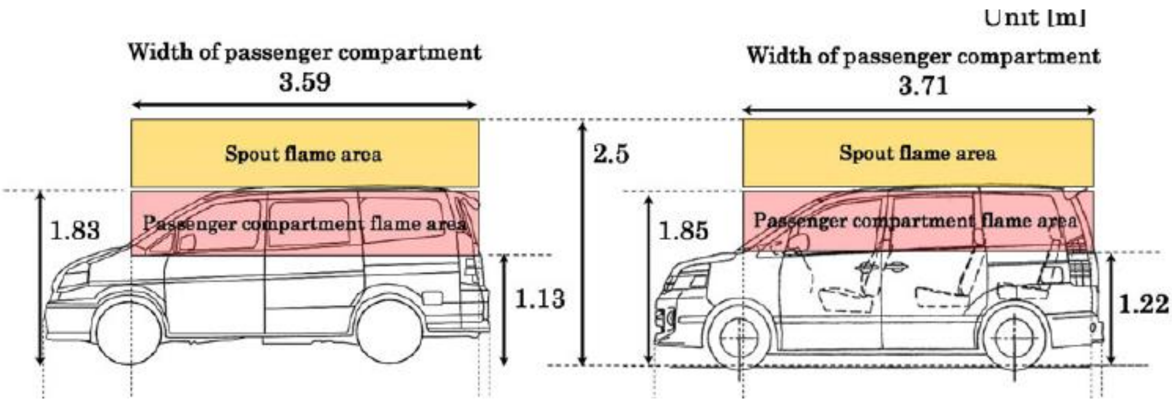

Figure 14: Spout and passenger compartment flame shapes for radiation calculation [76]

The calculated heat flux values were in good agreement with the measured heat flux.

The same method is adopted in this work for calculating the radiation from an EV. In addition to the compartment and spout flame, the battery jet flame is also considered here, as shown in Figure 15.

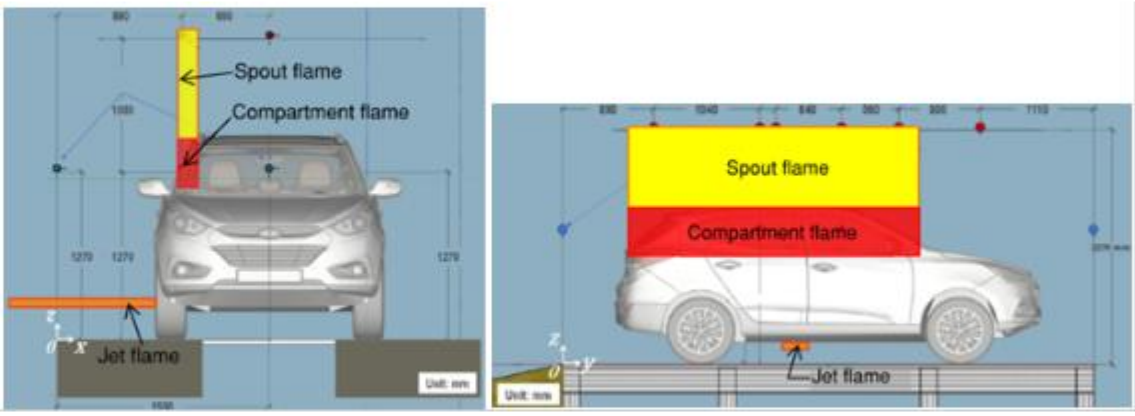

Figure 15: Flame shapes used in this work for radiation analysis

3.1.3 View Factor Calculations

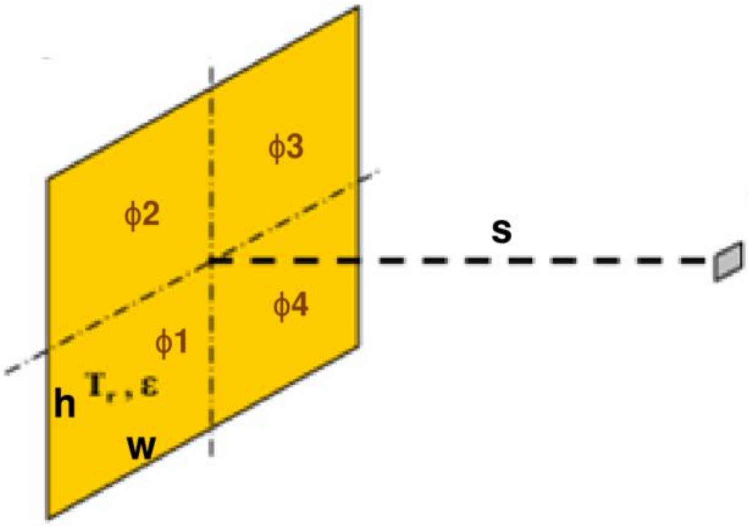

Figure 16: View Factor from an emitter to a parallel receiver

The view factor from an emitter to a parallel receiver is given by,

$$\phi = \phi 1 + \phi 2 + \phi 3 + \phi 4 \qquad (6)$$

$$\phi 1 = \frac{1}{2\pi}[\frac{a}{(1+a^2)^{1/2}}\tan^{-1}\frac{b}{(1+a^2)^{1/2}} + \frac{b}{(1+b^2)^{1/2}}\tan^{-1}\frac{a}{(1+b^2)^{1/2}} \qquad (7)$$

$$a = \frac{h}{s} \quad \textbf{(8)}$$

$$b = \frac{w}{s} \quad \textbf{(9)}$$

3.1.4 Total Radiation

The total radiative heat flux received at a distance S from the vehicle can be calculated as,

$$I_T = I_b + I_p + I_s \quad \textbf{(10)}$$

The radiative heat flux can be calculated as

$$I = \varepsilon\phi\sigma T^4 \quad \textbf{(11)}$$

Where I_T is the total radiative heat flux (kW/m^2), $I_b$is the radiative flux due to the battery jet fire, I_p is the radiative flux from the passenger compartment flame, I_s is the radiative flux from the spout flame, ε is the emissivity, ϕ is the view factor, σ is the Stefan-Boltzmann constant, and T is the temperature (K).

3.2 Analysis and Results

3.2.1 Flame Length and Flame Width

Flame length and width were calculated based on equations ***(3)*** & ***(5)*** for the 40 most commonly used BEVs in the UK. This includes 97.5% of all licensed BEVs in the UK. The calculated flame extension from the vehicle and flame width is presented in Figure 17 & Figure 18 respectively.

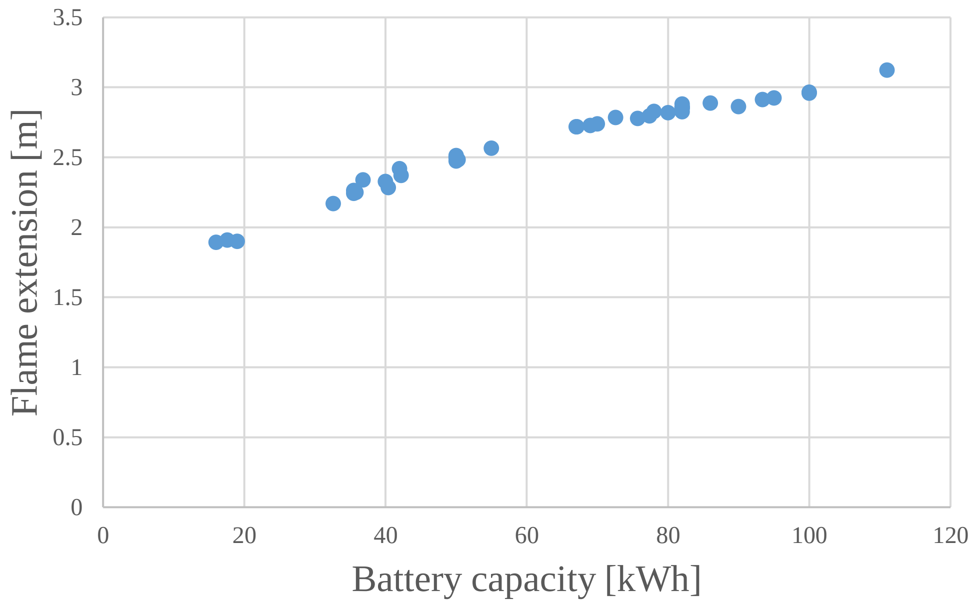

Figure 17: Variation of flame extension with the battery capacity

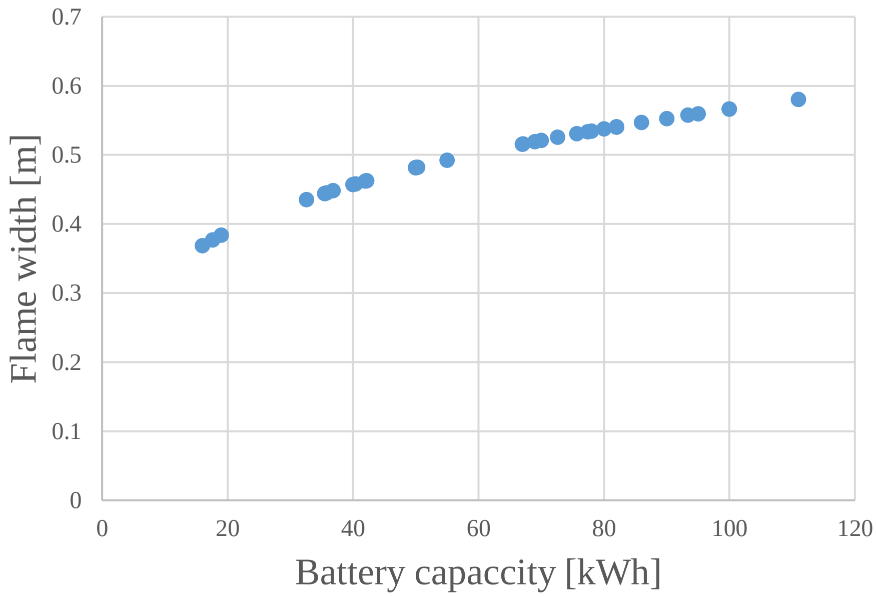

Figure 18: Variation of flame width with the battery capacity

The flame length varies from 1.8 to 3.1 m, and the flame width varies from 0.4 to 0.6 m. The jet flame dimension is conservatively assumed as 3.1 m × 0.6 m for the radiation calculations.

