Australian Building Codes Board

Fire safety in carparks

Literature review

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Executive summary

Modern day building codes must respond to the challenges of the climate crisis. Within the last decade in particular, a move towards more sustainable methods of construction and transportation methods has materialised, presenting unique fire hazards that need to be considered to help inform appropriate fire safety measures, either contained within the prescriptive provisions of building codes or be developed by designers to satisfy the Performance Requirements.

The Australian Building Codes Board (ABCB) is investigating the adequacy of fire safety provisions within carparking structures due to concern that current provisions within the National Construction Code (NCC) may not be adequate for modern vehicle designs.

Arup have been appointed by the ABCB to provide input into their investigations with this literature review of global sources up to August 2023.

The principal findings of this review are:

- Modern vehicles are larger, heavier, use more plastics and therefore have increased quantities of combustible materials when compared to cars manufactured earlier in the 20th century, as documented in Section 7. They're also more likely to have plastic fuel tanks, and leakage of fuel as a result of fuel tank failure is a common mechanism of fire spread between vehicles.
- Some modern vehicles utilise alternative fuels. This review has covered ICEVs, BEVs, PHEVs, HFCEVs and LPG vehicles. Each fuel type presents its own unique hazards. For example, ICEVs can lead to secondary liquid pool fires remote from the vehicle of fire origin, whereas BEVs can (more rarely) exhibit jet flames. Both of these phenomena can promote fire spread.
- The current body of evidence does not suggest that the fuel type is the most important factor in determining fire severity, rather the size and mass of the car and its components is more important. There are other key conditions which seem to lead to large fire events, namely carparks which are fully occupied, with little spacing between vehicles, and large, deep floorplates and low ceilings.
- The experimental research (described in Section 4) upon which contemporary building codes are still founded utilised vehicles which were common at the time. Those vehicles are no longer representative of modern vehicles.
- Vehicle fires are not uncommon, but the majority of these occur on the road or after collision rather than while parked, as noted within Section 6.
- The commonly cited assumption in fire safety literature from the 20th century is that fire spread between cars is a rare event. This is no longer appropriate for the modern car, particularly in unsprinklered carparks.
- Recently, a number of large-scale fires have occurred in carparking structures around the world. A sample is documented in Section 5. Some have involved multiple hundred or even over a thousand vehicles and led to large economic losses.
- The life safety impacts of carpark fires are currently relatively very small. The case for improvement of fire safety standards is largely driven by increased protection against low probability, high consequence events or for the improvement of fire-fighter ability to fight fire rather than a systematic improvement of occupant life safety. However, as technology evolves and the uptake of technology increases, there is a need to monitor the statistics periodically and keep this under review.

As documented in Section 3, the fire safety requirements for standalone carparking buildings within Australia are generally on the less conservative side based on the international guidance sampled. In particular, the below elements stand out:

- Permitting limited structural fire resistance (in the form of the ESA/M ratio for steel) for unlimited height open-deck carparks without fire suppression.

- No requirements for sprinklers in open-deck carparks. It is noted it is primarily guidance originating from the USA which explicitly require sprinklers in open-deck carparks.
- No requirements for specific smoke exhaust in enclosed carparking.
- The lack of specific requirements for car stackers within the NCC, whilst Australian Standards such as AS 2118.1:2017 provide requirements.

For these specific points the following observations have been made:

Structural fire resistance

- It is recommended that the ABCB consider whether restricting the use of the ESA/M ratio from open-deck carparks for at least Type A construction is appropriate. Included in this consideration could be the effect of requiring reliable fire suppression in structures that use the ESA/M method (it is noted that an international precedence exists in that NFPA 88A requires sprinklers for similar structural concessions).
- The above consideration could also apply to Type B carparks, however this ultimately depends on what the ABCB deem as acceptable for Type B buildings. Alternatively, continued use of the ESA/M concession may be appropriate (and is consistent with international guidance), given the overall lower rise / consequence of fire in these buildings.

Suppression

- Some jurisdictions now require sprinkler protection in open-deck carparks (the IBC and NFPA standards in the USA in particular). While clearly of benefit for fire life safety and property protection purposes, it may not be a justifiable sustainability (in terms of material use and carbon cost) or monetary cost to require all open-deck carparks to provide sprinkler protection given the low number of fatalities within open-deck carparks. This would require further detailed review taking into consideration the development of new technologies and frequency of fires as the technology develops.
- There has been limited research undertaken on the subject, but what is present has concluded that the cost is not justified. The research is specific to UK / US statistics, so a similar study for the Australian context would be of value. It is recommended that the ABCB evaluate this aspect.
- Similarly, as a fire involving up to 40 cars is a significant event in an enclosed carpark which poses challenges to fire-fighters as well as occupant safety, it is recommended that the ABCB consider whether suppression in enclosed carparks having less than 40 cars should be required. This literature review did not uncover an evidence basis for the 40 car limit within the NCC, and this arbitrary limit was not proved or disproved.

Smoke exhaust in enclosed carparking

- Smoke exhaust is beneficial for firefighting but limited research into the pure merits means that cost to society (sustainability & monetary) is hard to justify based on current research, however this should be studied further. Improvements to increase the resilience of the existing carpark exhaust systems (e.g., fire resistant fans and cabling) provided for day-to-day ventilation may be worthy for the ABCB to explore as part of future studies, considering the changing hazards.

Car stackers

- Rules should be defined for car stackers as there is a clear indication that they change both combustible fuel load density as well as the severity of fire.
- Suppression is frequently required in other jurisdictions for car stackers.
- The 40-car concession may not be appropriate for enclosed carparks which use car stackers.

The structure of this report reflects the scope set by the ABCB in the Request for Proposal (RfP), with minor alterations by Arup as agreed with the ABCB.

Some of the topics covered are emerging fields, and future research efforts are expected. As and when new information becomes available, the findings in this literature review may require revision.

Please cite this document as: Arup, ‘Fire safety in carparks – ABCB literature review’, 2024.

Disclaimer

The research undertaken to identify relevant sources of information referenced in this document was concluded in August 2023. Therefore, research publications that have been issued after August 2023 are not considered in this work.

Glossary

This literature review includes the following terms:

ABCB	Australian Building Codes Board.
AFAC	Australian Fire Authorities Council.
AFV	Alternative fuel vehicle, meaning any vehicle not powered solely by the more ‘conventional’ internal combustion engine.
AIBS	Australian Institute of Building Surveyors.
AV	Autonomous Vehicle
AVPS	Automated Vehicle Parking Systems, which covers car stackers but also any other mechanical device that moves vehicles into storage positions.
BCA	Building Code of Australia, which consists of Volumes One and Two of the NCC.
BEV	Battery electric vehicle, meaning vehicles which are solely powered by electricity stored in a battery pack. Often described as “all-electric”.
Carpark	As per the NCC; A building that is used for the parking of motor vehicles but is neither a private garage nor used for the servicing of vehicles, other than washing, cleaning or polishing [1].
Car stacker	A lifting device which allows multiple cars to be parked in a vertically ‘stacked’ arrangement.
Enclosed carpark	Any carpark building which doesn’t satisfy the open-deck carpark requirements.
ESA/M	Exposed surface area to mass per unit length ratio for structural steelwork. Used as a threshold for concessions within the current NCC.
EV	Electric vehicle
EVCP	Electric vehicle charge point
HEV	Hybrid electric vehicles, powered by a combination of an internal combustion engine and electricity stored in a battery pack. The battery is charged through regenerative braking and the internal combustion engine itself.
HFCEV	Hydrogen fuel cell electric vehicles, powered by an electric motor using electricity generated by a fuel cell powered by hydrogen.
LPG	Liquified petroleum gas.
Modern car	Vehicles manufactured in the 21st century.
MTVSD	Multi-tiered vehicle stacking device.
NCC	National Construction Code.
Open-deck carpark	As per the NCC; A carpark in which all parts of the parking storeys are cross-ventilated by permanent unobstructed openings in not fewer than 2 opposite or approximately opposite sides, and – (a) each side that provides ventilation is not less than ⅙ of the area of any other side; and (b) the openings are not less than ½ of the wall area of the side concerned [1].
PHEV	Plug-in hybrid vehicles, powered by a combination of an internal combustion engine and electricity stored in a battery pack. The battery is charged through

	regenerative braking, the internal combustion engine itself, and through plugging into charging stations.
Unprotected	Used to describe bare (exposed) structural steel members without any applied fire protection.

1. Introduction

1.1 Scope and structure of this report

The Australian Building Codes Board (ABCB) is investigating the adequacy of fire safety provisions within carparking structures due to concern that the current provisions within the National Construction Code (NCC) may not be adequate for modern vehicle designs.

Arup have been appointed by the ABCB to provide input into their investigations with this literature review.

Firstly, it must be clarified what is meant by a "carpark", as definitions and interpretations vary around the world. In this report, as in Australia and the UK, "carpark" takes the same definition as within the NCC. That is; a building that is used for the parking of motor vehicles but is neither a private garage nor used for the servicing of vehicles, other than washing, cleaning or polishing. In the U.S., a "carpark" is termed as "parking garage", which is often a cause for confusion.

The structure of this report reflects the scope which was initially set by the ABCB in the Request for Proposal (RfP) and subsequently subject to minor alteration by Arup as agreed with the ABCB. The initial RfP asked for "*a comprehensive outline of fire safety in modern carparks, including but not limited to:*

- *Review of the existing concessions for sprinkler protected and open deck carparks in the NCC and whether they are still valid.*
- *Review of the previous BHP research program and results and whether the research is still applicable within modern carparks.*
- *Outline of fire safety requirements for carparks under international buildings codes and standards.*
- *Outline of recent fire events in carparking structures and what has been learnt.*
- *Outline likelihood of fires within carparking structures and also statistics in relation to fatalities or injuries associated with fire events.*
- *Fire hazard summary of modern vehicles based on latest testing.*
- *The review should consider modern carpark hazards, such as increased vehicle fuel loads, EVs and car stackers.*
- *Provide an opinion, based on the completed review, on whether the current fire safety provisions in the NCC are adequate or not.*
- *Outline any gaps in knowledge.*
- *Suggest possible wording to guide building designers.*"

A detailed review of Australian Standards referenced by the NCC was outside the scope of this literature review. This review focuses on the DtS provisions within the NCC. Ultimately, the ABCB are not responsible for changes to Australian Standards. However, it is acknowledged that the NCC needs to consider the Australian Standard which it cites. Where there have been recent changes to Australian Standards which are relevant to carpark design, and those changes are deemed significant, they are discussed.

Initially, the existing fire safety provisions for carparking structures within the NCC are reviewed in Section 2. A focus is placed on NCC Volume One, but short commentary is also provided on NCC Volume Two. This is complimented by a review of fire safety guidelines published by brigades across Australia.

Then, the aforementioned fire safety provisions are compared to other codes, standards and guidance documents from around the world in Section 3 - International precedent. This has focused on jurisdictions in which Arup operates and has the necessary skills and expertise to inform this review.

Section 4 revisits notable experimental research efforts investigating the fire dynamics of natural fires in large, open-plan carparks. Whilst the brief from the ABCB was solely to cover the experiments carried out by BHP Steel in Australia in the mid-to-late 1980s, other seminal research is also touched upon at a high level. These experiments informed the NCC at the time, and it is our understanding that this has not altered since. The experiments were primarily focused on performance of exposed structural steel. Smaller experiments aiming to quantify the heat release rate (HRR) of single vehicles through hood calorimetry for design fire purposes are not covered by this review.

Then, significant carpark fire events from which lessons can be learned are documented in Section 5, and statistical data from such carpark fire events is presented in Section 6.

Section 7 provides a summary of the fire hazards which may be expected in a modern-day carpark.

Finally, conclusions are drawn from the review in Section 8.

1.2 Methodology for undertaking this literature review

Arup's fire safety engineers have worked collaboratively with Arup's in-house librarians to conduct this literature review. Key words were identified and formulated into search strings to then run through various literature databases. These are documented in Appendix A.

Arup were also recently appointed by the UK Government's Office for Zero Emission Vehicles (OZEV) to conduct a literature review specifically on electric vehicles [2]. That work followed a similar methodology, albeit solely focused on EV-related literature published before April 2022. The search for EV-related literature for this ABCB project has therefore only focused on work published between April 2022 and August 2023.

Whilst every effort has been made to cover all relevant sources published to-date, there may be some which were not available whilst conducting this review. Additionally, literature was screened by Arup's fire safety engineers for both relevance to this project and quality. Some sources deemed irrelevant or of poor quality have been omitted. The bibliography at the end of this report cites every source relied upon.

Abstracts from each key word search were first screened for relevance, with potentially relevant papers then subsequently screened using the inclusion/exclusion criteria set out below.

Inclusion criteria for the first pass review included the date of the research, relevance to the key research questions, and whether the article is already represented in other research. Exact key words used can be found in Appendix A.

Table 1: Inclusion/exclusion criteria for sources in key word search results.

Inclusion criteria	Exclusion criteria
Published in the last 10 years.	Older than 10 years. Exceptions to this rule apply: – original research which influenced code requirements from ~1960-1990 – Research done in the early 2000s which has not been revisited (e.g. car stacker fire testing)
Relevance to modern car hazards.	No mention of modern carparking hazards.

From Arup's key word search, approximately 400 sources were analysed for their compatibility. Around 300 of which were academic papers, with the remainder best described as 'grey' literature such as newspaper articles, web pages, building codes and standards. 184 sources that were found to be related to modern hazards in car parks and/or related to original research underpinning code requirements are cited in this document and summarised accordingly in the bibliography.

2. Fire safety provisions for carparks in Australia

This section recalls the provisions within Australia's National Construction Code (NCC). Particular focus is paid to specific NCC clauses on carparks. Some other clauses which are relevant to carpark design are touched upon.

The NCC is published in three volumes. The 'Building Code of Australia (BCA)' is Volumes One and Two of the NCC. A focus is placed on the fire safety provisions within Volume One in this literature review. Volume Two – which applies to Class 1 dwellings – is not the primary focus of this work. It is discussed briefly towards the end of this section.

The Plumbing Code of Australia (PCA) is Volume Three of the NCC. It is not covered by this review.

Extracts from the NCC are highlighted blue.

2.1 NCC Volume One

The provisions within NCC Volume One are specified based on building classification and construction type. Carparks are classified as Class 7a buildings [3]. Type of construction required is determined in accordance with Clause C2D2 and Table C2D2, which is repeated below for Class 7 buildings.

Table 2: Type of construction required for Class 7 buildings.

Rise in storeys	Type of construction required
4 or more	A
3	B
2	C
1	C

The Deemed-to-Satisfy (DtS) provisions within the NCC for carparks are generally based on whether a carpark is open-deck or closed, and (if closed) whether it is provided with a sprinkler system or not.

An open-deck carpark is defined as:

Open-deck carpark: A carpark in which all parts of the parking storeys are cross-ventilated by permanent unobstructed openings in not fewer than 2 opposite or approximately opposite sides, and –

a) each side that provides ventilation is not less than ⅙ of the area of any other side; and

b) the openings are not less than ½ of the wall area of the side concerned.

2.1.1 Smoke exhaust

Part E2 of the NCC covers smoke hazard management. Clause E2D12 covers Class 7a buildings (carparks). It states that carparks provided with a (day-to-day) mechanical ventilation system in accordance with AS 1668.2 must comply with Clause 5.5 of AS 1668.1, which covers carpark ventilation systems. It clarifies that carpark ventilation systems are intended to be operable in the event of a fire, but are not considered to be smoke control systems.

Where there is a detection system and/or suppression provided in the carpark; activation of one of those systems shall cause the ventilation system to operate at full ventilation rate. Supply air systems are to shut down upon detection of smoke in the supply air, and restart once the detector is cleared.

Carpark ventilation fans not used for fire-isolated exit pressurisation relief are not required to be served by fire-resistant cabling. Fans that are not required to be shut down on initiation of fire mode in the carpark shall be provided with control switches at the building entry, such that the fire brigade can manually control the fans if desired. This is the typical approach to carpark ventilation systems in Australia.

2.1.2 Detection

A smoke detection system must be installed to operate a zone pressurisation system and/or stair pressurisation systems (Clause E2D3). However, this is not required for open-deck carparks, as Clause E2D2 states that the DtS provisions of Part E2 do not apply. Clause E2D12 covers Class 7a buildings, and simply refers to AS 1668.2 and AS 1668.1.

AS 1670.1:2018 Clause 7.6.8.1 requires carparks and loading docks that have (day-to-day) ventilation systems installed (in accordance with AS 1668.2), and fire-isolated pressurised exit paths, to be provided with smoke detection in circulation spaces and at each required exit and lift landing door. Clause D2D4 of the NCC states that every stairway or ramp serving as a required exit must be fire-isolated in Class 7 buildings, unless it serves not more than two consecutive storeys. Therefore, most carparks have detectors installed because they have fire-isolated exits.

There is a scenario, however, where a two-storey basement (enclosed) carpark is not provided with fire-isolated (pressurised) stairs (as they are not required by D2D4), thus the requirement for detectors in circulation spaces and at each required exit and lift landing door is not triggered. The only detectors required in such a carpark by AS 1670.1:2018 are within the supply air. Activation of these detectors would shut down the smoke exhaust system.

2.1.3 Egress

Clause D2D5 covers exit travel distances. For Class 7 buildings (which includes carparks, being Class 7a), the single direction travel distances to an exit, or a point of choice from which travel in different directions to two exits is available, must not be more than 20 m. If the latter is the case (i.e., more than one exit is provided), the maximum distance to one of those exits must not exceed 40 m.

Clause D2D15 covers discharge of exits. On first reading, there is some ambiguity over whether exits can discharge into the ground level of a carpark. One may first navigate to Clause D2D14 Discharge of exits. It requires that “an exit must not be blocked at the point of discharge”. An “exit” is defined in the NCC as; an internal or external stairway, a ramp, a fire-isolated passageway, a doorway – if they provide egress to a road or open space. “Open space” is then defined as “a space on the allotment, or a roof or similar part of a building adequately protected from fire, open to the sky and connected directly with a public road.

Clause D2D12 covers travel via fire-isolated exits, but also covers their discharge. Clause D2D12 (2) states that fire-isolated exits can discharge to a carpark if that carpark is open for at least ⅔ of its perimeter, and if there is an unimpeded path of travel not further than 20 m from the discharge point (into the carpark) to a road or open space.

2.1.4 Fire hydrants

In line with Clause E1D2; fire hydrants must be provided to serve a carpark when the carpark’s total floor area is greater than 500 m^2. The fire hydrant system must be installed in accordance with AS 2419.1. The 2022 edition of the NCC references AS 2419.1:2021, whilst the 2019 Amendment 1 edition of the NCC references AS 2419.1:2005. It is noted that AS 2419.1:2017 was not referenced by the NCC. It is understood that this revision of the standard was not endorsed by AFAC or FRNSW [4]. AS 2419.1:2021 is endorsed by FRNSW [5].

Whilst detailed review of Australian Standards is outside the scope of this literature review, it is noted that the previous design requirements within AS 2419.1:2005 were more onerous – it required concurrent supply to both the hydrant system and sprinkler system in a multi-storey carpark. We understand that practitioners typically aimed to (and successfully) circumvented this requirement through Performance Solutions. As part of the 2021 update, common Performance Solutions were codified. Effectively, it is our understanding that a lot of carpark designs (in terms of hydrant and sprinkler water supply) to AS 2419.1:2005 ended up being the same as would be the case now, if designed to AS 2419.1:2021.

2.1.5 Fire hose reels

In line with Clause E1D3, fire hose reels must be provided to serve the whole carpark when one or more internal fire hydrants are installed, or, where internal hydrants are not installed, to serve any compartment with a floor area > 500 m^2.

2.1.6 Atrium provisions

It should be noted that Part G3 *Atrium construction* is not triggered by a multistorey carpark with storeys connected solely by a ramp, as the NCC definition of an 'atrium' is "a space within a building that connects two or more storeys and … (c) does not include a … rampwell". Clause D2D17 also states that a "pedestrian ramp (b) may connect any number of storeys if it is (ii) in a carpark". Therefore, it is understood that the atrium provisions of the NCC do not apply to such carparks: another atrium well connection (in addition to the ramp) would be needed to trigger these provisions.

2.1.7 Concessions

The NCC contains a number of concessions for open-deck carparks and sprinkler-protected closed carparks. These existing concessions are reviewed within the following sub-sections.

2.1.7.1 Those applicable to both; open-deck carparks, and closed carparks with a sprinkler system

Compartment size

Clause C3D2 (Application of Part C3 Compartmentation and separation) provides a concession whereby Clauses C3D3 (General floor area and volume limitations), C3D4 (Large isolated buildings) and C3D5 (Requirements for open spaces and vehicular access) do not apply to an enclosed carpark provided with a sprinkler system complying with Specification 17 (other than a FPAA101D or FPAA101H system), and open-deck carparks.

In other words, the NCC places no limitation on the compartment sizes (floor area and volume) of sprinkler-protected closed carparks, and open-deck carparks, regardless of the building's type of construction. The compartment floor area and volume limits within Table C3D3 only apply to unsprinklered closed carparks.

C3D2 Application of Part

(1) C3D3, C3D4 and C3D5 do not apply to a *carpark* provided with a sprinkler system (other than a FPAA101D or FPAA101H system) complying with Specification 17, an *open-deck carpark* or an *open spectator stand*.

(2) C3D13(1)(e) does not apply to a Class 8 electricity network substation.

Note: An FPAA101D system is a fire sprinkler system fed from the building's drinking water supply system for buildings which are less than 25 m in effective height and contain Class 2 and 3 parts. An FPAA101H system is a combined fire hydrant and fire sprinkler system for buildings which are less than 25 m in effective height and contain Class 2 and 3 parts. Both of these Technical Specification documents are published by Fire Protection Association Australia.

In practice, this means that **there is no upper size limit on open-deck carparks and sprinkler-protected closed carparks**.

Structural Fire Resistance Levels (FRLs)

Clause C2D1 outlines the DtS pathway for specifying FRLs. As per Table 2 of this report; 3-storey carparks require Type B construction, and taller carparks require Type A construction. Specification 5 then outlines the required FRLs for different building elements based on the Type of construction. Readers should refer to these tables, but in general, both Type A and Type B carparks (Class 7a) require FRLs of (120)/120/120 for certain elements (e.g., floors, fire-resisting lift/stair shafts).

It is noted that Clause C2D4 outlines the design requirements for buildings of multiple classification. In such a case, the Type of construction required is the most fire-resisting Type resulting from the application of Table C2D2. Therefore, if a 1- or 2-storey carpark is beneath a 4-storey office (Class 5), for example, that building as a whole will require Type A construction.

Specification 5, specifically Clauses S5C19, S5C22 and S5C25, permits significant concessions in structural fire resistance levels for open-deck carparks and sprinklered closed carparks. These are:

S5C19 Type A fire resisting construction – carparks

(3) For building elements in a carpark as described in (1) and (2), the following minimum FRLs are applicable:
- a. External wall
  - i. Less than 3 m from a fire-source feature to which it is exposed:
    1. Loadbearing 60/60/60.
    2. Non-loadbearing: -/60/60
  - ii. 3 m or more from a fire-source feature to which it is exposed: -/-/-
- b. Internal wall:
  - i. Loadbearing, other than one supporting only the roof (not used for carparking): 60/-/-
  - ii. Supporting on the roof (not used for carparking: -/-/-
  - iii. Non-loadbearing: -/-/-
- c. Fire wall:
  - i. From the direction used as a carpark: 60/60/60
  - ii. From the direction not used as a carpark: as required by Table S5C11d
- d. Columns:
  - i. Supporting only the roof (not used for carparking) and 3 m or more from a fire-source feature to which it is exposed: -/-/-
  - ii. Steel column, other than one covered by i and one that does not support part of a building that is not used as a carpark
    1. 60/-/-; or
    2. An ESA/M of not greater than 26 m^2/tonne.
  - iii. Any other column not covered by i or ii: 60/-/-
- e. Beams:
  - i. Steel floor beam in continuous contact with a concrete floor slab-
    1. 60/-/-; or
    2. An ESA/M of not greater than 30 m^2/tonne
  - ii. Any other beam 60/-/-.
- f. Fire-resisting lift and stair shaft (within the carpark only): 60/60/60.
- g. Floor slab and vehicle ramp: 60/60/60.
- h. Roof (not used for carparking): -/-/-

(4) For the purposes of sub-clause (3):
- a. ESA/M means the ratio of exposed surface area to mass per unit length.
- b. Refer to specification 17 for special requirements for a sprinkler system in a carpark complying with (3) and located within a multi-classified building.

S5C22 Type B fire resisting construction – carparks

(3) For building elements in a carpark as described in (1) and (2), the following minimum FRLs are applicable:
- a. External wall
  - i. Less than 3 m from a fire-source feature to which it is exposed:
    1. Loadbearing 60/60/60.
    2. Non-loadbearing: -/60/60
  - ii. 3 m or more from a fire-source feature to which it is exposed: -/-/-
- b. Internal wall:
  - i. Loadbearing, other than one supporting only the roof (not used for carparking): 60/-/-
  - ii. Supporting on the roof (not used for carparking: -/-/-
  - iii. Non-loadbearing: -/-/-
- c. Fire wall:
  - i. From the direction used as a carpark: 60/60/60
  - ii. From the direction not used as a carpark: as required by Table S5C21d
- d. Columns:
  - i. Supporting only the roof (not used for carparking) and 3 m or more from a fire-source feature to which it is exposed: -/-/-

S5C22 Type B fire resisting construction – carparks

- ii. Steel column, other than one covered by i and one that does not support part of a building that is not used as a carpark
    1. 60/-/-; or
    2. An ESA/M of not greater than 26 m^2/tonne.
- iii. Any other column not covered by i or ii: 60/-/-

e. Beams:
- i. Steel floor beam in continuous contact with a concrete floor slab
    1. 60/-/-; or
    2. An ESA/M of not greater than 30 m^2/tonne
- ii. Any other beam 60/-/-.

f. Lift shaft: -/-/-

g. Fire-resisting lift and stair shaft (within the carpark only): 60/60/60.

h. Roof, floor slab and vehicle ramp: -/-/-

S5C25 Type C fire resisting construction – carparks

(3) For building elements in a carpark as described in (1) and (2), the following minimum FRLs are applicable:

a. External wall
- i. Less than 1.5 m from a fire-source feature to which it is exposed:
    1. Loadbearing 60/60/60.
    2. Non-loadbearing: -/60/60
- ii. 1.5 m or more from a fire-source feature to which it is exposed: -/-/-

b. Internal walls: -/-/-

c. Fire wall:
- i. From the direction used as a carpark: 60/60/60
- ii. From the direction not used as a carpark: 90/90/90

d. Columns:
- i. Steel column, less than 1.5 from a fire-source feature
    1. 60/-/-; or
    2. An ESA/M of not greater than 26 m^2/tonne.
- ii. Any other column not covered by i or ii: -/-/-

e. Beams:
- i. Steel floor beam, less than 1.5 m from a fire-source feature, in continuous contact with a concrete floor slab-
    1. 60/-/-; or
    2. An ESA/M of not greater than 30 m^2/tonne
- ii. Any other beam 60/-/-.

f. More than 1.5 m from a fire-source feature: -/-/-.

g. Roof, floor slab and vehicle ramp: -/-/-

In summary, while slightly different, Type A and B construction can be characterised as typically requiring a 60-minute structural fire resistance for structural elements which are not constructed of steel (where the fire resistance requirement is significantly reduced via the ESA/M ratio which is permitted to be used for structural element which are not columns that support other classifications). Type C construction does not require any fire rating unless in the vicinity of a fire-source feature.

These concessions have previously been summarized graphically by Liberty Steel (see Figure 1) [6].

