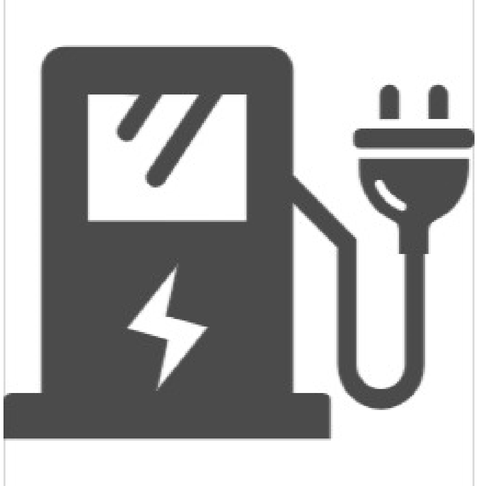
EV Risk Assessment



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Summary

This report for the Australian Building Codes Board (ABCB) describes a first-pass, engineering assessment of the fire risk of a carpark populated by internal combustion engine vehicles (ICEV) compared to the same carpark populated by Electric Vehicles (EV) and their charging equipment. The findings are to help us understand if EV charging facilities can be accommodated under National Construction Code (NCC) provisions for the fire safety design of carparks for Class 2 to 9 buildings.

There is no persuasive evidence at present to show EV fires are significantly worse than ICEV fires, or that EV fire rates are significantly higher than ICEV. EV charging equipment is not expected to have a significant impact on carpark fire rates or fire severity. The cautious conclusion is NCC requirements do mitigate the hazards and risks of EV charging in building carparks. However, emerging knowledge about EV fires must be kept under review in the following key areas.

- Battery fires are linked to battery age and state of charge (SOC), so as the EV fleet ages, carpark fires from EV charging may become more frequent.
- EV fires could prove worse than ICEV if new EV models with larger batteries are tested.
- EV fires have distinctive features with implications for firefighting intervention.
    - EV batteries need to be cooled by firewater for extended periods, possibly up to days, to be sure of controlling and eventually extinguishing the fire.
    - EV fires produce more smoke and toxic gas, including notable quantities of hydrogen fluoride, which will be a significant health hazard for firefighters.

NCC provisions for carpark fire safety design were informed by research last century showing fires largely confined to single vehicles and causing only local damage. Australia’s experience has backed in that research. Carpark fires are infrequent, multi-car fires rare, fatalities and injuries almost unknown, structural damage limited, and fire spread to other premises of little concern. Carpark fires have been the epitome of low risk; a well-understood hazard with low frequency and low consequences that is managed adequately by long-established and effective controls.

But recent major carpark fires give cause for unease. Modern cars cause more severe fires with greater propensity for fire spread. Major carpark fires are more likely, and the conditions for a major life loss event are more readily created. It is not certain that carpark fire safety design standards remain fit-for-purpose. Any safety margins in current provisions may have been eroded by modern car designs. It would not be prudent to wait until rising accident trends confirm this before acting.

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1. Introduction

1.1. Context

Electric Vehicles (EV) are predicted to displace internal combustion engine vehicles (ICEV) as the dominant mode of private transport. By 2030, it is expected that 50% of all new vehicle sales will be EV, rising to 100% by 2040 [1]. Carparks will see their proportions of EV vehicles rise in line with the growth in EV sales. Additionally, carparks are expected to introduce (in existing) or incorporate (in new) battery charging equipment to service the growing EV fleet.

This transformation will affect existing buildings and those being constructed from 2022. The Australian Building Codes Board (ABCB) is therefore proposing to introduce changes to the NCC to make it easier to retrofit EV supply equipment (EVSE) in Class 2 to 9 Buildings. The introduction of EV and EVSE to carparks is anticipated to present a different type of fire hazard to that posed by ICEV.

There is a need to understand if EV pose any risks to a building when parked and charging in a building carpark.

1.2. Goals

The goals are to establish if EV and EV charging equipment pose different fire risks to ICEV in carparks, if the differences are significant, and if they have significant implications for the adequacy of NCC provisions.

1.3. Method

This is an engineering risk assessment, and the report is framed around the Australian Risk Management Framework [2]. The assessment has qualitative, quantitative and control perspectives.

The term "risk" in the context of this study means risk of vehicle fire and multi-vehicle fire spread, but it does not mean formal metrics for life safety risk such as individual risk or societal risk.

The assessment is based on a literature search and review of material relevant to:
- Reports and investigations into major carpark fires;
- Research into the nature and severity of EV and ICEV fires;
- Data on fire frequencies for carparks, EVs, EV charging equipment and ICEV;
- Fire safety standards for carparks and vehicles; and
- Facilities for Fire Brigade intervention in carpark fires.

The literature search has considered open sources and fire research publications, but this discovery stage has been limited by the short timescales available for the study. It is not intended to be an exhaustive search and this report is not intended as a state-of-the-art review. The author has decided what references to select and quote as sources.

1.4. Exclusions

The assessment excludes carparks that are not buildings or structures and ignores (for example) situations like the 2010 Stansted Airport long-term parking fire that destroyed 26 cars in an open-air carparking facility with a capacity of 26,500 vehicles, or the 2020 South West Florida Airport fire that destroyed 3,500 rental cars parked across a 15-acre overspill area.

The assessment excludes:

- commercial charging facilities that are not provided as part of a carpark, such as EV charging networks outside shopping centres;
- domestic charging installations for the family car at home;
- charging via a standard domestic 10A socket that is not dedicated EV charging equipment; and
- Direct DC charging equipment.

The assessment excludes equipment such as solar panels or other renewable energy sources installed as dedicated local electricity supplies for EV charging stations. It also excludes commercial-scale battery energy storage systems (BESS) provided for the same purpose. (These arrangements are certainly being planned by developers, but no working examples were found for this study.)

The assessment is confined to presently available charging equipment and excludes technology in development, such as Vehicle-to-Grid (VTG) technology [6] – where the energy in EV batteries is returned to the grid via the charging connection.

The assessment does not consider the specific chemistry of lithium-ion battery types. This is a known risk factor e.g. lithium-manganese-oxide (LMO) batteries perform significantly worse in fire tests than other types, like lithium-iron-phosphate (LFP) or lithium-nickel-oxide (LNO). Lithium nickel manganese cobalt oxide appears to be gaining popularity for EV batteries. There was not enough time to allow this important factor to be investigated.

2. Carparks, EVs & Fires

2.1. Origins

The histories of electric vehicles and of multistory carparks date back to the earliest days of the motor car. In 1901, a British motoring journal 'The Autocar' published an article [**3**] from which the following was extracted.

> *"The Queen's electric carriage is a victoriette seated for two persons. It is upholstered in dark green morocco, with folding hood of polished grain leather, lined with dark green cloth. The side panels are, as will be seen from the illustration, very gracefully curved, and the front dash is also curved, and of patent leather, as on the wings. The colour of the car panelling is rose madder lake, the remainder of the body being black, picked out with deep red lines. The carriage has 28in. bicycle pattern wheels, with 3in. pneumatics, and weighs, together with the battery, about 12 cwt. The capacity of the battery is forty miles on the one charge, and a speed of twenty miles an hour can be attained. We understand that Her Majesty is in the habit of driving the vehicle herself, and is delighted with the ease and simplicity of control and manipulation.*
>
> *The carriage was supplied to H.M. by the City and Suburban Electric Carriage Co., of 6, Denman Street, Piccadilly Circus, who also have a number of orders in hand from members of the nobility of both sexes. The depot of the company is very central, and consists of a new building of seven floors, having a total area of 19,000 square feet, with accommodation for over a hundred carriages. The firm not only supply the carriages, but undertake for a fixed sum per annum to keep them in full going order, charge batteries, and, if desired to do so, they also send out a driver with each car. All the owner has to do when he or she wants the electromobile is to telephone to Denman Street, and in a few minutes it will arrive ready for work in the charge of a competent driver."*

The City & Suburban Electric Carriage Company built EVs between 1901-05 and also built two multistorey carparks in the centre of London to house its fleet of 330 EVs. These may have been the first multistorey carpark structures ever built. Unfortunately, there is no information about the fire safety design of those structures, how they were considered under London's building regulations at the time, or about any fire incidents. But it is reasonable to think that – being the first of their kind – their design had a significant influence on subsequent carpark developments.

2.2. Present Day

Vehicle fires and carpark fires were studied last century and led to a general expectation for single vehicle fires in carparks, with a small potential for multi-vehicle spread. Carpark fire safety design standards in Australia and other countries reflect that work. The notional basis of current NCC provisions for carparks is a multi-vehicle fire. This was established from full-scale fire tests by BHP [7] in the 1980s. The tests used Australian sedan cars and typically involved fire spread to 3 or 4 cars. The tests were focused on structural steel construction methods, passive fire protection and sprinkler protection. The following comment from a carpark design guide of the time is typical of prevailing attitudes.

> *"Irrespective of the benefits obtained from the carpark levels being sprinklered… it is known that fires in carparks will tend to be localised due to the fact that each car body will act as a form of enclosure and limit fire spread. Thus, the overall stability of the building is unlikely to be affected, even in the very unlikely circumstance of sprinkler failure."* [7].

Incident data has tended to support this view. No records of major carpark fires with structural collapse, injuries or fatalities in Australia were sighted for this risk assessment. Overseas studies have found consistently that carpark fire injuries are rare (USA 1972, USA 1993, France 2001, NZ 2004, USA 2008, USA 2020) and fatalities are even rarer – in fact none were recorded in any of these studies. Over the period 2014-18, Ahrens (NFPA) found the USA had an annual average of 1,858 vehicle fires in commercial parking facilities, causing on average 20 injuries but no deaths.

However, since 2000, an increasing number of countries have become concerned that modern cars present a new, more serious fire hazard. Recent research (covered in Section 4) contradicts past assumptions about car fire intensity and car fire spread. Modern-day car fires are more intense in terms of peak heat release rate (HRR) and total heat output. It is no longer tenable to think car fires are unlikely to spread to adjacent vehicles, or that fire spread will be limited to just 5 to 7 cars.

This view appears to tally with an apparent (but not yet confirmed) rising trend in major carpark fires since 2000, including in Australia. A selection of these events is provided in **Table 1**.