3.2.2 Radiation from an ICEV and EV Fire

The radiation calculations are based on the assumption of flame shapes for the jet fire, spout flame and compartment flame for an EV, whereas for an ICEV, the radiative heat flux was calculated based on the spout and compartment flame. The passenger flame shape is chosen such that it includes the vehicle's body parts. The temperatures for the spout and compartment flames are based on the experimental results [77]. The temperature measured at the height of 2.2 m above the floor does not exceed 350°C, and this is assumed as the spout flame height. It is assumed that the contribution to radiative heat flux from the region above this is negligible as the temperature is less than 350°C. The passenger compartment temperature measurement is shown in Figure 19.

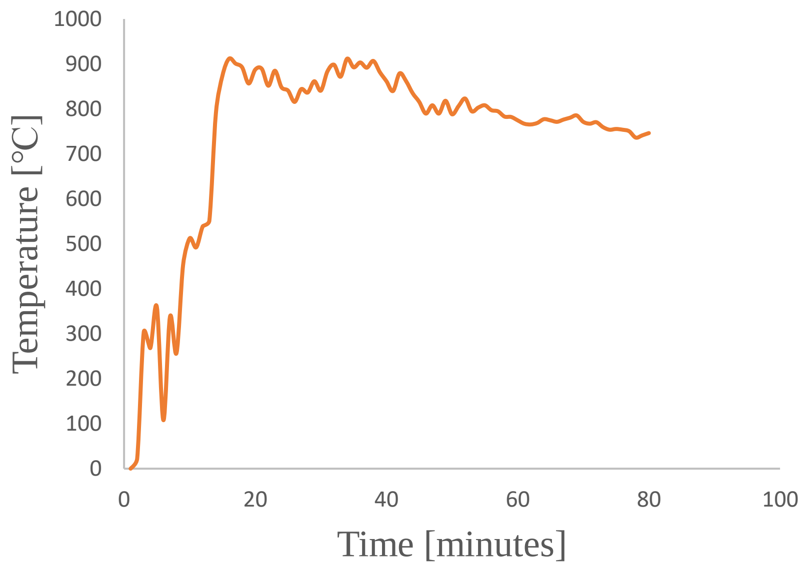

Figure 19: Passenger compartment temperature [77]

The maximum temperature for the passenger compartment is 900°C. For the spout flame, the temperature is assumed as 700°C, as temperature measurement at the centre of the spout flame region is not available. The battery jet fire temperature is assumed as 900°C (Section 1.4.1). The flame emissivity is conservatively assumed as unity.

The peak heat flux calculated for the ICEV and EV at a height of 1.2 m above ground and at different distances from the vehicle is presented in Figure 20.

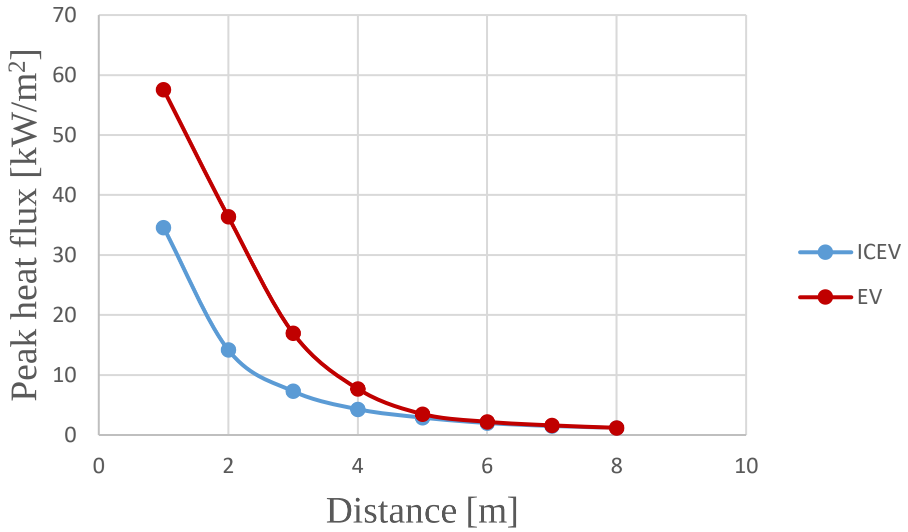

Figure 20: Calculated peak heat flux for EV and ICEV

The peak heat flux from an EV fire at a 1 m distance is approximately 1.6 times higher than that of an ICEV fire. The effect of the radiation due to the battery jet fire is significant only near the EV. The radiation from an EV and ICEV become similar at a distance further than 4 m from the vehicle. This implies that, at short distances from the vehicle, the radiation from an EV fire is much higher than an ICEV fire.

The safe distance for occupants, firefighters and parking of adjacent vehicles for EV and ICEV, based on the critical heat flux for ignition, is presented in Table 7.

Table 7: Safe distances based on radiation calculation

Safe distance based on radiation calculation (m)					
Adjacent car (10 kW/m^2)		people (1.4 kW/m^2)		firefighters (7 kW/m^2)	
ICEV	**EV**	**ICEV**	**EV**	**ICEV**	**EV**
2.5	3.8	7.2	7.4	3	4

Based on the radiation analysis, it can be inferred that the distance between two adjacent EVs parked in a car park should be increased to have a similar degree of fire safety, in terms of fire spread, as that of an ICEV. The firefighting operation for an EV fire should be carried out at a farther distance.

Chapter 4 Vehicle HRR and THR

4.1 Methodology

4.1.1 Battery PHRR Estimation

Willstrand et al. [36], based on the analysis of battery cells, modules, and packs with a SOC ranging from 80% to 100%, developed a correlation to estimate the PHRR from the battery capacity. The correlation for the estimation of the PHRR of a battery is given by,

$$\dot{Q}_p = 1.56 \times E^{0.67} \tag{12}$$

Where $\dot{Q}_p$ is the PHRR (kW), and E is the energy capacity of the battery (Wh).

The HRR depends on several factors, and it is challenging to estimate the HRR of a battery pack. There is a large variation in the HRR test results. However, this correlation predicts a rough estimate of the PHRR of a battery based on its energy capacity.

4.1.2 THR from the Fuel System of Vehicle

Depending on the powertrain of the vehicle, the Total Heat Release (THR) of the fuel can be calculated.

THR from the Battery Pack

Willstrand et al. [36], based on an analysis of several battery cells, modules, and packs, found a linear correlation to predict the THR based on the energy capacity.

$$THRR = 48.5 \times E \tag{13}$$

The analysis results and the trend line are shown on a log-log scale in Figure 21. This correlation overestimates the THRR for lower-capacity batteries, especially for battery cells. However, the correlation provides a good estimate for THR of higher-capacity batteries, such as battery modules and battery packs.

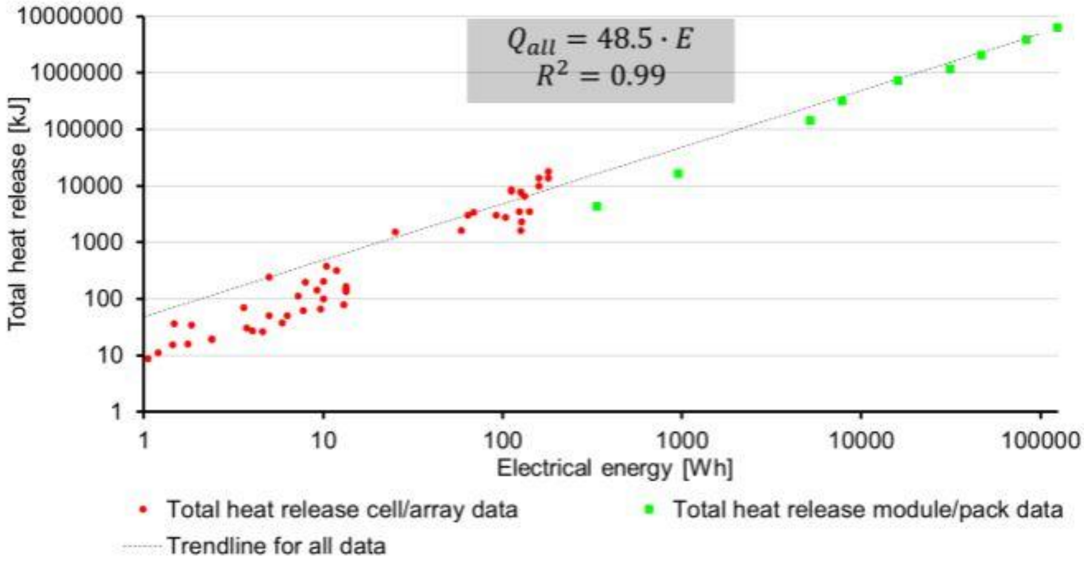

Figure 21: Variation of THR with battery capacity on log-log scale [36]

THR from Gasoline/Diesel Fuel

The THR from the gasoline/diesel fuel can be estimated based on the equation below,

$$THR = V \times \Delta H_c \times \rho \qquad \textbf{\textit{(14)}}$$

Where V is the volume of the fuel (L), ΔH_c is the heat of combustion of the fuel (MJ/kg), and ρ is the fuel density (kg/L).

The fuel properties of gasoline and diesel are listed in Table 8.

Table 8: Fuel properties of gasoline and diesel

Parameter	**Gasoline**	**Diesel**
The heat of combustion (MJ/kg) [78]	46	46
Density (kg/L) [79]	0.75	0.85

4.1.3 Vehicle Classification

The vehicle class, including hatchback, sedan, compact/subcompact crossover SUV, and SUV, has been classified into three categories based on analysis of the kerb weight of the top forty most used ICEVs and EVs in the UK. The information regarding commonly used vehicles in the UK was obtained from statistics published by the Department for Transport [72,80]. The vehicle classification for ICEVs and EVs is presented in Table 9 & Table 10, respectively.

Table 9: ICEV classification based on the kerb weight

Vehicle Classification	**Weight range (kg)**	**Body types considered**	**Examples of vehicles**
Small	770 to 1300	Hatchback	Citroen C1, Fiat 500, Peugeot 208, Ford Fiesta, Mini Cooper, etc
Medium	1301 to 1600	Sedan, compact/ subcompact SUV	Nissan QashQai, Toyota Corolla, BMW 3 series, Ford Kuga, etc.
Large	Above 1600	SUV	Land Rover Freelander, BMW X3, X5, Land Rover Discovery, etc.