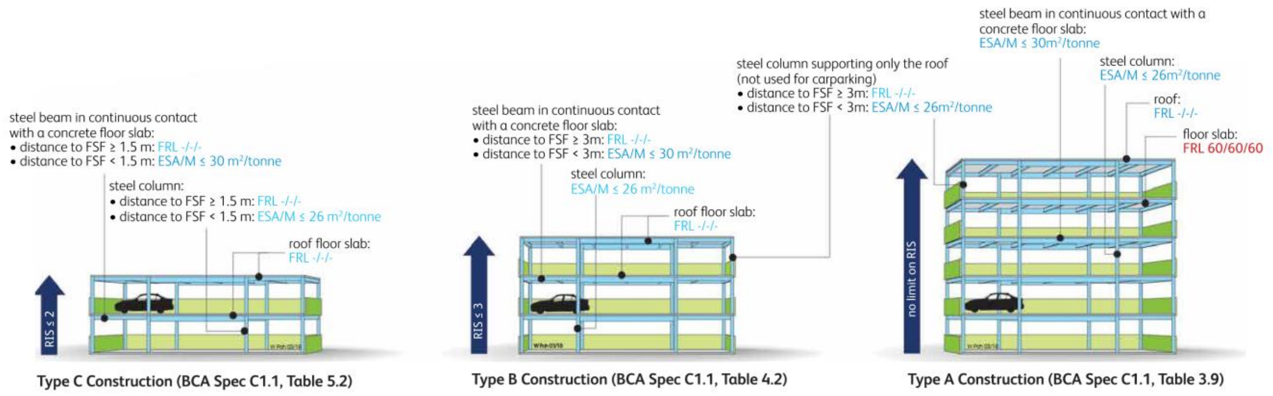


Figure 1: Structural FRL requirements for carparks within the NCC 2019. Reproduced from [6]. © Liberty Steel.

2.1.7.2 Open-deck carparks

As per Clause E1D5, open-deck carparks built as separate buildings are not required to have sprinkler systems and can be built to any height.

Interestingly, open-deck carparks technically do not currently need to meet the Performance Requirements of E2P2 Safe evacuation routes.

2.1.7.3 Closed carparks

As per Clause E1D9, carpark compartments where less than 40 vehicles are accommodated are not required to be provided with sprinklers. Notably, this concession may be overridden by the requirement to provide a sprinkler system throughout the building if required to do so by any of Clauses E1D5 through E1D13, for example if the overall building is higher than 25 m in effective height, or the building is Class 2 (apartment) or 3 (residential) or contains Class 2 or 3 parts and has a rise in storeys of 4 or more.

Other enclosed carparks must have a sprinkler system.

2.2 NCC Volume Two

Volume Two of the NCC primarily covers the design and construction of smaller scale buildings, including houses [7]. It is not the focus of this literature review, but it is prudent to briefly recall some relevant requirements pertaining to private garages.

NCC Volume Two defines a private garage as any garage associated with a Class 1 building (house), or any separate single storey garage associated with another building where such garage contains not more than 3 vehicle spaces.

The private garage space itself is classified as Class 10a (non-habitable building). Clause H3D5 covers fire separation of garage-top-dwellings. This refers to Part 9.4 of the ABCB Housing Provisions [8]. Fire separation between the house and the garage is only required when the Class 10a and Class 1 spaces are not associated with one another.

Ultimately, this means that private garages do not currently need to be fire separated from an associated adjoining house.

2.3 Brigade fire safety guidelines

2.3.1 Australian Fire and Emergency Services Authorities Council (AFAC)

AFAC is the Australian and New Zealand National Council for fire and emergency services. AFAC is made up of members from the government fire, emergency service and land management organisations from each jurisdiction in Australia and New Zealand. Senior representatives of the member agencies form the AFAC National Council [9].

Automated Vehicle Parking Systems (AVPS)

AFAC have produced a guideline on AVPS [10]. AVPS include so-called ‘car stackers’ but also includes any other mechanical device that moves vehicles into storage positions. Such storage spaces can use a vertical layout (i.e., stackers) or conventional horizontal carparking configurations. The document is relatively comprehensive. It begins by highlighting that, traditionally, carparks have involved vehicles stored in a horizontal configuration. An increase in the number of AVPSs in recent decades is discussed, and described that the BHP Steel experiments (which are discussed in Section 4.3 of this report) did not consider vehicles in a vertical configuration.

The subsequent BRE research is cited [11], which included a single test on a vertical car stacker with a car stacked above the other. Accelerated fire spread was observed. AFAC’s opinion is that the current DtS provisions do not consider the fire behaviour demonstrated in the BRE car stacker experiment.

Automated parking systems may be able to store cars closer together than if the cars were parked by humans. The guideline notes the limitations of the sprinkler system clauses within the BCA, and identifies the special hazards clause as relevant for such systems. The guideline goes on to propose design measures for sprinkler systems in such AVPS. This is discussed further in Section 7.3.

Impulse (jet) fans

The second AFAC guideline of relevance is on impulse fans [12]. Whilst not directly relevant to this work and therefore not fully reviewed, the guideline generally outlines that jet fan(s) can be installed in carparks via a DtS pathway. It notes that the relevant Australian Standards (AS 1670.1 and AS 1668.1) were updated in 2015, introducing additional fire safety requirements when impulse fans are installed. These standards were considered by AFAC as adequately addressing previous concerns raised regarding early shut down of jet fans in a fire, thus facilitating a DtS route. The current NCC cites AS 1670.1:2018 (and AS 1668.1:2015), which still has the same requirements for jet fans.

Electric vehicles and EVCPs

In 2022, AFAC published a position paper on electric vehicles (EVs) and EV charging equipment in the built environment [13]. The purpose of this document is to “state AFAC Member agencies’ approach towards Electric Vehicles (EVs) and the installation of EV charging equipment in the built environment in relation to fire prevention and preparedness”. The document begins by identifying various hazards that may exist with EVs, noting that failure events are currently reported to be occurring at a low frequency with potentially high consequence. Notable hazards include exposure to electricity, toxic and combustible vapour production, extended fire duration, potential for secondary ignition, potential for rapid fire spread and potential for impact on the building’s structure.

AFAC recommends that Clause E1D17 and E2D21 (both being Provision for special hazards) of the NCC are implemented by the certifier [when a building includes EVs and/or electric vehicles charge points (EVCPs)]. Various considerations for building designers are then outlined. It is noted that this list is non-exhaustive and non-mandatory; each building is unique and will require a different suite of fire safety measures.

In theory, the AFAC position paper should summarise the areas of mutual positioning across all Australia and New Zealand’s fire and rescue services. However, the AFAC position paper is supplemented by standalone guidelines published by individual fire and rescue services. These are summarised in subsequent sections.

2.3.2 Australian Capital Territory (ACT) Fire & Rescue (ACT F&R)

ACT F&R provide links to *FSG – 11 Fire Safety Requirement for Automated Vehicle Parking Systems* and *FSG – 14 Fire Safety for Impulse (Jet) Fans in Car Parks* on their website. However, these documents are simply the AFAC guidelines previously discussed, and therefore are not mentioned further in this literature review.

ACTF&R have produced their own guideline titled *FSG – 22 Electric Vehicles (EV) and EV Charging Equipment in the Built Environment* [14]. However, that document states that ACTF&R supports the AFAC position paper previously discussed, and that forms the basis of their guideline. Therefore, this is not discussed further. Please refer to Section 2.3.1.

2.3.3 Fire and Rescue Victoria (FRV)

FRV have published three fire safety guidelines relevant to carparks. They cover carparks without sprinkler systems [15], buildings incorporating Automated Vehicle Parking Systems (AVPS) [16], and the use of impulse (jet) fan systems in enclosed carparks [17].

Carparks without sprinkler systems

The first guideline (GL-03) communicates FRV's position on Performance Solutions looking to (part) delete or vary automatic fire sprinkler system provisions within enclosed or partially open carparks. It goes on to imply that any design must be justified holistically, and assessed against performance requirements covering structural stability, spread of fire, access for brigade, fire suppression, occupant evacuation and brigade intervention [15]. The guideline cites the BRE research, which studied fire behaviour when modern cars were involved, which "demonstrated the ease with which a car fire in a carpark might spread to nearby cars" [11]. This research is covered further in Section 4.4. The FRV guideline reinforces that "automatic fire sprinklers have been demonstrated as an effective means of preventing fire spread and development in car fires".

Car stackers

GL-32 covers AVPS [16]. As cited in the AFAC's guideline, the Metropolitan Fire and Emergency Services Board – Melbourne (MFB Fire Safety Advisory Group) helped produced the AFAC guideline. The content of the two documents is therefore highly similar – please refer to Section 2.3.1.

Impulse (jet) fans

The third guideline (GL-47) covers the design of impulse (jet) fan systems in enclosed carparks. FRV highlight concerns around the design of such systems in Melbourne in particular, where they have observed jet fan systems which were designed as alternatives to a typical ducted ventilation system as per AS 1668.2. FRV's primary concerns are around the jet fans not shutting down upon fire detection, and pushing hot gases away from the sprinklers directly above the fire, whilst also causing turbulent mixing of the smoke layer. They recommend immediate shut down of jet fans upon fire detection, to ensure the sprinkler(s) above the seat of the fire activate, and the unnecessary / ineffective activation of sprinklers downstream of the jet fan is avoided.

2.3.4 Fire and Rescue New South Wales (FRNSW)

Impulse (jet) fans

FRNSW have published a single guideline relevant to carparks, which – like FRV's GL-47 – covers impulse fans [18].The guideline was published prior to AS 1668.1 2015 that now covers jet fan shut-down in fire mode. The guideline has not been fully reviewed, as it is not directly relevant to this literature review. However, it appears to be similar to FRV's GL-47.

2.3.5 Western Australia (WA) Department of Fire & Emergency Services (DFES)

Car stackers

The DFES have published a guideline (GL-14) on car stackers [19]. The document states that the scope "predominantly relates to all closed carparks containing multi-tiered car stacking devices". This doesn't specifically exclude open-deck carparks with stackers, but could be interpreted as such. The only specific guidance provided on open-deck carparks is that, when they incorporate so-called Multi-tiered Vehicle Stacking Devices (MTVSDs), building surveyors should be cognisant of whether they impact on the 50% cross ventilation requirements. It is the opinion of the authors of this literature review that such designs should be considered holistically, by the majority of the design team, not just the building surveyor.

GL-14 cites the research carried out by BHP Steel in the mid-1980s, noting the horizontal configuration of the vehicles in those tests and highlighting that MTVSDs were not considered in the testing regime. The primary concern of DFES is carpark designs which utilise MTVSDs which accommodate less than 40 cars, and therefore not providing a suppression system, without considering the fuel load storage arrangement, stating that this has occurred in the past. DFES states that all MTVSDs fall outside the scope of the BCA (i.e., no DtS solution exists), and they must therefore be subject to a Performance Solution.

2.3.6 Queensland Fire and Emergency Services (QFES)

QFES have published four guidelines relevant to carparks; one on Automated Vehicle Parking Systems (AVPS) [20], a second on basement carpark exits [21], a third on electric vehicles (EVs) [22], and the last on jet fans [23]. All are comparatively short (single page only).

Automated Vehicle Parking Systems (AVPS)

QFES outline their interpretation that the NCC's DtS provisions for carparks "do not distinguish between the risk of vehicles stowed via AVPS in either a vertical, horizontal or a combination storage arrangement." QFES considers AVPS that store vehicles in a vertical array as outside the scope of Clause E1D4 (Sprinklers) of the BCA, irrespective of the number of vehicles stored. The guideline goes on to state that any proposal to install one or more AVPS in a carpark is considered as requiring a Performance Solution by QFES.

Basement carpark exits

QFES "considers fires in basement areas, including basement carparks, to be extremely hazardous". For that reason, they clarify that, where the BCA asks for two exits from a basement carpark, QFES expects two separate exits (not one exit served by two doors).

Electric vehicles

The second short guideline from QFES states that they consider the electrical distribution installations for EVs and the design of dedicated EV carpark spaces to represent special hazards for firefighters under the NCC. It is Arup's experience that, currently, all brigades take this view. The guideline is very light-touch, and presents some design considerations for the design team and certifier to consider, namely:

- Emergency shutdown controls
- Block plans showing EV charging stations and associated distribution boards and shutdown controls
- Vehicle impact protection (i.e., bollards) for charging stations

Jet fans

At the time of this literature review, QFES provide guidance on jet fans on their website [23]. They state that the use of jet fans in a carpark should not contribute to evacuation routes being compromised by smoke or impede the effective operations of a building's fire safety systems. The hazard identified with jet fans is where a fan continues to operate during a fire scenario, which then forces the mixing of smoke instead of formation of a stratified layer, leading to smoke-logged conditions occurring more quickly. Concerns are also raised with 'skipping' of sprinkler heads and activations of sprinklers remote from the fire location (where suppression is needed).

2.3.7 South Australian (SA) Metropolitan Fire Service (MFS)

SA's MFS has published a position statement on EVs [24], and a guideline on car stackers [25]. In addition, the MFS website provides a link to the AFAC *Fire Safety for Impulse (Jet) Fans in Carparks* guideline.

Electric vehicles

The MFS position statement is relatively short (two pages) and raises the same design considerations as the QFES guideline. They also mention that tactical location of EV charging stations, and their proximity (or lack of) to exits and other fire safety systems, may be an appropriate design mechanism.

Car stackers

Like FRV's GL-32 and WA DFES GL-14, the fire safety guideline on car stackers produced by SA's MFS is relatively comprehensive. Again, the fuel load per unit area increase is highlighted, as well as the configuration's natural tendency to promote vertical fire spread. Two key points are raised as primary design objectives for car stackers; (1) limiting a vehicle fire's potential to impact on the structure, and (2) making sure a vehicle fire can be safely extinguished by fire fighters.

The MFS does not accept that automatic fire sprinkler systems should only be provided for car stackers containing more than 40 vehicles, as "car stackers present a significantly more complex and severe fire hazard than conventional carparks". In terms of the design of such a sprinkler system; "consideration needs to be given to location of sprinkler heads, water shielding and utilisation of side wall heads where appropriate".

The guideline also calls for mechanical smoke exhaust where natural ventilation is not provided.

MFS also highlight the potential increased risk of car stackers incorporating charging facilities within each bay for electric vehicles.

3. International precedent

As part of this project, Arup's international expertise has been utilised to determine international code requirements as they pertain to stand-alone carparks (open-deck or enclosed) from selected countries, at the time of writing this report.

It is noted that, within recent years, some codes have been updated in response to modern car hazards. For example, in the United States, both NFPA 88A *Standard for Parking Structures* and NFPA 13 *Standard for the Installation of Sprinkler Systems* have been revised (in 2023 and 2022 respectively). The 2023 edition of NFPA 88A requires all car parks ('parking garages') to have sprinkler systems installed in accordance with NFPA 13. Prior to this edition, sprinklers were not mandatory in open-deck car parks. The 2022 edition of NFPA 13 has increased the recommended hazard classification for car parks from Ordinary Hazard Group 1 to Ordinary Hazard Group 2. It is acknowledged that the codes and standards summarised below are likely to also be subject to ongoing review processes similar to the NCC, and may also be revised in the future.

However, conversely to the NFPA, the European Fire Sprinkler Network released a Position Paper in 2022 which stated: "in the absence of evidence that the current EN 12845/CEA 4001 hazard category of OH2 for car park sprinkler systems for EVs is inadequate, and with the peak heat release rate and fire load being similar for EVs and ICEVs, the EFSN recommends OH2 continue to be applied" [26].

It is also acknowledged that, in many jurisdictions, carparks that are incorporated with other building uses (e.g., residential) will have different requirements derived from those other uses which have not been covered here for the sake of simplicity.

Each country has its own classifications, definitions, concessions and sometimes unique rules. The overall approach to fire engineering also differs from country to country; some legislative frameworks are performance-based, such as the NCC, which facilitates alternative design solutions, whereas other environments are more prescriptive, such as the US. This must be noted when making comparisons between codes.

It must also be noted that, for the sake of this comparison, some nuances within the codes have been simplified and the information provided within this section should not be taken to construe a comprehensive overview of code compliance within the respective countries.

However, the following countries have been covered as part of this project:

Table 3: Countries and regulations / guidance sampled as part of this literature review.

Country	Regulation / guidance covered	Publication year
Australia	NCC BCA Volume One	2022
New Zealand	C/AS2	2020
England and Wales	Approved Document B – Volume 1 & 2	2022
Scotland	Non-Domestic Technical Handbook	2022
United Kingdom	BS 9999	2017
Ireland	Technical Guidance Document B	2020
Germany	Muster einer Verordnung über den Bau und Betrieb von Garagen (Muster-Garagenverordnung M-GarVO) Model Regulation on the Construction and Operation of Garages (Model Garage Regulation M-GarVO	2020
Netherlands	Until 31 Dec 2023: Bouwbesluit 2012, NEN 6098, municipal guidelines; From 1 Jan 2024: Besluit Bouwwerken Leefomgeving, NEN 6098	2023 2024

Country	Regulation / guidance covered	Publication year
Denmark	Bilag til BR18's vejledning til kapitel 5 – Brand. Bilag 9 - Præ-accepterede løsninger - Bygningsafsnit med garageanlæg	2019
United Arab Emirates	UAE Fire and Life Safety Code	2018
Hong Kong	Code of practice for fire safety in buildings 2011 Code of practice for minimum fire service installations (FSI) and equipment AND inspection, testing and maintenance of installations and equipment, September 2022 (FSI code) FSD Circular letter No. 4/2020 Additional fire safety requirements for car parking facilities installed with electric vehicles charging facilities.	2011 2022 2020
Singapore	Code of Practice for Fire Precautions in Buildings 2023	2023
United States	International Building Code (IBC)	2021
United States	NFPA 5000 & NFPA 88A	2021

A visualisation of the range of requirements and where the NCC fits in in terms of conservatism (ranked from most to least for various fire safety categories) is provided within the following sections.

3.1 Open-deck carparks

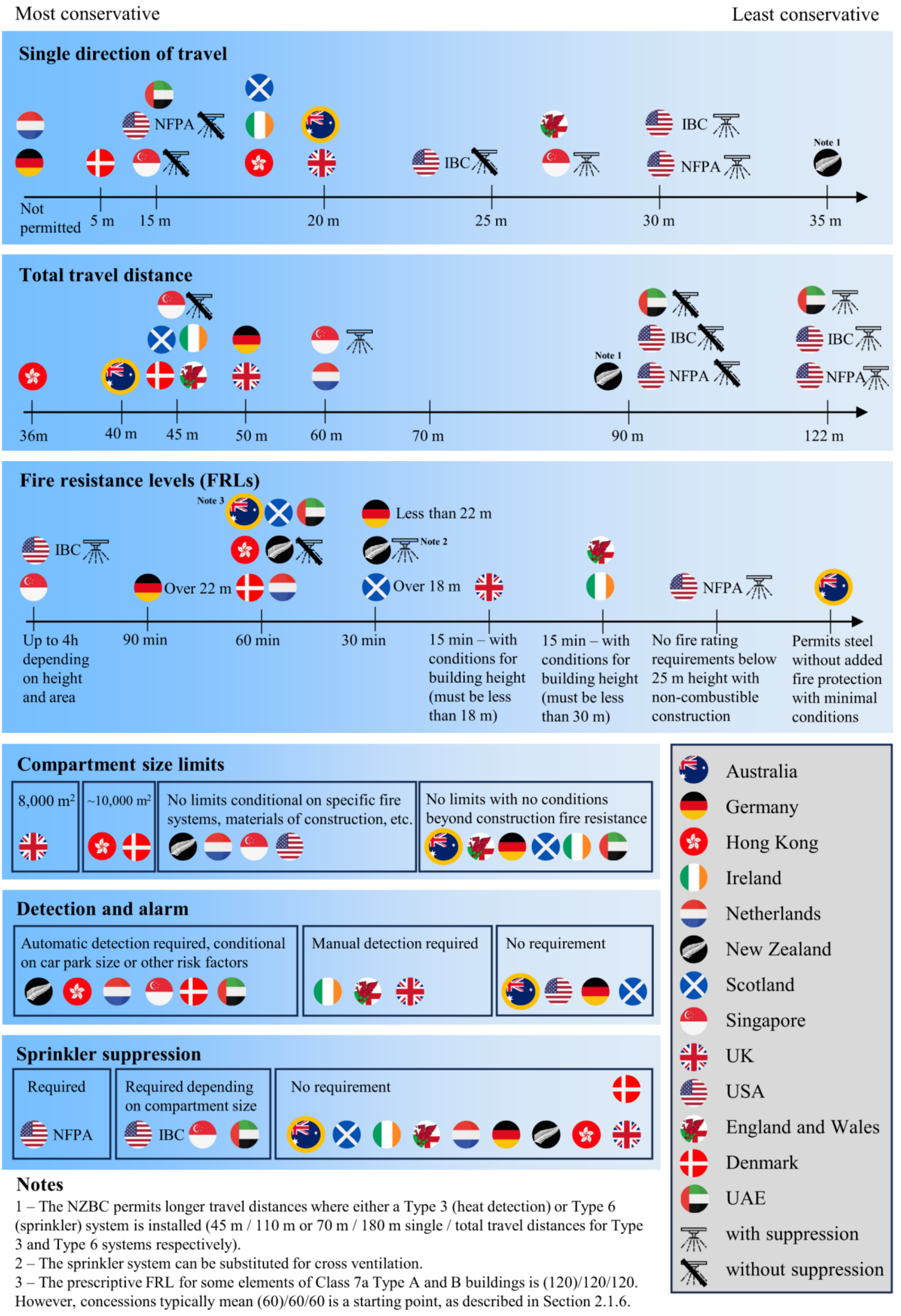
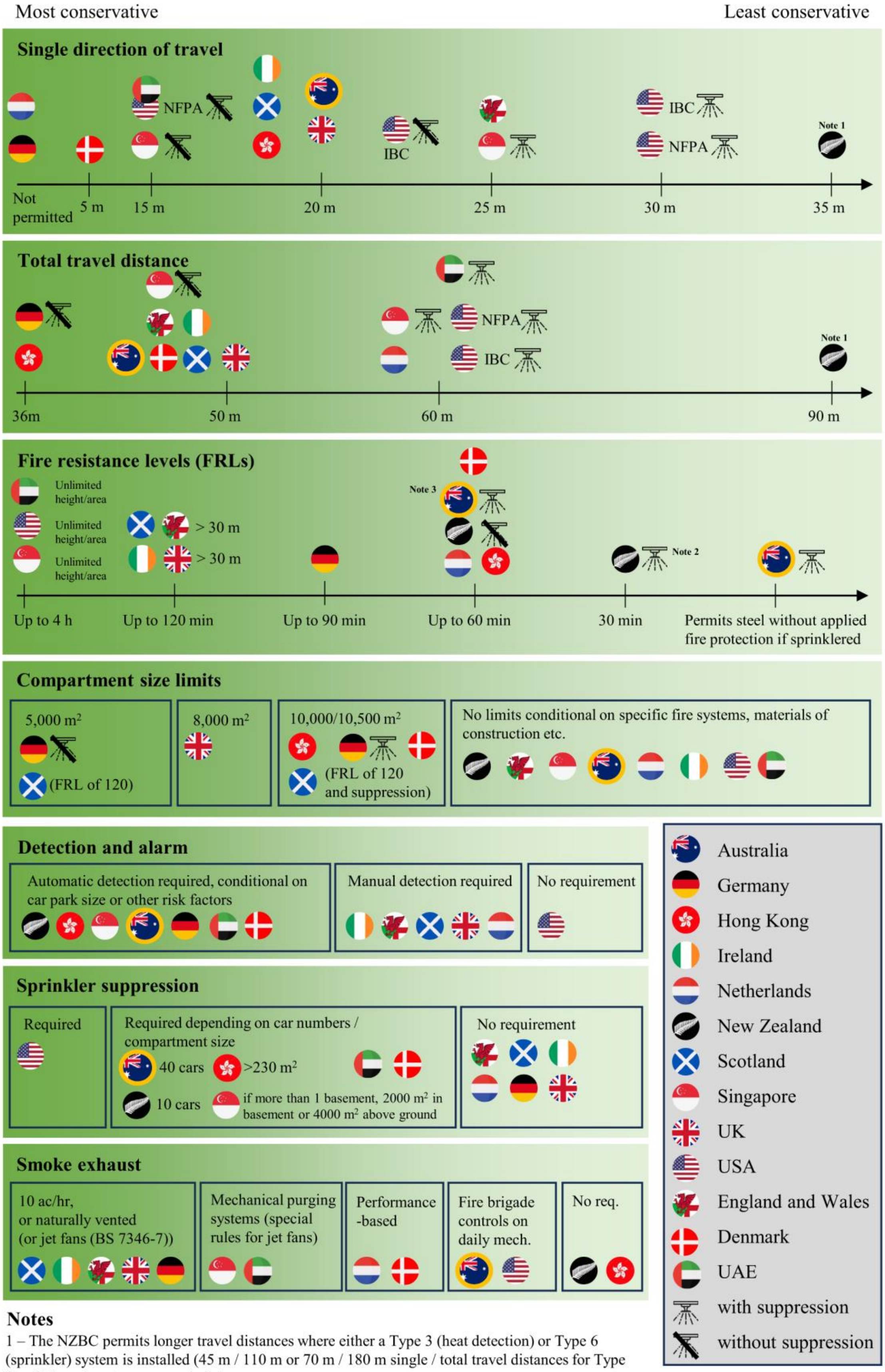


Figure 2: Summary of global fire safety DtS provisions for open-deck carparks.

3.2 Enclosed carparks



Notes

1 – The NZBC permits longer travel distances where either a Type 3 (heat detection) or Type 6 (sprinkler) system is installed (45 m / 110 m or 70 m / 180 m single / total travel distances for Type 3 and Type 6 systems respectively).
2 – The sprinkler system can be substituted for cross ventilation.
3 – The prescriptive FRL for some elements of Class 7a Type A and B buildings is (120)/120/120. However, concessions typically mean (60)/60/60 is a starting point, as described in Section 2.1.6.

Figure 3: Summary of global fire safety DtS provisions for enclosed carparks.

3.3 Car stackers

For the purpose of this literature review, a 'car stacker' is broadly defined as a lifting device which allows multiple cars to be parked in a vertically 'stacked' arrangement. The phrase 'Automated Vehicle Parking System' (AVPS) is often used to envelope more automated parking systems, including those that may operate within a 'conventional' carpark space.

Whilst some guidance documents such as that produced by AFAC differentiate between AVPS and semi-automated VPS, this literature review does not. Vehicle lifts – which are rare – may be used to transfer vehicles between carpark levels in lieu of a ramp. This section does not apply to such scenarios, as cars would not then be parked in a vertically 'stacked' arrangement.

Global guidance on carparks incorporating car stackers is somewhat limited, perhaps due to the ambiguity as to whether car stackers sit within carpark buildings, or storage buildings, or warrant their own classification.

In the U.S. – where suppression is now frequently required to the latest standards for carparks regardless of whether a car stacker is present – NFPA 88A *Standard for Parking Structures* refers (Clause A.9.2.4.1) to other NFPA standards (including NFPA 13) for fire protection features of "automated-type parking systems" [27].

NFPA 13 *Standard for the Installation of Sprinkler Systems* introduced requirements for car stackers in the 2022 edition. Either car stackers are provided with sprinklers under each level of cars (with those sprinklers designed in line with typical carpark sprinkler systems i.e., Ordinary Hazard (Group 2)), or the overhead system must be designed to Extra Hazard Group 2. The standard notes that not all car stackers may be able to have side-wall sprinklers installed due to the particular design of the car stacker [28].

The San Francisco (SF) Fire Department has produced a supplementary guidance note, which provides additional SF-specific brigade requirements [29].

Elsewhere, some codes and standards do now cover sprinkler system requirements for car stackers, thanks to the BAFSA-funded BRE experiment [30].

The UAE Fire and Life Safety Code is the most onerous, requiring a deluge system be provided for car stacking systems.