Table 1: Significant Carpark Fires since 2000

Location	Year	Type & Size	Fire Size (cars)	Control Time (Hrs)	Casualties/ Damage	Notes
Schiphol, NED	2002	?	51	?	Unknown Partial collapse of heavy RC structure	Fully-occupied, new cars with full tanks
Bristol, UK	2006	Ground floor 38-bay resident carpark	22	?	1 fatality Building uninhabitable	Brand new aged care facility; 77 rescued
Apelaar, NED	2010	Underground, 2-level, 4,500m2 ea.	26	7	Nil Significant RC damage	
Markenhoven, NED	2013	Below ground, 2-level, 11,500m2 ea.	5	5	Nil Local damage	Low occupancy, fire spread in 1 hour, skipping empty bays,
Cork, IRE	2019	5-storey, adjacent shopping centre	60	12	Steel structure destroyed, Shopping centre closed	Fuel tank exploded. Carmaker Opel sued over known fire hazard with Zafira B model
Bergen, NOR	2015	Ground level resident carpark, 2,000m2	9	3	Nil Local damage	Required ladder evacuation of residents
Liverpool, UK	2017	6-storey, 1,600 bays, 24,000m2	1,400	36	Nil Structure destroyed	Full occupancy, fire spread c.30 cars in 1 hour, fire brigade stopped spread to adjacent buildings
Stavanger, NOR	2020	5-storey airport open carpark	200-300	26	Nil Partial collapse, airport closure	Fully occupied, fire spread c.10 cars in 1 hour. Opel Zafira named as source
Kulmbach, GER	2020	underground	1	?	Nil Local damage	ICEV fire but still led to ban on EV parking
AUSTRALIA						
Chatswood NSW	2018	Resident CP	1	1	‘Severely damaged’	8-storey apt bldg
Chadstone, VIC	2018	Shopping centre	11	?	Significant damage	‘car exploded’
Fremantle, WA	2021	Apt basement	4	2	One smoke injury	
Geraldton, WA	2021	Shopping centre carpark under shade	7	1	Nil Shade structure destroyed	Hot & windy, customers tried to save own cars

Some of these fires have involved structural collapse, fire spread to adjacent buildings, and dozens of lives put at risk. And deaths have occurred.

- In 2004, a basement garage fire in Gretzenbach, Switzerland led to structural collapse that killed 7 fire fighters. The car fire was not thought severe enough to have caused serious structural damage; collapse may have been related to excessive loads from the gardens and playground built above the garage roof.
- In 2006 in Bristol, UK, in a brand-new aged care apartment development (‘Monica Wills House’ [19]) a fire in the residents’ carpark on the lower ground floor spread quickly to involve 22 cars. Smoke and flames affected all 5 apartment levels above, and 77 occupants were rescued by fire brigade actions. One elderly resident on an upper floor subsequently died in hospital a week later. In a public statement, the CFO said this.
    - *“I am absolutely convinced that had it not been for the sprinkler system and fire safety measures in the building, alongside the prompt arrival of firefighters on the scene, we would have seen scores of lives lost at this incident."*

This new potential for large life loss was also seen with the Liverpool Echo fire in 2017. This was a large multi-storey carpark with a capacity of 1,600 vehicles. It served a large shopping centre and an entertainment venue. The carpark was full due to the combination of Christmas shoppers and people attending a popular equestrian event. The fire involved approximately 30 vehicles after one hour then spread to all levels. A strong wind helped encourage the fire spread. Floor drains and other plumbing details contributed to the spread of leaked fuel. Advertising hoardings interfered with fire brigade intervention. The fire could not be controlled, and fire brigade efforts focused instead on stopping spread to nearby apartment buildings.

There was no general structural collapse, but the carpark was effectively destroyed, along with the estimated 1,400 vehicles in it at the time. However, in the subsequent investigations, it was pointed out that the outcome could have been much more serious.

- If the fire had happened on a lower level during peak exodus, with hundreds of customers heading to their cars, and all levels and exit ramps clogged by queueing cars, then there was clearly the potential for multiple fatalities.
- If the wind direction had been towards the adjacent buildings, then it would have been difficult to avoid fire spread into a general conflagration.
- The fire brigade would have faced a far worse situation – lives at risk inside and outside vehicles across multiple smoke-logged levels, plus fire spread to occupied apartment buildings.

2.3. EV Charging Infrastructure

Australia has had a relatively small penetration of EV to date, but that is expected to change rapidly, irrespective of government policies. Major car manufacturing countries have already adopted policies that ensure EV choice in Australia will grow rapidly, while ICEV choice lessens. EV infrastructure is building in all States and Territories in anticipation, and EV charging solutions are being marketed strongly across the country.

- In Canberra in October 2020, an apartment building strata committee retrofitted a charging station in their basement carpark to serve residents and visitors. This is an example of what is expected to become a significant market in retrofitting EV infrastructure to existing apartment developments and commercial carpark structures.
- A new apartment block in Sydney's Lane Cove in 2020 offered 10 buyers their own EV charging stations – but in response to demand, ended up installing fast charging stations for all 40 apartment car bays. EV infrastructure is being adopted widely into new private and commercial property developments.
- The first 'destination charging' network station was installed in Sydney in 2010. Westfield installed 40 stations in 10 of their business locations across the country in 2017. Network installations – at shopping centres, hotels, restaurants and other venues – are becoming common across Australia.
- 'Workplace charging' is not common in Australia yet, but it is expected to grow as part of a company's efforts towards its sustainability goals, as well as providing employees with an attractive new benefit.

2.4. Charging Equipment

Charging infrastructure essentially consists of an electrical supply from a charging point to the EV via a captive electrical lead with plug that connects to the EV's charging socket. (The EV's own lead is usually reserved for domestic charging and may not be rated for higher powered stations.) A board supplies either AC or DC electrical power to the EV, and the power rating of the charging station dictates charging time. One equipment categorization (broadly in line with the four modes given in IEC61851) is shown in **Table 2**. Note that this area of EV technology is still developing rapidly, for example new, 'ultra' high-powered DC charging equipment is now available that requires an active liquid cooling system to manage heat dissipation.

Table 2 – EV Charging Equipment Types

Type	Description	Comments
Level 1	Standard domestic AC 'trickle charging'	Single phase, 10A or 15A, (30kWh in c.13 hrs) (excluded from assessment)
Level 2	Standard commercial AC, slow charging,	Single phase, 32A, <50kW (30kWh in c.4 hrs), cord has pilot function, circuit breaker
Level 3	'Fast" commercial AC	3-phase, >50kW supply, protection built-in to charging station
Level 4	'Fast/Ultra Fast' commercial DC, off-board AC/DC convertor	'ultra-fast charging', 75/150/350/475kW versions (30kWh in c.5 minutes), control, protection & cable in charging station
Level 5	(Emerging technology, high power DC)	(500kW & more, needs active liquid cooling of leads; excluded from assessment)

Level 1 equipment is not covered in this assessment. (It is likely that some premises will allow people to plug their EV into a standard 10A socket, but that is not considered to be dedicated charging equipment.)

AC equipment is powered from the upstream grid to supply the EV's on-board charger, which converts the AC current to give the DC charging supply to its battery pack. Depending on the charging station mode, safety protection is provided by the EV's own on-board software and instrumentation (Level 1) or by the charging station (Level 2, 3, 4). The charging station acts as an electrical distribution board, interfacing with the EV's battery management system. The station may be connected directly to the upstream grid, or (more likely) be connected via the building's electrical services switchgear. Larger developments may have connections to local transformers or sub-stations.

Commercial DC charging equipment is mentioned here for completeness, but it is not expected that Class 2 to 9 buildings will accommodate that scale of electrical installation.

DC equipment is also powered from the upstream grid, but the station incorporates an AC-DC rectifier stage to substitute for the on-board unit in the vehicle. DC is supplied direct to the battery pack and the station controls the rate of charging via its own software and instrumentation via handshake protocols with the battery management systems in the EV. The DC station can have a much larger (higher power) rating than a typical EV on-board charger and can therefore deliver much faster charging performance, subject to thermal limits. Some proprietary stations already incorporate liquid cooling, allowing them to deliver higher charging rates to several vehicles at the same time.

Common assumptions for this assessment are as follows.

- The building's electrical supplies and equipment are suitably sized for the demand from the EV charging loads.
- Electrical supplies to the charging station will have standard protection and isolation devices (RCD, overcurrent, earth continuity).
- Charging equipment is suitably rated for the environment of each carpark (IPX4, IP54, IP65).
- Level 2, 3 and 4 equipment should have dedicated (equipment-specific) in-cable control and protection devices (IC-CPD); that layer of protection should be in addition to, and separate from, the standard protection systems serving the building's electrical installations.
- All installations will be designed to present-day electrical standards and be installed by approved bodies.
- All EV charging equipment and building electrical equipment will be subject to periodic inspection, testing and maintenance routines carried out by approved bodies.

A carpark installation is assumed to consist of stations serving two adjacent car bays, or possibly 4 bays depending on the layout of the bays. A typical charging station is assumed to provide twin 90kW fast charging points.

3. Hazard Identification

The hazardous situation is a full carpark and a vehicle catching fire, the two options being:

- Carpark full of ICEV
- Carpark full of EV, with most of these connected to EV charging equipment.

These hazardous situations can develop in several ways, so **Table 3** described the representative fire scenarios identified for this assessment.

A Single Vehicle fire scenario – either EV or ICEV – is not expected to challenge the fire safety design features of any carpark. This assumption will be tested later.

The type of carpark design is not specified. In general, a carpark can be open or closed (included semi-closed). At this stage, it is assumed that carpark design is not a differentiating factor in the ignition, growth and spread of a vehicle fire. This assumption will be tested later.

Table 3 – Carpark Fire Scenarios

ID	DESCRIPTION	SIZE	LIFE SAFETY	DAMAGE	INTERVENTION
I	**Single car**	Single vehicle self-ignition and fire, consuming the whole vehicle.	No injuries	Local damage only	Quickly & easily controlled
II	**Multi-car**	Single vehicle fire spreads to involve one or more adjacent vehicles by direct flame impingement, thermal radiation, etc.	Injuries possible Significant smoke production, not an impediment to escape	Potential for serious damage	Controlled inside 1-2 hours
III	**Carpark**	Multi-vehicle fire that spreads to involve all vehicles on the level or whole carpark	Potential for injuries, possible fatality Major smoke production impedes escape	Large-scale property loss and structural damage, potential collapse.	Requires significant & sustained firefighting efforts over several hours.
IV	**Conflagration**	Carpark fire spreads to adjacent buildings. Potential for injuries and fatalities. Structural collapse likely. Requires major firefighting intervention sustained over 24 hours or more.	Injuries, potential for multiple fatalities Major smoke production impedes escape	Large-scale property loss and structural damage, potential collapse.	Requires significant & sustained firefighting efforts over several hours.