Table 10: EV Classification based on the kerb weight

Vehicle Classification	**Weight range (kg)**	**Body types considered**	**Examples of vehicles**
Small	1125 to 1530	Hatchback	Mini cooper, Fiat 500, Peugeot 208, Nissan Leaf, Vauxhall Corsa
Medium	1530 to 2000	Sedan, compact/ subcompact SUV	MG 5, Hyundai Ioniq, Peugeot 2008, Kia Niro, Hyundai Kona
Large	Above 2000	SUV, Sportback, Luxury sedan, Luxury crossover SUV	Tesla Model Y, Mercedes- A, B, C class, BMW IX3, Porche Taycan

Detailed information regarding the commonly used ICEVs and EVs in the UK is provided in the Appendix.

4.2 Analysis and Results

4.2.1 Vehicle HRR

The HRR of a vehicle depends on several factors. A thorough analysis of each of the test results is required to judge the contribution of the vehicle body and the fuel system to the HRR measured during each of these experiments.

Factors Affecting HRR of a Vehicle

1. Type of powertrain

Depending on the type of vehicle- ICEV (petrol, diesel)/EV/hydrogen-powered vehicle, the burning characteristics and the HRR of the fire will vary.

2. Class of vehicle

The class of vehicle, i.e., Hatchback/Sedan/SUV/minivan, does influence the HRR results of the vehicle fire. The fuel load of an SUV will be significantly higher than that of a small hatchback car.

3. Amount of fuel

The amount of fuel stored in the fuel tank during the experiment and the involvement of this fuel in the vehicle fire will affect the HRR measured for the ICEVs. In some experiments, the fuel stored in the tank was not involved in the burning process, in which case the measured HRR will be lower.

For EVs, the capacity of the battery and the state of charge of the battery can influence the HRR measured. Higher the capacity of the battery, the higher the HRR. In most of the EV fire experiments, two peaks in the HRR curve are observed- one due to the burning of combustible material, and the other occurs when the battery is involved in the burning process [32]. The effect of SOC on the HRR is discussed in section 1.5.1.

In addition to the influence of battery capacity and SOC, the number of battery cells/modules inside the battery pack undergoing TR also affects the HRR results. In the battery cell fire experiment conducted by Willstrand et al. [36], the HRR of burning two battery cells was found to be higher than burning a single battery cell. The involvement of battery cells depends on the cell arrangement and their exposure to the abuse condition.

4. Ignition source and its location

The ignition source used to initiate the vehicle fire and its location will affect the HRR of the vehicle fire. Commonly used ignition sources include burner fire outside the vehicle, seat fire, etc., for both ICEV and EV. Ignition sources specific to EVs include short circuits, nail penetration and furnace/burner heating of the battery pack.

While comparing the HRR of ICEV and EV, consideration of the fire ignition source is essential. The ignition source should also reflect realistically possible conditions. Fire starting from the battery is a realistic condition, but for ICEVs, fire due to fuel tank rupture is not a realistic condition. However, fuel involvement in the fire at an early stage would reflect a worst-case scenario. Fuel tank rupture occurs in a vehicle crash, which is highly unlikely in a car park [81].

In some experiments, the fire was initiated on the car seat with the window seats open. Windows of vehicles are generally kept closed, especially in car parks. Fire initiating from the battery and then spreading to the other parts of the vehicles should be analysed to understand the actual worst-case behaviour of EV fires. For fires originating from the passenger compartment, the burning of the battery occurs at a later stage of the fire, sometimes in the decay phase, and in some cases, the battery would not go into TR before the burnout. If the battery is not involved in burning, then the HRR of ICEV and EV would be similar. If the battery TR occurs in the decay phase, then it does not contribute to the PHRR. In such cases, the THRR of EV and ICEV should be compared to understand the fire severity.

In the case of EV fires, the battery is one of the primary sources of fire, so for a test to reflect real fire conditions, the fire should be initiated on the battery. In the case of conventional car fires, it is less likely for the fire to start in the fuel tank. The fuel tank will be involved in the combustion but at a later stage.

5. Test environment

The test environment can affect the burning of the vehicle. If the vehicle is burned in an enclosed space, the heat feedback from the hot layer and the hot surfaces can influence the burning rate of the vehicle. The experiment conducted by Lecocq et al. [37] was in a small enclosure, and the test results show that the PHRR of the vehicles tested was higher when compared to the test results of experiments conducted in large enclosures and open environments.

4.2.2 Vehicle THR

The fire severity of an EV and ICEV cannot be judged just by the comparison of PHRR. Comparison of THR of these vehicles will provide a better understanding of the fire severity.

Several EV and ICEV fire test results were analysed to evaluate the THR and PHRR for each class of vehicle (Small, medium, and large). The objective of this analysis is to find the THR contribution of the vehicle body. The vehicle body of an EV and ICEV has different parts (Figure 7 & Figure 8), and the THR from each of these vehicles could be different. By knowing the vehicle body THR and the THR of the fuel, the THR of a car can be predicted based on the classification of the vehicle and the fuel capacity.

In this analysis, test results of experiments conducted in tunnels and small enclosed spaces with forced ventilation are not considered as these fires will be more severe than those in the open air, and the measured HRR would be higher [82].

Test Results Not Considered for THR Analysis

The following test results were not considered for the analysis,

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Lecocq et al. [37] conducted a set of vehicle fire experiments in a small enclosed space with forced ventilation, similar to that of a tunnel. The PHRR, in general, was found to be higher when compared to other tests. For the EV fire, the ignition was started inside the vehicle compartment, and the battery was involved in the burning at a later stage. The EVs tested had smaller-capacity batteries. The battery capacity of the EVs tested was 16.5 and 23.5 kWh. For the ICEV fire, the fuel stored in the fuel tank and their involvement were not mentioned. Based on the test results, it was found that the PHRR and THR are similar for ICEVs and EVs. Here, the ICEV and EV have similar weights, but an EV is much heavier than its equivalent ICEV. It can be inferred that the ICEV is compared to an EV with a lower-capacity battery.

Vehicle tests conducted at NRC, Canada

EV, PHEV, and ICEV fire experiments were conducted by Lam et al. [32]. However, this data is not taken for analysis in this study as the exact capacity of the battery is not revealed. Moreover, the vehicles were burned only for 30 mins. In this case, the measured THR will be lower than the actual THR. Typically, EVs burn for approximately 60 mins.

Test Results Considered for the THR Analysis

The following test results were considered in this study. All of the tests were conducted in open/large enclosed spaces where the effect of heat feedback from the smoke layer is not relevant.

Vehicle tests conducted at Korea Conformity Laboratory (KCL)

Kang et al. [77] conducted a series of vehicle fire experiments at KCL. The test results are listed in Table 11.

Table 11: Vehicle fire test results [77]

Car type	**Weight (kg)**	**Type of fuel**	**Capacity**	**Source and location of ignition**	**PHRR (MW)**	**THR (GJ)**
Compact Crossover (Body)	1206	-	-	Propane burner- car bottom	7.8	7.5
Compact Crossover	1540	Battery	39 kWh	Propane burner- car bottom	6.5	8.4
Compact Crossover	1685	Battery	64 kWh	Single-cell heating inside the pack	7.2	9
Compact Crossover [1]	1320	Gasoline	38-50[2]	Compartment fire	7.7	8

Notes
1. The ICEV was identified as Hyundai Kona from the test images.
2. Fuel stored in the fuel tank was not mentioned. Hyundai Kona has a fuel tank capacity of 38 to 50 L.

Based on the test results, it can be observed that the PHRR of an ICEV is higher than an equivalent EV. However, the THR of EV is almost 1 GJ higher than ICEV. Even though the PHRR is lower, the THR is higher. In this test, the fire was initiated by inducing TR in a single battery cell. However, TR in a majority of the remaining cells occurred in the fire decay stage (after 40 mins). This can also be observed as spikes in HRR in the decay phase. This also exhibits the dependence of the PHRR on the ignition source.

Vehicle fire test conducted by Watanabe et al. [33]

Watanabe et al. conducted ICEV and EV fire in a large enclosed space (15 m×15 m×15 m). The test results are presented in Table 12.

Table 12: Vehicle fire test results [33]

Car type	**Weight (kg)**	**Type of fuel**	**Capacity**	**Source and location of ignition**	**PHRR (MW)**	**THR (GJ)**
Hatchback (Nissan Leaf)	1520	Battery	24 kWh	The vehicle body ignited with alcohol gel fire	6.3	6.4
Hatchback (Honda fit)	1275	Gasoline	10 L	“	2.1	4.3
Sedan (Toyota)	1360[1]	Gasoline	10 L	“	-	5.1

Car type	**Weight (kg)**	**Type of fuel**	**Capacity**	**Source and location of ignition**	**PHRR (MW)**	**THR (GJ)**
Luxury Sedan (Toyota Luxury)	1990[2]	Gasoline	10 L	"	-	7.4
Notes 1. The Toyota Sedan was assumed to be Toyota Corolla. 2. The Toyota Luxury Sedan model was not mentioned, and it was assumed to be Toyota Century II. The Kerb weight of 1990 kg was assumed [83]						

In all tests, the battery/gasoline was involved in the burning. The battery TR occurred before the PHRR. In the case of ICEVs, fuel did not leak from the fuel tank but instead vaporised and was burning from the fuel filler pipe.

The PHRR and THR of a hatchback EV with a 24-kWh battery capacity were found to be higher than the ICEV hatchback. The THR of a 24-kWh hatchback vehicle was compared to that of the sedan-type ICEVs (keeping the amount of fuel in the tank as 10 L), and it was concluded that the THR of both types of vehicles is comparable. However, it should be noted that the comparison is not made for a similar class of vehicles.

Vehicle fire tests- ETOX project [36]

The test results are presented in Table 13,

Table 13: Vehicle fire test results [36]

Car	**Weight**	**Type of fuel**	**Capacity**	**Source and location of ignition**	**PHRR (MW)**	**THR (GJ)**
Van	-	Diesel	44 L	Diesel pool fire under the vehicle	5.7	5.9
Van	-	Battery	40 kWh-80%	Propane burner-under the battery pack	7	5.2
Hatchback (Small family car)	1430[1]	Battery	24 kWh, 80%	"	5.2	6.7

Notes

1. The hatchback model was not mentioned. The assumed weight is based on the average of hatchback EV vehicles (Appendix)

The experiment was designed such that the battery fire peak and vehicle fire peak coincide to reproduce the worst-case scenario. The fire growth was faster for ICEV because of the pool fire used for the ignition. However, the pool fire, which was a representation of a fuel tank leak, burned out at an early stage, which could be the reason for the lower PHRR for the ICEV van. The THR was higher for the hatchback car, even though the battery capacity was lower; this was because the combustible content of the hatchback car was higher than that of the van.