In the UK, BS 9999:2017 provides guidance on car stackers, whereas AD B does not [31]. Section 8: Special risk protection of BS 9999:2017 states that "car stackers should be protected with an appropriately designed sprinkler system, to ensure that water reaches every vehicle and to contain fire spread" [32]. The standard goes on to note that car stackers pose an increased risk within carparks, because of:

a. The increased risk of vertical fire spread up the stack and the potential for a very large fire involving numerous vehicles;
b. Rapid evolution of elevated temperatures and combustion products within the car park;
c. Potential structural damage to the fabric of the building;
d. Potential for early structural collapse of the unprotected framework of the car stacker, with associated hazards for fire-fighters.

BS 9999:2017 also states that car parks utilising car stackers, or a similar method where there is no fire separation between stacked cars, warrant an ultra-fast fire growth rate and therefore a high risk profile.

BS 7346-7:2013, which is the design standard for smoke and heat control systems in covered carparks, states a steady-state design fire size (2 m x 5 m, 14 m perimeter, 6 MW heat release rate) for a 2-car stacker protected by sprinklers, based on the BRE and BAFSA experiment. BS 7346-6:2013 also highlights the potential for rapid fire spread from one car to another within car stackers, but goes on to state that "experiments have shown that this spread can be significantly controlled by a suitably designed and installed sprinkler system" [33], citing the BRE experiments [11], [30].

However, the standard for automatic sprinkler systems (BS EN 12845:2015), does not provide guidance on how to design a sprinkler system for a car stacker [34]. So, the UK fire safety design guidance document recommends sprinkler protection is provided to car stackers, but the sprinkler standard doesn't give guidance on how to do so. Conversely, in Australia, the NCC doesn't provide requirements for when / whether sprinkler systems should be provided for car stackers, but the sprinkler standard does give guidance on how to do so. The global consensus appears to be that car stackers should be provided with sprinklers.

3.4 Observations

Australian requirements for carparks appear to be generally on the less conservative side when compared with international regulations.

Notable differences within Australian requirements include:

1. Concessions for low fire protection of steel (ESA/M method).
2. No requirements for sprinklers in open-deck carparks (in contrast to the US, which is notably conservative).
3. No requirements for specific smoke exhaust in enclosed carparks.
4. No explicit requirements exist for car stackers within the NCC, however Australian Standards provide details on sprinkler systems.

4. Experimental research on fires in carparks

4.1 Introduction

Since the late 1960s, various research efforts have investigated fires in carparks. This section focuses on research carried out by BHP Steel between 1985 and 1989 as those experiments took place in Melbourne, Australia. They are therefore the most directly applicable to this report. However, for wider context, other notable carpark fire experiments are briefly touched upon.

It should be noted that this section focuses on large-scale experimental research, primarily investigating fire dynamics and structural response under natural fires. Various experiments have been conducted under hood calorimeters which aim to quantify the heat release rate (HRR) of vehicles, to inform ‘design fire’ decisions. Those experiments are outside the scope of this literature review.

4.2 Global research effort before 1985

The earliest experimental study on fire behaviour in carparks was completed in the UK at the Joint Fire Research Organisation (JFRO) [35], [36]. Butcher et al. carried out three full-scale burns within a single storey test building, consisting of a steel scaffolding structure and a corrugated iron roof, with a concrete floor slab / ramp and an insulated wood wool ceiling slab. The compartment was approximately 18.5 m x 9 m, with a floor area of approximately 167 m^2 and a floor-to-ceiling height of approximately 2.25 m. Low ceiling heights are characteristic of many carparks design. The setup (see Figure 4) aimed to simulate a storey of a carpark.

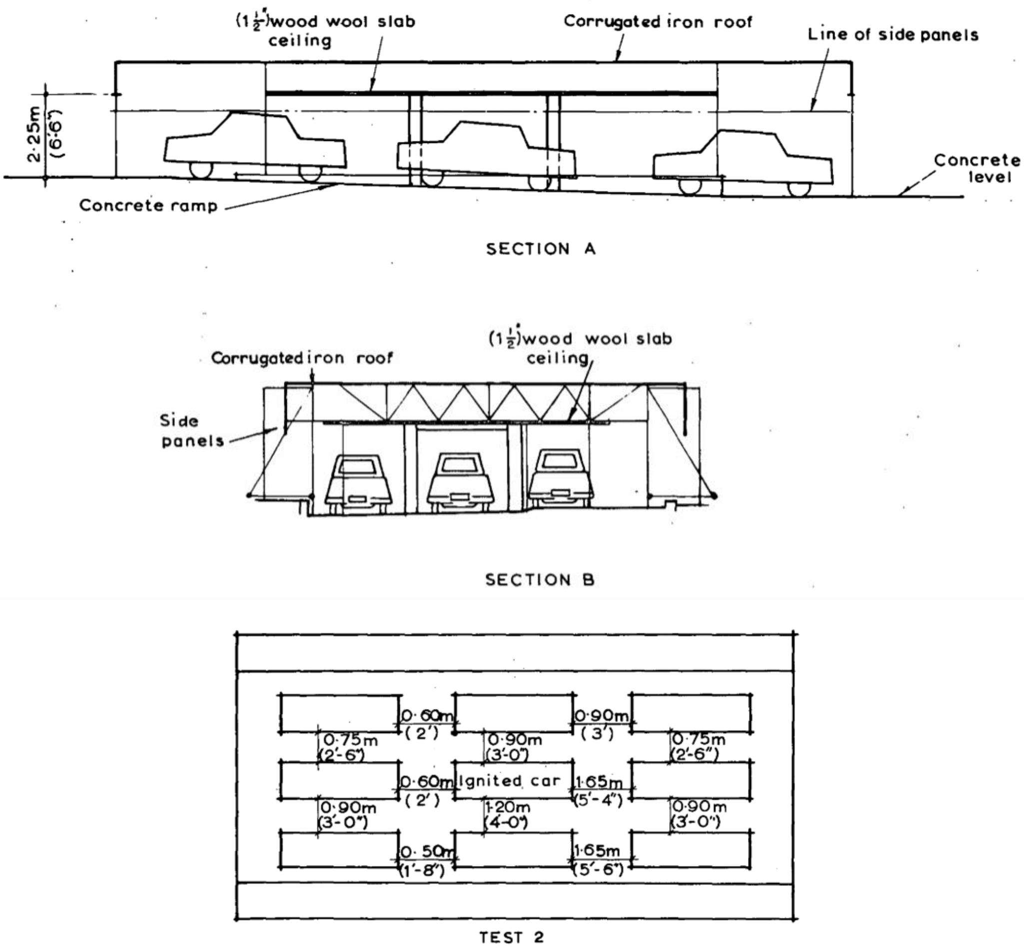


Figure 4: Section and plan views of the UK JFRO carpark experiments. Reproduced from [35].

The longer façades had approximately 50% ventilation. Two of the experiments had the shorter façade completely open. In the third, it was closed.

Each experiment involved nine vehicles in a 3x3 configuration. The research note does not provide detail on each car model, but states that the cars were selected with the intent of replicating typical vehicles at the time, and they were fuelled with approx. 19 L of petrol. Combustible materials were placed within the cars to represent personal luggage. A fire was ignited involving the central vehicle and allowed to burn without intervention. Spacing between the ignited vehicle and neighbouring vehicles varied from 0.60 m to 1.65 m between the experiments.

They found that the closed configuration produced the most rapid fire growth, but the open-sided setup with a van as the ignition vehicle produced the most severe fire. The least severe fire resulted from an open-sided setup with a car constructed primarily from steel as the ignition vehicle, which restricted the fire size. There was no fire spread to neighbouring vehicles in any of the experiments. "It is likely that the fuel load of these cars [is] certainly different from modern cars" [11].

The steel members were not provided with fire protection ("unprotected" here on in). The maximum temperature recorded within the steel beams was 275 °C, and 360 °C within the columns. Butcher et al. reported the wood-equivalent fire load density for a carpark to be 17 kg/m^2. This research has underpinned the recommendations in [Approved Document] AD B" [11].

After the UK experiments, various experiments followed. The Nippon Steel Company of Japan carried out a series of five tests in 1970. They varied ventilation and included an open-deck case [37]. Maximum temperatures in the unprotected steel members did not exceed 245 °C [38].

At the same time, five experiments were carried out in an underground carpark building in Switzerland scheduled for demolition [39], [40]. The authors concluded that the main hazard was posed by the dense smoke generated, as "the temperatures measured in these tests were not high". They found that the probability of fire spread was low, and the sprinkler system was effective [38]. The original research paper summarising this work has not been found, so actual temperatures are unknown.

Shortly after, a single open-deck carpark experiment was carried out in the US in 1972 in a previously operational building [41]. Funded by the American Iron and Steel Institute (AISI), Gewain carried out a full-scale experiment in an existing carpark which measured approximately 69 m x 55 m (i.e., a floor area of 3,800 m2). The structure was an unprotected steel frame with a concrete deck. However, the experiment involved only three "late-model American automobiles". Crumpled-up newspaper was placed in the cars, and approx. 38 L of fuel in each tank. The central car, located directly under the exposed steel beam, was ignited. The cars were approx. 600 mm apart. The fire did not spread to either of the adjacent vehicles, and it was concluded that the results of Butcher et al. were confirmed.

The above represents a summary of large-scale carpark fire experiments conducted pre-1985. Experiments which studied car fires in isolation (i.e., measuring heat release rate (HRR) using cone calorimetry) are acknowledged but are not covered by the literature review within this section.

4.3 BHP Steel research programme, Australia (1985-1989)

After the experimental research documented above, there was an increase in the use of plastics in cars. Design of carparks and growing car geometry led to a reduction in parking area per car. Also, plastic became the material of choice for petrol tanks, and there was an increasing emphasis on light steel structures. This led to the findings of the above tests being scrutinised. Therefore, BHP conducted a series of experiments with the aim of alleviating those doubts between 1985 and 1989 [42], [43], [44], [45].

4.3.1 Brief history of BHP

Broken Hill Proprietary Company Limited was formed in 1885, two years after Charles Rasp discovered silver and lead at Broken Hill in the Barrier Ranges of New South Wales whilst working on a sheep station. The company became colloquially known as BHP (an abbreviation of its full name), and mined base metals in Broken Hill [46].

Some thirty years later, in April 1915 – when BHP had largely exhausted its mine at Broken Hill – the company opened its steelworks in Newcastle, New South Wales. BHP went on to primarily manufacture iron and steel. It was soon the nation's largest ship owner and the largest miner of coal. Australia was industrialising, and local demand grew strongly. BHP Steel was "a flat steel products business serving customers in the building and construction, automotive and manufacturing industries" [47].

By the 1930s, BHP was the largest industrial company in Australia. Much of the Australian war effort in munitions and defence relied on BHP. In the 1950s, the company became interested in oil, and went on to partner with Esso to search for oil in the Bass Strait between Victoria and Tasmania. They found natural gas and then oil in the mid-1960s – the first major oil discovery in Australia.

In the mid-to-late 20th century, BHP were mining, drilling and manufacturing. However, towards the end of the century, BHP thinned and rationalised its steel empire. In 1999, it ceased production of steel.

The company formally became BHP Limited in 2000. In 2001, BHP merged with Billiton plc – an Anglo-Dutch mining company formed in the Netherlands in 1860 – to form BHP Billiton. In 2002, BHP Steel demerged [46], [48]. It was renamed BlueScope in 2003: a company which remains as a multi-billion dollar steel manufacturer today.

In summary, BHP were a large steel manufacturer, interested in selling their products alongside providing experimental evidence.

4.3.2 Experimental programme

Between 1985 and 1989, BHP conducted self-funded experimental research investigating the performance of carpark structures in fire. BHP's experimental series aimed to use vehicles and building construction more typical to Australia [6], [49]. However, the experimental setup was similar to previous work in that it involved multiple cars placed within a mock-up unprotected structure representing a portion of a carpark.

Prior to this work, building regulations in Australia required carpark structures to be constructed from fire-resisting construction, with fire resistance levels (FRLs) of up to four hours. This made structural steel non-competitive against concrete. Therefore, the motivation behind BHP's research was to improve steel's competitiveness against concrete on the market.

The first experiments investigated open-deck carparks [42]. The second series focused on closed carparks [43]. The final experiments looked at partially-open carparks [44] and those forming part of a multi-classified building [45].

4.3.2.1 Open-deck carparks (1985)

Two experiments were conducted on an open-deck carpark constructed from unprotected steel with a composite (steel and concrete) floor slab (see Figure 5). The aim of the experiments was "to determine whether fire protection of steelwork from fire within the carpark is necessary" [42].

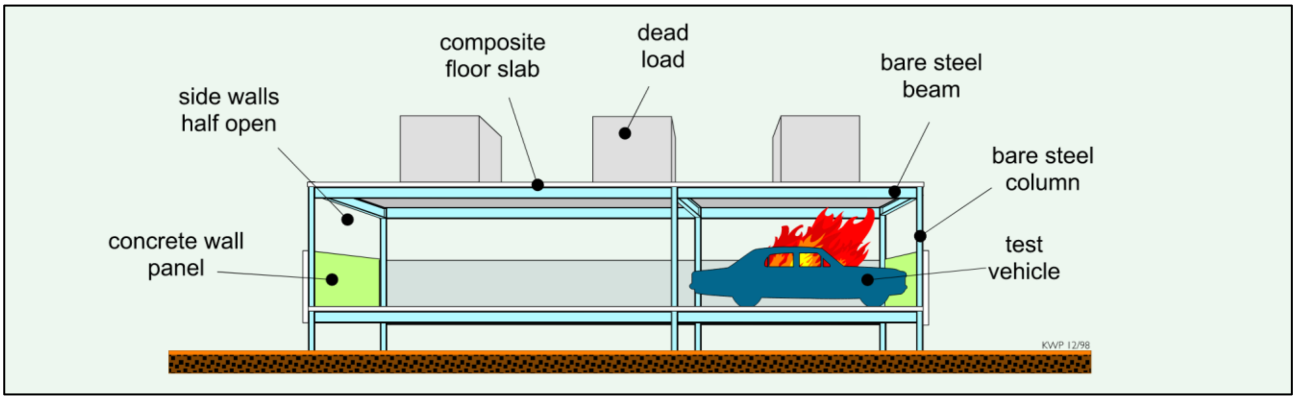


Figure 5: Isometric section drawing showing open-deck carpark experiment arrangement. Reproduced from [49]. © BHP.

The structure used thin steel members which aimed to be representative of the smallest members likely to be used in practice, which was not the case in the US tests [41]. The compartment had a floor-to-ceiling height of approximately 2.4 m, and measured approximately 11.4 m x 10.4 m in plan, therefore had a floor area of approximately 120 m^2. No suppression system was installed.

The perimeter walls had 50% ventilation. Five vehicles were placed within the space; four were parked parallel to each other, with the fifth parked perpendicular (see Figure **6**). The cars were located towards the south of the storey. Fire was started within the test car by igniting rags soaked with petrol placed below the front seat. The front right window was left open to assist with fire development. The front left window of Car No 1 (i.e., the window facing the ignited car) was also open to assist fire spread between cars. The setup simulated a portion of a large open-deck carpark.

The cars used in the test were manufactured between 1973 and 1982. The test car in the first experiment had a steel petrol tank, whereas the second test used a car with a plastic fuel tank and a liquified petroleum gas (LPG) tank. The petrol tanks of all cars were filled to one-half capacity. The 1987 paper states that this was considered "to give rise to a most severe fire situation" [43], however the logic behind this isn't explained and is unclear. The authors may have simply meant 'a severe fire situation' as opposed to 'the most severe fire situation'. Or, they may have been suggesting that a half-filled tank may have potential for increased pressure build up within the tank, with explosion potential if the vapours were above the lower explosive limit (LEL). It is noted that a fully-filled tank would lead to a larger (more severe) pool fire, should the tank leak. The LPG tank was filled to 80% capacity (the maximum permissible volume).

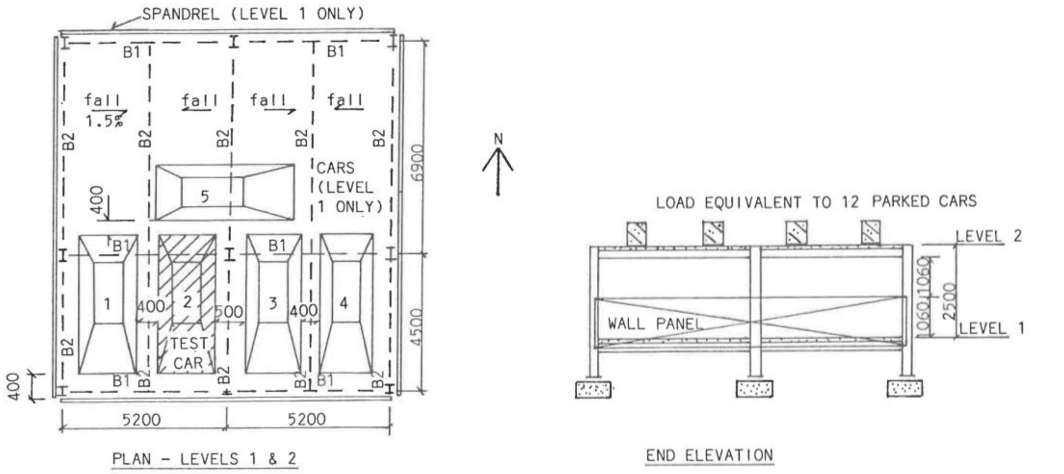


Figure 6: Plan and elevation drawings showing test building. Reproduced from [42]. © BHP

The model of test car in test one (a Ford Falcon XC Sedan) had a length of 4.9 m, width of 1.9 m and height of 1.4 m. It has a curb weight of 1,475 kg [50]. An example of this car model is shown in Figure 7. It is worth noting that this earlier 1979 car didn't have much plastic on its exterior, whereas the 1982 Ford Falcon XD Sedan used in the second test did.

The cars were 400 mm apart, which was described as "closer than normally expected in practice" [42]. Butcher went on to conduct a survey where 300 spacings were measured [51]. The most frequent spacing was found to be 762 mm (2 ft 6 in.). A similar survey in the late 1990s studied 18 different carparks in five European countries (Netherlands, Spain, France, Belgium and Luxembourg). 1,624 parking distance measurements were taken. The data followed a normal distribution, and a mean parking distance of 719 mm was found [38]. Therefore, the cars were relatively tightly packed in the BHP experiments.

Figure 7: Images of the model of car used as the test car in the first of the BHP open-deck experiments. Note the car has metal grilles, hub caps, and no plastic wing mirrors. © Trade Unique Cars. Available at: https://www.tradeuniquecars.com.au/feature-cars/1804/1978-ford-falcon-xc-500-review.

Test 1
During the first test, there "was a gentle breeze from the south".

One minute after ignition, the windscreen shattered. Other windows broke during the next five minutes, until Car No 2 was fully involved. The car burned for 25 minutes, before the flames spread to the petrol tank filler pipe. The fuel then burned for a further 30 minutes. The fire lasted for around 70 minutes in total.

Large quantities of smoke were emitted throughout, indicating incomplete combustion, even in a relatively well-ventilated space. Gas temperatures peaked at around 725 °C. The fire did not spread to any adjacent vehicles.

Test 2
In the second test, the test car was changed to a slightly larger and newer model, with a plastic fuel tank and an additional LPG tank, and more plastic on its exterior. Everything else remained constant except the wind conditions; "there was a constant breeze from the north".

The test car was fully involved after ten minutes, and a large amount of black smoke was given off. The pressure relief valve of the LPG tank vented after 14 minutes, due to excess pressure caused by heating. Gas then vented, but never ignited. At this time, fire spread to Car No 1 (placed to the right of the test car and with its front window open). Flames from Car No 1 impinged directly on the structural beam overhead.

"The carpark structure was not damaged and measured steel temperatures showed a very adequate margin of safety for unprotected open-deck carparks under fire conditions". However, after 30 minutes, the concrete slab began to spall. Five minutes later, fire spread to a third car (Car No 3). 50 minutes from ignition, the petrol tank of Car No 1 became involved, and flames from the filler pipe directly impinged on the overhead beams [42].

Compartment gas temperatures are reported as peaking at around 550 °C, representing a relatively cool fire.

Observations
The top flanges of the beams were generally cooler than the web and bottom flange, due to the composite connection to the concrete slab meaning that heat dissipated into the concrete i.e., the slab acted as a heat sink. In test one, the steel reached a peak temperature of 285 °C (with a corresponding upper flange temperature of 170 °C). In the second test, values of 340 °C and 180 °C respectively were recorded.

The experiments showed that open-deck carparks can be constructed using unprotected steel without collapsing from a car fire event, under the specific conditions and structural design of these tests.

The results indicated that vehicle-to-vehicle fire spread can vary depending upon wind conditions and the materiality of the vehicle of fire origin, i.e., the quantity and location of plastics around the vehicle exterior and the fuel tank construction. The authors mention that the vehicles which fire spread to in the second test had already been exposed to a fire in the first test, hypothesising that this may have affected the results.

After these experiments, the building code was amended to allow open-deck carparks to be constructed from unprotected steelwork.

4.3.2.2 Closed carparks (1987)
In 1987, BHP adapted and reused the experimental setup to investigate closed carparks [43]. The aim of the experiments was to investigate the effect of a car fire in a closed carpark with either a sprinkler system installed, a ventilation system installed, or both. The activation of the sprinkler system was automatic in four of the experiments, and manual in the other five experiments.

Additionally, BHP were motivated to influence code changes that permitted lower / omission of FRLs. The test setup is shown in Figure 8. These were the first experiments of their type.

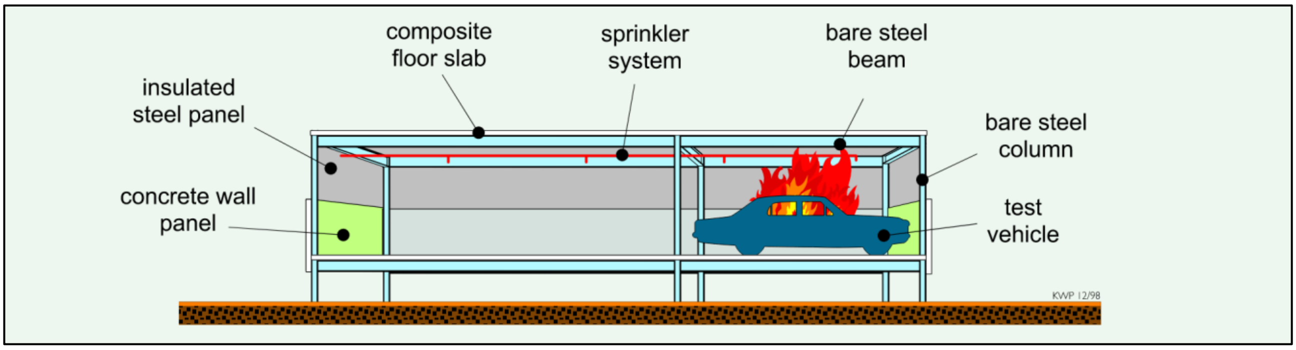


Figure 8: Isometric section drawing showing closed carpark experiment arrangement. Reproduced from [49]. © BHP.

The experimental program was created by BHP Research, the Australian Uniform Building Regulations Co-ordinating Council (AUBRCC) and the Australian Institute of Steel Construction (AISC). Interestingly, no dead load was applied to the structure in these experiments, unlike the previous open-deck tests.

A series of nine experiments were completed. In all but one of the experiments, the fire was ignited in the same way as the open-deck experiments – by igniting an approximately 1 kg rag soaked in 1 litre of petrol, placed under the front seat. In the eighth test, four litres of petrol were ignited in an open tray placed directly below the petrol tank of the test car.

The building structure from the 1985 experiments was adjusted – insulated steel infill panels were installed above the concrete wall panels (see Figure 9). The building was almost entirely closed, with the exception being three small peep holes (approx. 0.1 m x 0.2 m) and the ventilation system's inlet and outlet ducts.

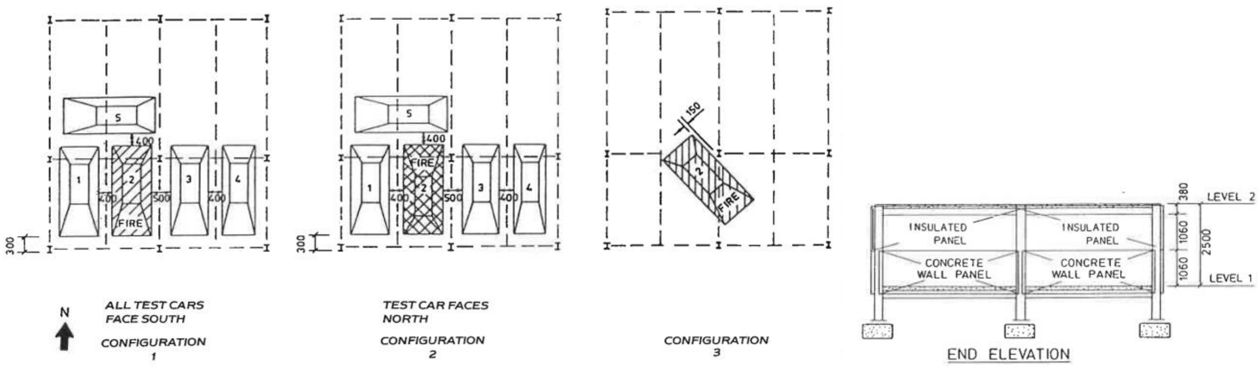


Figure 9: Plan and elevation drawings showing test building. Reproduced from [43].

The sprinkler system was designed following AS 2118-1982. The sprinklers were spaced at approximately 10.6 m^2 per head (within the 12 m^2 limit), on a grid which suited the structural layout. Sprinklers were suitable for OH2 occupancy, with 15 mm nominal (11 mm actual) diameter orifices and 68 °C activation temperature.

Whilst the total volume of water used in each experiment was not recorded, in most tests the tank supplying the sprinklers had a capacity of 5000 L and the water was not exhausted. The published report does not specify which test, but states that in one, a smaller 1000 L tank was used and the water was not exhausted. In another, "slightly more than 5000 L was used". Flow rates per head were calculated as being between 99 and 123 L/min across the seven experiments with sprinkler activation, at a mean of 113 L/min. Flow was calculated based on a K factor of 8.1 in all but one test (where a different sprinkler manufacturer was used, whose product had a K factor of 7.6), and discharge pressures of between 150 and 230 kPa.

In experiments where the operation of the sprinkler system was not automatic, the steel temperature was monitored. If the steel exceeded 500 °C, the sprinkler system was turned on manually.

The mechanical ventilation system was designed based on what the researchers felt would be acceptable to approval authorities at the time, following AS 1668.2-1980. The design airflow rate of 1 m^3/s (which represents approximately 12.7 ac/h, based on a compartment volume of approx. 285 m^3) was based on one in ten cars operating simultaneously. This is a relatively high ventilation rate when compared to international codes and standards (see Section 3.2).

Seven of the experiments used the same configuration (car layout) as the open-deck tests (configuration 1 in Figure 9). In one experiment, the test car was rotated 180 degrees. In another experiment, the test car was rotated 45 degrees, and was the only car in the compartment.

Due to the prevailing wind conditions during the experiments, the effect of the mechanical ventilation system is reported as being minimal. However, interestingly, two tests (5 and 7) which were the same except 5 had the ventilation system operating and 7 did not, exhibited different results. This is not discussed in the original paper [43]. Test 7 exhibited a “secondary flashover” style temperature-time curve, whereby there is an initial peak, followed by a decay phase (like test 5), but then a period of regrowth and a second, higher peak temperature is observed in test 7. In test 7, the fire eventually burnt out the rear of the car and involved the fuel from the tank.

The tests generally observed that the automatic sprinkler system prevented significant damage to the paint or bodywork of the test car and contained the fire to the test car (i.e., there was no fire spread between vehicles). When the sprinkler system was operated manually (much later), the fire grew to a bigger size, burned outside of the car, and (in most cases) involved the petrol tank.

A difference was observed between the older cars (with less plastic used in/on their exterior and metal fuel tanks) and the newer cars (with more plastic including the fuel tank). Spread of fire from the test car to other cars only occurred when the newer cars were used.

The rate of smoke buildup in all tests was “extremely rapid”.