3.1. Ignition Sources

Ignition sources for ICEV and EV fires have been summarized from various sources. They are listed in **Table 4** along with brief notes and comparisons. Many sources are common to both vehicle types. Causes of EV fires include self-ignition (or spontaneous/auto ignition) in parked vehicles, or malicious acts like arson, or sustained abuse (e.g. fire during the charging process), or self-ignition while driving, or fire after a traffic accident such as a high-speed collision. The key differentiators for fires in parked cars are these:

Source	**ICEV**	**EV**
Fuel leak	Primary cause	Not relevant
Electrical	Primary cause	Battery thermal runaway found to be the primary cause to date
Overheating	Engine & exhaust hot surfaces	Not relevant

Logically, ignition rates due to electrical faults should be broadly similar between ICEV and EV, given that they use similar fused, 12V electrical circuits for in-cabin, non-motor related loads (lights, heating & ventilation, ICE, instruments, seat & window motors, etc.). From an engineering risk perspective, the difference between ICEV and EV depends on the magnitude of the fuel leak, electrical and overheating sources compared to battery thermal runaway. The risk delta then depends on how the ignition rate from ICEV fuel leaks compares with that for EV thermal runaway. The next section covers the EV thermal runaway mechanism.

Table 4 – Ignition Sources as Risk Differentiators

IGNITION SOURCE	ICEV	EV	DELTA?	COMMENTS
MALICIOUS ACT / ARSON	Y	Y	NO	Ignore the possibility that EV cars, being newer & having more affluent owners, attract more attention from malicious actors
ACCIDENT / IMPACT	Y	Y	NO	Assume carpark accidents are low energy & do not initiate either ICEV fire (fuel tank intact) or EV fire (battery undamaged)
EXTERNAL (NON-CAR) FIRE	Y	Y	NO	Materials & construction are similar for both types, so consider them to be equally vulnerable to external fire sources
HYDRAULIC LEAK	Y	Y	NO	EV arguably has lower risk since it has no clutch (or gearbox) to leak hydraulic fluid, but ICEV hydraulics fires are uncommon anyway, or are related to specific equipment faults on specific models (e.g. fluid ingress to ABS control unit that is electrically live at all times).
FUEL LEAK	Y	N	YES	Is specific to ICEV & a primary cause of ICEV fire in parked cars
ELECTRICAL FAULT				(This is the main cause of ICEV fires along with fuel leak)
CIRCUIT FAULT	Y	Y	NO	No obvious differences between the types in the nature & amount of electrical equipment in each, or in circuit protection design
BATTERY FAULT	N	Y	YES	Is specific to EV & main cause of EV fires in parked cars
MOTOR FAULT	N	?	?	Assume (pending more data) that the EV motor itself is not a significant ignition source
OVERHEATING / EXHAUST / CAT	Y	?	YES	ICEV overheating is common, fires less so but still a differentiator, if it is a given the EV motor & battery are protected from external heating
SMOKING / INTERNAL IGNITION	Y	Y	NO	Occupant behaviour in / usage of cars does not depend on vehicle type
CHARGING EQUIPMENT				(This is a main differentiator between ICEV and EV)
SOCKET / CABLE / LEAD / PLUG	N	Y	Y	23off S.Korean fires were attributed to unapproved 3rd party leads; potential source if the CP outlet lets drivers use their own leads if damaged/ unapproved/ incompatible
D-BOARD / S-BOARD	N	Y	?	Incremental risk only; unlikely to be a differentiator if specified, installed, tested & maintained to approved electrical standards
CHARGER PANEL	N	Y	Y	Incremental risk only; unlikely to be a differentiator if specified, installed, tested & maintained to approved electrical standards
CONTROL SOFTWARE	N	Y	Y	Potentially a significant differentiator given the complexity of load balancing for different EV models within a CP installation's parameters

3.2. Lithium Ion Batteries

The main components of a lithium-ion battery cell are the anode, electrolyte, separator and cathode, usually within a battery container of plastic or metal. A large number of different lithium-ion chemistries are possible, but only a few are used for large-scale commercial purposes. The anode is commonly based on lithium intercalated natural or synthetic graphite but lithium titanate (LTO) is also used. The first cathode material was lithium cobalt oxide (LCO), however, today cobalt is often mixed with other metals; nickel, manganese and aluminum. Phosphates are also used as cathode material e.g. lithium iron-phosphate (LFP).

The electrolyte typically consists of organic solvents, lithium salt and additives, and is both flammable and toxic. The exact composition differs between the manufacturers and is usually a commercial secret, especially regarding the additives. Typical organic carbonate solvents such as ethylene carbonate (17.2kJ/mL) or diethyl carbonate (20.9kJ/mL) have known combustion properties. One of the more flammable solvents used is ethyl acetate (EA), which has a very low flashpoint (-3.0degC), and dimethyl carbonate has a boiling point of 90 °C. However in comparison to the petrol (gasoline) used by ICEV, these solvents are said to be relatively safe [18].

The separator is a porous polymer where the pores are filled with the electrolyte; its primary function is to avoid direct contact between anode and cathode. It is typically a microporous polyolefin layer in the Li-ion cells and a glass or ceramic paper in oxyhalide cells.

Battery containers and packaging materials are usually plastics like ABS, or metals.

3.3. Battery Thermal Runaway

> *"General Motors was recalling more than 50,000 Chevrolet Bolt electric cars in the United States over the potential for fire in its high-voltage battery pack, after the (NHTSA) confirmed there were five known fires involving the vehicle, resulting in two injuries. The (agency) advised owners to park their cars outside until the problem is repaired. General Motors… said dealers were updating the cars' battery software to limit their charge capacity to 90 percent while the company addressed the issue. The batteries, he said, "may pose a risk of fire when charged to full, or very close to full, capacity."*

Sun et al [3] state that most EV fire accidents are caused by thermal runaway of the Lithium Ion Battery (LIB). This hazard of self-ignition due to thermal runaway – while driving or parked – is unique to EVs.

Thermal runaway happens when a battery fault causes a short circuit and a rapid release of energy that heats up the cell and starts an exothermic reaction. In simple terms, an incipient fault causes a short-circuit, the cell overheats, transitions to thermal runaway, the heat and pressure causes the cell to swell or burst, or vent offgases from the internal pressure relief device. This heats up adjacent cells, progressively involves the whole battery module, then adjacent modules, and finally the whole battery pack. The fault tends to be revealed only during normal use, typically while the battery pack is being charged, or when the battery is at or near fully-charged.

Overheating can be caused by thermal, electrical, or physical effects. Known causes are external short circuits, internal short circuits, cell overcharging, cell over-discharging, physical abuse such as crush, or exposure to high ambient temperatures. More specifically, LIB failure is associated with a flawed or damaged separator, resulting in an internal short circuit that produces enough heat to vaporize the electrolyte (or melt the anode, if it is primary metallic lithium) allowing massive internal shorting and direct anode-catholyte reactions that result in a violent venting or explosive reaction. The separator can fail due to internal defects (production issues), physical damage (handling issues), exposure to high temperature (fire), and in the case of secondary cells, overcharging resulting in bridging of the separators.

The cathode, anode, electrolyte, and separator are stable up to temperatures around 80degC. At higher temperatures, the passivation layer on the surface of the graphite negative electrode starts a progressive dissolution in the electrolyte, becoming significant at 120-130°C. Due to this mechanism, the electrolyte further reacts with the least protected surface of graphite, generating heat.

When the electrolyte is heated and then vented or released as an aerosol, vapour or liquid, there is partial decomposition to lower molecular weight species, and properties like flash point and auto-ignition temperature may be lower. These offgases include Hydrogen and various low molecular weight hydrocarbons (C2H4, C2H6, C3H6 are common), usually represented as Propane. Cells start producing offgases at a so-called Temperature of No Return (TNR) stage – about 150degC depending on the precise battery materials, electrolyte chemistry and construction.

So, heating LIB batteries to around 120-150degC will trigger exothermic chemical reactions or 'thermal runaway' within the cells, and the electrolyte will start to boil off.

Battery failure can occur very rapidly after a cell is damaged, or slowly over a long period of time, causing delayed failure long after the damage is initiated. The time in between is usually referred to as the "incubation period" which can last from several hours to years, depending on the cause and failure mechanism. The battery failure mode dictates the incubation period and therefore dictates the nature of the battery fire.

3.4. Battery Fires

Several references cover the combustion behaviour of lithium ion batteries as individual cells, fewer consider in packs and modules, only two for the battery as installed in an EV.

Thermal runaway can transition to flaming combustion either gradually or suddenly. A sudden transition often seems associated with torch flames, indicating sufficient offgas generation for pressurized venting or release. At the temperatures where a cell is damaged enough to lose integrity, electrolyte vapour is venting from the cell, normally to find an ignition source and ignite. This behaviour is seen in many fire tests. One common feature is a fireball lasting several seconds or tens of seconds. Another common feature is a jet flame, or sometimes multiple jet flames, issuing from the battery pack.

Gehandler (2017) [21] states that the energy released during the combustion of a battery is moderate in relation to that of the rest of a vehicle, and contributes less to the fire load as compared to an ICEV petrol tank. The maximum contribution of a battery (for LIB of 8-16 kWh capacity) to the heat release rate of a fire is in the range of 250-600 kW. That represents about 6% to 12% of the heat output of a medium-sized car fire (but see more discussion in section 4). Importantly, these are significantly smaller battery capacities than found in newer EV.

Gehandler quotes Hofffmann's (2013) findings that the combustion energy of various electrolyte mixtures relative to a battery's electrical energy-storage capacity is 16-18MJ/kWh. EV battery capacities presently range from 30-90kWh, but larger EV batteries are expected to become more popular. A 100kWh battery capacity would correspond to 1.8 GJ of available thermal energy through combustion of the electrolyte, or roughly the same as a 50 litre petrol tank having about 2 GJ of combustion energy.

The US Navy has also found the combustion energy potential to be proportional to the electrical energy potential [17] because the amounts of combustible electrolyte and separator material are broadly proportional to the electrical energy potential of a cell. The combustion energy potential is estimated to be approximately 6 (six) times the electrical energy potential of a cell (which ties in with other work suggesting a factor of between 5 and 10). That would indicate the combustion energy in a 30kWh battery pack is 648MJ, and for a 100kWh pack it is 2.2GJ. Those estimates tie in well with Hoffmann's findings.

The total combustion energy can be lifted up by 30%-40% with other battery construction materials e.g. a hard shell plastic case. The packaging for the battery pack is also likely to be combustible plastic, and overall the plastic casing and packaging can contribute up to 70% of the total combustion energy. No data for specific quantities of electrolyte and other combustible materials in typical batteries were found. This was surprising. It should be straightforward to estimate the fuel loads and (theoretical) quantities of combustion energy for a battery pack just from knowing its construction.

Various researchers consider that battery fire dynamics are still poorly understood, but at an engineering level, the general behaviour of battery fires is known in qualitative terms. Following thermal runaway (see previous section 3.2), the transition to flaming combustion happens when offgases are released as cells fail or rupture or are released via a pressure relief vent. These flammable vapours are ignited by electrical or heat sources.