HRR of Large (SUV) EV car

Fire test results of EVs are limited. Most of the fire testing of EVs is performed with small or medium-class vehicles. Fire Test results conducted in an open environment with large-type (SUV) EVs are not available. The only available test results for SUV EVs are from the experiment conducted by Sturm et al. [40] in a tunnel with ventilation arrangements as part of the BRAFA project. Hence, for analysis of Large EVs, these results were taken.

The result of this experiment is shown in Table 14.

Table 14: Vehicle fire test result [36]

Car	**Weight**	**Type of fuel**	**Capacity**	**Source and location of ignition**	**PHRR (MW)**	**THR (GJ)**
SUV	2235[1]	Battery	80 kWh	Seat fire, later TR was induced by a short circuit in all cells	10.5	12.5[2]

Notes

1. The Weight of the SUV is taken as the average of SUV vehicles (Appendix)
2. The fire was extinguished in the test, and the THR measured is not the actual THR. The HRR curve was extended based on the assumption of the burning duration (approx..70 minutes). The THR value is estimated from the area under this curve (Figure 22).

The experiments were conducted in a tunnel, and the validity of these results in a car park is uncertain. The smoke layer feedback would result in higher PHRR.

HRR was not experimentally measured but calculated from the mass flow. There exists an additional uncertainty in this approximation of HRR in this experiment.

In this experiment, the battery combustion has a significant contribution to the PHRR. TR is induced in all the cells of the battery pack at the same time, which results in a sudden peak in the HRR.

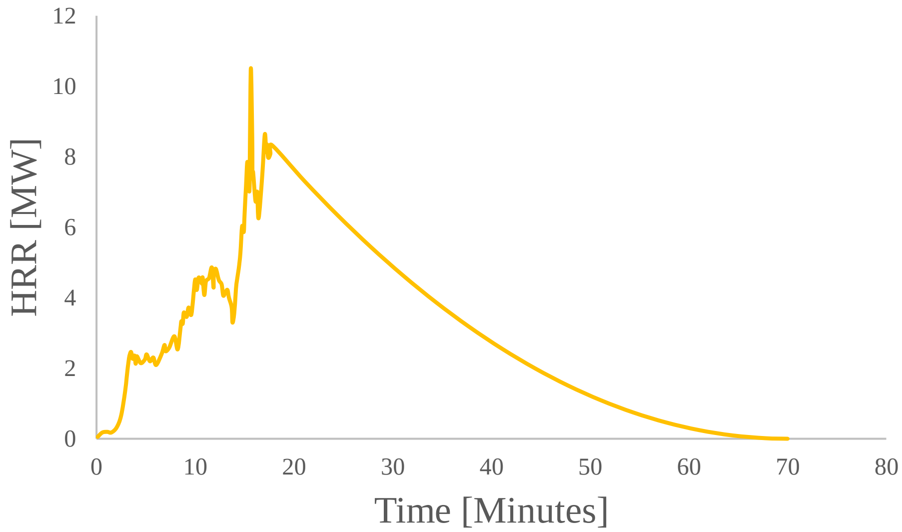

Figure 22: HRR curve of an SUV [40]

THR of the Vehicle Body

Based on the amount of fuel in each of the above experiments, the THR of the fuel (gasoline/diesel/battery) was determined using equations ***(13)*** & ***(14)***. The THR of the vehicle body is calculated as the difference between the measured THR and the THR of the fuel. The calculated THR of the fuel and vehicle body for different classes of vehicles is presented in Table 15.

Table 15: THR of the vehicle body

EV/ICEV	Source	Car type	Car Class	Weight (kg)	Vehicle (body & fuel)		Fuel capacity	Fuel THR (GJ)	Vehicle Body THR (GJ)
					PHRR (MW)	THR (GJ)			
EV	[33]	Hatchback	Small	1520	6.3	6.4	24 kWh	1.2	5.2
	[36]	Hatchback		1430	5.2	6.7	24 kWh	1.2	5.5
	[80]	Compact Crossover	Medium	1540	6.5	8.5	39 kWh	1.9	6.6
		Compact Crossover		1685	7.3	9	64 kWh	3.1	5.9
	[40]	SUV	Large	2235	10.5	12.5	80 kWh	3.9	8.6
ICEV	[32]	Hatchback	Small	1275	2.1	4.3	10 L	0.3	4.0
	[3]	Hatchback		1280	4.8	4.7[1]	20 L	0.7	4.0
	[84]	Sedan	Medium	1311	3.7	5.4[1]	-	-	5.4

	[80]	Hyundai Kona (Compact Crossover)		1320	7.7	8	40 L	1.4	6.6
	[32]	Sedan		1360	-	5.1	10 L	0.3	4.8
	[32]	Luxury Sedan	Large	1990	-	7.4	10 L	0.3	7.1

Notes

1. THR is calculated as the area under the HRR curve.

Based on the analysis results, the THR of the vehicle body was plotted against the vehicle kerb weight for both types of vehicles and is depicted in Figure 23. For both ICEV and EV, the THR increases with the kerb weight of the vehicle. A similar trend for the THR was also observed in the analysis conducted by Tohir and Spearpoint [85].

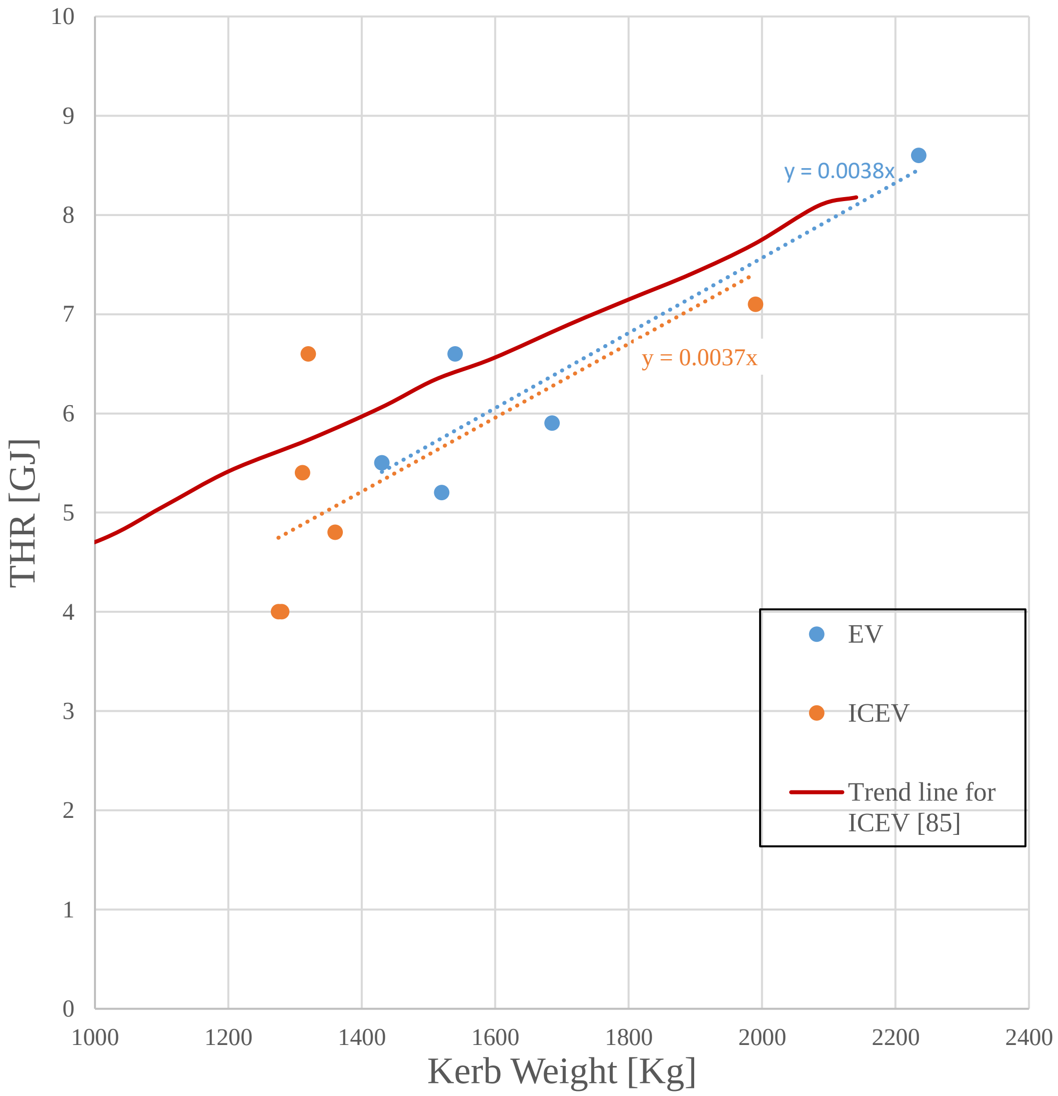

Figure 23: THR-Kerb weight for ICEV and EV body

For the ICEV, the trend line developed by Tohir and Spearpoint [85] predicts a higher THR for the same kerb weight. This is because the THR plotted by Tohir and Spearpoint includes the THR of the fuel as well.

On comparison of the THR-kerb weight trend line of ICEV and EV body, it is observed that the THR of both types of vehicles is similar.

Estimation of THR for Different Class of Vehicles

For the different classes of vehicles, the kerb weight and the fuel capacity vary. Based on the fuel capacity and the kerb weight, the THR for ICEVs and EVs for each class of vehicles is estimated and is presented in Table 16 & Table 17, respectively.

Table 16: THR of ICEVs based on vehicle class

Vehicle Classification	**Weight range (kg)**	**Vehicle Body THR (GJ)**	**Fuel capacity (L)**	**Fuel THR (GJ)**	**Combined THR (GJ)**
Small	770 to 1300	2.8 – 4.8	35 to 45	1.4 to 1.8	4.2 – 6.6
Medium	1301 to 1600	4.8 – 5.9	45 to 60	1.8 – 2.3	6.6 – 8.2
Large	1600 to 2385	5.9 – 8.8	60 to 90	2.3 to 3.5	8.2 –12.3

Table 17: THR of EVs based on vehicle class

Vehicle Classification	**Weight range (kg)**	**Vehicle Body THRR (GJ)**	**Fuel capacity (kWh)**	**Fuel THRR (GJ)**	**Combined THR (GJ)**
Small	1125 to 1530	4.3 – 5.8	16 – 50	0.8 – 2.4	5.1 – 8.2
Medium	1530 to 2000	5.8 – 7.6	50 – 80	2.4 – 3.9	8.2 – 11.5
Large	2000 to 2455	7.6 – 9.3	80 – 100	3.9 – 4.9	11.5 – 14.2

Based on the comparison of the above results, it can be inferred that the THR of EVs is significantly higher than that of ICEVs. The THR of a medium-class EV could be up to 40% higher than that of a similar-class ICEV variant.