In the experiments without automatic suppression, burning plastics often dripped to the floor and formed a flaming pool fire. In test 6, both plastics and petrol from the fuel tank spilled onto the floor, forming a pool fire and contributing to fire spread between vehicles.

At the time, there was particular interest in the hazards presented by vehicles with LPG tanks. Being a gas, LPG may be released from tanks and then form an explosive mixture with air. However, no cars with LPG tanks were used in these experiments, unlike in the prior work on open-deck carparks [42]. It is postulated by Bennett et al. that provision of an automatic sprinkler system would mitigate the risk of dangerous LPG buildup (and subsequent explosion risk) [43], however there is no experimental evidence of this within this work. No discussion is presented on the potential benefits of ventilation in this regard.

4.3.2.3 Partially open carparks (1989)

The first two sets of experiments conducted by BHP fit within the rigid code framework of open-deck and closed carparks. However, building designs often don’t fall neatly into one of these typologies. This led to many carparks with partially open façades being classified as closed carparks, as engineers and regulatory authorities erred on the side of caution. It was hypothesized that this was leading to conservative designs.

Therefore, BHP carried out further experiments with a partially open façade [44]. The previous test building was modified (see Figure 10). An additional storey was constructed prior, although it is not relevant at this stage: it was installed for subsequent experiments covered in Section 4.3.2.4.

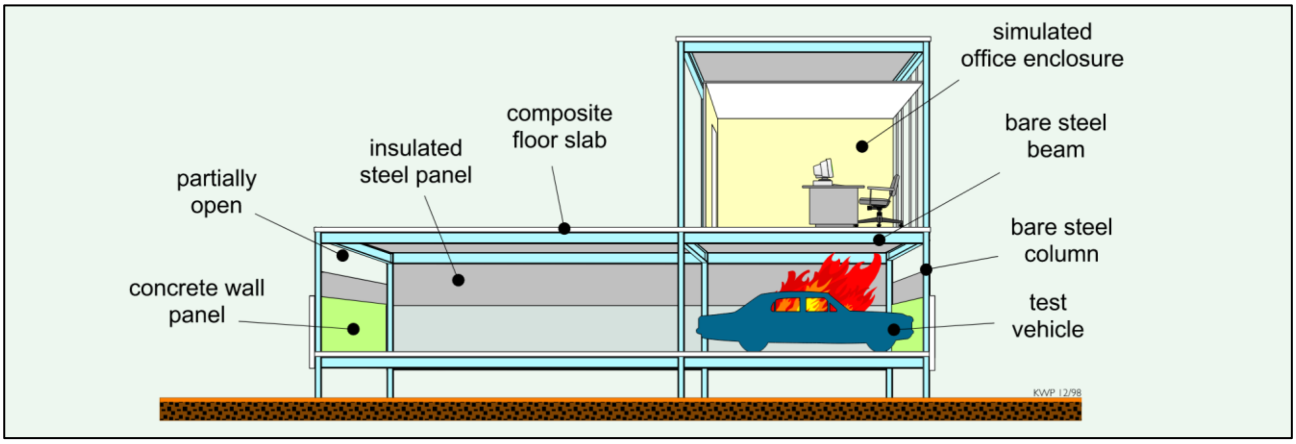


Figure 10: Isometric section drawing showing partially open carpark arrangement. Reproduced from [49]. © BHP.

The first three of these tests used car(s) as the fuel load. Newer Ford Falcon XD and XE sedans were used, which had more plastic parts than most of the cars used in the 1985 experiments. The subsequent 11 experiments investigated various natural ventilation and wind conditions and used liquid pool fires contained in trays as the fuel source.

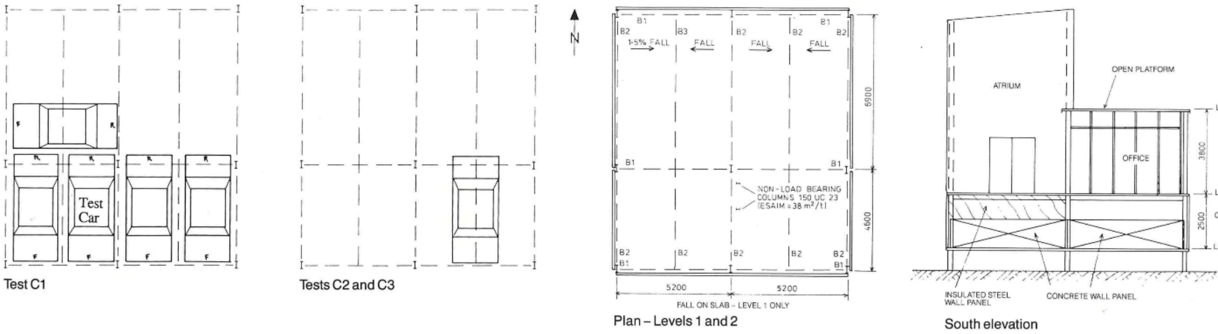


Figure 11: Plan drawings showing the test building. Reproduced from [44].

The sprinkler system was retained from the 1987 tests, but only operated twice, manually in test C1 and automatically in test C2. In all other experiments, the sprinkler system was decommissioned.

The first test had 25% of the North and South façades open. The fire developed quickly; car windows broke within the first two minutes, and after five minutes, large volumes of thick black smoke were being emitted through the compartment openings.

After 10 minutes, plastic elements of the test car were involved in the fire. Some dropped from the car and burned on the floor. After 15 minutes, the petrol tank broke and petrol spread over the floor and below adjacent cars. This led to fire spread between vehicles, and the neighbouring cars became involved.

After 22 minutes, the sprinklers were manually operated. A hose stream was also used to suppress the fire in areas which were not covered by sprinklers.

Whilst previous experiments reported no structural damage, this test saw minor local buckling of the bottom flange of the beam placed directly above the test car [44]. Three of the four panes of glass in the office enclosure above were cracked. The first test also produced significantly higher gas temperatures within the compartment than in the previous work. Within three minutes, the gas temperature reached nearly 1100 °C, and then peaked at around 1150 °C. Manual sprinkler operation successfully cooled the compartment.

The second and third experiments were similar. They both involved a tray with liquid fuel placed under the vehicle’s plastic petrol tank. In both experiments, the fuel tank ruptured, and petrol became involved. However, the results were very different due to the different wind conditions.

In the second test, flames appeared out of the opening. They did not appear to directly impinge on the office façade above, but all four glass panes cracked. In the third test, the wind pushed the majority of the hot gases / flames back into the compartment, meaning the office façade was undamaged. The fire severity in the third experiment was therefore worse for the carpark structure (as fewer hot gases escaped). However, no damage of the steelwork was reported.

The test report states that “the most striking characteristic of all of these fires was the huge quantity of black smoke generated by the burning materials in the cars and by the burning petrol” [44].

The experimental regime “concluded that in a partially closed carpark with a functioning sprinkler system there is no need for fire protection of the structural steelwork” [44]. Only two experiments had an operational sprinkler system installed.

Generally, BHP found that the conditions in the partially open carpark fire experiments were broadly similar to conditions in the closed carpark fire tests, and “substantially more severe than … the open-deck tests”. It was recommended that any carpark which does not clearly comply with the requirements for an open-deck carpark should be treated as a closed carpark. Thus, the existing design approach remained.

4.3.2.4 *Carparks in multiclassified buildings (1989)*

BHP went on to reuse the experimental setup to carry out further experiments where the fire originated in other parts of the building (see Figure 12) [45].

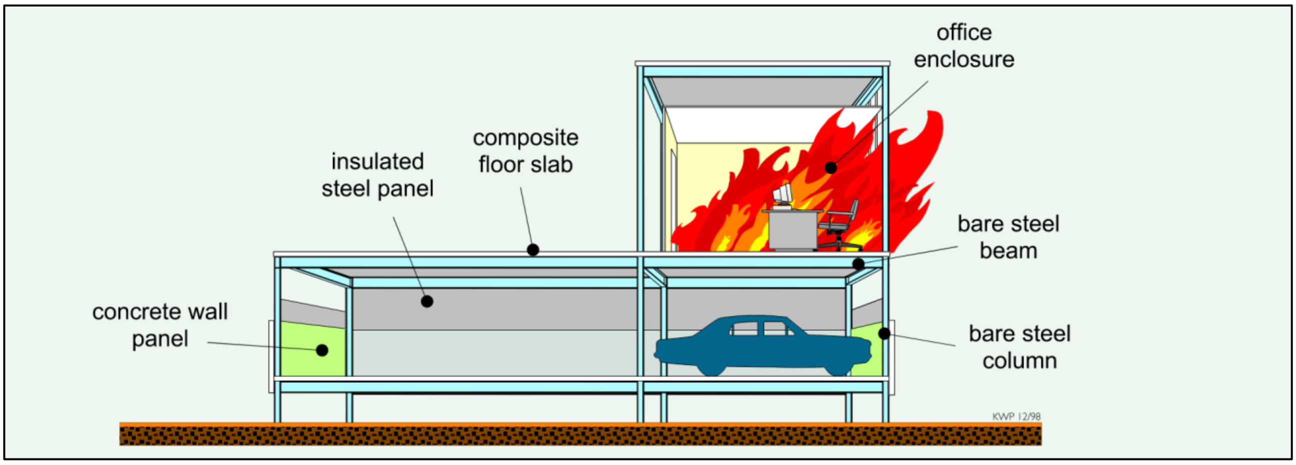


Figure 12: Isometric section drawing showing experiment arrangement with fire originating in another part of the building. Reproduced from [49]. © BHP.

These experiments have not been reviewed as part of this literature review, as they are not directly relevant to the scope of this work.

4.3.3 Summary of the BHP experiments

Overview

BHP carried out 25 experiments in a compartment test building with a floor area of approximately 120 m^2 between 1985-1989. 14 of these experiments used cars as the fuel load. The experiments are summarised in Table 4.

Table 4: Summary of carpark fire experiments conducted by BHP between 1985-1989.

Year	Ref.	New ref.	Fuel	Portion of walls open		Suppress.	Vent.	Load
1985	1	OPEN-1	Cars	50 %	Top ½ of all walls	✕	✕	20.75 T
1985	2	OPEN-2	Cars	50 %	Top ½ of all walls	✕	✕	20.75 T
1987	1	CLOSED-1	Cars	0 %	-	Auto	1 m^3/s	✕
1987	2	CLOSED-2	Cars	0 %	-	Auto	1 m^3/s	✕
1987	3	CLOSED-3	Cars	0 %	-	Auto	✕	✕
1987	4	CLOSED-4	Cars	0 %	-	Auto	✕	✕
1987	5	CLOSED-5	Cars	0 %	-	Manual	1 m^3/s	✕
1987	6	CLOSED-6	Cars	0 %	-	Manual	1 m^3/s	✕
1987	7	CLOSED-7	Cars	0 %	-	Manual	✕	✕
1987	8	CLOSED-8	Car^{+}	0 %	-	Manual	✕	✕
1987	9	CLOSED-9	Cars	0 %	-	Manual	✕	✕
1989	C1	PARTIAL-1	Cars	12 %	Top ¼ of N and S walls	Manual	✕	✕
1989	C2	PARTIAL-2	Car^{+}	12 %	Top ¼ of N and S walls	Auto	✕	✕
1989	C3	OPEN-3	Car^{+}	24 %	Top ½ of N and S walls	✕	✕	✕
1989	C4	PARTIAL-3	Tray (10 L)	12 %	Top ¼ of N and S walls	✕	✕	✕
1989	C5	PARTIAL-4	Tray (10 L)	12 %	Top ¼ of N and S walls	✕	✕	✕
1989	C6	PARTIAL-5	Tray (10 L)	12 %	Top ¼ of N and S walls	✕	✕	✕
1989	C7	PARTIAL-6	Tray (10 L)	12 %	Top ¼ of N and S walls	✕	✕	✕

Year	Ref.	New ref.	Fuel	Portion of walls open		Suppress.	Vent.	Load
1989	C8	PARTIAL-7	Tray (30 L)	12 %	Top ¼ of N and S walls	✕	✕	✕
1989	C9	PARTIAL-8	Tray (30 L)	12 %	Top ¼ of N and S walls	✕	✕	✕
1989	C10	PARTIAL-9	Tray (60 L)	12 %	Top ¼ of N and S walls	✕	✕	✕
1989	C11	PARTIAL-10	Tray (60 L)	12 %	Top ¼ of N and S walls	✕	✕	✕
1989	C12	OPEN-4	Tray (60 L)	24 %	Top ½ of N and S walls	✕	✕	✕
1989	C13	OPEN-5	Tray (80 L)	24 %	Top ½ of N and S walls	✕	✕	✕
1989	C14	OPEN-6	Tank*	24 %	Top ½ of N and S walls	✕	✕	✕

+ One car placed within the compartment, with a tray containing 4L of petrol placed on the ground below the petrol tank of the test car. The tray of petrol was ignited.

* A plastic petrol tank was placed in the same position as the petrol tank of the test cars in C1-C3. 60L of petrol was placed within the petrol tank, with a tray containing 4L of petrol placed below it and ignited.

The BHP experiments represent a significant research effort and are still recognised as one of the most comprehensive experimental series on carparks. The NCC was amended following the experiments, and those amendments are still included within the latest revision (as covered in Section 2.1).

The test building was specifically constructed for the experiments. The experiments are large-scale; however, it must be noted that they had a floor area which is much smaller than most carparks constructed today, and included a limited number of older-model cars as the fuel load. It is acknowledged by the authors of this literature review that this will always be the case with large-scale fire experiments due to their significant monetary and carbon cost.

Maximum steel temperatures

The major influence of these experiments is the concessions subsequently introduced within the NCC which permitted open-deck carparks to be both non-sprinklered and constructed from unprotected steelwork with an exposed surface area to mass per unit length ratio (ESA/M) of 26 m^2/tonne. This was deemed acceptable by the authors and the code authorities as the steel within this set of experiments (and other prior experiments) remained relatively cool (a peak of 340 °C). These concessions remain within the NCC today (2022 Edition), some 30+ years after the experiments.

Vehicles used in the experiments

The experiments used cars which were typical at the time. BHP found that a car with higher plastic content caused very different fire dynamics to occur; in the open-deck experiments, vehicle-to-vehicle fire spread only occurred when a more modern car with various plastic components (including the fuel tank) was used as the ignition vehicle.

As stated in [43], “the amount of flammable material in vehicles appears to have been increasing and the distribution of flammable material appears to have changed”. Bennetts et al. noted that, in cars manufactured after 1980, much greater quantities of plastic were present, and plastic and other flammable materials were present around the exterior of the car (e.g., mirror and light housings, bumpers, wheel caps, grilles, body panels etc).

Some 30+ years on from the experiments, cars today have changed significantly; they’ve increased in size, and now feature many more plastic components. This has potential to alter the findings of the experiments. Building regulatory authorities cannot control the fire load of cars themselves. Their only mechanism to reduce fire load would be to decrease vehicle density (by increasing the required size of carparking spaces).

At the time, LPG-fuelled consumer cars were relatively novel. LPG emerged as a retail option around the time of the global oil crisis of 1973, when the price of oil rose by nearly 300% [52], [53]. The research made a conscious effort to investigate the hazards posed by such vehicles, but only in the open-deck experiments, when any explosion risk would be lower.

Nowadays, such vehicles are decreasing in numbers, however other novel fuels have emerged on the market such as electric and hydrogen vehicles. These are discussed further in Section 7.

Placement and design of openings

In the open-deck and partially-open experiments, the ventilation (i.e., openings) was always placed in the uppermost portion of the façade. In other words, the openings were always placed at the upper layer, which meant that hot smoke and gases could escape with maximum efficiency. This is evidenced by the reports observing lots of smoke spilling from the compartments. If the openings were placed below the neutral plane of the compartment in the fire scenario, this would mean that hot gases from the fire would be less likely to vent to outside. Instead, they would be trapped by the downstand façade, causing the hot gas / smoke layer to descend before venting to outside. This may impact the findings of the results in open-deck carparks. It is noted that such a design is unlikely in practice, however placement of openings within an open-deck carpark façade is not covered in the BCA, which only specifies that an open-deck carpark must be cross-ventilated with openings that are not less than 50% of the wall area placed in not fewer than two opposite sides.

Furthermore, modern carpark designs often feature meshing across a façade. The BCA requirements do not mention whether the 50% openings should be taken as a geometric area or aerodynamic free area. Utilising a mesh façade which has 50% geometric area will perform less efficiently as a vent than a single opening.

Proximity of adjacent buildings to the openings

The idealised compartment fire experiments and the subsequent BCA provisions also do not consider the placement of openings within façades in relation to neighbouring buildings. Openings placed close to a boundary with neighbouring construction may perform differently than those in open space.

Smoke production

The experiments reported large quantities of thick black smoke being produced, even by old model cars. As discussed by FRV [15], it is reasonable to expect that modern-day vehicles would produce even more smoke due to their increased plastic and rubber content. The NFPA suggest similar, stating that polymeric and plastic materials produce more toxic smoke than the materials they replaced [54]. However, old vehicles did still contained four rubber wheels, petrol/diesel fuel, and some hydrocarbons within the vehicle interior, all of which produce large volumes of smoke when burning.

Loading of the structure

Only the open-deck experiments had the ceiling slab loaded. No discussion is presented in the work as to why the loading was removed from the closed and partially open carpark experiments. Those experiments exhibited signs of structural damage, even when the structure was unloaded.

4.4 Global research effort post 1990

More recently, the Centre Technique Industriel de la Construction Métallique (CTICM) carried out experiments in France around the turn of the century [55]. Three experiments were carried out within a two-level carpark with an unprotected steel brace frame and concrete slabs. The carpark measured 15 m x 32 m, i.e., had a floor area of 480 m^2. This made it a much deeper floorplate than the previous experiments, with greater spans (of 16 m). The building had a relatively high floor-to-ceiling height (for carparks), of 3 m.

The experiments involved three cars within the first two tests, and two cars within the third test. No fire service intervention or suppression was used in the experiments – all cars were left to burn out. Whilst the steel structure remained stable for the duration of the fires in all experiments [56], a report by the Research Programme of the Research Fund for Coal and Steel (RPRFCS) describes that there was “cambering of the two exposed beams”, “local instabilities in these two beams: lateral buckling and flange instabilities”, rigid connection (bolt) breakages, and maximum temperatures of 640 °C in the unprotected steel columns and 700 °C in the beams [57]. Such temperatures exceed typically agreed failure temperatures for steel approx. 550 °C for columns and 620 °C for beams, according to Corus [58]).

Whilst local structural damage was observed, “the experimental results have given convincing evidence that fire protection of the steel structure is not necessary to obtain overall stability” [59]. This work was sponsored by the European Steel and Coal Community, which must be noted. Similar conflicts as in the BHP work exists, whereby the funders of the research had a vested interest in the work concluding that applied fire protection was not required, such that steel was a viable alternative to concrete in such structures.

Subsequently, the Building Research Establishment (BRE) were appointed by the UK Government in 2006 to carry out research into the growth and spread of fires in carparks. The work showed that, without suppression or fire service intervention, fire can spread between vehicles. Their 2010 report highlighted an elevated risk in split-level carparks with parking spaces located nose-to-nose across a level change [11].

4.5 Observations

The experiments reviewed on both open-deck and closed carparks are still relevant as they represent a significant dataset of large-scale carpark compartment fires. Such experiments are very expensive to undertake (in monetary costs and carbon costs) and should only be completed if absolutely necessary. However, attention must be paid to the motivation behind some of the studies, and the limitations of the work, particularly when making comparisons to modern carparks.

The compartments were all constructed to represent portions of carparks. The relatively small volumes would mean that heat and smoke could fill the spaces quicker than in a larger building. However, the peak fire size is limited by the size of the building and the number of vehicles within it. In large, open-plan spaces, travelling fires can occur, which may preheat the structure and pose a completely different design fire and subsequent fire exposure than a 'traditional' flashover compartment fire. This was highlighted as a possible fire scenario for carpark fires as early as 1999 [38].

Open-deck carparks have received more research attention than enclosed carparks. The BHP experiments on enclosed carparks and partially open carparks had broadly similar observations. Conditions were "substantially more severe than … the open-deck tests". It is our understanding that the BHP experiments did not significantly impact the code in the same way as the open-deck experiments. It's important to note that the BHP experiments concluded that any carpark which does not clearly comply with the requirements for an open-deck carpark should be treated as a closed carpark.

Peak steel temperatures for the open-deck carpark experiments reviewed are presented in Table 5. Interestingly, the experiments carried out in France recorded significantly higher temperatures than any of the previous work. This may indicate that more severe fires are to be expected from more modern vehicle fires, involving more plastics. The compartment used by CTICM was much larger than the previous work, so there was greater volume for heat and smoke to dissipate, but further for fresh air to travel before reaching (and cooling) the atmosphere local to the fire.

Table 5: Summary of maximum steel temperatures recorded during open-deck experimental series reviewed.

Experiment(s)	Year(s)	Maximum steel temperature recorded (°C)	
		Beam	Column
JFRO, UK [35], [36]	1967	275	360
Nippon Steel, Japan [37]	1970	245	242
AISI, US [41]	1972-1973	226	-
BHP Steel, Australia [42], [43], [44]	1985-1989	340	320
CTICM, France [55]	2002	700	640

Since the experiments, much has changed. Vehicles have evolved significantly since the research summarised above. Hazards in the modern-day carpark are discussed in more detail in Section 7.

There have also been significant fire events in carparks which were designed to similar principles as those set out in the BCA and other international guidance documents, which were based on the experiments summarised in this chapter. These fire events are covered in Section 5. They provide additional knowledge and evidence of fire behaviour in real-scale carparks loaded with modern vehicles.

5. Fire events in carparks

This section summarises notable fire events which have occurred in carpark buildings in the 21st century.

First, a selection of the most significant events is presented through individual case studies. These fires have been chosen due to their size, severity, impact and/or specific lessons which can be learned from them. Then, a more comprehensive summary is provided in Table 6, which documents a greater number of fire events in a more concise manner.

5.1 Case studies

Stavanger Airport

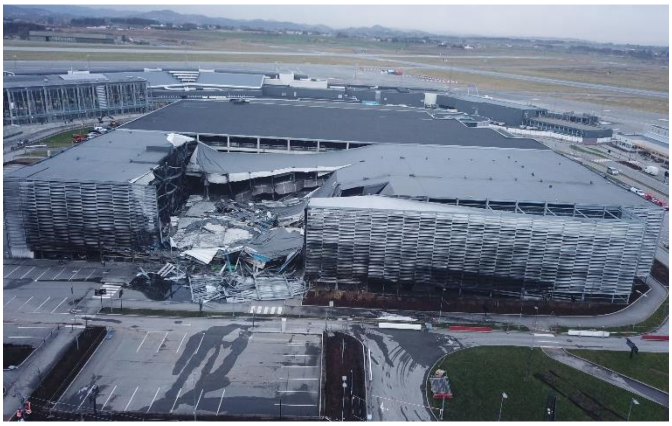


Figure 13: Stavanger airport carpark collapse after the fire. Reproduced from [60]. © Nordic Unmanned.

Date:	07/01/2020
Location:	Stavanger, Norway
Vehicles involved:	200
Carpark type:	Open-deck
Storey area:	18,500 m^2
Sprinklered?	No
Smoke exhaust?	No
Injuries:	0
Fatalities:	0

Lessons learned:

The incident investigation reported that the fire spread rapidly to several vehicles, aided by both strong winds (around 11-12 m/s with 19 m/s gusts) and the leakage of fuel from burning vehicles.

The carpark consists of three distinct parts, each using different construction methods and opened in 1991, 2001 and 2014 respectively. The fire broke out in a diesel vehicle on the ground floor of the central portion of the building (constructed in 2001), which was a concrete structure using elements with a fire resistance level (FRL) of 60 minutes.

The newest portion of the carpark was constructed from steel primary structure and a composite (steel and concrete) deck. The fire strategy specified 15 mins of load-bearing capacity for the columns and 10 mins for the beams, citing the BHP Steel research (discussed in Section 4.3) as evidence of suitability. After around two hours, parts of the 2014 building down-wind of the fire origin location collapsed.

This case study is therefore an indication that fire can spread to involve multiple modern-day vehicles in open-deck carparks without a suppression system installed, and steel structures with minimal FRL can collapse when exposed to such a fire.

The report also concluded that the classification of the building was inappropriate, and that it should have received "fire class 4" due to the *very large* potential consequence of a fire due to the building's position near major infrastructure (i.e., the airport).

The size of the fire was attributed to several factors within the fire investigation report, including:

- The absence of an automatic fire alarm system in the building, which delayed fire service notification.
- Available handheld extinguishers were not used during the early stages of the fire.
- Access for fire trucks to the carpark was restricted, and the brigade struggled to locate the hydrants.
- A lack of compartmentation, which – if implemented – would have limited the extent of the fire.

Whilst there were no life safety impacts, there were significant financial and operational / business continuity impacts: several hundred vehicles were damaged, and the airport was shut down for over a day.

Norway had the most electric vehicles on the road per capita in the world at the time, however the investigation report stated that "electric vehicles did not contribute to the fire development beyond what is expected from conventional vehicles", despite initial media reports falsely stating the fire originated from an EV [60], [61].

Echo Arena, King's Dock

Figure 14: Echo Arena carpark after the fire. Reproduced from [62]. © Merseyside Fire and Rescue Service (MF&RS).

Date:	31/12/2017
Location:	Liverpool, UK
Vehicles involved:	1,150
Carpark type:	Open-deck
Storey area:	5,000 m^2
Sprinklered?	No
Smoke exhaust?	No
Injuries:	0
Fatalities:	0

Lessons learned:

The carpark measured approximately 77 m x 64 m (using a floorplan reproduced in the MF&RS's report) [63], and had eight storeys (G+7). It complied with local building regulations for open-sided carparks. On the afternoon of the fire (on New Year's Eve) an event was being held at the arena, therefore many vehicles were present in the carpark. The fire originated on Level 3.

Two stages of the fire were identified by MF&RS: an early stage in which the tactics employed by the brigade were having a positive impact in terms of fire extinguishment, and it was considered that the fire was going to be confined to level 3 and eventually extinguished, and a second stage in which an exponential fire growth was observed and breathing apparatus crews conducting internal firefighting operations had to be evacuated. After the escalation, the fire grew beyond the capability of the firefighting resources of the brigade. Smoke spread through air conditioning ducts into the service area of the arena and its surroundings, causing staff and members of the general public needing to be treated on the scene for smoke inhalation.

It is thought that the high patronage contributed to the quick spread of the fire from one vehicle to another. Additionally, it took a relatively long time for the alarm to be raised. The first emergency call was 13 minutes after the first signs of fire. Some of the first occupants to witness the fire did not raise the alarm.

It was originally thought that the "waterfall" of fire which was reported (i.e., downwards vertical fire spread) was via the central ramps, but MF&RS concluded that the drainage system was the likely cause. The drainage system consisted of slots within the floor which fed into an aluminium tray and then plastic pipes. The aluminium trays were 2 mm thick and would've failed at around 660 °C.

Due to the subsequent construction of the neighbouring serviced apartment buildings, MF&RS's ability to apply water externally was hindered.

The building had a 15-minute FRL. Remarkably, the concrete structure remained standing after the fire, even though there were clear signs of explosive spalling, floor failure and structural element damage (see Figure 14). The entire building has subsequently been demolished [62], [63], [64], [65].

This event led to multiple articles stating that fire safety guidance should be revisited, particularly where there is a carpark beneath a block of flats or offices or a timber-framed building [66]. The MF&RS protection report stated that the fire could have been contained if a sprinkler system had been installed [63], [67].

Monica Wills House

Figure 15: Monica Wills House after the fire. Reproduced from [68]. © Avon Fire and Rescue Service (AFRS).