The SOC (state of charge) has significant influence on the fire behaviour; cells with lower SOC burn for shorter times and with weaker flames. This is related to the Joule heating effect; a higher-charged cell achieves higher temperatures because of the stronger flow of electrons in the internal short circuit. This would tend to confirm (so far anecdotal) evidence that EV battery fires are more likely when the battery is at, or nearing, the fully charged state.

Fire severity is governed by the rate of production of the offgases, which is in turn governed by the rate of heating due to the thermal runaway. Research and incident reports show that fire severity can vary significantly, depending on a number of factors related to the initiating fault or event.

One potential scenario discussed by Gehandler (2017) [21] is LIB thermal runaway and offgassing without ignition or fire. In that scenario, large amounts of toxic gas might be produced e.g. hydrogen fluoride (HF) and be unnoticed. HF is highly toxic in low concentrations.

A distinctive feature of LIB fires is their long duration, possibly up to several days. Once the thermal runaway reaction is triggered, it will continue until the exothermic conditions end (the battery pack loses reaction heat faster than it is being produced). Experience tends to indicate the whole battery pack will be consumed before this condition is reached. Firefighting intervention to cool down the battery pack does eventually halt the reaction, but this has been observed to take at least several hours and in some cases days.

Associated with the extended fire duration is the observation that battery fires reignite multiple times during an incident or test. External flaming might be extinguished for a period by cooling water from firefighting intervention, but the thermal runaway reaction is still propagating through the body of the battery pack, because water cannot penetrate there, and the fire breaks out again once water cooling stops.

It is not clear if or how an EV passenger cell fire will involve the battery pack. It should be expected that external heating of the battery, or at least a significant proportion of it, will trigger thermal runaway in a significant number of cells. A large proportion of cells could start to rupture and vent at the same time. It is not clear if EV fire tests have observed this behaviour. It is reported that General

Motors conducted external pool fire exposure tests on battery packs. GM concluded there was no evidence that battery packs cause an increase in the severity of a car fire.

Fire tests on large-scale EV battery packs are expensive and rarely published. At a recent Engineers Australia webinar [5] presenters for the testing and product certification bodies Underwriters Laboratory (UL) and Factory Mutual (FM) both highlighted the confidentiality of battery fire test results for clients, also the current lack of large-scale fire test standards for battery energy storage systems (BESS).

3.5. Battery Explosions

Reports of EV fires have often used terms like "explosion" when describing them. Videos of EV fires often show flames or fireballs erupting from the vehicle, usually from underneath, or via the wheel arches. While these incidents to not seem to involve overpressure effects, vehicle displacement, fragmentation, missiles or structural damage, there is still a concern that batteries might cause explosions if they could generate enough offgases to create a flammable vapour cloud.

Larsson (2014) [20] notes that the mechanical packaging of the battery (e.g. cylindrical, soft or hard prismatic can or pouch-prismatic) affects the cell behavior during a thermal event, and the pressure at which it vents or fails. For example, a cylindrical cell allows a much higher internal pressure to build up than a pouch cell. It is easier to control the venting direction with a cylindrical cell by the placement of the safety vent, but higher internal cell pressure build up can be potentially more dangerous, especially in case of safety vent malfunction.

Battery fire tests [17] have shown evidence of sudden, violent cell rupture with fragmentation, debris, substantial pressure pulse and the ejection of cells from containments. Flaming debris can be expelled (sprayed or thrown from the battery). Pressure relief ports can fail to operate correctly (or the battery is not equipped with ports), causing internal pressure to rise until the cell integrity fails. Explosive-type reactions can vary from firecracker type bangs to as loud as shotgun blasts or greater. Reports on EV fires often mention the "popping" sounds heard.

For an explosion to occur, offgases must be able to vent and accumulate somewhere to form a flammable mixture that is eventually ignited. The scenario requires continuous venting into a space to allow a large enough flammable mixture to form, then delayed ignition.

Considering the issue from first principles, hydrocarbon gases forming a flammable mixture in air can ignite to give a flash fire, or a deflagration, or an explosion. These are different hazards, distinguished by the flame speed achieved by the combustion zone as it propagates through the mixture. Flame speed dictates whether the event produces significant pressure effects or not. A flash fire has the slowest flame speed, usually one that does not accelerate, and its impact is limited to thermal effects of short-duration flame contact. A deflagration exhibits flame acceleration, achieves higher speeds and produces overpressures. An explosion has higher flame speeds and more severe pressure effects than a deflagration, but the threshold between the two is vaguely defined, if at all. They both have subsonic flame speeds, so they are not detonations.

(Detonations with sonic flames and shock waves rarely happen as accidental events. They are not considered to be relevant for this assessment. Flash fires are also discounted.)

The minimum conditions necessary for a deflagration/ explosion can be derived from a rule-of-thumb that an explosion needs the flame to accelerate for at least 5 metres to achieve a velocity associated with significant overpressure effects. Back-calculating from this, the minimum quantity of hydrocarbon liquid that needs to volatilize to create an explosion potential is approximately 4.0kg, which is equivalent to about 180MJ of combustion energy. Literature searches did not manage to find data on electrolyte quantities in batteries, or ways of estimating that. It would be useful to have some values for cross-checking purposes. US Navy estimates [17] indicate a 30kWh battery pack has 648MJ of combustion energy, which is enough to create an explosive hazard.

But consider that an ICEV also poses an explosion hazard because petrol is as volatile and explosive as the EV battery electrolyte. A typical 75 litre fuel tank might contain 55kg of fuel with a typical combustion energy of 45MJ/kg, giving approximately 2,500MJ. This is about 4 (four) times the combustion energy of a 30kWh battery pack, and about 15% more than a 100kWh battery. But this liquid fuel can readily spill, volatilize and disperse if the plastic fuel tank fails.

It is not certain that an EV battery contains 4.0kg of electrolyte in dispersible form i.e. the battery pack can release all that material rapidly into a space to form a flammable cloud. One possibility is that volatiles vent into the passenger cell, and ignite there. The confinement would be expected to cause faster flame acceleration and higher overpressures. But it is difficult to propose how offgases could vent into the garage space from one or more EV battery packs over a period of time, sufficient to allow the build-up of a flammable cloud, and then to experience a delayed ignition.

4. Consequence Assessment

This section considers fire growth in the vehicle of origin, fire spread to other vehicles and general conflagration in terms of hazard loading and hazard response. It also considers explosion potential.

4.1. ICEV Fire Severity

There are numerous references covering ICEV fire research. Most of the work is focused on characterizing Heat Release Rate (HRR) curves and explores the influence of vehicle size and age. For example, Swift (2012) is quoted as finding the weight of plastics and composites in cars has increased from around 20lbs in the 1960s to around 400lbs in 2010, and this is likely to be the main reason why fire severity is observed to be worse in modern cars.

NFPA cites a report by French researchers that shows parking garage fires have evolved over the space of a couple of decades. The researchers had gathered data in 2001 [26] from a survey of several hundred French parking garage fires between 1995 and 1997. The data were analyzed in 2015 against fires that occurred between 2010 and 2014 (original paper not sighted). The conclusion was that fire hazards in carparks have increased *'a lot'* in 20 years '*with the evolution of activities and the new car technologies'*. Further conclusions were:

- Between 1995-97, 98 percent of garage fires involved fewer than four vehicles; only 1 percent of fires involved more than five vehicles, and none of the fires reviewed involved more than seven vehicles.
- By contrast, 8 percent of fires between 2010-14 involved more than five vehicles, and 6 percent involved more than seven vehicles.
- In 1997, 95 percent of garage fires analyzed were extinguished in under 60 minutes, and fewer than 1 percent took longer than two hours.
- Between 2010-14, only 40 percent were extinguished in under an hour; 30 percent of the fires took more than two hours to extinguish, and 10 percent took more than four hours.

The data suggests that (a) modern garage fires are much more likely to involve multiple vehicles than two decades ago, therefore suggesting fires are more severe, and (b) modern garage fires appear to be much harder to extinguish, which also supports the notion that fires have become more severe.

Tohir and Spearpoint [9] collated fire severity data from 41 off ICEV fire tests covering 7 vehicle size categories, with around 70% of the cars built in the 1990s. Fire severity was characterized by the total energy released, peak rate of heat release and the time to peak rate of heat release, and showed a rough correlation with vehicle kerb weight. As one example, Medium Cars (1,360-1,690kg) gave a mean peak HRR of 6,843kW at 37.2 minutes. Gehandler (2017) [21] quotes Ingason (2015) who found the fire load of modern cars to be between 4-8MW. Other recent meta studies find HRR ranges between 1.5-8.0MW, but the majority of medium sized cars have HRR less than 5MW.

Ignition sources should have a significant influence on fire development, which is dictated by the nature and disposition of the fuel, and the ventilation conditions. Intuitively, a fire starting inside the passenger cell (e.g. smoking materials that ignite upholstery) should develop differently to one starting inside the engine compartment (e.g. fuel leak onto hot surface).

BRE (2010) [12] finds that passenger compartment fires grow rapidly, particularly if windows are left down, while engine compartment fires grow slowly, but will spread to involve the whole car. This seems counter-intuitive. Engine compartment fires might be expected to develop more quickly, given the proximity of flames to other flammable and combustible liquids, while passenger compartment fires should grow more slowly, given the solid nature of the fuel and the restricted ventilation of the passenger cell. What the BRE work suggests is the interior fuel load in a modern car is more hazardous and burns more readily than the fuel load in the engine bay.

BRE (2010) [12] goes on to find fire spread between cars by radiant heat can be slow. Fire can spread between cars by direct flame contact from spilt fuel or molten plastics (or, presumably, if air flow and/or ceiling confinement causes flame tilt/drag). Ignition of exterior trim or body work does not necessarily spread into the car’s interior; some physical failure is needed such as a breaking window, for the interior to become involved.

As a general comment, none of the research to date investigates the influence of the ignition source on fire development, or how different materials become involved. It is difficult to predict fire severity using specific design features of a vehicle, other than its age and size category. Research does not, for example, explain the contribution of the vehicle’s fuel tank contents to the fire development or its HRR profile. (In fact, few studies report on the amount of fuel in the ICEV tank.)

So, while research into ICEV fire severity provides a reasonably consistent picture, it only considers the influence of a limited number of vehicle design factors. That limits the degree to which comparisons can be made with EV fires.

4.2. EV Fire Severity

Only two references were found describing EV fire testing. This was surprising. It appears that research is inhibited because EV are simply too expensive, even second-hand, and manufacturers seem unwilling either to support fire research or share any of their own internal fire research. Fire test programs in France (2012) and Japan (2012) yielded the following conclusions.