4.2.3 HRR Curves for Small and Medium-Class Vehicles

The representative HRR curves for small and medium-class cars are presented in Figure 24. The HRR curves represent the fire growth after the initial ignition of the vehicle.

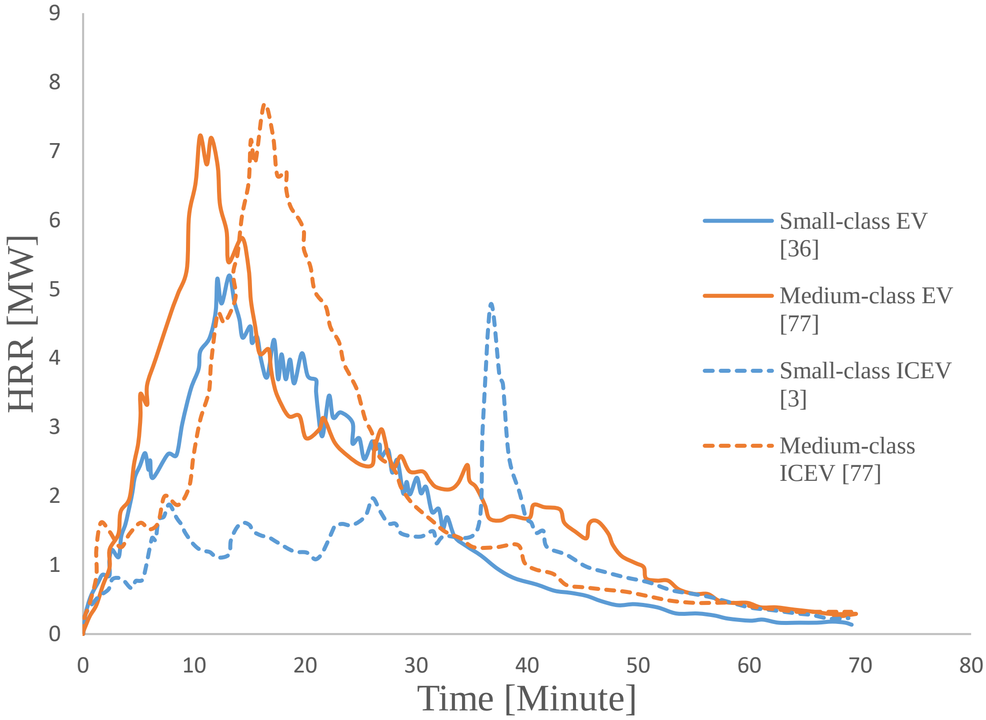

Figure 24: HRR curves of a small and medium-class EV and ICEV [3,36,77]

The PHRR and the growth rates for small and medium-class EV and ICEV are shown in Table 18.

Table 18: PHRR and Fire growth rate for ICEV and EV

	Source	Car class	Ignition Source	PHRR (MW)	Time to PHRR (s)	Growth factor (kW/s^2)
EV	[36]	small	Propane burner under the battery	5.2	786	0.008
	[77]	Medium	Heating a single cell inside the battery pack	7.3	632	0.02
ICEV	[3]	small	Engine fire	4.8	2202	0.001
	[80]	Medium	Compartment fire	7.7	978	0.008

The PHRR is highly dependent on the ignition method. For the ignition methods adopted in each of the tests, the PHRR of EVs and ICEVs are similar for each class of vehicle. The growth rate of EVs is much higher than ICEVs. The fire spread within an EV occurs much faster due to the jet fire from the battery pack heating the vehicle body parts at an early stage.

Chapter 5 Fire Spread Analysis

5.1 Methodology

5.1.1 Fire Spread- Point Source Model

The point source model (PSM) is a widely used model to predict the heat flux received at a distance r from the radiation source. This model assumes that the radiating source is a point source.

$$q_f'' = \frac{\dot{Q}\lambda_r}{4\pi r^2} \quad \textbf{\textit{(15)}}$$

Where $\dot{Q}$ is the HRR (kW), λ_r is the fraction of radiation received, and r is the distance (radial) from the point source to the target.

In the study conducted by Tohir et al. [26], the PSM was used to predict the ignition times of the second vehicle, and it was found that using a radiative fraction of 0.3 and the location of the point heat source at the far end of the vehicle predicts reasonable results. The same approach was used in this work to predict the HRR corresponding to the critical heat flux (10 kW/m^2). From the HRR curves, the time for ignition of the second vehicle can be estimated.

5.2 Analysis and Results

Once a car ignites in a car park, fire will spread quickly to the adjacent vehicles. In the UK, the parking slot is 2.4 m × 4.8 m [86]. The typical width of cars is between 1.2 m to 2.2 m. Based on the width of the cars, the distance between the two adjacent cars would be between 0.2 m and 1.2 m. In addition to the short distance between cars, car parks have a low ceiling level, which could cause the smoke layer to form and descend faster and cause rapid fire spread due to heat feedback from the smoke layer in a car park with no ventilation arrangements.

Fire spread will occur at a faster rate between EVs when compared to ICEVs. One of the main causes for the faster spread is the jet fire from the battery. The jet fire can extend up to 3.1 m and could cause the ignition of combustible body parts of the adjacent vehicle or can cause the TR of the battery pack of the adjacent EV, which would again result in a secondary jet fire. Based on the analysis presented in Table 18, the growth rate of an EV fire is much faster than an ICEV fire.

To evaluate the combined HRR of two cars burning, two scenarios, as described in Table 19, were developed for both EVs and ICEVs. The scenarios are illustrated in Figure 26 & Figure 25.

Table 19: Scenarios for fire spread analysis

Scenario	Description
1	Fire spreads from a medium-class car to a small-class car.
2	Fire spreads from a medium-class car to a medium-class car.

The width of medium-class and small-class vehicles are assumed to be 1.8 and 1.6 m, respectively. Based on the assumed widths, the distance between the cars parked in a standard parking slot in the UK will be 0.7 and 0.6 m, respectively.

Figure 26: Scenario 1

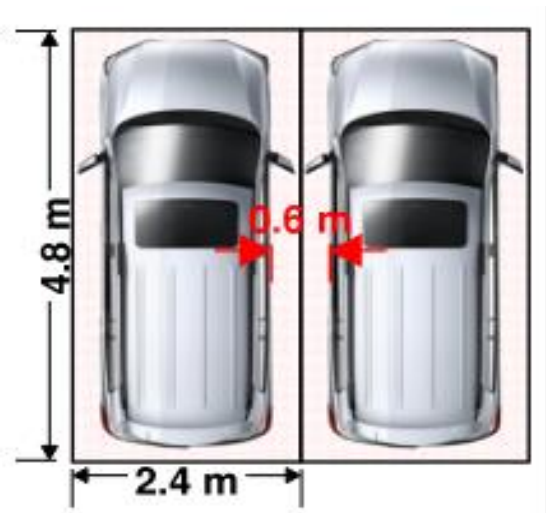

Figure 25: Scenario 2

5.2.1 Fire Spread Time Based on Heat Flux Measurement

In some of the vehicle fire test experiments, the heat flux was measured at the vehicle's sides, front, and rear. The fire spread from an EV, and ICEV can be compared based on these heat flux measurements. In the fire tests conducted by Kang et al. [77] and Watanabe et al. [33], the peak heat flux measurements were higher for EVs when compared to ICEVs of a similar class. The peak heat flux measured in these tests is listed in Table 20.

Table 20: Measured peak heat flux during vehicle fire tests

EV/ICEV	**Vehicle Class**	**Peak heat flux (kW/m^2)**		
		Front [3]	**Side**	**Rear**[3]
EV	Small[1]	41	61[4]	32
	Medium[2]	110	64[5]	59
ICEV	Small[1]	31	50[3]	25
	Medium[2]	56	71[5]	59

Notes

1. Fire test conducted by Watanabe et al. [33].
2. Fire test conducted by Kang et al. [77].
3. Heat flux sensor location at a height of 1.2 m and distance of 0.5 m
4. Heat flux sensor location at a height of 0.3 m and distance of 0.5 m.
5. Heat flux sensor location at a height of 1.2 m and distance of 0.7 m

In both tests, heat flux measurement on the sides of the EV reached the critical heat flux for ignition (10 kW/m2) faster than that of ICEV. The time at which the heat flux meter measured 10 kW/m2 (critical heat flux for ignition) for the small and medium-class vehicles was obtained and is presented in Table 21.

Table 21: Time of critical heat flux measurement

EV/ICEV	Vehicle Class	Distance of heat flux measurement (m)	Time of measurement of critical heat flux (Minutes)
EV	Small[1]	0.5	11
	Medium[2]	0.7	4.5[3]
ICEV	Small[1]	0.5	20
	Medium[2]	0.7	9

Notes

1. Fire test conducted by Watanabe et al. [33]
2. Fire test conducted by Kang et al. [80].
3. After the onset of the TR

Table 21 gives the approximate time of ignition of the second vehicle when it is parked at a distance of 0.5 to 0.7 m from the ignited vehicle. It indicates that, for both classes of vehicles, the fire spread to an adjacent vehicle parked next to an EV will occur twice faster when compared to a fire spread from an ICEV.

5.2.2 Fire Spread Time from Fire Spread Experiments

The fire spread time can also be obtained from fire tests involving two cars parked next to each other. Such experiments are very minimal, especially for EVs. The time of ignition of 2nd vehicle from such experiments is presented in Table 22.

Table 22: Time of ignition from fire test involving multiple cars

EV/ICEV	Car class	Ignition source	Distance between the cars (m)	Time of ignition of the second vehicle (minutes)
EV	Medium[1] (Sedan)	Battery TR by external heating	0.6	3.2
ICEV	Medium[2]	Engine fire	0.8	14
	Medium[3]	Passenger compartment fire	0.5	8.3
	Medium[4]	“	0.7	20
	Large[4]	“	0.3	9.5

Notes:

1. Based on the fire test conducted by Cui et al. [28]
2. Based on the fire test conducted by Terziev et al. [87]
3. Based on the fire test conducted by Park et al. [84]
4. Based on the fire test conducted by BRE [3]. Tests performed in an enclosed space. The impact of the smoke layer on fire spread is not considered in this analysis.