Date:	20/12/2006
Location:	Bristol, UK
Vehicles involved:	22
Carpark type:	Underground, open on two sides
Storey area:	3,000 m^2
Sprinklered?	No (residential area was)
Smoke exhaust?	No
Injuries:	0
Fatalities:	1

Lessons learned:

The fire occurred in the underground carpark of a newly constructed residential care home. The construction complied with the Building Regulations; the care home was sprinklered, but the carpark was not. The fire destroyed 22 cars and subsequently spread to the upper residential levels through external windows. One fatality was caused by smoke inhalation and 60 residents had to be evacuated. It is believed that the residential sprinkler system delayed the fire spread into the residential area [68], [69]. Extensive spalling of the carpark concrete was observed [11].

Sydney Olympic Park

Figure 16: Molten aluminium from one of the cars involved in the Sydney Aquatic carpark fire. Reproduced from [70].

Date:	13/10/2013
Location:	Sydney, Australia
Vehicles involved:	80
Carpark type:	Open air
Storey area:	23,000 m^2
Sprinklered?	Not applicable
Smoke exhaust?	Not applicable
Injuries:	0
Fatalities:	0

Lessons learned:

The fire initiated in a garden, ignited by a cigarette butt. Several factors contributed to the fast fire spread in this incident, despite being an external parking area. Contributing factors included elevated ambient temperature, strong winds, a higher-than-normal carpark occupancy due to high patronage of the site, small separation between parked cars, as well as the presence of large quantities of mulch and vegetation in the surroundings, and high bushfire activity in the surrounding area, which limited the fire brigade response capacity. The control of the fire was hindered because of the restriction to not use foam as an extinguishing agent, considering the environmental damage to surrounding wetlands.

Gretzenbach apartment complex

Figure 17: Site of the Gretzenbach carpark fire after demolition. Reproduced from [71].

Date:	27/11/2014
Location:	Gretzenbach, Switzerland
Vehicles involved:	100
Carpark type:	Enclosed
Storey area:	Unknown
Sprinklered?	No
Smoke exhaust?	No
Injuries:	3
Fatalities:	7

Lessons learned:

Fire investigation revealed there where errors in the structural calculations for the structure and on the construction resulting in an overload of soil and a decreased punching shear capacity, which caused the roof to collapse. 10 firefighters were trapped. Three were rescued, but seven died [72]. Smoke spread to the stairs leading out of the building on top of the carpark. A technical defect in a parked car was thought to have initiated the fire.

Ravensburg electric vehicle fire

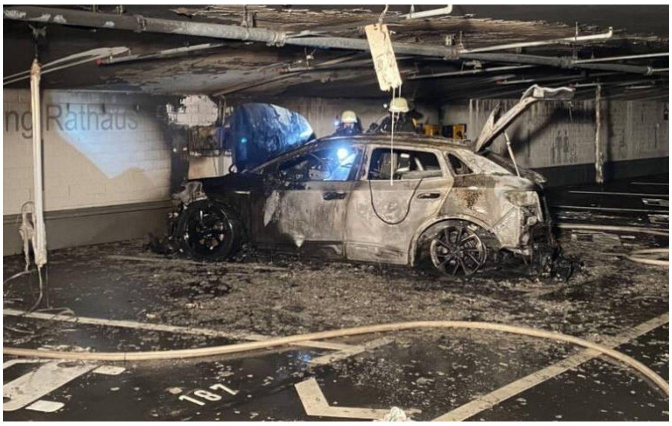


Figure 18: EV burnt out after the fire. Reproduced from [73].

Date:	24/11/2021
Location:	Ravensburg, Germany
Vehicles involved:	4
Carpark type:	Enclosed
Storey area:	Unknown
Sprinklered?	Yes
Smoke exhaust?	Unknown
Injuries:	0
Fatalities:	0

Lessons learned:

A fire started within an electric vehicle (EV) when it was charging in an underground carpark. The carpark was relatively new. The fire broke out in the middle of the night and the entire EV became involved, including the batteries [73]. “The position of the e-parking spaces apparently prevented worse things from happening” [74].

The carpark was provided with a suppression system; sprinklers designed to Ordinary Hazard 2 (OH2) criteria as per European standards (with an application density of 5 mm/min over an area of operation of 144 m^2). Whilst temperatures above the fire were high enough to cause minor spalling, the suppression system was effective at controlling the fire until the fire brigade arrived [26].

5.2 Summary table

The following table provides a non-exhaustive summary of other carpark fires since the turn of the century.

Table 6: Significant recent fire events in carparks. In reverse chronological order.

Location	Year	Vehicles involved	Injuries / fatalities	Type	Description
Oaklands Park (Australia) [75]	2023	5	None	Open air	Two vehicles destroyed, another three damaged.
Bankstown (Australia) [76]	2023	6	1 injury (smoke)	Open	Fire controlled by early intervention of fire and rescue services.
Ravensburg (Germany) [73]	2021	4	None	Closed	EV caused the fire. OH2 sprinkler system controlled the fire, before brigade suppressed.
Märsta (Sweden) [77]	2021	200	None	Closed	Roof collapsed, building demolished.
Fremantle (Australia) [78]	2021	4	1 injury (smoke)	Closed	Fire in the underground carpark of a residential block. Did not cause any structural damage.
Geraldton (Australia) [79], [80]	2021	7	None	Open	Caused by an electrical fault. 125,000 AUD damage.
Warsaw (Poland) [81]	2020	22	None	Closed basement	150 residents evacuated. Reoccupation delayed hours by high temps. Considerable spalling.
Epe (Netherlands) [82]	2020	1	None	Closed	EV fire in shopping centre carpark controlled by sprinkler system.
Gaithersburg (MD, USA) [54]	2020	4	None	Open	Significant damage – up to 150,000 USD in losses.
Stavanger (Norway) [61]	2020	200	None	Open	*See detailed summary above*.
Richmond (VA, USA) [54]	2019	3	None	Closed basement	The fire destroyed one vehicle and heavily damaged two others. Heavy smoke spread over several floors of the structure.
Cork (Ireland) [83], [84]	2019	60	None	Open	Fire spread to 60 cars. Prompt evacuation prevented injuries. Part of the structure unsafe and demolished. 30M EUR in damage.
Chicago (IL, USA) [54]	2019	4	None	Open	Fire in a 10-storey carpark.
Houston (TX, USA) [54]	2019	2	None	Open	Smoke spread past nearby high-rise buildings.
Hong Kong [85]	2019	1	None	Closed	Shopping mall carpark EV fire.
Shanghai (China) [54]	2019	3	None	Closed	EV was the ignition vehicle.
Newark (USA) [54], [86]	2019	17	None	Open air	Caused by a faulty alternator at roof level.
Chadstone (Australia) [79], [87]	2018	11	None	Closed	Fire in a shopping centre carpark. Controlled partial evacuation of the shopping centre.
Liverpool (UK) [62], [63], [64], [65], [67]	2017	1400	None	Open	*See detailed summary above.*
Jecheon (South Korea) [88]	2017	Unknown	29 deaths, 36 injuries	Closed	Fire began above the carpark. Slab failed, and cars below became involved. Fire then spread through eight storeys above (fitness complex).
Edinburgh (UK) [89]	2014	21	None	Open air	External airport carpark.
Odense (Denmark) [90]	2014	10	None	Open air	Residents of apartments above evacuated.
Sydney (Australia) [70]	2013	80	None	Open air	*See detailed summary above.*
Markenhoven (Netherlands) [91]	2013	5	None	Open	Suppression system and the fire service controlled and extinguished fire.
Appelaar (Netherlands) [91]	2010	26	None	Closed	Structural damage led to repairs that took four months.
Stansted (UK) [92]	2010	24	None	Open air	High winds caused the flames to spread rapidly.
Bristol (UK) [68], [69]	2006	22	1 fatality	Open basement	Fire in a lower ground floor carpark which spread to the care home above.
Gretzenbach (Switzerland) [71], [72]	2004	100	7 fatalities, 3 injuries	Closed basement	Parts of the concrete ceiling fell down and buried 10 firefighters during the extinguishing work.
Schiphol (Netherlands) [93]	2002	90	None	Open	Caused by arson. Cars were only 40 cm apart. Some beams collapsed. 5M EUR damage.

5.3 Observations

Upon review of carpark fire events since the turn of the century, it's clear that large-scale fires involving multiple vehicles can and do occur. The evidence also shows that the life safety risk posed by these fires is low. Fatality and injury numbers are generally low, due to carparks being transitionary vehicle storage spaces where occupants do not have a long residence time. However, a large fire can pose threats to the fire brigade (as per the incident in Gretzenbach), or if the carpark is located under a building with higher numbers of occupants (as per the Monica Wills House and Jecheon fires).

The trends in carpark fire events seem to indicate that the distance between vehicles, and the number of vehicles with the carpark, are key factors. A number of fires in carparks involving multiple vehicles have occurred at airports (e.g., Stavanger, Edinburgh, Stansted, Schiphol and, recently, Sydney [94]), where cars are kept for significant periods of time in large carparks, with small distances between vehicles.

As may be expected; suppression (or lack of) influences the fire development. This was found in the BHP research in Section 4, and further supported by the examples in Ravensburg (Germany), Epe (Netherlands) and Markenhoven (Netherlands) where the sprinkler systems controlled the fire. Timely brigade intervention has also been noted as important. For example, in Bankstown (Australia), early intervention of fire and rescue services was noted as controlling the fire, whereas in Stavanger (Norway), access for fire trucks to the carpark was restricted and the brigade struggled to locate the hydrants, which, in combination with the lack of a sprinkler system, were found as key reasons for the catastrophic fire spread.

Stavanger (Norway) also showed that wind conditions, coupled with the area of openings within the façade (and the positioning of those openings), can lead to much greater fire spread than observed in the smaller-scale experimental research.

The Kings Dock fire in Liverpool (UK) showed that the time until the fire is detected and the alarm is raised is also important, as well as the provision of compartment floors and adequacy of fire-stopping in line with compartmentation.

The experimental research and the case studies commonly made observations that the material used for the vehicle's fuel tank (i.e., whether it is a non-combustible metal, or combustible plastic) is an important factor. Similarly, the amount of combustible material within the vehicle of fire origin and adjacent vehicles will contribute to the likelihood of vehicle-to-vehicle fire spread.

The carpark fire events summarised in this section also demonstrate a fundamental difference in terms of the geometry of actual carpark buildings (including the storey area, depth of the floorplate, and the floor-to-ceiling height) when compared to the previous research upon which codes and standards have been based. Carparks can be very large buildings, with storey areas which are multiple thousand square metres, greatly exceeding the largest experimental research project (CTICM) of around 500 m^2.

6. Statistical data on carpark fire events

Fire statistics for a number of countries have been collected via government websites (UK [95], [96], [97], [98], [99], US [100]) or by fire and rescue services (New Zealand [101], Scotland [102], Wales [103], Norway [104]), where available. Data for Australia is harder to access than in most other countries. However, data from the Australian Incident Reporting System (AIRS) was published by Arup and UQ for the ABCB as part of previous work done on code changes associated with NCC 2022. The available data was collected during different time periods for each country, so separate findings are presented first before being compared.

It is noted that fire statistics (within Australia and elsewhere) have a number of limitations and are not generally freely available which limits the ability to make firm conclusions based on these. This is a broader subject and has been identified by the Society of Fire Protection Engineers (SFPE) as a primary research focus to allow for the quantification of the cost of fire safety in order to demonstrate the importance of fire safety with respect to a range of outcomes often associated with sustainability in the built environment. A better understanding of the total cost of fires can improve the decision-making process, update codes and regulations, and determine the return on investment of resilient and sustainable building and fire protection practices.

6.1 Australia

In 2021, Arup and The University of Queensland (UQ) were appointed by the ABCB to analyse available fire statistics in the context of Quantitative Risk Assessment (QRA) methodologies. QRA provides a potential route for assessing whether the fire safety measures proposed within a building provide an adequate level of life safety. 'Adequate' was going to be defined – quantitatively – within the NCC's Performance Requirements. As part of that work, a report was produced using fire statistics shared by the Australian Fire Authorities Council (AFAC). Specifically, the Australian Incident Reporting System (AIRS) database was shared, covering the financial years 2011/12 to 2018/19 [105]. The information provided in the published report has been reused for this literature review.

There was an average of 352 fires in carparks (Class 7a buildings) in Australia per year, between 2012 and 2019 (see Figure 19). This equates to 2.1% of all fires recorded, on average. The number of carpark fires remained relatively steady between the five-year period of 2015 to 2019.

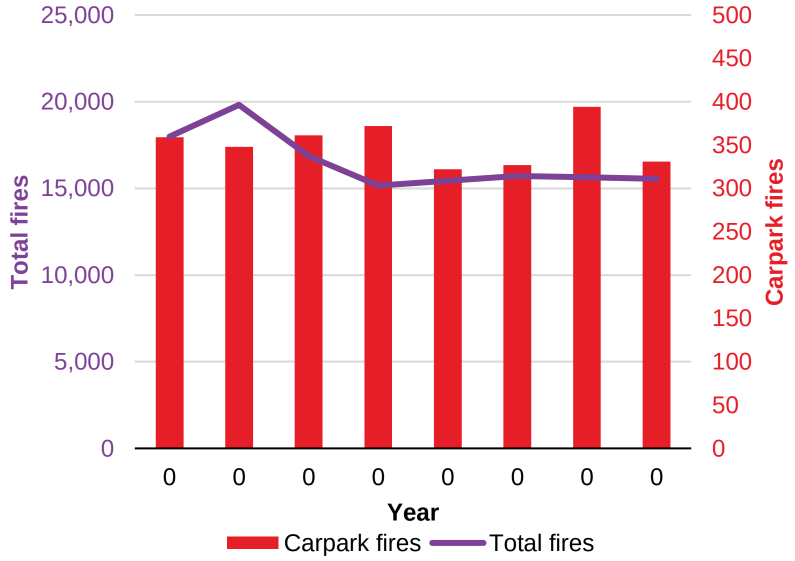


Figure 19: Total fires and carpark fires in Australia (2012-2019).

The work by Arup and UQ also provided some context. Figure 20 presents the number of parking spaces in Australian Central Business Districts (CBDs) between 2009 and 2015, from the work of RPData / PCA / Colliers Edge [106]. Whilst, over the six-year period, the number of carparking spaces in CBDs increased, the number of carpark fires (across Australia) decreased.

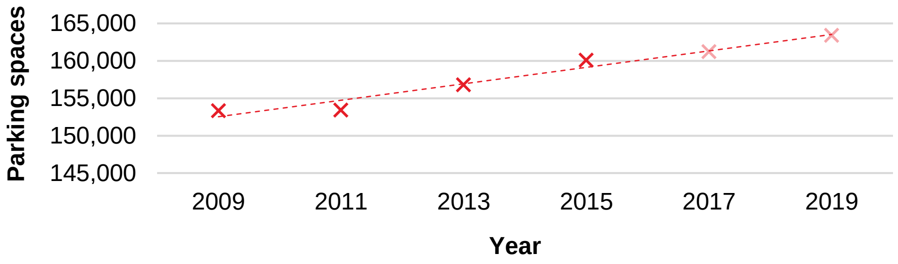


Figure 20: Number of carparking spaces in Australian CBDs per year (2009-2019), noting 2017 and 2019 are forecasts.

Furthermore, fires in carparks represented the third largest frequency when expressed as fires per unit / bed / capacity, after prison cells and childcare centres, as depicted in Figure 21. The average frequency for a fire in a carpark per unit (i.e., per parking space) per year was found to be 0.0022%. It is noted that the carparking spaces sampled were for CBDs only rather than overall carparking spaces in total and thus the actual frequency could be reasonably expected to be lower.

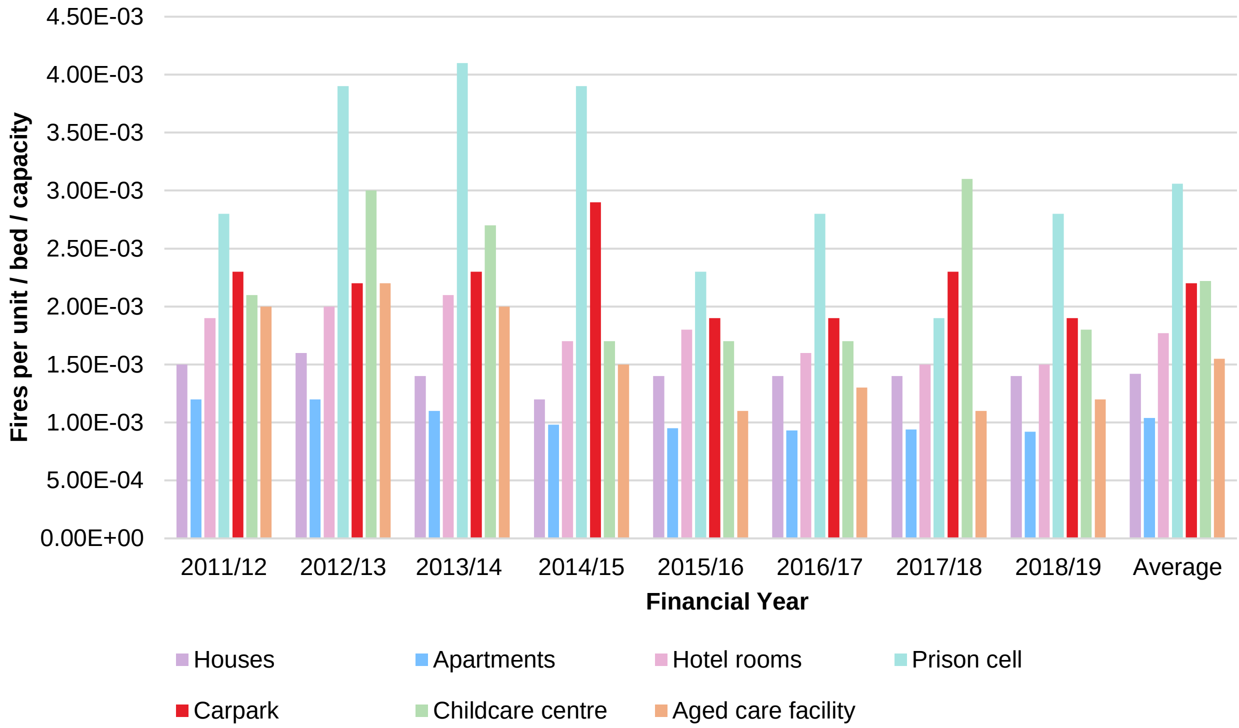


Figure 21: Yearly reported fires per unit / bed / site capacity.

Carpark fire injuries and fatalities in Australia are logged by AFAC within the AIRS database. However, that data is not freely available.

6.2 New Zealand

Li [101] compiled data for the 1995 to 2003 period in New Zealand. A total of 96 carpark fires with just 3 involving multiple vehicles were identified. 60% of the incidents occurred in private buildings and the remaining 40% started in public buildings. Fire spread did not occur in open and ventilated carparks, whereas fire spread occurred in private enclosed garages. It was concluded that fire spread happened in just 3% of fires, and was therefore deemed as ‘unlikely’. However, it was highlighted that changes in the properties of vehicles and their age profile could shift, hence affecting the accuracy of this conclusion [107].

6.3 United Kingdom

The UK Home Office regularly publishes fire statistics within the UK [97], [98], [99]. Additionally, in 2021, the Home Office published two datasets specifically on carpark fires in England between 2010-2020 [95], [96]. Alimzhanova et al. produced a concise summary of the latter [108].

For the 2010-2020 period in England, 79 carpark fires occurred annually, on average. As a percentage of total fires, carpark fires made up a very low percentage of 0.05% each year on average. There was only a single fatality and 20 injuries over the ten-year period.

The number of carpark fires in England as a portion of the total number of fires recorded is presented in Figure 22. This can be directly compared with Figure 19. Carpark fires make up a much smaller proportion (0.03-0.06%) of total fires in England than Australia (2.1%).

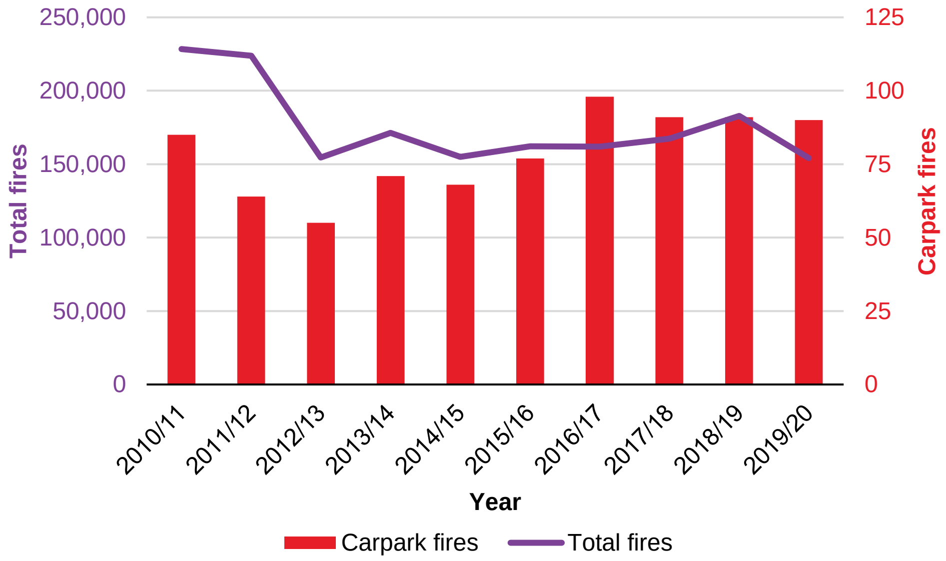


Figure 22: Total fires and carpark fires in England (2010-2020).

Between 1 April 2009 and 30 September 2022, the Scottish Fire and Rescue Service (SFRS) recorded 114 carpark fires, at a frequency of 8.4 carpark fires per year [102]. 34 of those (i.e., 30%) were accidental, or the cause was not known or specified. This is lower than the average rate of 42% of total fires being accidental over the same period, indicating that arson is more likely in carparks than in other building types. Across the 114 carpark fires, no fatalities and only one injury is reported, at an accidental fire in Edinburgh in 2015.

In Wales, there were 25 carpark fires reported between 2009 and 2020, which gives 2.3 fires annually [103].

The BRE carried out a comprehensive collective review of carpark fire statistics across the UK (England, Wales, Scotland, and Northern Ireland) for the period 1994 to 2005. They identified a total of 3,096 carpark fire incidents, at an average rate of 258 incidents per year, indicating that carpark fire events were more likely between 1994-2005 than 2010-2020 in the UK.

The number of carparks represented a very small percentage of all fire incidents in the UK (e.g., less than 0.1% in 2006). Two fatalities and 87 injuries were recorded in this period, at an average of significantly less than a fatality per year and approximately seven injuries per year. Both of those fatalities, and 39 of the 87 injuries, occurred in multi-storey carpark (MSCP) fires. A higher injury rate was obtained for carparks in buildings labelled as “flats” compared with other types of buildings. Conversely, if the building was exclusively classified as a “carpark”, the injury rate was low compared with other types of premises [11].

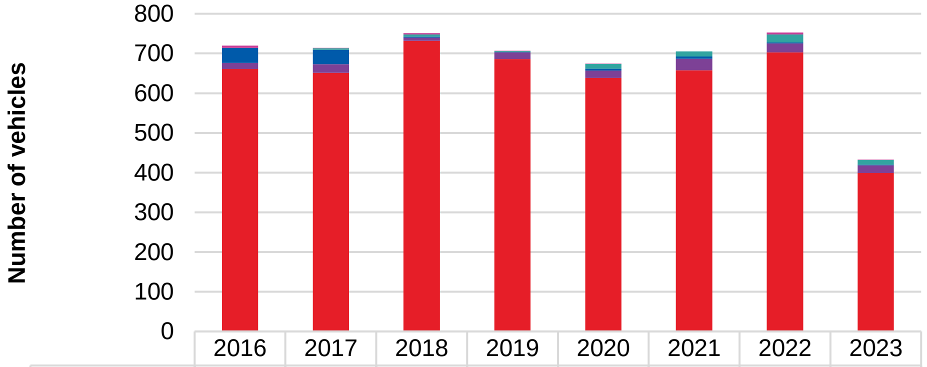
6.4 United States

Limited data for vehicle fires within the U.S. was published by the U.S. Fire Administration [109]. Fires starting in parking areas (29,000 on average) accounted for 16% of all vehicle fires in the US. A high share of the associated car fire fatalities resulted from fires that initiated around the fuel tank, fuel line or in the passenger area (12%). Also, an estimated 212,500 vehicle fires caused 560 fatalities, 1,500 injuries (firefighters’ injuries excluded), and $1.9 billion in direct property loss in 2018.

The aforementioned data does not distinguish between fires initiated in carparks and other locations. Therefore, the statistics mentioned by the NFPA research and compiled by Ahrens [110] for the 2013-2017 period are relied upon. There were 1,858 ‘commercial parking garage’ fires with no fatalities and 20 injuries in this period.

6.5 Norway

Data is also presented from Norway, as it is the nation with the highest proportion of electric vehicles (EVs) in the world. The rescue operation reports database in Norway identified 4,136 vehicle fires for the 2016-2021 period, including 110 EVs [104]. Figure 23 depicts all fires in passenger cars, grouped according to the type of fuel they have and the year in which the incident occurred. Passenger cars were defined as cars with a maximum of 8 seats in addition to the driver's seat.



	2016	2017	2018	2019	2020	2021	2022	2023
Gas	6	1	3	1	1	0	5	1
Hybrid	0	4	6	2	12	13	20	12
Other	38	36	2	1	5	5	3	2
EV	15	22	8	17	19	29	22	19
Petrol/diesel	661	651	732	686	638	658	703	399

Figure 23: Number of vehicles involved in a fire in Norway sorted by the vehicle's energy source (2016-2023).

The statistics only contain incidents where the fire and rescue services have responded. Cars that burned as the result of being involved in traffic accident were not excluded from the statistics [111]. Whilst over 25% of passenger vehicles in Norway are either all-electric or plug-in hybrid electric vehicles [112], EVs make up a much smaller percentage of vehicle fires; around 3% in 2022 and just over 4% so far in 2023. However, it is noted that EVs are expected to generally be newer than existing petrol/diesel vehicles on the roads currently.

6.6 Observations

The statistics presented in this section provide a general overview of carpark fires. A focus has been placed on Australia and nearby New Zealand, the UK, U.S., and Norway.

The data provides useful insight into the likelihood of carpark fire events in each country, and – in the case of Norway – initial insight into whether EVs pose a particular fire risk. That is discussed further in Section 7.2.1, however fire statistics data so far does not indicate that EVs are more likely to be involved in a fire. In fact, quite the opposite. It is noted that EVs are generally newer than existing petrol/diesel cars on the roads.

The data is somewhat limited, in that it needs to be processed further to provide greater insight. For example, it could be interrogated in a similar manner to Alimzhanova et al. [108], where the figures are correlated based on the number of carparks that exist within each country, and/or by the floor area of those carparks. Such further data processing would be needed if the intention were to unlock probabilistic design approaches. This was outside the scope of this literature review. Standardised statistical data reporting across nations would assist in this regard, such as recommended by the EU FireStat project [113]. As a starting point, data in Australia such as that recorded by AFAC in the AIRS database could be made freely available to allow better informed design approaches.

Furthermore, as noted by the BRE [11], the samples will be biased when it comes to considering the proportion of all fires. Because the statistics are only based on fire brigade reports, there will be a large number of small fires that are unreported. Nevertheless, the statistics show that:

- Upon initial review, carpark fires may appear unlikely: they make up relatively small proportions of the total number of fires in both Australia and England.

- Carpark fires make up a much smaller proportion (0.05%) of total fires in England than Australia (2.1%). This is demonstrated in Figure 24 below. However, this difference seems somewhat unrealistic, and may be caused by different reporting mechanisms across the two countries.
- Data from the UK appears to indicate that MSCP fires are the most likely to result in injury, particularly when the building is mixed-use (i.e., with a non-carpark use adjoining the carpark itself) and/or incorporating residential use.
- Arson is more likely in carparks than the average across other building types in Scotland.
- Despite being the nation with the highest uptake of EVs in the world, Norway has not witnessed an increasing number of vehicle fires.
- The data indicates that the number of carpark fires is generally remaining stable in Australia. Whilst modern cars are larger and contain more combustibles (as discussed further in Section 7.1), they do not appear to represent an increased ignition risk.