- Similar EV and ICEV from two French car makers were tested. Fire growth and development was similar for both vehicles for an internal fire source. The maximum HRR was similar for both vehicles, 4.2 MW for the EV and 4.8 MW for the ICE vehicle. The ICEV and EV lost roughly the same amount of mass in the tests – around 275kg, or 20% of their total vehicle mass. The "effective" heat of combustion of the ICEV was 36MJ/kg and that for EV was 30MJ/kg.
- Different EV and ICEV were tested. Total energy released for the EV was approximately 50% more than the ICEV but 15% less than that of a luxury ICEV sedan. The peak HRR of the EV was approximately three times greater than that of the ICEV; however, they were not otherwise identical vehicles so it is not certain their peak HRRs can be directly compared.

Overall, researchers considered the tests indicated the fire load of an EV is similar to an ICEV and they behave in fire similarly. There are uncertainties though.

- It is not clear why peak HRR in an EV fire was significantly higher (x3) than the ICEV.
- The EV tests do not isolate the battery's contribution to the HRR curve. It is not clear if those tests involved battery thermal runway, either actual or simulated.

Logically, HRR curves should exhibit peaks when (i) a fuel tank fails and releases its contents suddenly, or (ii) a battery ruptures suddenly and transitions to flaming combustion. But the report does not relate the observed behaviours with ICEV or EV parameters. The current situation is that EV fires exhibit a wide range of behaviour, so their HRR curves, total heat outputs, peak temperatures, fire durations or the nature and quantities of combustion products are subject to wide variation depending on the specific circumstances of the fire.

EV fire tests to date involve smaller batteries than those in newer EV models, and much larger batteries are expected in future models. A 100kWh battery has about the same combustion energy as 55 litres of petrol, but that only considers the electrolyte energy. Plastics used in the battery casing and packaging can add between 30%-75% to the fire load. Clearly, more fire testing is required to provide robust data on battery fire severity and a clearer understanding of battery fire behaviour.

4.3. Charging Equipment Fire Severity

The fire load in Type 1, 2 and 3 charging stations is judged to be low, essentially the plastic materials in the electrical equipment, equipment enclosures and cables. The amount of material is judged to be low in comparison to the amounts of plastics in a typical vehicle. The fire hazard relates to the possibility of an electrical fault/ short circuit that generates heat and causes combustible material to ignite.

A Type 4 EVSE installation is larger and therefore must present a greater fire load. However, the specification sheets for various commercial Type 4 EVSE do not detail the nature and total amounts of combustible materials in the product. The fire load in Type 4 equipment is uncertain and depends on the type of rectifier (or more likely, bank of rectifiers). The fire hazard still relates to the possibility of an electrical fault or short circuit that generates heat and ignites local combustible materials, with fire severity dictated by the amount of combustible material.

There may be a potential new hazard with liquid coolant, where active cooling has been incorporated into a high-powered DC charger. No specific design details were found for any EVSE active liquid cooling systems. Various cooling media might be used, such as glycol-based liquids (combustible, depending on composition and concentration) or hydrocarbon liquids (similar to oil-cooled transformers for example). More data is needed.

There is little evidence to date that EV charging equipment present new fire hazards. In South Korea, 23 incidents of EV charging fires have been attributed to various causes: inadequate electrical protection standards for 3rd party equipment such as cables; inadequate systems integration design; faulty installations; or equipment specifications that were inadequate for the local service conditions i.e. environments with high moisture and condensation.

4.4. Fire Spread

BRE (2010) [12] measured the fire conditions causing various parts of an adjacent car to ignite, and from this derived critical irradiance values needed to cause ignition, along with ignition times under various thermal radiation levels.

Table 5 – Irradiance Values & Times for Fire Spread

Component	Critical Irradiance Value (kW/m2)	Time to Ignition (s) @ 10Kw/m2	Time to Ignition (s) @ 20kW/m2
Bumper	18.5	-	184
Hubcaps	17.5	-	205
Bumper grill	17.5	-	114
Fuel tank	16.5	-	293
Roof box	12.5	-	121
Wheel arch	12	-	81
Bumper Trim	11.5	415	83
Tyre	11	-	240
Mud flaps	10	380	57
PVC soft top	9	67	22

Their results show that external exposed plastics on modern vehicles ignite if exposed to radiant heat flux levels between 10kW/m2 and 20kW/m2, after around 1 to 5 minutes. The data relate to ICEV, but they can be applied equally to EV given that there is no difference in the external construction materials used for both types of vehicles.

One matter not mentioned in the research is the fact that a torch fire flame has a higher Surface Emissive Power (SEP) than a buoyant diffusion flame. For flames involving similar quantities of fuels with similar heats of combustion, a pressurized release causes more turbulent mixing of fuel with air, resulting in faster and more efficient combustion, and therefore higher flame temperatures and higher SEP.

Higher flame temperatures and higher SEP will both lead to faster fire spread. The hazard impact is likely to be limited, though, since the typical times to ignition given above are relatively quick.

4.5. Major Fire Spread

Major fire spread can be expected to happen if the carpark is full, with no empty bays to act as fire stops. Fire spread will be by direct flame impact, by thermal radiation from the vehicle fire and the hot ceiling layer. In open carparks, fire spread will be influenced by external wind conditions, and in closed carparks, by the lower rate of heat losses from the fire compartment. Once the fire takes hold in the vehicle of origin, it should be expected to spread to all vehicles unless there is intervention.

There is no empirical evidence to indicate ICEV and EV present materially different fire spread risks. However, EV battery fires involving torch flames are expected to cause faster fire spread because that type of flame has higher temperatures and higher emissive power than is found with buoyant diffusion flames typical of ICEV fires.

Of note, it is reported that fire spread in the Stavanger airport fire was not observed to involve the batteries of the numerous EV in that carpark.

4.6. Smoke & Toxicity

Fire tests indicate that ICEV and EV produce similar quantities of smoke and toxic gases [17, 21]. Their combustion products are primarily CO2 (>95%) and CO with trace amounts of toxic gases. In a webinar, Barnett [5] said that EV smoke density was about twice that of ICEV.

EV battery fires produce significant quantities of hydrogen fluoride (HF). In Sweden, full scale fire tests to compare ICEV and EV smoke toxicity found that HF is a distinct by-product from overheating and burning EV batteries. Swedish tests on individual cells during thermal runaway (not fire) found 100ppm peak and from this it was estimated that a 100kWh battery pack could theoretically yield between 1.2-8.0kg of HF. French tests found peak HF production rates of 450ppm early on in the fire, before the battery became involved, so this was attributed to refrigerant from the air conditioning system. About 30 minutes later, after the battery was involved, HF production was then about 50ppm.

The Immediately Dangerous to Life or Health (IDLH) limit for HF is 30ppm (0.025 g/m^3) so the lethal concentration for a 5-minute exposure is in the range 50 to 250 ppm. The permissible exposure limit (8-hour time weighted average) is given as 3ppm with a not-to-exceed value of 6ppm in any 15-minute period. The data indicate that a battery thermal runaway and fire incident can render an enclosed space of 5,000m3 untenable under low ventilation conditions.

More recent ICEV fire tests have recorded HF production at about 25ppm, attributed to the higher plastics content in modern vehicles.

4.7. Explosion

Accidental explosions in the open air are relatively rare events. The ‘5 metre’ rule mentioned in section 3.5 relates to industrial settings with significant amounts of turbulence-inducing equipment congestion. Those conditions are not present in an open carpark.

Flammable clouds in closed carparks and/or underground carparks pose a greater hazard because overpressure development is affected by confinement. Using another rule-of-thumb, if an enclosed space contains a stoichiometric cloud of 15% of the space, that can produce a 2.0bar (static) overpressure, easily enough to cause significant structural damage in most buildings. A cloud size of just 1% is still considered to have damage potential. If our 40-bay carpark benchmark has a volume of (say) 5,000m3, then a single 75 litre ICEV fuel tank produces a stoichiometric cloud size of around 3.5%, enough for explosion damage.

ICEV pose a more significant explosion hazard than EV because petrol is volatile and explosive, and it is more readily released, volatilized and dispersed if the fuel tank fails. Fuel is not likely to be released under pressure though; ICEV fuel tanks are designed with pressure-relief to prevent any pressure build-up in the fuel system.

The quantity and rate of release of flammable material from the battery will determine the chances of an explosion. To date, there have been no explosion incidents. While new, higher capacity EV batteries have enough theoretical combustion energy to create an explosion hazard, it is questionable whether the battery pack can release enough flammable material in a short time to create an explosive hazard.

The design of an EV battery cell allows internal pressure to rise when the cell is subject to normal ambient heating. Cells (in most cases) have pressure-relief devices to prevent excessive pressure build-up and catastrophic failure. EV battery packs have been observed to ‘erupt’ when a number of cells fail catastrophically at the same time, releasing flammable electrolyte vapour or aerosol or gas at pressure. This explains the ‘fireball’ observations in real fires and fire tests. There have also been observations of energetic expulsion of cells from test rigs.

However, it is difficult to imagine the combination of very rapid heating to cause widespread, simultaneous cell failure, then venting/release of flammable offgases to form an explosive hazard, and then delayed ignition to cause an explosion. It might be possible if the battery vents into the passenger compartment, but that is a limited volume.

5. Frequency Data

ICEV carpark fire statistics are available for Australia and some other countries. Surprisingly, one statistic was also found for EV carpark fires. Sweden (RISE) reports an average of 1 EV carpark fire per year; unfortunately there is no population data given either for carparks or EVs. That apart, there are no readily available EV fire statistics. EV vehicles still comprise a small proportion of the vehicle fleets in many countries (typically <1%) and EV have been driving on the roads for relatively few years. For these reasons, accident and incident reporting appear not to recognize EV as a distinct vehicle category warranting separate data collection. No dedicated statistical studies were found either.

5.1. Carpark Fire Frequency

Australian carpark fire statistics have been taken from a recent study by ARUP [23] and summarized in **Table 6** below.

Table 6 – Australian Carpark Fire Statistics

YEAR	NO. OF BLDG CLASS **7A** FIRES	NO. OF CBD PARKING BAYS	FIRE FREQUENCY/BAY
2012	359	153,412	2.34E-03
2013	348	156,787	2.22E-03
2014	361	160,236	2.25E-03
2015	372	163,762	2.27E-03
2016	322	167,364	1.92E-03
2017	327	171,046	1.91E-03
2018	394	174,809	2.25E-03
2019	331	178,655	1.85E-03
TOTALS	2,814	1,326,071	2.13E-03

[NCC Class 7a: General vehicle parking garage. Parking of vehicles of various ownership in facilities under the direction of one management.]