Based on the available fire spread test results, it is evident that the ignition from an EV fire could occur much faster compared to an ICEV fire.

5.2.3 Fire Spread based on PSM

The ignition time of the second vehicle for both scenarios can also be estimated based on the point source radiation model (PSM) for comparison with the ignition times presented in Table 21 & Table 22.

The distance (r) from the far end position of the first vehicle to the second vehicle was calculated as 2.5 m and 2.4 m for scenarios 1 and 2, respectively. The time of ignition of the 2nd vehicle based on the PSM is presented in Table 23.

Table 23: Fire spread time based on PSM

EV/ICEV	Time of ignition of 2nd vehicle (minutes)	
	Scenario 1	**Scenario 2**
EV	4.7	4.5
ICEV	10	9.8

Based on the PSM for both scenarios, the ignition time of the second vehicle from an EV fire is 4-5 minutes, and from an ICEV fire, it is 9-10 minutes. The results from this analysis also show that the ignition times of a second vehicle will be twice faster when parked next to an EV.

5.2.4 Combined HRR Curve for the Fire Spread Scenario

Based on the analysis results in Table 21, Table 22, & Table 23, the most onerous fire spread time from a medium-class EV is 3.2 minutes (at a distance of 0.6 m), while for a medium-class ICEV is 8.3 minutes (at a distance of 0.5 m). This fire spread time is assumed to obtain a conservative HRR curve for the fire spread scenario. The combined HRR curves for the two vehicles burning are presented in Figure 27. This Fire spread analysis assumes that the car park is well-ventilated and has a sufficient oxygen supply.

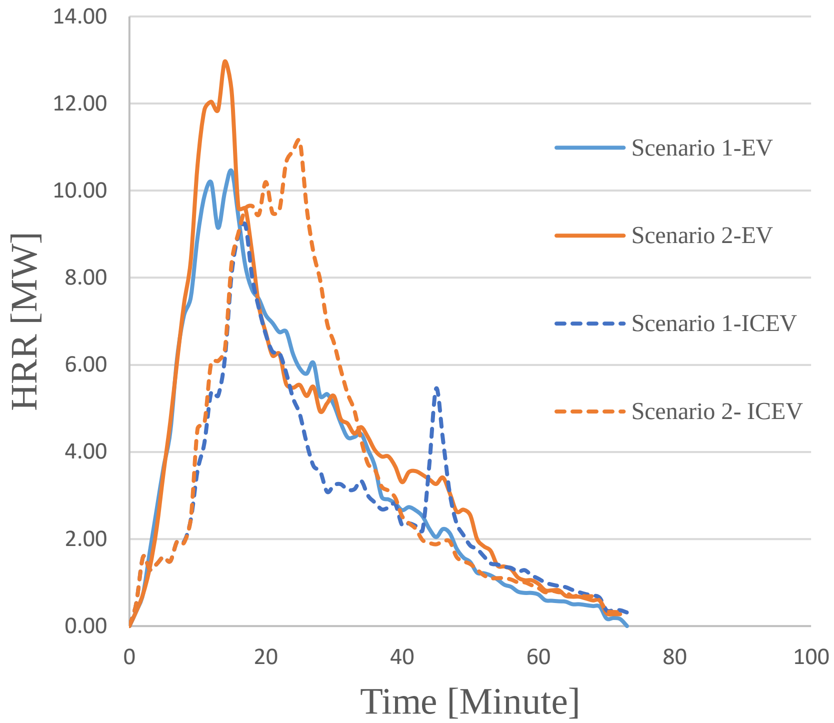

Figure 27: The combined HRR for the burning of two EVs

The PHRR and the THR for the two scenarios considered are presented in Table 24.

Table 24: PHRR and THR of two scenarios

EV/ICEV	**Scenario 1**		**Scenario 2**	
	PHRR (MW)	**THR (GJ)**	**PHRR (MW)**	**THR (GJ)**
EV	9.6	15.4	13	18
ICEV	9	12.7	11	16

The results show that both the PHRR and THR for two EVs burning are higher than for two ICEVs burning. The analysis has been carried out only for small and medium-class vehicles. For large-class vehicles, the difference in PHRR and THR will be significantly higher.

Even though the PHRR of an individual EV and ICEV is similar, the PHRR of 2 cars burning is higher for EVs. This is due to the much faster fire growth and fire spread rate for EVs.

From the experiments conducted by BRE [3], it was observed that when more than two vehicles are fully involved in the fire, a rapid-fire spread occurs. This was also observed in the Kings Dock car park fire incident; the firefighters reported that the fire spread from one car to another occurred every 30 seconds [88]. The onset of such rapid-fire spread will occur much earlier when EVs are fully involved in the fire when compared to ICEVs.

5.2.5 The fire spread until the arrival of the fire service

The average response time of fire services in England is 8 minutes 35 seconds [89]. For the analysis of fire spread before the arrival of the fire brigade, two scenarios were developed for each type of vehicle, as described in Table 25.

Table 25: Scenarios for fire spread analysis until the arrival of fire service

Scenario	**Description**
1	Fire spreads from a medium-class car parked at the end of a parking row.
2	Fire spreads from a medium-class car parked in between two cars.

Based on the assumption of fire spread time as discussed in section 5.2.4, before the arrival of fire service, for scenarios 1 and 2, the number of EVs burning would be three and five, respectively. For ICEVs, in scenario 1, the fire would spread to only one adjacent vehicle, whereas for scenario 2, the fire would spread to two vehicles.

The HRR curves for the two scenarios for EV and ICEV medium-class vehicles are depicted in Figure 28.

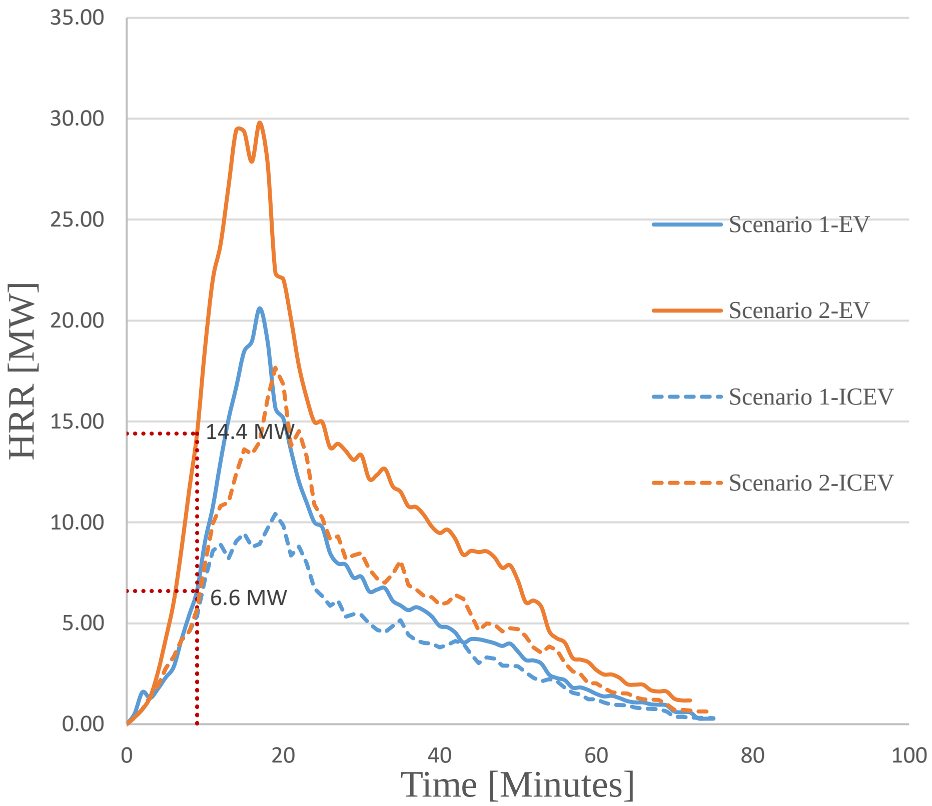

Figure 28: Combined HRR for EVs until the arrival of fire service

Such high peaks can be expected when two or more cars are involved in the fire. In the test conducted by BRE [3], when three ICEVs (two medium and one small class) were burned, the PHRR measured was 16 MW, which is comparable to the PHRR for scenario 2 in the case of ICEV. However, the PHRR for scenario 2 in the case of EVs is much higher than for ICEV. This is due to the faster spread and higher number of EVs being involved in the fire.

The PHRR and the THR corresponding to the fire service arrival time (approximately 9 mins) are listed in Table 26.

Table 26: PHRR and THR for the two scenarios

EV/ICEV	**Scenario 1**		**Scenario 2**	
	PHRR (MW)	**THR (GJ)**	**PHRR (MW)**	**THR (GJ)**
EV	6.6	1.4	14.4	2.6
ICEV	5.4	1.3	5.7	1.3

Chapter 6 Discussion

6.1 Building Regulations

The current building regulations for car parks were developed and revised based on a thorough analysis of the fire risks associated with conventional vehicles [3,88,91]. The adequacy of the building regulations for car parks to mitigate the risks imposed by EVs is uncertain.

The approved document B [90] is the regulatory guidance applicable for car parks in England and Wales. In addition, BS 9999 is also widely used as a regulatory guidance for buildings. The regulations for car parks recommended in the ADB are based on the ventilation of the car park. Car parks are subdivided into open-sided and enclosed car parks. The inherent assumption behind the regulations is the assumption that the fire spread probability is low in an open-sided car park.

During the period 2006 to 2009, the Building Research Establishment (BRE) carried out several fire tests on ICEVs and cars with LPG as fuel in car parks [3]. The purpose of this test was to analyse the effect of the fire risk imposed by the latest trends in car designs of that period, including plastic fuel tanks, and to suggest a revision of the ADB guidance with respect to the test results. The effect of EV fires was not analysed in this test series.

The current regulations for car parks were developed based on fire experimental data pertaining to cars available during the development of the regulations [91], which did not include EVs.