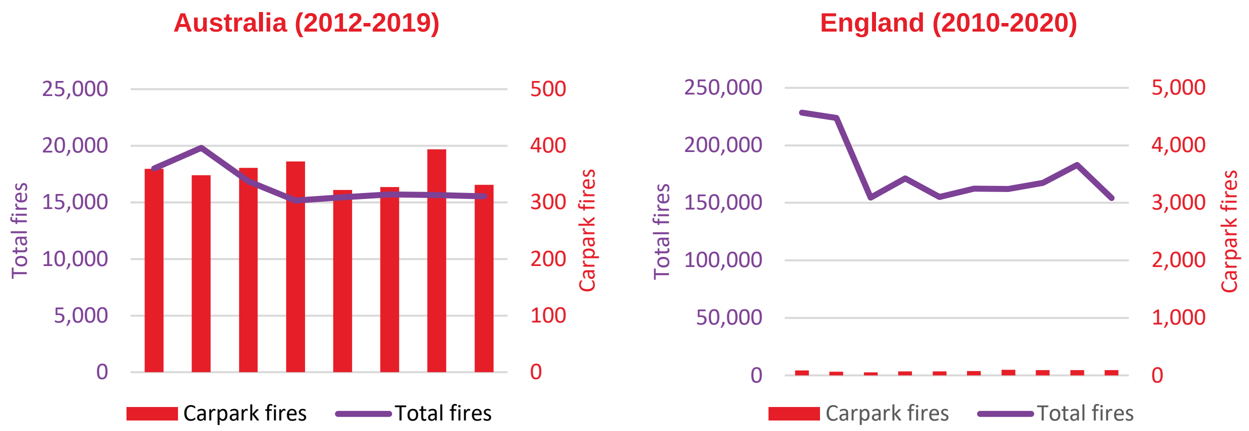


Figure 24: Normalised comparative plot showing the difference in proportional makeup of carpark fires out of total fires between Australia and England over similar time periods.

It is acknowledged that, in the above plot, the number of carpark fires in England is hard to estimate because the y-axis has been normalised for comparison with the data from Australia. Therefore, the data is also plotted in a standalone figure below.

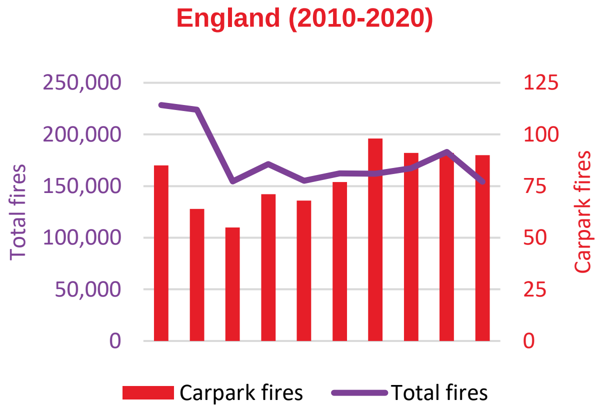


Figure 25: Carpark fire data from England between 2010-2020.

7. Fire hazards in the modern-day carpark

In this review, 'modern-day' refers loosely to the 21st century. This period has been chosen because it follows the period within which the seminal experimental research on carpark fires was conducted (between 1967 and 2002), as described in Section 4. Thus, a clear comparison can be made between the vehicles and carparks of the time (of the experiments), and those of the modern-day.

A recent report by the National Fire Protection Association (NFPA) in the U.S. is widely considered as the most comprehensive document on the topic [54]. It splits modern-day carpark hazards into two categories:

1. Modern vehicles which are larger, heavier and have increased quantities of combustible materials (e.g., fuel, plastics, synthetic materials) when compared to cars manufactured in the 20th century [54], [114], whilst also being parked closer together.
2. Rapid, widespread market growth of alternative fuel vehicles (AFVs).

This literature review follows a similar structure. First, modern internal combustion engine vehicles (ICEVs) are covered, before alternative fuel vehicles (AFVs) are discussed. In addition, car stackers are reviewed, due to the specific novel hazard they pose.

7.1 The evolution of the internal combustion engine vehicle (ICEV)

Whilst the original invention of the automobile cannot be confidently attributed to a single individual [115], it is clear that the car has evolved significantly over the past one hundred or so years. Henry Ford is widely credited with catalysing the automotive revolution; his concept of the production line conceived in the early 1900s has transformed all product design industries. Since then, the car has developed considerably.

7.1.1 Vehicle size and weight

Modern-day carparks typically optimise spacing of vehicles, and tend to have narrower parking spaces than before [54]. It is often postulated that modern vehicles are larger and heavier, and that "spaces are smaller".

As part of this literature review, the size and weight change between an early model and today's model of six different vehicles has been assessed. This is documented in Table 7. To ensure consistent comparisons, the cheapest model of each vehicle was chosen, where an option existed. Effort has been made to select vehicles which are popular in Australia. Three different vehicle types have been covered.

Table 7: Comparison of size and weight from early models of various vehicles against today's models.

	Size change (H x W x L) [mm]		Weight change [kg]	
	Early model	Today	Early model	Today
Hatchbacks				
Toyota Corolla (1985 to 2023) [116], [117]	1385 x 1635 x 3970	1460 x 1790 x 4375	935	1360
VW Golf (1980 to 2023) [118], [119]	1410 x 1610 x 3815	1456 x 1789 x 4284	830	1304
SUVs				
Honda CR-V (1997 to 2023) [120], [121]	1675 x 1750 x 4520	1679 x 1855 x 4635	1410	1504

	Size change (H x W x L) [mm]		Weight change [kg]	
	Early model	Today	Early model	Today
Nissan X-Trail (2001 to 2023) [122], [123]	1675 x 1765 x 4510	1725 x 1840 x 4680	1395	1540
Utility vehicles ('utes')				
Toyota Hilux (1980 to 2023) [124], [125]	1570 x 1610 x 4305	1750 x 1800 x 5330	1075	1785
Ford Ranger (2007 to 2023) [126], [127]	1755 x 1807 x 4841	1886 x 1910 x 5225	1770	1994

It can be clearly seen that vehicles have gotten larger (in all three dimensions) and heavier. This is evident across all six vehicles analysed, including hatchbacks, SUVs and utility vehicles.

This crude study and observation is generally supported by data recently published by the Australian Government's Bureau of Infrastructure and Transport Research Economics (BITRE) [128]. Their data shows that sales of SUVs have rapidly (almost exponentially) increased between the end of the 20th century and the beginning of the 21st century (see Figure 26 (left)), thus taking up a greater portion of the market. A gradual increasing trend in gross vehicle mass (GVM) for total new light vehicles purchased in Australia since the 1980s can also be seen (see Figure 26 (right)), with some fluctuations over time. Their dataset includes cars, SUVs and light commercial vehicles (LCVs).

It is worth noting that, for 'cars', the average weight of a new car purchased in 2013 was lower than at the turn of the century, and similar to the 1980s (see Figure 26 (right)). That is indicative of a consumer shift in the 21st century towards smaller models of cars in Australia. In other words, whilst the same car model can be expected to weigh more now than an older version of that model, those consumers who buy cars are shifting to select smaller cars (perhaps for fuel efficiency reasons), thus causing the average weight of a new car purchased in 2013 to be lower than previously. However, a greater proportion of buyers are now selecting SUVs instead of cars.

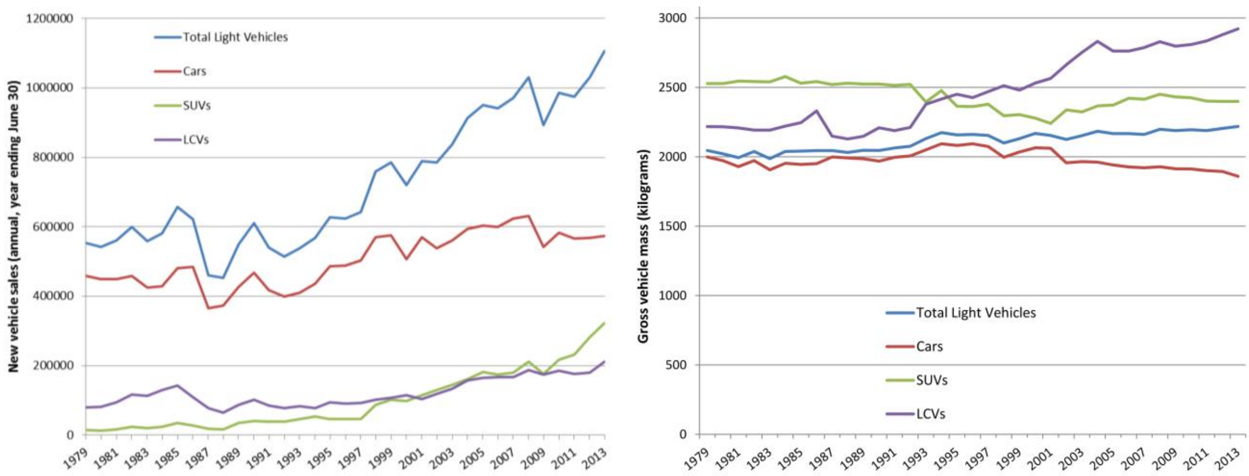


Figure 26: Left: New light vehicle sales in Australia. Right: Average Gross Vehicle Mass (GVM) for new light vehicles purchased in Australia. Data from 1979-2013. Reproduced from [128].

An effort has been made to source more recent data from the BITRE, but this was not freely available / easily accessible.

Width is the key parameter when considering vehicle separation distances in carparks. Over the six vehicles reviewed, widths increased by between 75 mm and 190 mm. The average width increase was 135 mm.

Considering the Australian standard parking space dimensions (of 5400 mm x 2400 mm); if two vehicles were 1700 mm wide and parked centrally within each parking space, the separation distance between them would have been 700 mm. If each vehicle increased in width by 135 mm and remained centrally parked, the spacing would become 565 mm (a 19% reduction). This could have implications for vehicle-to-vehicle fire spread. Heat transfer first principles are that the incident radiative heat flux increases the closer the receiver is to the emitter.

Whilst work by Mohd Tahir and Spearpoint suggests that “the width of the vehicle is unimportant” when estimating the probability of fire spread between vehicles, the equation proposed in their work focuses on parking space width only [129]. I.e., it infers that the probability of vehicle-to-vehicle fire spread is only influenced by parking space width. Therefore, it has not been applied to the above example. Their work did show a correlation of increased probability of vehicle-to-vehicle fire spread for smaller carparking spaces (thus reduced spacing).

It is postulated that; the most important factor in whether vehicle-to-vehicle fire spread will occur in a carpark is whether a car is parked in the space(s) next to the ignition vehicle or not. If one is, the separation distance is important. If vehicles are parked closer together, the potential for direct flame impingement increases, and the received heat flux will also be greater.

7.1.2 Use of plastics

There has been a steady increase in the use of polymers / plastics in the automotive industry. Cars used to be largely manufactured from metals, but today, plastic is commonly used for wing mirrors, smaller body panels, wheel caps, etc. Boehmer et al. combined two U.S. data sources to plot the amount of plastic in light vehicles over time [54]. Light vehicles are defined as passenger vehicles, excluding trucks. The plot shows a steady increase in plastic weight from around 80 kg per light vehicle in 1980 to 160 kg per light vehicle in 2020. I.e., the amount of plastic in light vehicles appears to have approximately doubled over the past 40 years in the U.S.

Polymers / plastics present a higher fuel load than their metallic alternatives, as they have a higher heat of combustion (also known as the ‘calorific value’ – this describes the total energy released when a substance undergoes complete combustion with oxygen under standard conditions) [130]. It is logical to expect a higher energy release per weight of vehicle, or, in other words, more potential energy in the same volume [131].

Plastics also ignite and sustain burning more easily than metals, and they melt and drip. This can lead to secondary fires, remote from the vehicle of fire origin. If a carpark floor slab is not flat (which it is unlikely to be), molten plastic can pool in locations away from the vehicle of fire origin, and potentially drip / leak through penetrations in the floor slab, as was thought to be the case at the Echo Arena, King’s Dock fire [63], [64]. Plastics also produce more toxic smoke than metals.

Furthermore, plastic is now commonplace for vehicle fuel tanks. The BRE estimated that 85% of European vehicles had plastic fuel tanks when conducting their research in 2006-2009 [11]. The use of plastic for fuel tank construction increases the risk of fuel leakage in a vehicle fire scenario. Liquid fuel presents a similar albeit greater risk than molten plastic in that it can leak and run, causing a secondary fire which can, in turn, lead to a fire involving multiple vehicles, particularly if the fuel pools under neighbouring cars. It should be noted that metal fuel tanks will also leak when exposed to a sufficiently severe fire [54], but testing has shown that this occurs slower than the melting of a plastic tank [132].

This was also evident in the research by BHP. In the closed carpark experiments involving slightly older cars with metal fuel tanks, vehicle-to-vehicle fire spread did not occur. When the ignition vehicle was changed to a slightly newer car with a plastic fuel tank, vehicle-to-vehicle fire spread occurred. It was reported that plastics often dripped to the floor and formed a flaming pool fire. In one test, both plastics and petrol from the fuel tank spilled onto the floor, forming a pool fire and contributing to fire spread between vehicles [43].

7.1.3 Autonomous vehicles (AVs)

Experiments have been conducted on self-driving cars since 1939 [133]. The Australian Government ‘expects vehicles to become more and more automated over the coming decades’ [134]. It is expected that automation will help to reduce the number of deaths in road traffic accidents [135], as around 90% of road accidents are caused by human error [136]. There have been over a million road traffic deaths per year for the past 30+ years [137] – a much greater life safety issue than fire.

Autonomous vehicles have received little fire safety attention. As statistics show that most vehicle fires are a result of collisions, it is reasonable to expect a reduced number of vehicle fires if autonomous vehicles can reduce the number of traffic accidents. That will have little impact on carparks, though.

It would appear that the carpark is an ideal space for autonomous innovation. The concept of 'autonomous valet parking' has been discussed previously, whereby an autonomous vehicle 'drops off' its passengers at the entrance of a carpark, or another destination nearby, before self-parking within the carpark [138]. Such a concept will require the highest level of autonomy (i.e., fully self-driving cars). Regulation is seen as the bottleneck to widespread adoption of such AVs [139].

Autonomous valet parking would free humans from the burden of parking, thus removing the human behavioural aspect of carparking. Often, humans may park their cars in spaces with free adjoining spaces, due to the comparative ease of such a parking manoeuvre, and subsequent ease in terms of exiting the vehicle. Autonomous valet parking could be programmed to do similar (i.e., spread cars out where carpark capacity permits), or follow a more sequential approach. The former would be a better scenario from a fire safety perspective.

If cars were able to self-park within carparks after dropping off their passengers, they could park much closer together, as there would be no need to leave space for doors or boots (trunks) to open. This would lead to a scenario where vehicle-to-vehicle fire spread is much more likely. Such parking arrangements are seen in vehicle shipping scenarios, also known as roll-on/roll-off or 'roro'. There is evidence to support this hypothesis, such as the recent freighter fire off the coast of the Netherlands [140], and fires on similar carriers in the Atlantic [141] and Pacific [142]. Furthermore, the fire load density within the space will increase [143], which would mean the suite of fire safety measures, such as the structural fire resistance level (FRL) and ventilation design, would need to be reassessed.

7.2 Alternative fuel vehicles (AFVs)

For a few centuries, problems of pollution from ICEVs combined with the climate crisis has led to society seeking AFVs with potential of replacing petrol and diesel vehicles. This section aims to summarise a range of AFVs. As AFVs have become more popular, concerns have been raised regarding their unique fire hazards. While some of these concerns are legitimate, others appear to be inflated based on research findings.

First, Figure 27 through Figure 32 present diagrams from the Alternative Fuels Data Center in the US which illustrate the variety of fuelling methods available [144]. These are each discussed further in their respective sections.

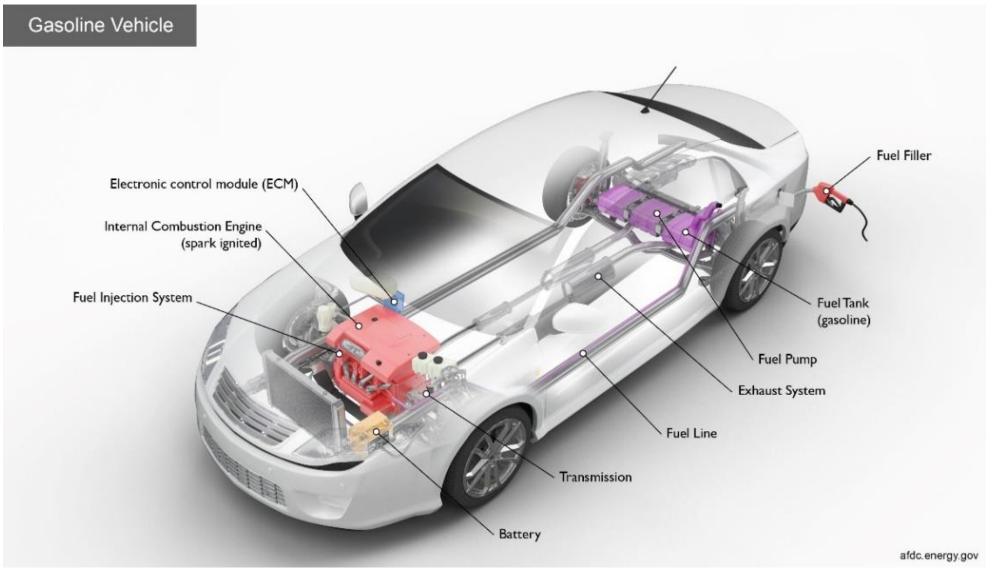


Figure 27: Typical petrol or diesel powered internal combustion engine vehicle (ICEV). © Alternative Fuels Data Center.

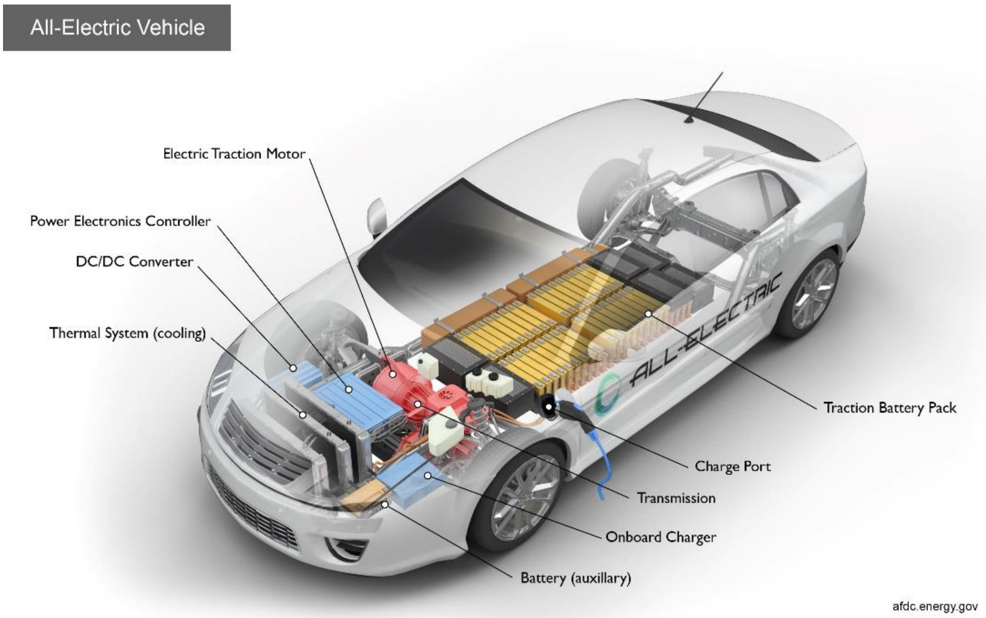


Figure 28: Typical battery electric vehicle (BEV) layout. © Alternative Fuels Data Center.

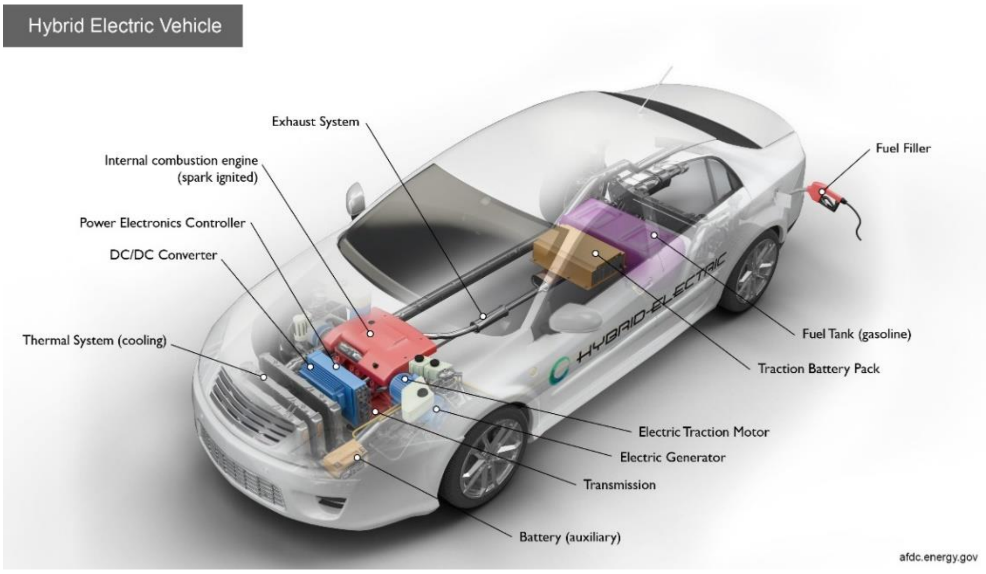


Figure 29: Typical hybrid electric vehicle (HEV) layout. © Alternative Fuels Data Center.

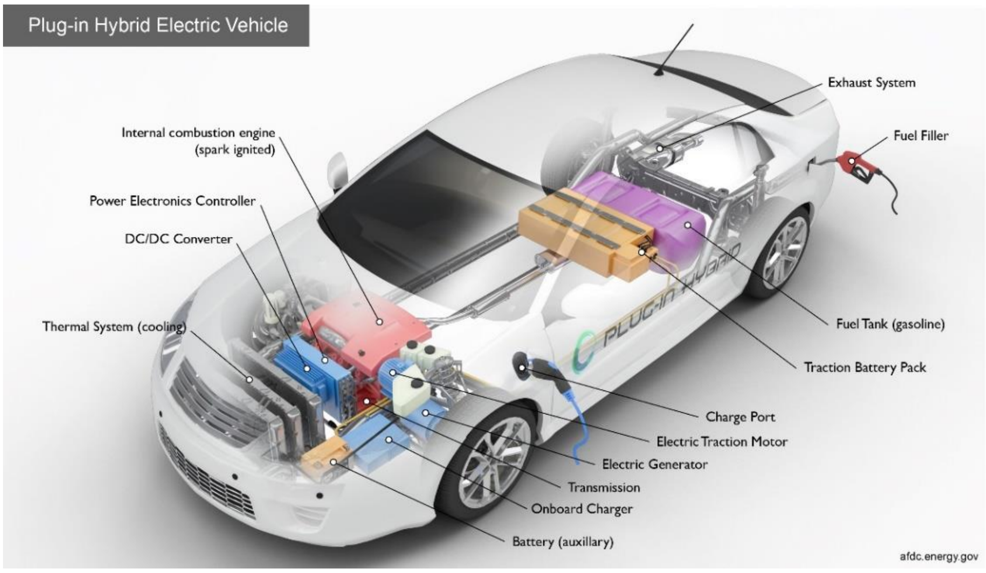


Figure 30: Typical plug-in hybrid electric vehicle (PHEV) layout. © Alternative Fuels Data Center.

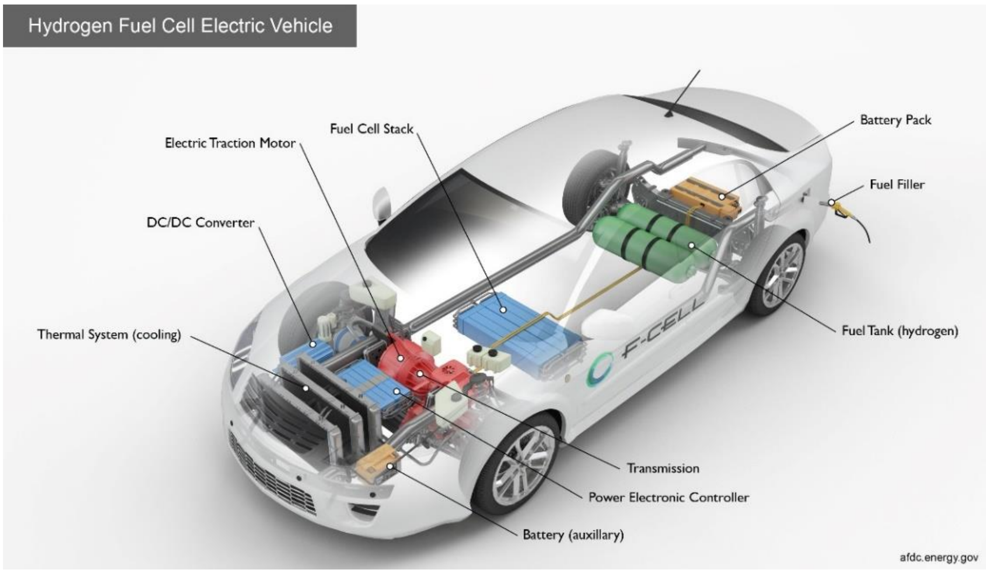


Figure 31: Typical hydrogen fuel cell electric vehicle (HFCEV) layout. © Alternative Fuels Data Center.

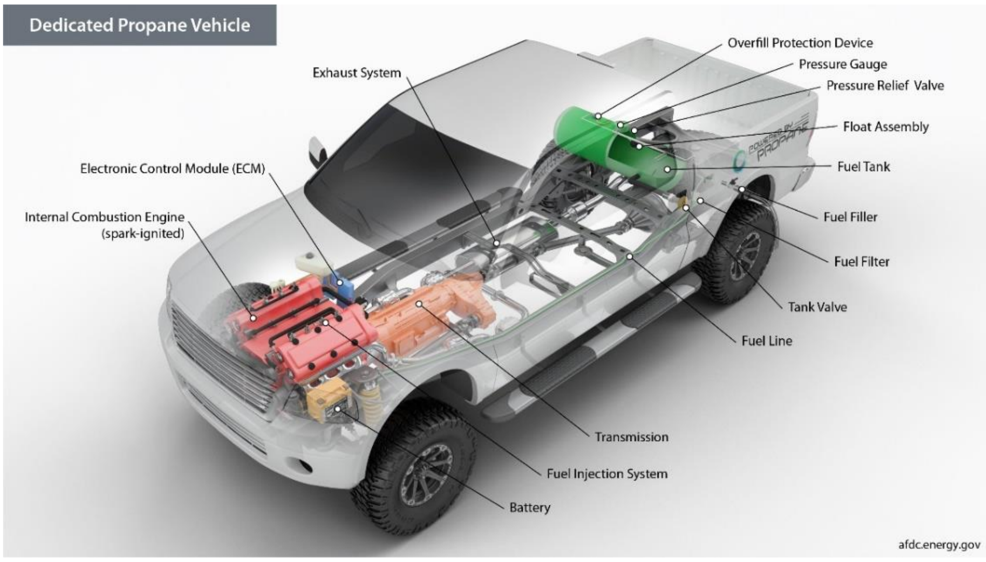


Figure 32: Typical liquified petroleum gas (LPG) vehicle layout. © Alternative Fuels Data Center.

7.2.1 Electric vehicles (EVs)

When "electric vehicles" are mentioned, typically people are referring to battery electric vehicles (BEVs). However, "electric vehicles" is a broad term covering a range of vehicles which are powered by electricity as opposed to petrol, diesel or gas.