The average fire frequency of 2.13 per 1,000 parking bays is a useful metric, but it includes all types of vehicles and all causes of fire. The data should be conditioned to remove malicious/arson incidents and distinguish between EV and ICEV. However, EV penetration in Australia is less than 0.1% as at 2020 [11] so the contribution from EV to these statistics is likely to be trivial, so further conditioning would not be justified.

Overseas carpark fire statistics yield the following.

- New Zealand (NZ) expresses carpark fire frequency in terms of fires per carpark visit and finds the average annual frequency is 1.71E-07 fires per vehicle visit. NZ suggests the average number of visits per day per parking bay is one.

- NZ fire statistics (pre-2004) give an annual ‘carpark building’ vehicle fire frequency of 4.74E-06 fires/building. Later (2004-11) this becomes 1.15E-06 fires/carpark building. Over the whole period (up to 2012) the probability of a vehicle fire in a carpark is 2.76E-06 per year.
- NZ statistics (1996-2003) yield an average annual carpark fire incidence rate per parking bay of 6.0E-05/bay-yr.
- Netherlands reported 53 carpark fires over the period 2006-16 in about 500 public carparks, yielding a frequency of 7.1E-07 fires per m2 of carpark floor area. That value is said to be similar to the fire rates in other types of buildings. The value given for carparks in the Eurocode is a fire frequency of 4.1E-07/m2.
- France reviewed carpark fire data mainly from Paris along with other French and European cities [26] but only general conclusions are drawn about the probabilities of multi-vehicle fire spread; no fire incidence rates were given.
- UK carpark fire frequency is quoted as 2.0E-05 per vehicle-year in a Netherlands paper (original UK source was not sighted) but the units used here are unclear and are assumed to relate to each car parked in a bay.
- BRE (2010) [12] finds the average number of fires in carparks each year reported by UK fire and rescue services is 258 (which is less than 0.1% of all fires) but does not give the carpark population. About 50% of these did not start in a car.
- The UK Car Parking Association estimated in 2015 there were between 17,000 and 20,000 non-residential carparks in the UK. That indicates an annual carpark fire frequency of approximately 7.0E-03 fires/carpark.

There is some limited data on fire spread to involve multiple vehicles. Data suggest the proportion of carpark fires involving multiple vehicles are 3% (NZ), 7% (USA) and 14% (France, for underground carparks).

5.2. Vehicle Fire Frequency

- Finland reports 3 EV fires while charging in the period 2015-19 to give a fire frequency of 6.4E-05 fires/car-year (from a small data set).
- NZ found the annual fire frequency to be 1.28E-03 fires/vehicle (1996-2003) and then later 9.1E-04 fires/vehicle (2004-11) giving an overall average fire frequency of 1.07E-03 fires/vehicle.
- Norway's insurers provided statistics showing EV fires comprise between 2.3% and 4.8% of vehicle fire insurance claims, with the annual average over a 10-year period being 2.6%. Norway has the highest penetration of EV in the world, at 14% in 2018, which tends to indicate that EV fire rates are lower than ICEV rates. This is likely to be true given these data include collision-related vehicle fires which will be (almost exclusively) ICEV crashes.
- China, with the world's largest market of EVs, records 31 LIB fires per year on average, most being sudden ignition (36.9%), followed by charging (26.2%) but EV population data was not provided.
- USA (NTSB) has reported 17 Tesla and 3 BMWi3 LIB fires out of 350,000 and 100,000 vehicles respectively giving a frequency of 4.4E-05 fires/vehicle over an undefined period.
- London Fire Brigade dealt with 54 EV fires in 2019 compared to 1,898 ICEV fires and in 2020 (part-year) it was 27 EV and 1,021 ICEV fires. That indicates EV fires comprise 2.7% of all vehicle fires, but without a breakdown by cause or location, or data on vehicle population in London, it is not clear if EV fires are more, or less, prevalent than ICEV fires. [25].
- Tesla (USA) gives 5 fires per billion miles travelled for their vehicles versus an average of 55 fires per billion miles for ICEV. These statistics have not been challenged so we accept them as accurate. But ICEV have higher post-collision fire frequency than EV, which is to be expected. The more useful comparison would be non-collision fire frequencies.

5.3. Fatalities & Injuries

No injuries or fatalities have been recorded in carpark fires in Australia. Overseas, incident data show carpark fire injuries are rare (USA 1972, USA 1993, France 2001, NZ 2004, USA 2008, USA 2020) and fatalities are even rarer – in fact none were recorded in those studies. UK fire statistics [24] over the 10-year period 2010-20 recorded 117 fatalities in 86,515 accidental fires involving cars or vans, but those data do not discriminate carpark fires from post-accident fires. BRE found about 7 people injured in UK car park fires each year and very few fatalities, on average less than one per year. Ahrens (NFPA) found over the period 2014-18, the USA had an annual average of 1,858 vehicles fires in commercial parking facilities, causing 20 injuries but no deaths.

5.4. Discussion

Fire frequencies are difficult to extract from the data above, however a few of the sources appear to give reasonably consistent estimates.

- UK carpark fire incidence rate is 7.0E-03 fires/yr.
- NED fire incidence rate is 8.2E-06 to 1.4E-05/bay-yr assuming a standard car bay is 20m2.
- NZ carpark fire incidence rate is 6.0E-05/bay-yr.
- UK 'parked vehicle' fire incidence rate is 2.0E-05/car-yr.
- FIN fire incidence rate for EV carpark fires is 6.4E-05/car-yr (small data set).
- USA gives an EV battery fire incidence rate as 4.4E-05/car (limited car makes, no period).

The data above suggest an average for carpark fires in the order of 3.4E-05 fires per car (or per car bay) per year. That indicates the annual probability of a carpark fire in a 40-bay facility is 1.4E-03 per year. Given a 40-bay carpark floor has an area of 2,000m2, then the equivalent values using Dutch and Eurocode area-based fire frequencies are between 0.8-1.1E-03/yr, which are broadly in line with that. It is also broadly in line with the UK estimate of 7.0E-03/yr per carpark (obviously noting that carpark capacities can range between a few dozen parking spaces up to 1,000 or more).

There is no evidence in these data to suggest EV and ICEV carpark fire rates differ significantly. Norway's statistics indicates EV fire rates are lower relative to the proportion of EV in the total car population; however, it is not clear if the picture is being distorted by including post-collision ICEV fires. London FB statistics might indicate EV fire rates are higher than ICEV, assuming EV comprise less than 2.7% of London's car population; but again, it is not clear if the picture is distorted by including post-collision ICEV fires.

The data indicate Australia's fire incidence rate of 2.13E-03/bay-yr is anomalous, being about two orders of magnitude higher than other countries. One potential reason for the anomaly is the car fires attended by fire brigades have happened in a much larger population of carparks than is represented by those in the CBDs alone. It would not be prudent to use the Australian figure pending further investigation.

Time constraints prevented a deeper probe into vehicle and carpark fire statistics.

6. Control Measures

6.1. Prevention Measures

Fire prevention measures for the EV and its battery pack are managed by the design and construction standards for vehicles. Fire prevention measures for EV charging equipment are likewise governed by electrical safety standards for the equipment and its installation. EV and EVSE safety standards are a matter for international agreement between manufacturers, trade bodies, consumers and governments (see section 9). Those standards are still evolving, as is EV technology like battery management systems.

The BMS could become an important fire prevention measure. We know that LIB thermal runaway happens because of battery abuse or an incipient fault from manufacturing. We also know the fault tends to be revealed as the battery reaches its fully charged state. It is reasonable to suggest the BMS might in future monitor the condition of individual cells and provide the driver with advanced warning of a potential critical damage state, so that thermal runaway can be avoided. However, that falls under the remit of the relevant international EV and EVSE electrical safety standards.

The remit of the NCC Performance Requirements does not extend to controlling the likelihood of fire with EV or EVSE. The NCC might be used to control the likelihood of carpark fires by limiting the proportion of EV charging bays provided in a carpark. Fire frequency is a first-order risk factor and risk changes in direct proportion to the change in frequency. Limiting the number of EV charging bays to 50% (for example) of a carpark's capacity would mean a 50% lower fire risk than if all the bays allowed EV charging. However, the data in this study are not sufficient to evaluate the risk benefit of such a measure.

6.2. Mitigation Measures

The NCC contains several performance requirements relevant to limiting the impact of an EV fire. They are considered sufficient; however it would be sensible to produce guidance on their application in respect of EV and the EVSE in carparks. **Table 7** summarises the performance requirements potentially impacted by EV fires in carparks.

C1P1 Structural Stability

NCC fire resistance levels for carparks are challenged by the intensity of fires in modern cars in general, and not because EV and EVSE fires are any worse than ICEV fires (on current knowledge). Low intensity EV battery fires can last several hours or days, but they should only have local impact on the structure.

One plausible carpark fire scenario is multiple simultaneous EV battery fires with wide impact on the structure. The question is how the overall heat release profile challenges the structure. Peak heat release rates and total heat outputs of EV fires vary much more than with ICEV. The theoretical heat load of an EV and its battery pack is not significantly greater than a similar-sized ICEV. But there is a need to test the latest EV models with larger battery packs, also large-scale tests to replicate multi-EV fire scenarios.

Table 7 – Performance Requirements Potentially Impacted by EV Charging in Carparks

Ref.	**Title**	**Comment**
Fire Resistance		
C1P1	Structural stability during a fire	Very long duration fires are possible
C1P2	Spread of fire	More rapid spread than NCC expects
C1P3	*Spread of fire and some in health and residential care buildings*	N/A
C1P4	Safe conditions for evacuation	N/A – relates to materials
C1P5	Behaviour of concrete external walls in a fire	N/A – not influenced by EV fire
C1P6	Fire protection of service equipment	N/A – EVSE are not high fire hazard
C1P7	Fire protection of emergency equipment	N/A – not influenced by EV fire
C1P8	Fire protection of openings and penetrations	N/A – not influenced by EV fire
C1P9	Fire brigade access	Higher smoke & toxic gas production
D1 Access & Egress		
D1P1	Access for people with a disability	Interface with EV charging equipment
D1P2	Safe movement to and within a building	Interference with escape
D1P3	Fall prevention barriers	N/A
D1P4	Exits	Blocking exits
D1P5	Fire-isolated exits	Blocking exits
D1P6	Paths of travel to exits	Blocking exits
D1P7	Evacuation lifts	N/A

D1P8	Carparking for people with a disability	Interface with EV charging equipment
D1P9	Communication systems for people with hearing impairment	N/A
E1 Firefighting Equipment		
E1P1	Fire hose reels	N/A
E1P2	Fire extinguishers	Media selection for EV battery fires
E1P3	Fire hydrants	Long interventions, runoff
E1P4	Automatic fire suppression systems	Sprinklers for EV carparks
E1P5	Fire-fighting services in buildings under construction	N/A
E1P6	Fire control centres	N/A
G1 Ancillary Provisions		
-		N/A

C1P2 Fire Spread

NCC does not have specific provisions to limit carpark fire spread. Arguably, it does not anticipate the rate and extent of fire spread with modern cars, which are wider and park closer together. Common sense says EVSE charging points in carparks will have minimum space requirements to accommodate the cabinet, charging cable layout between cabinet and EV socket, and the driver's interactions with the EVSE control panel and cable. That has multiple fire safety benefits; it should help separate EV and contribute to limiting fire spread.