6.2 Fire resistance requirements

The fire resistance requirements for an open-sided car park suggested in ADB are based on the research conducted by The Ministry of Technology and Fire Offices' Committee Joint Fire Research in 1968 [88]. The research experiment concluded that a fire spread in a car park is very unlikely, and even if the spread occurs, the fire brigade would be able to control the spread with a response time of 3-4 minutes. The fire resistance values in ADB are based on this research, and it involves fire service intervention. Even though additional research experiments were conducted, such as the one undertaken by BRE, the fire resistance values are still unchanged.

In accordance with Table B4 of ADB, the minimum structural fire resistance required for an open-sided car park is 15 minutes, where the top floor is below 30 m and 60 minutes where the top floor is above 30 m. For an enclosed car park, the recommended structural fire resistance varies from 30 to 120 minutes, depending on the top floor height. A fire resistance period of 15 or 30 minutes implies that the structure is not meant to withstand burnout and assumes intervention by the fire service [92]. A fire resistance period above 30 minutes implies that the structure should withstand burnout.

As discussed in section 4.2.2, the THR of an EV could be 40% higher than an ICEV of a similar class. Higher energy released implies that the effect on the structure will be higher. The structural damage will be higher when an EV burns in a car park when compared to an ICEV fire. When two or more EVs are involved in the fire, the difference in THR and PHRR will be much higher than in ICEV fires. This would result in higher gas temperatures, rapid fire spread, and significantly higher structural damage.

After the arson fire incident that occurred in the car park in Alkmaar, Netherlands, which led to the complete burning of an EV and an ICEV in different locations of the car park, a higher degree of structural damage was observed on the ceiling above the EV than on the ceiling above the ICEV. The EV was a medium-class vehicle, while ICEV was a small-class vehicle, and the THR from the EV would have been much higher than the ICEV [93].

By the time of arrival of the fire brigade, the EV fire would have spread and would have involved a much higher number of vehicles when compared to a fire originating in ICEVs, as discussed in section 5.2.5. Hence, the effect on the structure would be much higher when a greater number of EVs are parked in a car park. This analysis is based on the average response time. However, the response time of fire service depends on several factors. In the Kings Dock car park fire incident, the fire crew arrived at the site 16 minutes after the fire occurrence [88]. Such longer response times would have a significant impact on the structural stability and would endanger the firefighting operation, especially in an open-sided car park with EVs.

The jet fire from the battery has a temperature of 700- 900℃ [31]. The jet fire emerging from the bottom of the vehicle could damage the floor of the car park if exposed to such high temperatures for a long duration. Firefighting of a single EV battery fire can take up to 50 minutes [63]. At the same time, an ICEV fire inside a car park can often be extinguished within 15 minutes (based on information from the London fire brigade). The structural effect due to exposure to high temperatures for such long durations should be further assessed.

EVs weigh much higher than ICEVs due to the heavy battery pack (see Table 9 & Table 10). Higher-capacity battery packs are used for better performance. With the increase in the number of EVs, existing car parks will be filled with EVs in the future. In addition, the weight of the large quantity of water used for fighting EV fire would add to the load on the structure. The added load would lead to a higher utilisation during the fire limit state, and structural failure could occur at an earlier stage.

Quick response is critical for the control of EV fire spread and to prevent structural damage to the car park, which is possible with early detection systems to detect TR.

6.3 Ventilation Requirements

In accordance with Section 11 of ADB, the ventilation system could be either natural or mechanical. For natural ventilation, the minimum vent area required is 1/40 of the total floor area. The mechanical ventilation system should be designed to function at 10 air changes per hour.

BS 7346-7 [81] provides recommendations for the design of smoke ventilation systems for car parks. Different types of ventilation systems are designed for car parks depending on the purpose they serve. A smoke and heat exhaust ventilation system (SHEVS) is used to protect escape routes for the safe evacuation of occupants. An impulse ventilation system is used to provide smoke-free access for the fire brigade for firefighting close to the fire origin.

The design fire recommended for the design of a ventilation system for a car park without a sprinkler system is an 8 MW steady-state fire.

For the ventilation system designed for the safe evacuation of occupants of the car park, the design based on 8 MW would still be suitable in the case of an EV fire. The evacuation of occupants occurs before the PHRR of an EV fire reaches 8 MW, even if the fire spread occurs. However, this also depends on the building design and is to be ensured for the specific building design.

For the ventilation system designed to provide smoke-free access for firefighters, the design based on an 8 MW fire would not be sufficient. As discussed in section 5.2.5, the PHRR of a fire involving EVs (scenario 2) would exceed 8 MW before the arrival of the fire brigade. A new design fire considering the fire spread across EVs should be considered for the design of such ventilation systems.

6.4 Sprinklers and Fire Suppression Systems

Generally, sprinkler systems are not expected to be provided in car parks in accordance with clause 18.11 of ADB. RC-59 recommends the installation of sprinklers for car parks with charging facilities [30].

Sprinklers are efficient in controlling an ICEV fire and in preventing fire spread between ICEVs [3]. The effectiveness of sprinklers for controlling EV fires is uncertain. If the battery is involved in an EV fire, the water from the sprinklers would not reach the fire source and would be ineffective in controlling the battery fire. Moreover, water application outside the battery pack was found to be ineffective in suppressing a battery fire. Battery fires require a huge amount of water to cool and prevent TR propagation through the cells inside the battery pack. A fire in an EV can spread within a short time to an adjacent vehicle, typically within 3-4 minutes. The activation sprinkler within this short time frame is doubtful, especially if the fire originated from the battery.

Water mist, due to its small droplet size, has good heat absorption properties. In the experiment conducted by the Danish Institute of Fire and Security Technology [94], it was found that a water mist curtain system installed between two cars may not have an impact on the battery fire but would prevent fire spread between EVs if it activates at an early stage of fire. Similarly, it was also found that a low-pressure water mist system installed on the ceiling level also has an influence in preventing fire spread in vehicle decks of ro-ro ferries.

The Drencher water spray system tested as part of the Lash fire project in a ro-ro deck of 5 m ceiling height was found to be effective in controlling the EV fire [12].

Experiments should be undertaken in a setup similar to a car park to investigate the effectiveness of sprinklers, a drencher system, and water mist systems on EV fires to update the regulations accordingly.

6.5 Fire Service Access Requirements

Firefighting of a single battery fire requires about 10000 L of water. This is much higher than the water storage capacity of a typical fire truck in the UK. This additional water source can be obtained from hydrants. In accordance with the guidelines in ADB, for buildings without fire mains, the hydrant should be located within 90 m of the entrance. An additional number of hydrants near the car parks or an alternative supply of water would be required for controlling EV fires. Further research into this area would be required.

6.6 Charging in car parks

A typical car park in the UK with charging facilities is shown below.

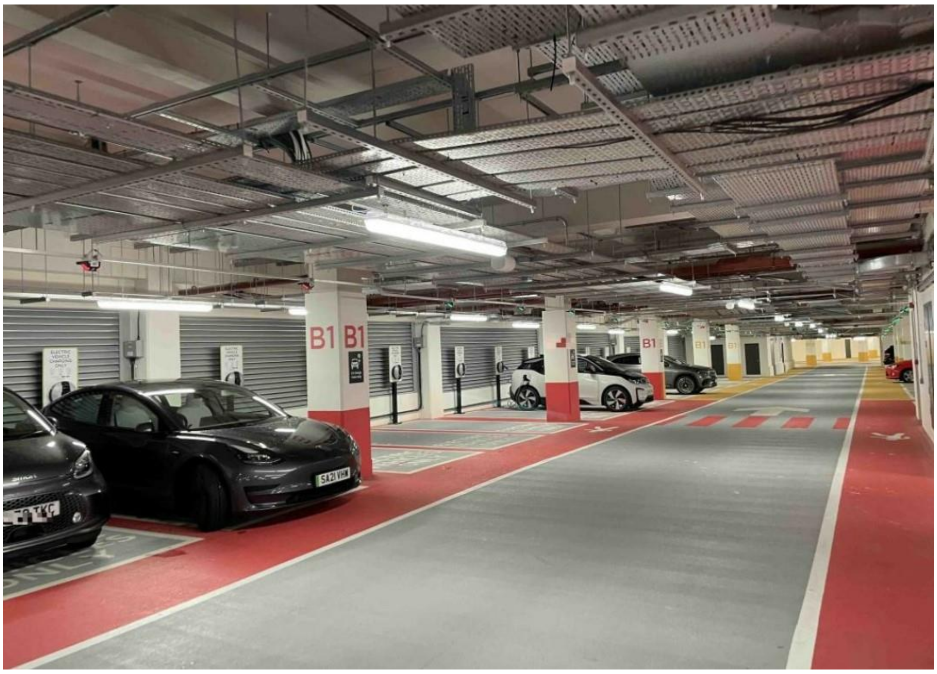

Figure 29: Typical car park with charging facilities

The analysis of the effect of SOC reveals that the type of risk is different at different SOC levels of the battery. At higher SOC levels, jet fires occur. In addition, the chances of TR and its severity are higher at higher SOC levels, whereas at lower SOC, VCE could occur after a TR, but the chances are lower. Providing charging facilities in car parks would lead to a higher SOC level of the EV batteries in car parks, leading to higher chances of TR and its severity if it occurs.

The charging process has a significant potential to initiate TR and fire. Based on statistics, 17% of all incidents occurred while or shortly after charging. The fast charging of EVs could create hot spots and could lead to short circuits. The increased fire spread for EVs in car parks, coupled with the increased fire ignition chances during charging, poses a significant threat to fire safety in car parks.

Currently, the regulation for charging an EV in a car park is based on RC-59. DC and AC charging is to be clearly differentiated. It recommends that all parking slots in charging areas be designed for disabled users, which includes a transition zone (min 1200 mm). It is recommended that the charging areas should be separated from other areas by a minimum 60 and 120-minute fire-resisting separation in above-ground and basement car parks, respectively. Any storage near the charging areas should be at a distance of at least 6 m.

The increased distance between the EVs and the increased fire resistance could benefit in improving the condition. However, further assessment is required to analyse whether the increased safety provisions are adequate to mitigate the increased fire risk during the charging of EVs in car parks.

6.7 Distance Between EVs in a Car Park

In accordance with the British parking association, a parking slot should be 2.4 x 4.8 m. The roadway width should be at least 6 m. With the present parking slot dimensions, the distance between two adjacent vehicles would be between 0.2 to 1.2 m (Section 5.2).