7.2.1.1 Battery electric vehicles (BEVs) ("all-electric")

Introduction

Battery electric vehicles, or so-called "all-electric" vehicles, are vehicles which are purely powered by electricity from a traction battery pack. BEVs make up the vast majority of total EVs in Australia and globally [145].

Lithium-ion (Li-ion) batteries are the most common type of battery found in BEVs, due to their high capacity, long life, and fast charging abilities [146], [147], [148]. Li-ion batteries replaced the previously popular nickel metal hydride batteries, which were used for many years but had significant limitations such as insufficient energy and power densities and high self-discharge rates [149]. Whilst there are new battery technologies emerging on the market, this literature review focuses on Li-ion as they are the most common on the market today.

Li-ion battery cells can be various shapes. The most common cell used in BEVs is a cylindrical cell termed the 18650 (representing the dimensions of the battery – 18 mm diameter and 65 mm long). A common AA battery has a 14 mm diameter and is 50 mm long [2], [146], [150].

The main fire safety risk with BEVs is associated with the energy storage within the traction battery pack. See Figure 28 for a typical location of the traction battery pack. The traction battery pack is designed such that electrical energy can be discharged and recharged regularly without sustaining any damage. The battery pack is made up of multiple battery cells, connected in series or parallel. A frame protects the battery pack and provides resilience against external shocks, heat and vibration. The battery management system (BMS) manages power, charging/discharging and monitors the temperature of the batteries. It plays a major role in managing the circumstances that lead to battery failure, but is outside the control of built environment professionals [2].

Thermal runaway

Batteries can enter what is termed 'thermal runaway' – a form of uncontrolled feedback loop or chain reaction, whereby a trigger causes an increase in temperature due to an exothermic reaction, which changes conditions, which causes a further increase in temperature (and so forth). Thermal runaway can be very hard to stop once it has started, and rates of heating can reach up to 60 °C/min. Once one battery has entered thermal runaway, it can then cause neighbouring batteries to also enter thermal runaway. The type of mechanical packaging can affect a battery's behaviour during thermal runaway [151]. Thermal runaway often leads to spontaneous ignition. It can be caused by strong electrical, thermal or mechanical impulses acting on the Li-ion battery cells [147], [150]. There are a number of circumstances which can lead to thermal runaway:

- Battery management system (BMS) failure.
- Battery failure.
  - Cell short-circuits.
  - Overcharging / deep discharge.
  - Insufficient battery ventilation or failure of the cooling system leading to overheating.
- Faults with an EV charge point (EVCP).
  - Incorrect charger selection (although this is unlikely due to the different charging hardware designs between manufacturers and models).
  - Under-voltage.
  - Over-voltage.
  - Over-current.
- External influences, such as collisions or other forms of mechanical damage.

The above are discussed in detail in Arup's previous EV-specific report for the UK Government [2]. The most common causes of thermal runaway are short-circuiting, overcharging, overheating and mechanical damage [152]. For many EVs, most types of electrical abuse (short-circuiting / overcharging / deep discharge) are not possible if their battery management system (BMS) is designed properly and functions correctly [153]. Further, management systems can be incorporated within EVCPs to provide additional safeguards, for example overcurrent protection and fault reporting. The remainder of this literature review focuses on specific areas for consideration when designing carparks.

EV fire scenarios

If thermal runaway does occur, a fire event is highly likely. The severity of the resulting fire can be impacted by the state of charge of the battery and the cell capacity. There are various fire scenarios which may arise:

1. A free-burning fire where ignition of the flammable gases occurs in the presence of an ignition source [148].
2. A jet flame, where the vented gases are released with some momentum in a particular direction and ignite, causing laterally-projecting flames. Some battery packs are designed to side vent in an emergency to minimise the overpressure as a result of accumulation of flammable gases within the battery.
3. A flash fire (or deflagration) where the vented gases exist in the right mixture so that a subsonic flame front can propagate through that mixture but in a manner that creates negligible or no damaging overpressure.
4. The severity of the deflagration event can increase and result in a vapour cloud explosion (VCE), where the vented gases form a cloud within the flammable range and there is sufficient confinement to generate an explosion [2].

Whilst fire scenarios three and four as listed above are possible, the data indicates they are highly unlikely events. The BHP research effort discussed in Section 4.3 raised the potential hazard of flash fires and vapour cloud explosions from LPG vehicles also. This hazard also exists for HFCEVs. There is a lack of data on these phenomena. EV manufacturers have to comply with a set of regulations when bringing a product onto the market. In Australia specifically, the government has recently published new safety requirements for electric and hydrogen-fuelled vehicles in Australia [154]. As the market becomes even more established and regulated, already unlikely fire scenarios are expected to become even less likely, although the data should be kept under review.

Heat release rate

One of the key questions around EVs is whether the presence of a traction battery pack in lieu of a fuel tank can significantly change the expected fire curve. Lecocq et al. carried out experiments to quantify the heat release rate (HRR) of two EVs and two ICEVs [155]. The ICEV contained a full tank of diesel, and the BEV was fully charged. The BEVs had 16.5 kWh and 23.5 kWh batteries respectively. They found that the EVs and ICEVs produced similar HRR curves. The peak HRR was greater for the ICEVs than the EVs. The HRR curves are reproduced in Figure 33.

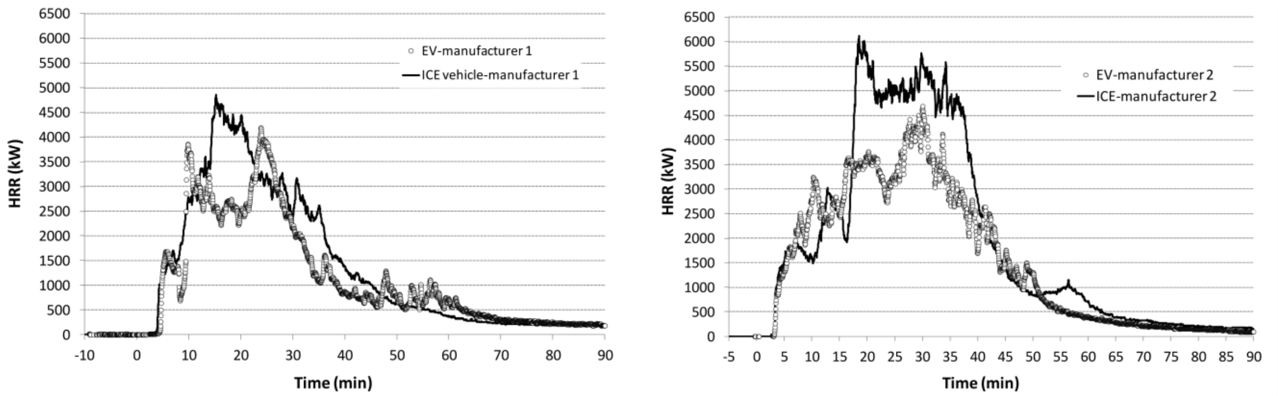


Figure 33: Comparison of the HRR from EV and ICEV tests from two manufacturers. Reproduced from [155].

Around the same time, Watanabe et al. conducted similar research [156]. They burned an EV and an ICEV whilst they were placed on a weighing platform, and estimated the HRR through multiplying the mass loss rate recorded and an assumed heat of combustion. It is worth noting that the EV weighed 1520 kg, and the ICEV weighed 1275 kg. The EV had a 24 kWh capacity battery. The peak HRR for the EV was 6.3 MW (although this was a sudden, short peak, and a more realistic peak may be estimated as around 4 MW), whereas the peak HRR for the ICEV was 2.1 MW. The HRR-time curves are reproduced in Figure 34.

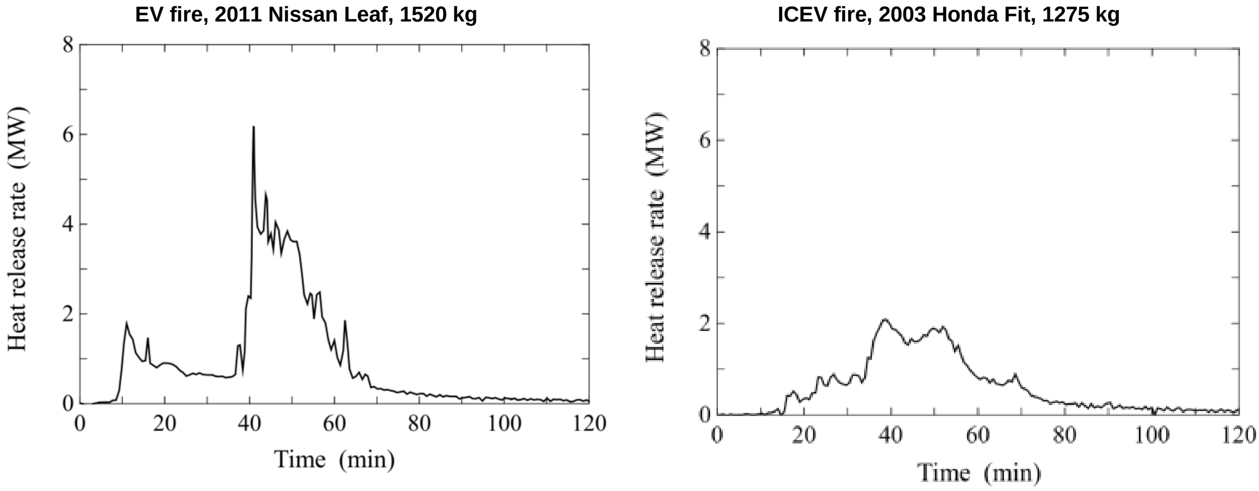


Figure 34: Comparison of the HRR from EV and ICEV tests from two manufacturers. Reproduced from [156].

Initial evidence at the small-scale suggested that the HRR is higher for charged cells than discharged cells [153], [157]. This research is limited to experiments on much smaller batteries than used in EVs. A similar observation would be expected between full and empty fuel tanks. However, the provision of EVCPs within carparks to support the increasing use of EVs could result in a higher state of charge of EVs in carparks.

Lam et al. carried out similar work to Lecocq et al. in the U.S., and also varied state of charge. Figure 35 shows an ICEV fire which has a single peak HRR, followed by a steady reduction as the fuel and combustible components of the vehicle are burnt. With the EV fires, there appears to be two peaks: the first, when the combustible materials in the car ignite, and the second, when the battery becomes involved in the fire. Whilst the fire size (peak HRR) and time to reach the peak HRR tends to be similar between ICEV and EV fires, the EV fires in Lam et al.'s experiments remained at that peak output for longer than the ICEV fire. This was not observed in Lecocq et al.'s work. This may be expected to lead to increased heating of the surroundings and fire spread to adjacent vehicles more likely.

Lam et al. also confirmed that the state of charge can influence the fire growth – the EV which was fully charged had a slightly faster fire growth rate than the EV which was charged to 85%.

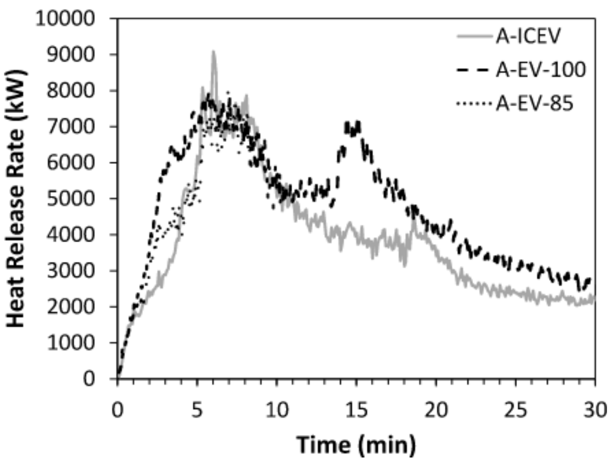


Figure 35: Comparison of the HRR from an EV at 100% and 85% charge, and an ICEV. Reproduced from [158].

More recently, Kang et al. carried out similar experiments on BEVs, ICEVs and HFCEVs [159]. Their research acknowledged that prior research had used BEVs with battery packs with capacities which were more common at the time, however highlighted that, in the US, the average capacity of BEVs had increased from 41.2 kWh in 2015 to 70.5 kWh in 2020. With higher call capacities, there is potential for greater energy contribution to the fire from the battery. Therefore, they selected a BEV with a higher capacity, of 64 kWh. Uniquely, they also burnt the Li-ion battery pack (LIB pack) and the BEV body separately. Figure 36 presents their results, which are summarised in Table 8.

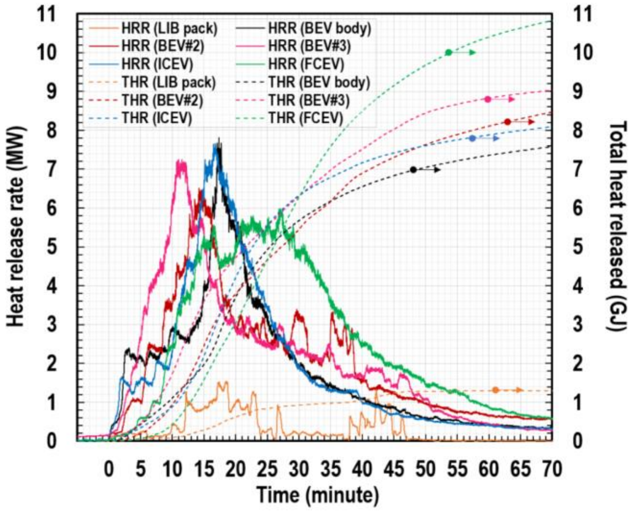


Figure 36: Comparison of the HRR from a BEV, ICEV and Hydrogen FCEV. Reproduced from [159].

Table 8: Summary of key results from the experiments by Kang et al. [159].

Measure	LIB pack only	BEV body only	BEV	BEV	ICEV	HFCEV
Peak HRR (MW)	1.5	7.8	6.5	7.3	7.7	6.0
Total energy released (GJ)	1.3	7.5	8.5	9.0	8.1	10.8

Interestingly, the BEV body in isolation gave the highest peak HRR. The ICEV had a greater peak HRR than the BEV and HFCEV. In one of the BEV experiments, they observed a jet flame from the LIB pack, which is reported as accelerating fire spread to adjacent combustible components, leading to a more rapid fire growth involving the whole car [159].

Total energy released

Watanabe et al. reported the total energy released from their experiments. The total energy released from the EV was 6.4 GJ, whereas the ICEV released 4.3 GJ, a c. 32% reduction. It is worth noting that the ICEV was c. 16% lighter than the EV, and that the ICEV contained only 10 L of petrol, whereas the EV was fully charged [156].

Data for total heat release also did not show a clear pattern between ICEVs and EVs in Lam et al.'s work; "for Vehicle A, the total heat release of A-ICEV [3.3 GJ] was 33% lower than that of A-EV-85 [4.9 GJ] (part of this may have been due to A-ICEV being slightly smaller), while for Vehicle B, the total heat release of B-ICEV [5.0 GJ] was 6% higher than that of B-EV [4.7 GJ]." [158].

In Kang et al.'s work, the HFCEV released the greatest amount of energy. "In the BEV fires, the major contribution to the quantity of heat release rate was determined by the combustion of the conventional materials of the BEV body, rather than by that in the LIB pack" [159]. The total energy released from the BEV fires were measured to be in a range of 8.5 to 9.0 GJ. These values were similar to the ICEV (8.1 GJ) and HFCEV (10.8 GJ). Interestingly, these values are approximately double those reported in Lam et al.'s work. Across both research efforts, there was not a large difference between the total energy released from BEVs compared to ICEVs. RISE have also carried out a comprehensive literature review on this specific topic, with similar findings [160]. A figure from their work is reproduced in Figure 37.

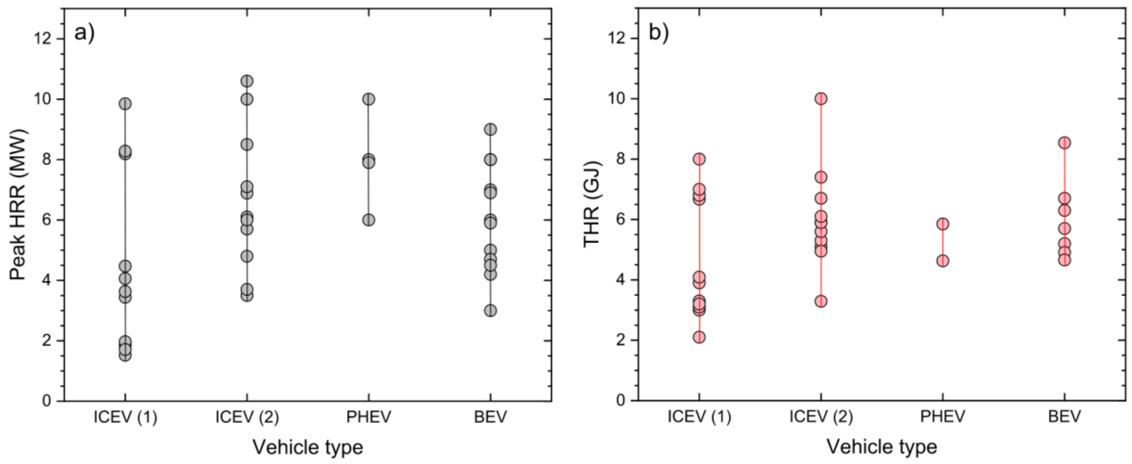


Figure 37: a) Peak HRR and b) Total Heat Released for ICEVs, PHEVs and BEVs. 'ICEV (1)' represents vehicles manufactured before 2000, whereas 'ICEV (2)' represents vehicles manufactures after 2000. Reproduced from [160].

Toxic gas production

Lecocq et al. also recorded toxic gas production by using a hood calorimeter in their work [155]. Similar findings were reported in terms of toxic gases – "analysis of the combustion gases from car fires highlighted that the cumulative masses of CO_2, CO, total hydrocarbons, NO, NO_2, HCl and HCN were similar for both types of vehicles".

Research by RISE also found that similar quantities of CO_2, CO, NO and NO_2 were released from BEVs and ICEVs. There was a slight increase in the amount of THC, HCl and SO_2 released from BEVs than ICEVs. "HF together with some specific metals, e.g., Ni, Co, Li and Mn (depending on the battery cell chemistry), in the smoke exhaust constitute a large difference between electrical and conventional vehicles" – this has been cited as a concern by some brigades in Australia. However, RISE concluded that this didn't pose a significantly increased health risk, and is instead more likely to have environmental impacts [161], [162]. However, this must be considered in the context of the environmental benefits that EVs also present.

Research involving a battery pack fire within a tunnel concluded that an EV battery fire within a closed carpark will not produce conditions that prevent occupants from escaping, or prevent the fire being fought by firefighting personnel, given they have suitable equipment and training [163].

It is expected that, if battery technology changes, the toxic gases produced by a fire involving the battery would change. It is also worth noting that BEVs are not unique in producing toxic gases – all fires produce toxic gases.

Peak temperatures

Some sources state that BEV fires exhibit greater temperatures than ICEV fires [164]. However, the literature is not conclusive on this. Recent experiments by Funk et al. recorded peak temperatures of around 1150 °C from BEV fires [165]. Research from the BRE recorded gas temperatures in excess of 1200 °C from ICEV fires [11]. Similarly, Cui et al. report "peak temperatures of the external and internal flames of the BEV compartment are consistent with that of internal combustion engine vehicles (ICEVs) since the two models were similar with respect to the material type and quantity of the combustible polymers" [166]. Peak temperatures, durations, and other fire characteristics are subject to wide variation depending on the specific scenario [79].

Ability to control/suppress and extinguish

RISE carried out suppression experiments on ICEVs and BEVs. They found that a fire in a BEV does not seem to be more challenging than a fire in a gasoline-fuelled vehicle for a sprinkler system designed in accordance with current international recommendations for a system with a discharge density of 10 mm/min [167], noting this is double the typical Ordinary Hazard discharge density of 5 mm/min. Their experimental setup aimed to replicate roll-on roll-off ('ro-ro') ferry spaces, with a relatively large floor-to-ceiling height (5 m). The suppression system was effective on both ICEVs and BEVs.

There is also anecdotal evidence, as described in Section 5.1, which seems to indicate that this is the case in real car fire scenarios in carparks. However, BEVs present a unique hazard in that the battery pack – which can itself be an ignition source – is hard to fully extinguish, as the cells are protected by the outer container. There is a case study of a BEV fire in Germany in which the battery itself did become involved, and the Ordinary Hazard 2 sprinkler system did still control the fire [26], [73], [74].

Firefighting tactics to extinguish a BEV fire is an area of concern for many fire brigades worldwide, and various methods have been explored. These range from applying a large volume of water (for an extended period, and potentially lifting the BEV with jacks such that the jet stream can be targeted on the underside of the battery pack), to placing the BEV in a large container full of water, to fire blankets. Innovations such as a Rapid Intervention Vehicle (RIV) have also been developed, which has capability of piercing the battery pack via water-borne abrasives, such that the battery pack can be flooded with water [168]. A selection of these methods have been tested on EVs in an open-sided enclosure [165]. Moveable steel plates to create an electric vehicle fire enclosure (EVFE) has also undergone a proof of concept [169].

Brigades often raise concerns around the potential hazard of re-ignition of the battery. Re-ignition of the battery occurs when other nearby cells within the battery pack become damaged in the initial incident and go into thermal runaway sometime after [2].

Research by EV FireSafe found that, following initial suppression, 13% of vehicles reignited, and two cases have been recorded where the EV re-ignited multiple times over several hours due to the residual heat that can remain in the battery even after the visible signs of fire (i.e. flame, smoke) have been suppressed [170].

This means that EVs can reignite hours after the initial fire event (in one study, 22 hours after the initial fire [171]). This is primarily an issue for fire-fighting personnel, but firefighting tactics may involve additional application of water, removal of the EV from the carpark, monitoring of the battery with thermal imagining technology, and listening for sounds which may indicate continued thermal runaway, such as popping, whistling and hissing sounds. Some countries submerge EVs to mitigate the reignition risk once the vehicle has been removed from the carpark, whilst others install a local bund.

Most of the research to date has focused on brigade firefighting methods. The suitability of occupant first-response firefighting techniques for EV fires has not received significant research attention. Occupants may tackle a fire in its early stages, before the brigade arrive.

Typically, this can be through use of either a fire hose reel or a portable fire extinguisher. Each method has pros and cons. Fire hose reels provide a continuous water supply. This might be more effective on an EV fire if the battery is involved. It is worth noting that ‘battery fault’ is listed as the third most common cause of EV fires by EV FireSafe (behind ‘unknown’ and ‘collision/debris’) [172]. However, using a fire hose reel could also mean that occupants are exposed to more severe fire conditions (if they fight a fire for longer). This could have an impact on occupant life safety, through direct exposure to a fire, burns from radiation, or inhalation of toxic gases. On the other hand, portable fire extinguishers provide a means for tackling a fire in its early stages, but then – once fully discharged – encourage occupants to escape. This can mean that occupants escape before conditions worsen, at which point the fire service can tackle the fire with more appropriate means, protection and expertise.

There is an outstanding question regarding suitability of extinguishers for Li-ion batteries, which may need further research. This was not fully reviewed as part of this work, however the authors were made aware during the peer review process of a potential solution existing; extinguishers using an F-500 extinguishing agent, which is purpose-developed for Li-ion batteries.

The influence of charging

Of the total number of EV fire incidents recorded by EV FireSafe from 2010 up to July 2023, 18% occurred when the EV was connected to energised charging. A quarter of all EV fires occurred in underground / enclosed spaces, and 31% occurred when the EV was parked outside [172]. In all incidents studied, charging could not be proven as the cause of thermal runaway, but may have pre-empted electric vehicles with an existing unknown fault and/or a cell defect (i.e., a fault during manufacturing) to go into thermal runaway sooner than expected. It should also be noted that electric vehicles, by definition, spend significant periods of time connected to energised charging, so the number of charging-related incidents should not be considered unexpected or unusual.

Brandt [111] states that the regulations in place in Norway and the U.S. for EVCPs seem to be adequate for ensuring that the risk of fire arising due to the charging of EVs in carparks is acceptable. EVCPs should be installed in accordance with the regulations for the product, and the recommendations from the car manufactures and producers of the EVCPs should be followed. Using approved EVCPs and approved competent persons to install them reduces the risk of faults developing within them.

Whilst no evidence has been found to date that confirms this; logically, the location of EVCPs may influence the effect of an EV fire on the carpark / life safety of occupants within the carpark. EVCPs are electrical equipment which present an ignition risk. It may be prudent to separate the ignition source (EVCP) from the means of escape, however this is a design decision that would be taken above the DtS requirements of the NCC. For example, if there is a single exit from a carpark, the EVCPs should be located as remote from the exit as far as is practicable to minimise the likelihood of that exit becoming unusable as a result of a fire at the EVCP. Where multiple exits are provided, fire safety design rules for means of escape expect one exit to be discounted in case of a fire blocking that escape route. Some tertiary guidance documents have also discussed this concept [13].

Statistics on EV fires

Australia is leading the way on data collection on EV fires. The most comprehensive dataset on EV fires is considered to be that collated by EV FireSafe, supported by the Australian Department of Defence (Defence Science & Technology Group). Their latest infographic, dated June 2023, states that there have been 393 verified EV traction battery fires globally since 2010 [172]. The data indicates that the number of EV fires each year has generally increased as the market share of EV cars has increased (as shown in Figure 38).

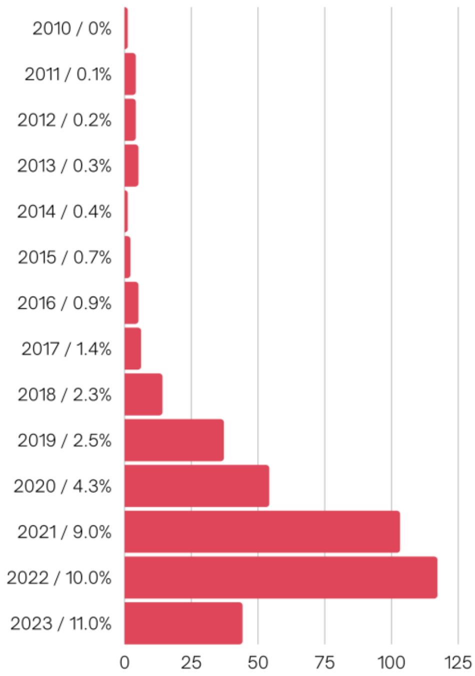


Figure 38: EV fire occurrences per year, and global market share of EVs. Note: 2023 statistics cover half of the year. Reproduced from [172].

Nordic countries, like Norway and Sweden, present one of the largest markets for EVs in the EU. The rescue operation reports database in Norway outlines 45 fires in passenger car EVs between 2016-2018, and from these cases, it was reported that the traction battery was involved in one of the fires. Other key findings about the fire incidents were not recorded i.e., if the EV was charging, the cause of the fire, or if the battery pack was involved [111].

It is acknowledged that as cars age, they are more likely to have a fire. This may be a factor given the oldest mass-produced EVs are only around 13 years old, compared to ICEVs which can be much older. The early research and available data suggests that EVs are less likely to catch fire than ICEVs.

Tesla have also compared the number of fire incidents in their EVs with ICEVs. Tesla's Vehicle Safety Report [173] evaluated data between 2012 and 2021. The frequency of a Tesla EV fire for every number of miles travelled is compared with data from the National Fire Protection Association (NFPA) and U.S

Department of Transportation (DOT). For the period 2012-2021, Tesla Vehicle Fire Data shows that there has been an estimated one Tesla EV fire for every 210 million miles travelled compared with the national average of one vehicle fire every 19 million miles in the U.S., according to the NFPA and DOT.

None of the research considers socio-economic factors associated with ownership of EVs. This is relevant, as EVs to date are generally more expensive than ICEVs. As EVs become more affordable to a wider user group, the frequency of fire incidents and associated consequences of such EV fires may change.