The Monica Wills incident [19] saw fire spread from the lower ground level carpark to involve combustible external cladding on the whole building elevation above. Current initiatives on ACM (aluminium composite material) cladding fire risk should be reviewed

C1P9 Fire Brigade Access

One difficulty with EV fires is carpark access for a heavy vehicle which can extract the EV to a safer, open location where the battery fire is easier to deal over the long term. Reports have mentioned low ceiling heights as being a key constraint. However, a recommendation for minimum clear heights in carparks would be a significant one. This should be considered in conjunction with existing or forthcoming fire brigade standard operational procedures and guidelines.

D1P1 / D1P8 Access & Carparking for People with a Disability

The layout arrangements for EVSE must take account of wheelchair users and other disabled persons.

D1P2 Safe Movement To and Within a Building

The layout arrangements for EVSE equipment must not interfere with means of escape. Charger cable routing must avoid impeding escapers. Cables should probably be visible in an emergency and not be trip hazards for escapers.

D1P4 / D1P5 / D1P6 Exits

The layout arrangements for EVSE equipment should not obstruct or hide fire exits from carparks or impede access to them. Likewise, EVSE equipment should not obstruct fire exits from other buildings or occupancies that open into a carpark.

E1P2 Fire Extinguishers

Fire extinguishers typically provided for ICEV fire hazards – dry power, foam – are not likely to be as effective against EV and the EVSE fire hazards. Carparks may need to feature a different range of fire extinguishers in future.

E1P3 Fire Hydrants

EV fires may require long duration firefighting intervention for several hours or days so sufficient firewater supplies will be needed. Firewater runoff and control will also be needed.

E1P4 Automatic Fire Suppression Systems

An effective automatic sprinkler installation will help to limit fire spread between vehicles. It is not likely to be effective against an EV battery fire though.

7. Risk Assessment

7.1. Previous Assessments

Of the many studies offering risk or safety assessments of EVs and/or carpark fires, only three were found to be formal risk assessments.

Norway conducted a fire risk assessment for charging electric vehicles in carparks [14]. Norway has the largest penetration of EV and public charging facilities of any comparable country. The study followed a public inquiry over proposals to amend building regulations to allow housing cooperative owners to retrofit EV charging facilities in their residential carparks. A consultation paper raised uncertainties regarding fire safety during EV charging in confined spaces. A risk assessment examined whether EV charging in parking garages resulted in unacceptable risk of fire and, if so, what sort of measures would be required to ensure acceptable risk levels. The study concluded:

- There were no indications that EV charging in parking garages would result in an increased probability of fire.
- Present building regulations were adequate.
- Requirements for fixed water-based firefighting systems in parking garages were not affected.
- EV charging equipment was assumed to comply with relevant standards and regulations and follow the requirements of car manufacturers and EV equipment makers.
- The biggest risk was found to be the use of non-complaint cables, leads and sockets for charging.
- There are unknown factors regarding the development of fire in parking garages and the potential for fire propagation to the battery pack.

The study findings hinge on one important assumption. Referring to '*battery damage*' and the chances of thermal runaway after the car has been parked, it concludes such incidents "*appear to be individual cases and not a widespread problem with electric cars in general*". The study did not in fact investigate battery fires for that reason, and only considered the scenario of a car fire spreading to the EV battery. The study basis is therefore questionable. EV batteries do carry an inherent fire hazard due to an incipient thermal runaway fault, and EV fire risk is uncertain compared to ICEV fire risk.

NZ (Spearpoint & Li, 2004 [27) conducted a cost-benefit analysis for automatic sprinklers in carparks. This used event tree analysis to express the range of potential fire scenarios, then Monte Carlo simulation methods in a cost-benefit ratio calculation. The paper did not reveal the intermediate results for fire frequency or fire risks on which the CBA was based. The work found automatic sprinklers were not economic.

Sweden (RISE [18]) conducted an assessment of LIB vehicle safety and published the records of its formal hazard identification workshop framed around the bowtie method (i.e. it considers the pre- and post-fire situations for separate treatment of prevention and mitigation measures). The exercise did not include a risk assessment. The work concludes that EV presented new types of fire risk but found no evidence that points at EVs being less safe than conventional vehicles.

7.2. Qualitative Assessment

A conventional, qualitative risk assessment was attempted using a standard approach and a generic (typical) Risk Matrix. ICEV carpark fire hazard scenarios were defined to cover the range from single vehicle fires to major spread and whole carpark involvement. The assessment found identical Low risk rankings for all hazard scenarios. This was true using both the Life Safety and Asset/Business Disruption severity categories. There were minor differences in Severity and Likelihood scorings for the various scenarios, but these differences were not significant enough to cause the risk score to fall into a different region.

The assessment then considered EV fire risks by difference, and this also found Low risk rankings for all hazard scenarios.

The exercise was useful in confirming that carpark fires are low risk, and that a qualitative approach does not have sufficient resolution to be able to discriminate between ICEV and EV fire risks.

7.3. Comparative Assessment

It is useful to conduct a qualitative comparison of the key fire characteristics of ICEV and EV in terms of the Ignition, Fire Growth and Fire Spread stages, and in terms of any differences in Fire Severity.

Ignition

We can eliminate most ignition sources because they are common to both vehicle types, leaving:

ICEV	EV
Fuel leak	Battery Thermal Runaway
Overheating	Charger electrical fire

There is no strong evidence so far to suggest ICEV and EV fire rates differ significantly, or evidence that ICEV fuel leaks and overheating causes are more (or less) likely than battery thermal runaway events. Battery thermal runaway / battery fire rates are difficult to source. It has been suggested the rate is in the order of one in one million to one in ten million – presumably that means over the life of the battery – but it is difficult to derive an annual figure.

Fire Growth

Car fires starting inside the passenger cell behave the same way and grow at the same rate, irrespective of vehicle type, so that is not a risk differentiator. The differentiators are:

ICEV	EV
Consistent fire growth patterns	Variable/uncertain fire growth due to battery thermal runaway
Rapid growth is more likely to happen with an internal (passenger cell) ignition source	Rapid or sudden/explosive fire growth has been observed in thermal runaway events

There does not seem to have been many full-scale EV fire tests involving simulated battery thermal runaway events. The initiating fire sources used in the few full-scale tests to date have been a gas ring in the internal passenger cell and an external fire under the battery compartment. There are no descriptions of EV fire growth either stemming from, or spreading to, the battery.

With that caveat, there is no evidence to indicate any significant differences between ICEV and EV in terms of the likelihood or rate of fire growth.

Fire Severity

Some fire tests have found significantly higher peak HRR with EV compared to ICEV, but it is not clear this is a consistent pattern, and the results were not ascribed to any specific differences between ICEV and EV fire parameters. In general, similar-sized ICEV and EV vehicles appear to have similar conventional fire loads. The theoretical fire load of an EV battery is on a par with that of an ICEV fuel tank, but that could be a misleading comparison because it does not account for plastics in the casings and packaging. EV fire test data is also limited; few full-scale vehicle tests have been conducted and battery fire tests have used much smaller batteries than found in EV today. The size of EV batteries is likely to trend larger in future.

ICEV	EV
Fire severity relates to vehicle size and age	Battery fire severity relates to its electrical capacity and is comparable to ICEV fuel tank fire load
Limited knowledge of how fire severity relates to ignition source and main car components	Actual battery fire behaviour is variable/ uncertain
	Battery fires can have very long durations

The evidence at present does not indicate any significant differences between ICEV and EV fire severity, but there is a need for more information about full-scale EV fire behaviour in realistic battery thermal runaway scenarios.

Fire Spread

Car fires starting inside the passenger cell appear to have a greater chance of spreading to adjacent cars, but the vehicle type has no clear influence over this, neither does it seem to influence the susceptibility of the adjacent car to catching fire. There are obvious differentiators related to fire spread mechanisms.

ICEV	EV
Fuel spill spreads towards adjacent car	Torch flame impacts adjacent car

However, in practical terms, those different fire spread mechanisms do not indicate one vehicle type has a higher propensity to cause fire spread than the other. Considering actual incidents, the large-scale fire spread noted in Liverpool Echo fire was enabled by fuel spreading via specific failures of compartment integrity (floor drains, rainwater plumbing). By contrast, EV batteries did not appear to contribute to fire spread in the Stavanger airport fire.

8. Uncertainties

8.1. Fire Severity

Fire incident reports suggest EV vehicle fires do not follow the consistent pattern that ICE vehicle fires have. They do not develop uniformly, or predictably. An EV fire may develop rapidly – similar to an ICE fire – or slowly, over several hours, with only modest growth.

An EV battery fire exhibits features of an exothermic, electrochemical process combined with conventional combustion. Fire research provides estimates of peak HRR and relates this to battery capacity. It is not apparent yet that fire tests have managed to capture the full or maximum fire potential of an EV.

Recent meta studies have concluded we still require detailed knowledge of the various key factors influencing the heat release rate from a battery fire, and the rate and toxicity of gases released. Many studies focus on cell and pack level fire safety, but there is little data published on system-level fire safety (e.g. EVs and EVSE). Comprehensive and methodological system-level fire testing is needed to shed light on important issues like: fire test repeatability, sensitivity to test conditions, scalability with mass or SOC, and fire suppression systems.

8.2. Fire Spread

It is reasonable to expect that heating the exterior of a battery module will trigger a thermal runaway event. It is not clear what external fire conditions are needed to induce an EV car battery to catch fire, or how long it takes.

EV battery fires produce torch flames and fireballs which should be expected to cause more rapid fire spread, but this needs to be confirmed through fire testing.

8.3. Charging Equipment Fires

To a degree, the term ‘charging equipment’ is a misnomer. Level 1, 2 & 3 charging equipment simply provide electrical power to the charger onboard the vehicle. Only Level 4 equipment supplies DC power direct to the EV’s battery installation, bypassing the onboard charger. Fire hazards should be limited to the amounts of combustible materials present in the enclosures, etc. which should be relatively small amounts.

However Type 4 equipment will use liquid cooling circuits and the nature of the coolant medium is not certain. Historically, electrical equipment (e.g. transformers) have been cooled using combustible oils or glycols, so there is a potential new fire hazard.