The fire spread between EVs would occur rapidly in a car park due to the short distance between the vehicles. The severity of the fire involving multiple EVs would pose a threat to the structure and to the safety of firefighters. Based on radiation calculations, the safe distance for an adjacent vehicle was found to be 3.8 m. Increasing the distance between two EVs would make the fire spread less severe and would improve the fire safety of car parks. During the fire incident that occurred in Alkmaar, Netherlands, it was observed that both EV and ICEV fire did not spread to adjacent vehicles due to the vacant parking slot in between the cars (distance of 4 m in between the cars) [95].

Considering the safe distance based on the radiation calculations, a distance higher than 4 m would not cause fire to spread to adjacent vehicles. However, this would have a significant impact on the cost and parking slot availability. The most appropriate safe distance could be decided based on a cost-benefit analysis.

6.8 Uncertainties and Limitations

The manufacturing date, i.e., the age of the vehicles, is not considered in the likelihood assessment. The likelihood of fire ignition could be higher for an old vehicle. The likelihood assessment is also limited by the lack of statistical data pertaining to EV and ICEV fires in the UK.

In this work, the 40 most commonly used EVs and ICEVs are only considered. The highest battery capacity considered was 111 kWh (Table 27). There are EVs with higher battery capacity, such as Tesla Roadster (210 kWh), for which the jet fire could be significantly longer and would radiation would be higher.

The jet fire emerges from the battery intermittently, which is not accounted for in the radiation calculations. However, for a conservative peak heat flux prediction a continuous jet flame assumption is reasonable.

In the radiation analysis, the flames from the tyres of the vehicles are not considered. The predicted radiative heat flux would be slightly lower. Moreover, the radiation analysis is carried out only in the lateral direction.

The fire test results of EVs are limited when compared to ICEV. There is an uncertainty in the THR analysis performed based on the limited data, particularly for a large-class vehicle. The study does not consider minivans and other types of EVs parked in car parks. The THR and the fire spread of these vehicles could be different. For minivans, the THR will be lesser than a small-class EV [36].

The fire spread analysis was performed only for medium and small-class EVs. Large-class EVs are not considered due to the lack of availability of HRR curves. The fire spread for a large-class EV would be higher and its implications on the structure would be greater.

The PSM used for the fire spread analysis assumes the fire as a point source. This method is valid for an ICEV fire [26]. However, the validity of this method for an EV fire is uncertain due to the additional jet fire, which is not taken into account.

However, in this study, an onerous fire spread time based on experimental results and the PSM is considered.

The fire spread analysis is partly based on the test results of experiments conducted in open/large enclosed spaces, where the effect of the smoke layer is not relevant. However, in car parks, due to the low ceiling height, the radiation from the smoke layer would result in faster fire spread and higher PHRR.

6.9 Future Work

Further research into certain aspects explored in this study can improve the current knowledge of the subject. Some of the future works possible are identified and are discussed below.

Radiation analysis in the longitudinal direction, based on the assumption of flame shapes from the engine compartment, could be performed to evaluate the safe distances in this direction [34].

The radiative heat flux and the safe distances predicted in this study could be compared with CFD simulations of an EV fire with consideration of the jet fires from the battery. Such simulations can also be performed to assess the time available for safe evacuation and for fire brigade intervention in relation to EV fires in car parks [96,97].

Stacker car parks are widely being used in large cities with parking space limitations. Rapid fire spread occurs from the lower vehicle to the vehicle parked above [3]. EVs parked in such arrangements could worsen the situation. The additional risks associated with EVs in stacker car parks require further evaluation.

Chapter 7 Summary and Conclusions

There has been a notable rise in the production and sales of Electric Vehicles (EVs) over recent years. The increasing popularity of EVs has resulted in a higher presence of EVs in car parks, contributing to additional fire risks and endangering the overall fire safety of car parks.

There are significant disparities in the fire risk associated with an EV and Internal Combustion Engine Vehicle (ICEV). The difference is primarily attributed to the use of lithium-ion batteries in EVs. Thermal Runaway (TR) of a battery could lead to the release of toxic and flammable gases. The jet fire emanating from the battery, which could extend over 3 m from the vehicle, leads to increased radiation and faster fire spread. The venting of the battery after a TR releases various toxic gases, and the concentration of these gases, particularly hydrogen fluoride, is significantly higher when compared to conventional vehicle fires. TR of the battery could result in the formation of a vapour cloud and potentially lead to a vapour cloud explosion if the conditions are favourable. Moreover, the practical challenges in extinguishment of an EV fire, particularly inside a car park, exacerbate the conditions.

Charging an EV in a car park increases the fire risk of an EV. Statistical data indicates that charging a battery has a significant potential to initiate TR. Providing charging facilities in car parks would lead to a higher SOC level of the EV batteries in car parks, leading to higher chances of TR and its severity if it occurs. Moreover, fast charging of EVs increases the chances of short circuits inside the battery.

The likelihood of fire ignition of an EV is not lower than that of an ICEV. The evaluation of the likelihood of fire ignition revealed that the chances of an EV fire are higher than that of an ICEV when the likelihood per 100k vehicles of each type is compared. However, both the distance travelled, and the number of vehicles of each type should be considered for an accurate assessment of the likelihood of fire.

The distance between two adjacent EVs parked in a car park should be increased to enhance the fire safety of car parks. The radiation analysis based on the assumption of the flame shapes for compartment, spout and battery jet flame indicated that the radiation from an EV fire is significantly higher than from an ICEV fire near the vehicle. The peak heat flux from an EV fire at a distance of 1 m is approximately 1.6 times higher than that of an ICEV fire. Moreover, the firefighting operation of an EV fire should be carried out at a farther distance.

The Fire spread risk is significantly higher for an EV. The fire spread analysis based on fire test results and the point source model stipulates that the fire spread occurs at a much faster rate for an EV. Due to the rapid-fire spread, an EV fire would spread to involve a greater number of vehicles before the arrival of fire service.

EV fires would lead to greater structural damage and pose a greater threat to firefighters, especially when multiple EVs are burning. The analysis of the Total Heat Release (THR) of EVs and ICEVs revealed that the THR of an EV is substantially higher than that of a similar class ICEV. For a medium-class EV, the THR could be up to 40% higher than its equivalent ICEV variant. The combination of faster fire spread and a higher energy release per vehicle would result in a greater impact on the structure when multiple EVs are burning.

The existing building regulations for car parks should be revised to address the risks associated with EV fires. The analysis of EV fire risks indicates that the fire resistance requirements should be enhanced, particularly for an open-sided car park. New design fires for the design of ventilation systems should be introduced. The effectiveness of suppression systems should be reassessed based on experimental analysis. Moreover, the standard parking slot dimension should be reviewed in light of EV fires. Furthermore, an assessment of the existing regulations pertaining to the charging of EVs in car parks is essential to analyse their adequacy to mitigate the heightened fire risk during the charging of EVs in car parks.

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Appendix

Table 27: Details of most commonly used EVs in the UK [80,98]

EV	Kerb Weight (kg)	% of licensed vehicles	Battery capacity (kWh)	Width (m)
Smart Fortwo	1125	0.8	19	1.66
Mitsubishi I-Miev	1160	0.3	16	1.47
Smart Forfour	1200	0.4	17.6	1.55
Volkswagen Up	1235	0.4	36.8	1.65
BMW I3	1345	4.9	42.2	1.78
Mini Cooper	1365	1.7	32.6	1.82
Fiat 500	1405	0.5	42	1.68
Volkswagen Golf	1485	2.4	35.8	1.79
Nissan Leaf	1505	20.7	40	1.79
Honda E	1527	0.3	35.5	1.75
Vauxhall Corsa	1530	1.5	50	1.77
Peugeot 208	1530	1.3	50	1.75
MG 5	1562	0.9	50.3	1.82
Renault Zoe	1577	7.7	55	1.79
Vauxhall Mokka	1598	0.5	50	1.79

EV	Kerb Weight (kg)	% of licensed vehicles	Battery capacity (kWh)	Width (m)
Hyundai Ioniq	1602	2.0	40.4	1.89
Citroen C4	1616	0.3	50	1.83
MG ZS	1620	2.3	72.6	1.8
Peugeot 2008	1623	1.2	50	1.77
Mazda Mx-30	1720	0.3	35.5	1.79
Kia Niro	1739	3.8	69	1.83
Kia Soul	1757	0.9	67.1	1.8
Hyundai Kona	1760	2.4	67	1.8
Tesla Model 3	1900	13.3	82	1.85
Volkswagen ID3	1952	2.7	82	1.81
Tesla Model Y	1995	1.0	82	1.92
Polestar 2	2000	0.9	111	1.86
Kia EV6	2015	0.3	77.4	1.88
Mercedes EQA Class	2105	0.8	78	1.83
Tesla Model S	2160	5.6	100	1.99
Mercedes B Class	2175	0.3	70	1.83
Jaguar I-Pace	2208	4.2	90	2.01

EV	Kerb Weight (kg)	% of licensed vehicles	Battery capacity (kWh)	Width (m)
Audi Q4	2215	0.6	82	1.87
Ford Mustang Mach-E	2238	0.5	75.7	1.88
Volkswagen ID4	2239	0.7	82	1.85
Skoda Enyaq	2255	0.5	82	1.87
BMW IX3	2260	0.5	80	1.89
Porsche Taycan	2395	1.3	93.4	1.97
Tesla Model X	2455	2.4	100	2
Mercedes EQC Class	2495	1.5	86	1.88
Audi E-Tron	2695	2.9	95	1.98

Table 28: Kerb weight of commonly used ICEVs in the UK [72]

ICEV	Kerb weight (kg)
Citroen C1	770
Ford Ka	846
Hyundai I10	921
Fiat 500	960
Ford Fiesta	979

ICEV	Kerb weight (kg)
Vauxhall Corsa	980
Peugeot 208	980
Volkswagen Up	980
Nissan Micra	1037
Audi A1	1090
Peugeot 107	1180
Mini One	1225
Audi A3	1225
Honda Jazz	1228
Mini Cooper	1230
Peugeot 207	1231
Volkswagen Golf	1264
Vauxhall Astra	1265
Toyota Yaris	1290
Nissan Qashqai	1300
Toyota Corolla	1360
Volkswagen Passat	1454
Ford Mondeo	1456

ICEV	**Kerb weight (kg)**
BMW 3 Series	1545
Audi A4	1555
Ford Kuga	1564
BMW 5 Series	1595
Honda CRV	1614
Land Rover Freelander	1805
BMW X3	1875
BMW X5	2295
Land Rover Discovery	2298
Land Rover Range Rover Sport	2385