8.4. Ageing

> *"A common concern…. is the effect of cell ageing on safety test results, a subject currently not covered by any standard. Differences have been observed in test outcomes between beginning of life (BOL) and end of life (EOL) cells. However, the aging influence on safety characteristics is not yet understood in the scientific community. Further research on this topic is encouraged by all industries."*

The risks associated with Li-ion battery systems derive fundamentally from the novelty of the technology and limited long-term experience base with its safety performance. Vehicle service is one of the most diverse and challenging engineering applications because of the diversity of environments, vehicle users and potential for misuse and abuse. There is limited experience in understanding how the rigors and challenges of severe vehicle duty cycles affect the long-term safety of Li-ion batteries and systems. Auto makers and battery manufacturers are working to ensure that the battery systems being deployed are safe for consumers, but it is an evolving field.

It is reasonable to think that as the LIB ages, any existing incipient faults are likely to degrade further and new faults will accumulate, so over time the likelihood of a thermal runaway condition will increase. Coupling this with the hypothesis that thermal runaway is more likely when a battery approaches or reaches its fully charged state, then as the EV fleet ages, we might expect a rising trend in carpark fire frequency involving older EV being charged.

8.5. Toxicity

Large emissions of toxic gases are expected as a result of a LIB fire, and containment or ventilation will be required. Further research is needed on the amount and toxicity of the products (gases and residues) released from LIB fires. It is also required for new methodologies for containing and cleaning these gases in sensitive areas where ventilation is not possible. While there is not an exhaustive knowledge of toxic emissions of battery fires, and with the exception of HF, it seems that they do not differ significantly from those of plastic fires in the case of stationary grid storage applications, or ICEV fires in the case of EVs. However, enhancing further knowledge in this area is demanded by most industries and stakeholders.

9. Design Standards

9.1. EV and LIB

Fire test standards for vehicles are limited. There is a 2-minute fire exposure test for plastic fuel tanks (most tanks achieve a 4-minute survival time before failing). For some reason, the same test is being applied to EV battery installations – the same test fire source being placed below the battery location.

Codes and standards for LIB and EV vehicle systems are in their early development stages and are immature at this time. Current industry standards do not consider the full duty cycle durability requirements for safety that can be found in industry standards for other vehicle fuel and high energy storage systems. As a consequence, current LIB battery vehicle standards do not support a line item level review of design, manufacturing, and test measures to prevent or mitigate potential failure modes that may be identified in (for example) a failure modes and effects analysis or fault tree analysis.

In-service abuse events damage cells, modules, or packs without causing immediate or near-term failure. These abuse events or damage may not be detectable with existing controls. Damage in cells, modules, or packs caused by abuse may grow to failure, undetected, in subsequent normal charge/discharge service duty cycles.

This potential for damage and long-term growth indicates the need for a clearly defined service duty cycle test that represents the charge/discharge duty cycle and maximum and minimum service conditions that a cell and battery must be able to withstand. It indicates that the cell and battery should be able to withstand damaging events such as drop/impact, vibration, impact, surface damage/scratches, penetration, chemical exposure, and extreme temperatures and then be able to survive normal duty without hazardous failure for the remainder of its service life, which can be well in excess of a decade in auto service.

Australia is a “technology-taker” in the EV market and so Australian regulatory requirements have to align with international standards and conventions such as the Open Charge Point Protocol (OCPP), IEC 15118 and IEC 61850-90-8 which include smart charging functionality. EVSE equipment safety standards are set by international bodies. The IEC 60364 series for Low Voltage Electrical Installations and the IEC 61851 series both contain parts dedicated to EVSE and safety measures for them. Fire safety is mentioned as a specific goal of the standards, but apart from requirements limiting combustible materials of construction, fire safety measures seem to be conflated with the electrical safety measures.

9.2. Carparks

The basis of the current fire provisions in the BCA reach back to a series of full-scale fire tests on carpark conducted by Bennetts, Thomas and others for BHP Research between 1985-89. The work was amalgamated into a fire safety design guide in 1999 [7], that publication being updated in 2018 [8]. The guide summarises BCA DTS requirements and solutions from the perspective of steel-framed carpark construction. The guideline contained the following quote, indicative of attitudes at the time.

> *It is known that fires in carparks will tend to be localised due to the fact that each car body will act as a form of enclosure and limit fire spread. Thus, the overall stability of the building is unlikely to be affected, even in the very unlikely circumstance of sprinkler failure.*

The fire tests covered open-deck, part-open deck, closed deck and multi-classified building (i.e. part-open with office above) configurations, with and without sprinklers. Fire sources were large (Australian) sedans with steel and plastic fuel tanks or LPG, or fuel tanks alone, or trays of fuel. Tests used multiple cars with windows down, but configurations varied. Open-deck tests found 3 cars eventually involved but fire spread "*took some time*". The closed-deck tests had (typically) 5 cars spaced 400-500mm apart. The closed-deck, part-closed deck and multi-classified building tests all showed rapid fire spread. Smoke production was assessed to be a major hazard for life safety.

The original reports were not obtained for this study – it is not known if they might have provided quantified information about fire severity and fire spread for comparison with more recent work. On the basis of the test program results, the BCA was amended to require sprinkler protection in closed carparks for more than 40 vehicles. The basis for selecting the number 40 is unclear, however. Unprotected steel was allowed in open-deck carparks, and in closed-deck ones if sprinklers were provided. The BCA also dropped the requirement for a carpark that is a supporting construction (say for an office above) to have equal fire resistance to that which it supports, since the tests indicated this was inappropriate for structural members in different enclosures.

9.3. Carpark Developments

There are two items of interest in the International Building Code provisions for carparks.

IBC 2021 eliminates the blanket exception for fire sprinklers in open parking garages. Instead, it provides two new thresholds to trigger fire sprinkler requirements: new open parking garages over 55 feet in height or new open parking garages over 48,000 square feet in fire area. It is not clear what has triggered the changes, but it can be speculated that recent fire events have influenced attitudes on the risks of carpark fires.

IBC 2018 had added a requirement for Battery Energy Storage Systems to have Thermal Runaway Containment because of the “significant fire threat” from LIB. A BESS installation must be able to contain a runaway lithium battery cascading event. UL modified UL 9540 to include runaway containment, noted as UL 9540a. It was widely anticipated UL 2580 and UL 1973 will also include UL 9540a, to test electric vehicles and repurposed batteries for use in energy storage systems. Also it was expected that NFPA 855 will include UL 9540a. To round out safety certification testing requirements, lithium battery packs should also exhibit resistance to an external fire, such as presented by a Class A fire.

10. Conclusions

A. Overall

i. EV carpark fire risks should be similar to the existing risks from ICEV in terms of their severity and (arguably) likelihood.
ii. EV charging equipment is not expected to introduce significant fire loads or fire rates, except for Type 4 (direct DC) equipment if combustible liquid coolant is used.
iii. The cautious conclusion is NCC provisions do not need changed to accommodate new hazards or risks from EV charging facilities in building carparks.
iv. Emerging knowledge about EV fires must be kept under review to provide assurance that these conclusions remain valid.

B. EV Fire Severity

i. EV and ICEV are substantially similar in terms of the nature and amounts of combustible materials, and fire tests mostly show similar heat release rates and fire behaviours.
ii. The theoretical fire load of an EV battery is broadly similar to an ICEV fuel tank, but the plastics used for battery casings and packaging add substantially to that.
iii. EV fire testing to date has been limited, and full-scale tests on new models with larger batteries are needed to establish their maximum fire potential with confidence.
iv. EV battery fires can produce torch flames or fireballs, so more rapid fire spread to adjacent cars is expected, but this also needs investigated in full-scale tests.
v. EV battery deflagration events may happen, but unconfined vapour cloud explosions are considered very unlikely.

C. EV Fire Frequency

i. An average ICEV carpark fire rate is about 3.4E-05/bay-yr.
ii. EV fire frequency is similar to ICEV, based on limited data, but this conclusion is uncertain because post-collision ICEV fires might be distorting the picture.
iii. EV battery fire rates (thermal runaway events) are similar to vehicle fire rates, but again this is based on limited data.
iv. EV battery fire rates are expected to increase with battery age, use and abuse, but the magnitude of that increase is not known.

D. EV Firefighting

i. Distinct aspects of EV carpark fires have implications for firefighting intervention and smoke control.
ii. EV fires produce significantly more smoke and toxic gases than ICEV, with hydrogen fluoride being a concern for firefighters tackling an EV fire in closed or underground carparks.
iii. EV battery fires need several hours or days of firewater cooling for control and extinguishment.

iv. Long duration fire intervention requires suitable and sufficient firewater supplies and firewater runoff control arrangements.

E. Other Conclusions

i. Recent carpark fires prove modern cars burn more intensely, and spread fire more rapidly, than was contemplated last century when carpark fire safety design guidelines were conceived.
ii. It is realistic to consider carpark fires having the potential to cause large life loss among users (Liverpool Echo) or residents (Monica Wills).
iii. Recent carpark fires have implications for ACM cladding initiatives.

11. Recommendations

NCC Performance Requirements address the fire risks of EV charging in carparks adequately. However, our fire knowledge is still developing, and it is important to keep EV fire research and fire statistics under review.

A. Overall

i. Monitor EV fire research and fire statistics and keep the report conclusions under review.
ii. Consider differentiating EV from ICEV in the Australian Incident Reporting System to allow any emerging trends in EV or EVSE fire frequencies to be identified.

The introduction of new technology posing different fire hazards also justifies new advice and guidance on the application of the NCC.

B. Fire Resistance / Reaction to Fire

i. Premises above carparks (residential apartments, offices, commercial & shopping premises, etc.) must consider the suitability of the fire resistance/reaction to fire ratings of the external building envelope and particularly that of any external cladding materials.

C. Means of Escape

i. Means of escape arrangements for carparks serving high-occupancy premises such as sports or entertainment venues, shopping centres, and similar, must consider mass evacuation under the maximum foreseeable challenge e.g. mass exodus of the crowd at the end of an event.
ii. The design of fire warning systems, fire signage, emergency lighting, fire exits and vehicle entry/exits must prevent or discourage people from returning to vehicles, or attempt to drive vehicles out of the carpark, after a fire warning is given.

D. Sprinkler Protection

i. Automatic sprinkler protection should be considered for all carparks with EVSE facilities.

E. Firefighting

i. Smoke control for closed or underground carparks must provide an adequate air change rate to limit HF toxic gas concentrations.
ii. Firewater supplies must be adequate to supply cooling hose streams for (potentially) several days.
iii. Firewater drainage capacity and runoff control arrangements must be adequate for such extended fireground operations.

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