Water run-off

The question of toxicity of water run-off from a suppressed EV fire has previously been raised. Whilst not the primary focus of this literature review, anecdotal and some scientific evidence exists on this topic.

Anecdotally, the fires at Stavanger Airport [60] and the Victorian Big Battery fire [174] can be referred to. Both reports into these incidents found that the level of contaminants in the water run-off was low. However, it should be noted that copious amounts of water were used in both cases.

RISE carried out research on the topic. Hynynen et al. found that "nickel, cobalt, lithium, manganese and hydrogen fluoride appeared in higher concentrations in the effluents from the battery electric vehicle and lithium-ion battery compared to from the internal combustion engine vehicle. However, lead was found in higher concentrations in the effluents from the internal combustion engine vehicle, both in the combustion gases as well as in the extinguishing water" [175].

7.2.1.2 (Plug-in) hybrid electric vehicles ((P)HEVs)

Hybrid electric vehicles (HEVs) are powered by an internal combustion engine and one or more electric motors, which use energy stored in a battery pack. They are of particular interest because that means they possess the previously mentioned risks associated with battery electric vehicles, as well as risks associated with ICEVs (such as plastic fuel tanks and subsequent pool fires, for example). The battery pack, which may itself be an ignition source, is often located close to the battery pack (see Figure 30).

Plug-in hybrid electric vehicles (PHEVs) are considered a sub-set of HEVs, and the same comments as above apply.

In summary, and in agreement with RISE, "there is no evidence that points at EVs being less safe than conventional vehicles" [152].

7.2.1.3 Hydrogen fuel cell electric vehicles (HFCEVs)

Vehicles fuelled by hydrogen are often termed hydrogen fuel cell electric vehicles (HFCEVs). HFCEVs are an emerging technology. They convert gaseous hydrogen fuel into energy through an electrochemical reaction with oxygen. This produces electricity, which powers the electric motor that drives the car [176]. Unlike BEVs, this is a continual process of energy production, as opposed to drawing electricity from a battery.

HFCEVs have benefits such as fast refuelling (approximately five minutes), zero harmful emissions (although the production method of hydrogen is key to its sustainability credentials), and long-range capacity. However, the technology is in its infancy, and there are barriers to widespread adoption.

The uptake of passenger HFCEVs has been slower than previously predicted. In 2022, HFCEVs represented just 0.02% of global passenger vehicle sales with 15,391 units sold compared to 10.5 million battery electric vehicles (BEVs) [177]. In fact, sales of passenger HFCEVs fell globally in 2022.

In Japan – which is generally considered a trailblazer for HFCEVs and is home to two of the largest manufacturers of HFCEVs – the sale of HFCEVs fell from 2,440 vehicles in 2021 to 844 in 2022 [178].

In Australia, there are only a handful of HFCEV fleets, and these are leased vehicles. In 2019, Australian National Hydrogen (ANH) was optimistic about the uptake of HFCEVs [179]. Dr Alan Finkel, who led the ANH strategy in 2019, has recently noted that HFCEVs are not able to compete with BEVs [180]. Australia does have the potential to be one of the world's largest hydrogen producers, however [181]. A local supply of hydrogen may help with future uptake of HFCEVs.

The uptake of passenger HFCEVs faces challenges In all aspects of the supply chain however the economics of hydrogen production is the key hurdle. For HFCEVs to compete with BEVs, significant reductions in cost need to be made. In addition to cost, equipment such as the required infrastructure, and HFCEVs themselves, will need to be more readily available to encourage HFCEV uptake.

Due to the limited number of HFCEVs in use, the development of safety standards is in its infancy and limited research has been conducted on the fire safety of hydrogen fuel cells.

In the European Union (EU), HFCEVs were certified under European Parliament resolution EC 79/2009 until it was repealed in 2022. EC 79 established type approvals for 14 components of the hydrogen energy system which were needed for commercialisation of HFCEVs. In 2022, EC 79 was replaced with ECE R134, which simplified the type approval to only the components around the hydrogen storage system, as well as a type approval for the vehicle itself [182]. The significance of this measure extends beyond the EU, as it was drafted under the United Nations Economic Commission for Europe which is the secretariat for the World Forum for Harmonization of Vehicle Regulations, on which Australia participates. This means that there is mutual recognition of the principles set in the agreement and each party's type approvals are recognised by all the other contracting parties. This is therefore a key step in the development of applicable safety standards for HFCEVs in Australia.

Hydrogen is a colourless, odourless, tasteless, nontoxic, non-metallic, and highly combustible gas. It has a very wide flammable range (4 to 75 % concentration in air), and burns with an almost invisible flame [183]. In HFCEVs, hydrogen fuel cells convert fuel to energy through a reaction between hydrogen gas and oxygen which produces electricity [176]. The key hazards with HFCEVs are vapour cloud explosions (VCEs), low visibility jet flames, and hydrogen tank explosions. An experiment found that a 52 L commercial hydrogen tank exploded at around 80 mPa after heating from a 800-1100 °C fire for 735 seconds, and in such an explosion, the safe distance in an enclosed carpark may be around 20 m [184]. Another experiment involving a HFCEV reported that injury could be expected within 10 m, and structural damage within 3 m [185].

Experiments involving HFCEVs have been conducted. Tramoni et al. burnt a HFCEV, and found that peak temperatures were similar to other fuel types [186]. However, the fuel cells and hydrogen did not become involved in the fire.

Tamura et al. investigated the potential for vehicle-to-vehicle fire spread from a jet fire from a HFCEV. It was found that adjacent vehicles were already ignited by flames from the interior and exterior materials of the HFCEV before the thermal pressure relief device (TPRD) activated and hydrogen combusted [187].

Ulster University completed computational fluid dynamics (CFD) modelling to assess the likely fluid dynamics of an unignited hydrogen release from a 700 bar hydrogen fuel tank within an open-deck carpark, with various orientations of TPRDs. They concluded that smaller TPRD valves (around 0.5 mm) are inherently safe, as the flammable vapour cloud is limited and disperses quickly. However, 'typical' larger TPRDs result in large vapour clouds in short time periods (around 20 seconds) [188]. Other similar studies have been completed [189], such that TPRD design can be as safe as possible.

In summary, HFCEVs are being explored as potential sustainable AFVs, but they are an emerging technology and present in very low numbers in Australia currently.

7.2.2 Liquified petroleum gas (LPG) vehicles

LPG is liquefied-compressed gas (propane/butane). The gas mixture condenses to liquid form when compressed. In LPG vehicles, the propane/butane is compressed in tanks with a normal operating pressure of around 7-10 bar [190], [191].

The significant unique hazard with LPG vehicles is vapour cloud explosions (VCEs). If an LPG tank were to leak at a rapid rate within a carpark, it could cause a large vapour cloud which could then ignite and cause an explosion [192], in a similar way to BEVs and HFCEVs. LPG tanks are also designed with pressure-relief valves which are, themselves, designed to withstand exposure to fire, and mitigate this risk. Such events are therefore very rare.

However, there have been some incidents involving LPG vehicles in buildings. In 1999, an LPG fuel tank exploded as a result of arson near Lyon, France. This particular LPG tank did not have a pressure-relief valve [190]. In 2002, a building collapsed when an LPG-powered vehicle leaked gas into a basement level, which caused an explosion. 39 buildings in a 200 m radius were impacted. The roof of the LPG vehicle was found 150 m from the incident [193]. In 2014, an LPG-powered vehicle in Germany that was experiencing flashover exploded and injured 10 firefighters, five seriously, who were attempting to extinguish the vehicle [194].

If an explosion does occur, it can cause extensive damage. However, numbers of LPG vehicles in Australia are declining significantly. Numbers peaked in 2013 with approximately 500,000 registered LPG vehicles in Australia, but there are now fewer than 200,000 [195]. Whilst this number is still approximately double the number of eVs, it is declining whereas the number of eVs is increasing. Similarly to HFCEVs, the explosion hazard exists for LPG vehicles, but such events are rare in Australia and LPG vehicle numbers are declining.

7.3 Car stackers

Car stackers provide a unique hazard in that fire may not only spread laterally but vertically. Whilst Automated Vehicle Parking Systems (AVPS) have existed for over 100 years [196], there is still very little codified guidance on their design (see Section 3.3). No guidance exists within the NCC. Fire and Rescue Victoria (FRV) "believes that the current DtS provisions pertaining to carpark buildings do not correctly distinguish between the risk of vehicles stored in both a vertical and horizontal storage arrangement" [16].

The Building Research Establishment (BRE) carried out an experiment in 2009 involving two cars located on a car stacker (stacked vertically). A steel-framed stacker with ramps was constructed below the BRE's 9 m hood. The two cars were a 2001 Land Rover and a 2001 Peugeot 406 Estate. "The fire grew rapidly once started and quickly reached the underside of the car above". Fire spread upwards as flames entered the wheel arch and then ignited the tyre of the Peugeot. Simultaneously, the fire grew within the passenger compartment of the lower car whilst growing in the engine compartment of the upper car. The heat release rate had an instantaneous peak of around 8.5 MW at around 12 minutes. The test "demonstrated that an unsprinklered and fast-growing fire in the lower car on a stacker could spread very rapidly to the car above", and showed that "these fires [are] a particular problem for firefighters" [11].

After the first experiment carried out by the BRE, which was unsuppressed, the British Automatic Fire Sprinkler Association (BAFSA) requested BRE to carry out the same experiment, but with sprinklers installed. It should be noted that older cars were used; a 1992 Land Rover and a 2001 Ford Mondeo hatchback.

The sprinkler system was designed and installed by BAFSA to be as compliant with BS EN 12845 incorporating the Loss Prevention Council (LPC)'s rules as possible, however it was noted that the standard provides no guidance for car stackers. Sprinklers were installed on both storeys of the car stacker, with four sprinkler heads positioned to provide coverage to each car (i.e., a sprinkler at each corner). Whilst fire did spread from the ignition vehicle to the second vehicle, the sprinkler system controlled (but did not extinguish) the fire. Temperatures were significantly reduced compared to the first unsuppressed experiment [30].

AVPS allows more vehicles to be stored in a space, as the vehicles can be more closely packed. Drivers park their car at the entrance, and the car stacker moves the car into position, therefore there is no requirement to leave spaces around the vehicles. Thus, the fuel load per unit area is higher than in a traditional carpark. Because of this, and due to the nature of the use of the space, it could be argued that carparks with AVPS are more akin to 'storage' classifications than 'carpark' classifications [196].

Lobel et al. highlight the need for designers of AVPS to consider the shut down procedures upon sprinkler activation or fire detection, noting that pallet movement has the potential to impact the life safety of fire service personnel [196].

Whilst the BRE experiment indicates that sprinklers may be able to control a car stacker fire if properly designed [30], and FRV believe that the best practice to limit exposure from a car stacker fire is sprinklers [16], other suppression systems such as gaseous suppression, hypoxic air systems (particularly for well-sealed underground carparks) and foam-based system may also be feasible [196]. However, research is limited in this space and the authors are unaware of any experimental evidence in support of such systems.

Figure 39 shows the suggested sprinkler arrangement from the FRV and AFAC guidelines [10], [16]. The guidelines also recommend fast response heads, as was the case in the BRE experiment [30]. Since 2017, AS

2118.1 has provided specific requirements for the installation of sprinklers within car stackers, based on the BRE experiment. This has been discussed further in Section 3.3.

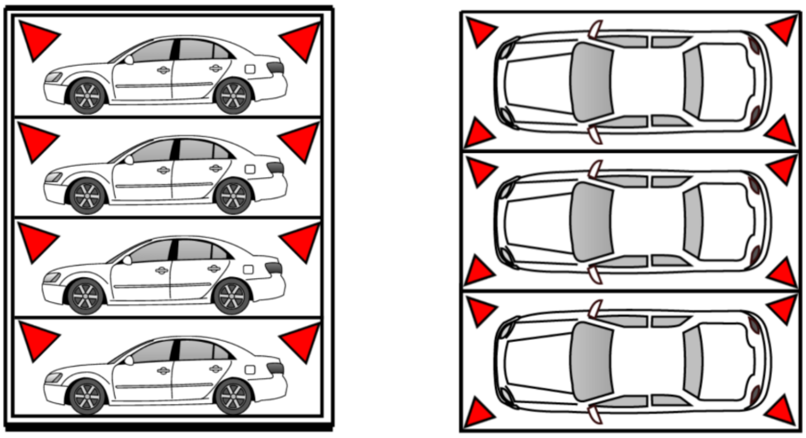


Figure 39: Sprinkler arrangement for AVPS suggested by FRV and AFAC. Reproduced from [16], [30].

If the NCC were to provide specific requirements on car stackers or AVPS, such terms would need to be clearly defined. Future provisions will need to be risk-based. Car stacker events may currently be low likelihood – there are no case studies of large car stacker fires yet, largely due to their relatively limited application so far. However, there may be higher consequences from a fire in a car stacker, as a fire may be more likely to spread between vehicles and become very large. Any requirement for protecting car stackers with a suppression system in future editions of the NCC should be commensurate with the perceived risk, which should be based on the extent and context of their application, to determine the appropriate requirements.

8. Conclusions

Modern day building codes must respond to the challenges of climate change. Particularly within the last decade, a move towards more sustainable construction and transportation methods has materialised. Some of these innovations present unique fire hazards that need to be considered such that buildings can be designed with appropriate fire safety measures. These measures may be contained within the prescriptive provisions of building codes, or be developed by designers to satisfy the Performance Requirements.

Fire safety measures included within the NCC must, amongst other objectives:

- Be appropriate for the risk they mitigate.
- Provide benefit and not be unnecessarily onerous.
- Balance sustainability and fire safety drivers.
- Be able to provide requirements for designers of carparks that incorporate common design aspects such as car stackers. This can be in the form of performance requirements or explicit prescriptive requirements.
- Respond to the drive towards more urbanisation & more multi-level carparks.

The principal findings of this review are:

- Modern vehicles are larger, heavier, use more plastics and therefore have increased quantities of combustible materials when compared to cars manufactured earlier in the 20th century, as documented in Section 7. They're also more likely to have plastic fuel tanks, and leakage of fuel is a common mechanism of fire spread between vehicles.
- Some modern vehicles utilise alternative fuels. This review has covered ICEVs, BEVs, PHEVs, HFCEVs and LPG vehicles. Each fuel type presents its own unique hazards. For example, ICEVs can lead to secondary liquid pool fires remote from the vehicle of fire origin, whereas BEVs can (more rarely) exhibit jet flames. Both of these phenomena can promote fire spread.
- The current body of evidence does not suggest that the fuel type is the most important factor in determining fire severity, rather the size and mass of the car and its components is more important. There are other key conditions which seem to lead to large fire events, namely carparks which are fully occupied, with little spacing between vehicles, and large, deep floorplates and low ceilings.
- The experimental research (described in Section 4) upon which contemporary building codes are still founded, utilised vehicles which were common at the time. Those vehicles are no longer representative of modern vehicles.
- Vehicle fires are not uncommon, but the majority of these occur on the road or after collision rather than while parked as noted within Section 6.
- The commonly cited assumption in fire safety literature from the 20th century is that fire spread between cars is a rare event. This is no longer appropriate for the modern car.
- Recently, a number of large-scale fires have occurred in carparking structures around the world. A sample is documented in Section 5. Some have involved multiple hundred or even over a thousand vehicles and led to large economic losses, many occurring at airports where cars are kept for significant periods of time in large carparks with narrow spacings.
- The life safety impacts of carpark fires are currently relatively very small. The case for improvement of fire safety standards is largely driven by increased protection against low probability, high consequence events or for the improvement of fire-fighter ability to fight fire rather than a systematic improvement of occupant life safety. However, as technology evolves and the uptake of technology increases, there is a need to monitor the statistics periodically and keep this under review.

8.1 Adequacy of the current fire safety provisions within the NCC

Current fire safety requirements in Australia are built upon the assumption that there will be limited fire spread between vehicles, both:

(i) Before suppression in closed carparks and partially-open carparks, and

(ii) Without suppression in open-deck carparks.

This assumption underlies the provisions and concessions within the NCC for fire resistance levels (FRLs) and suppression system requirements. This assumption may underestimate the hazards from a fire in a carpark as Section 7 illustrates.

As documented in Section 3, the fire safety requirements for standalone carparking buildings within Australia are generally on the less conservative side based on the international guidance sampled. In particular, the below elements stand out:

- Permitting limited structural fire resistance (in the form of the ESA/M ratio for steel) for unlimited height open-deck carparks without fire suppression.
- No requirements for sprinklers in open-deck carparks. It is noted it is primarily guidance originating from the USA which explicitly require sprinklers in open-deck carparks.
- No requirements for specific smoke exhaust in enclosed carparking.
- The lack of specific requirements for car-stacking.

As a result, this literature review against the provisions of the NCC, make the following observations. These have been split into categories, but it should be noted that fire safety measures should always be considered as a cohesive whole.

Structural fire resistance

- The ESA/M method seems to remain appropriate for scenarios where the parameters that were tested within the original research are not exceeded (~3 cars simultaneously burning). However, both real world (see Section 5.1) and more recent fire testing findings (documented in Section 4.4) seem to indicate that they can be exceeded given the evolving nature of the modern car (see Section 7) and therefore using the test findings method prescriptively without considering the specific circumstance of the carpark it has been applied to can lead to structural failure in a severe fire event.
- Overall structural fire resistance levels required by the NCC (60 min FRL for open-deck and enclosed with sprinklers) do not appear to be exceeded by fires in recent incidents, although it is noted that this finding does rely on case studies where sprinklers operated effectively in enclosed carparks and therefore there is a reliance that any installed sprinkler systems be maintained regularly against relevant Australian Standards and within a legislative framework of periodic compliance reporting for fire safety measures.
- It is recommended that the ABCB consider whether restricting the use of the ESA/M ratio from open-deck carparks for at least Type A construction is appropriate. Included in this consideration could be the effect of requiring reliable fire suppression in structures that use the ESA/M method (it is noted that an international precedence exists in that NFPA 88A requires sprinklers for similar structural concessions).
- The above consideration could also apply to Type B carparks, however this ultimately depends on what the ABCB deem as acceptable for Type B buildings. Alternatively, continued use of the ESA/M concession may be appropriate (and is consistent with international guidance), given the overall lower rise / consequence of fire in these buildings.

Suppression

- Some jurisdictions now require sprinkler protection in open-deck carparks (the IBC and NFPA standards in the USA in particular). While clearly of benefit for fire life safety and property protection purposes, requirement of a sprinkler system may not represent a justifiable outlay, from both sustainability (in terms of material use and carbon cost) and monetary (cost) perspectives, for all open-deck carparks given the low number of fatalities within such buildings. This would require further detailed review taking into consideration the development of new technologies and frequency of fires as the technology develops.

- There has been limited research undertaken on the subject, but what is present has concluded that the cost is not justified. The research is specific to UK / US statistics so a similar study for the Australian context would be of value. It is recommended that the ABCB evaluate this aspect.
- Similarly, as a fire involving up to 40 cars is a significant event in an enclosed carpark which poses challenges to fire-fighters as well as occupant safety it is recommended that the ABCB consider whether suppression in enclosed carparks having less than 40 cars should be required.
- Anecdotal evidence (from fires and fire testing of modern ICEVs in particular) appears to suggest that water discharge rates of 5 mm/min (or Ordinary hazard as defined by AS 2118) are capable of suppressing fires within modern cars. It is acknowledged that research into this area is not mature and thus needs to be monitored.

Detection and alarm

- The detection provisions within the NCC appear less conservative for open-deck carparks, and more conservative for closed carparks, when compared with international precedent.
- It is noted that there have been a number of cases internationally where lack of alarm connected to fire brigade response has been pointed towards as a source for delayed fire brigade intervention and thus more severe fires.
- The objective benefit of requiring detection and alarm in all carparks (both open-deck and enclosed) could be considered as limited, as there have been no major failures (from a life safety perspective) when analysing the carpark fire events, and smoke detection in carparks could lead to unwanted alarms.
- If sprinklers are mandated in open-deck carparks, they would provide a form of detection without the risk of false activation, although the detection time from sprinklers is generally longer than smoke detectors.
- The ABCB may want to consider whether mandating manual detection in carparks without smoke detection would be prudent.

Egress

- Whilst not the primary focus of this literature review, egress distances and general means of escape provisions within the NCC are comparatively robust and do not appear to warrant a change, as carparks are generally infrequently occupied with low occupancy numbers.
- It is noted that the NCC is perhaps conservative in terms of the DtS provisions, because of the performance-based framework allowing for Performance Solutions, whilst other jurisdictions may not be so open to alternative approaches. It is acknowledged that other codes may be undergoing similar review processes as the NCC. However, there appears to be no evidence to suggest that the egress distances within the NCC are unfit for purpose.
- It is recommended that the ABCB consider tightening Clause D2D12 in terms of the requirements associated with exit discharge. Clause D2D12 (2) states that fire-isolated exits can discharge to a carpark if that carpark is open for at least ⅔ of its perimeter. The BCA Guide (2019) provides an example of such an arrangement, but is not drawn to scale [197]. There may be a DtS-compliant design whereby the ⅔ perimeter openings are remote from the stair exit, thus the area around the stair is effectively enclosed. In such an arrangement, there may be a high consequence event resulting from a fire involving multiple vehicles in that area. However, the fundamental principles behind the clause appear reasonable.

Smoke exhaust in enclosed carparking

- A number of jurisdictions require a form of smoke purging (to assist with firefighting) within enclosed carparks.
- There is limited research available as to the objective benefits of these provisions.

- Modern cars can emit more toxic products but short travel distances and sprinklers in enclosed carparks may mitigate the risk from an occupant life safety perspective. This aspect warrants further review as limited research has been undertaken to date.
- Smoke exhaust is beneficial for firefighting but limited research into the pure merits means that cost to society (sustainability & monetary) is hard to justify based on current research, however this should be studied further. Improvements to increase the resilience of the existing carpark exhaust systems (e.g., fire resistant fans and cabling) provided for day-to-day ventilation may be worthy for the ABCB to explore as part of future studies, considering the changing hazards.

Fire hose reels

- Australia is an outlier in that fire hose reels are mandated as the only option for first aid firefighting. The ABCB may wish to evaluate whether this is the only suitable option, or whether other options (e.g., extinguishers) may be appropriate.
- This topic is not covered in detail in the available literature, however fire hose reels and extinguishers each have respective pros and cons. Fire hose reels provide a continuous water supply, but can encourage occupants to tackle a fire for a longer period, thus potentially exposing them to a more severe fire, which could lead to burns from radiation or inhalation of toxic gases. Portable fire extinguishers, on the other hand, can provide a means for occupants to tackle a fire in its early stages, before encouraging them to escape (once the extinguishant is discharged).

Firefighting water facilities

- This appears to be adequately addressed within the NCC. Any changes in water flow rates to accommodate modern car fuel loads would be expected to be derived from Australian Standards evolution rather than directly required as part of the NCC.

Car stackers

- Rules should be defined for car stackers as there is a clear indication that they change both combustible fuel load density as well as the severity of fire.
- Suppression is frequently required in other jurisdictions for car stackers. It is a consistent recommendation in international guidance and research suggests that suppression should be provided in car stacking systems.
- As noted above, the 40-car concession may not be appropriate for enclosed carparks which use car stackers.

8.2 Gaps in knowledge

This literature review has been based on global sources up to August 2023. Some of the topics covered, such as HFCEVs and autonomous vehicles, are emerging fields. Future research efforts are expected, and the findings in this literature review may require revision as and when new information becomes available.

One of the most fundamental gaps between experimental knowledge and contemporary practice is that of scale. Carpark buildings often have large floor areas (with deep floorplates), at a much greater scale than the experimental research summarised in Section 4. Carparks also typically have low floor-to-ceiling heights, and – as modern cars have increased in size as discussed in Section 7.1.1 – the space between vehicles has consequentially decreased. Built environment professionals (including building designers, developers, and regulatory bodies), must consider this. The dynamics of a fire are likely to vary significantly at such different scales. Conversely to the smaller experiments, where hot combustion gases can escape freely to air, deep floorplates can provide an environment where hot gases have to travel further before venting from the structure. This can lead to preheating of vehicles remote from the fire, which may promote vehicle-to-vehicle fire spread.

The review has distinguished between open-deck carparks and enclosed carparks, which is the current 'status quo' within the NCC and is a position taken generally by international codes. Enclosed carparks could be both above and below ground. Through experience liaising with various brigades, basement carparks can cause unique concerns, as there is no possibility of external application of water, firefighters have to descend below ground meaning there is limited opportunity for external retrieval, and reliance is places on constructed drainage channels as opposed to natural routes. As these are firefighting concerns, it is recommended that the ABCB liaise with firefighters on this item. Some international codes (such as BS 9999) require smoke exhaust systems in basements (regardless of whether the basement is a carpark or other usage).

One common gap that is hypothesised is whether existing Ordinary Hazard sprinkler systems are able to suppress modern car fires, particularly those involves battery packs within BEVs. There is evidence to support concluding that OH sprinkler systems are suitable [26], [73], [74], [167], albeit limited. There isn't evidence to suggest that such sprinkler systems are not able to suppress a modern car fire. Whether additional experimental evidence is required to support sprinkler system design is up for debate, and it may not be the most beneficial or sustainable use of resources.

Whilst outside the scope of this review, the increase in car size and weight may have structural implications, which should be investigated. Similarly, equitable egress, and prescriptive requirements that enable equitable egress may warrant investigation. It is noted that all occupant classes would benefit from equitable egress requirements as this is not isolated to carparks.

Looking forward, modern methods of construction may present new challenges not covered by this literature review. For example, modular construction is becoming more popular, and it lends itself to building disassembly and reuse. Carparks may benefit from such construction methods, particularly if the reliance on the car were to weaken in the future. Other sustainable building design features, such as green walls and mass timber structure, may pose other risks, and guidance should exist on these topics to enable safe, sustainable buildings. For example, carparks may wish to incorporate living façades and/or exposed mass timber structure, which may increase the fuel load and/or promote more rapid fire spread.

Similarly, future carpark designs may change. They may incorporate other spaces such as energy storage systems, or incorporate areas for storing and charging light electric vehicles (LEVs), such as bikes and scooters – these were outside the scope of this review. These aspects of modern carpark design are developing, but would also fall under separate occupant classification within the NCC and are quite difficult to analyse in isolation.

The success of such projects requires holistic fire safety engineering, where multiple design drivers are considered through various lenses, resulting in a well-balanced design outcome. Such an approach would be made easier by more freely-available fire statistics. This would allow cost-benefit assessments to be made. Probabilistic methods, which can allow more informed decision-making, would also benefit from such statistics.

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Appendix A

Search databases and strings

A.1 Search databases and strings

The following table documents the databases searched when carrying out this literature review, and the key words used when formulating search strings.

Table 9: Search databases and strings.

Database	Key words
Google Scholar	+(car or vehicle) +"fire load"
Google Scholar	+(car or vehicle) +"heat release rate"
Google Scholar	BHP steel + carpark*
Informit	BHP steel + carpark*
ProQuest	Parking lot + fire*
ProQuest	Parking + car* + fire
EBSCO	Parking + car* + fire
Google Scholar	Parking + car* + fire
ProQuest	Car stacker* + fire
Google Scholar	Car stacker* + fire
ScienceDirect	Car stacker* + fire
Google Scholar	Electric vehicle* + fire (since 2020)
ProQuest	Electric vehicle* + fire
ScienceDirect	Electric vehicle* + fire
EBSCO	Electric vehicle* + fire
Google Scholar	Carpark* + fire
ProQuest	Carpark* + fire
EBSCO	Carpark* + fire
Google Scholar	Automated + park* + fire
ProQuest	Automated + park* + fire
ScienceDirect	Automated + park* + fire
EBSCO	Automated + park* + fire
Google Scholar	Modern car* + fire
ScienceDirect	Modern car* + fire
EBSCO	Modern car* + fire
ProQuest	Modern car* + fire
ProQuest	(car OR vehicle) AND "fire load" AND ("carpark" or carpark)

Database	Key words
EBSCO	(Car* or vehicle) and “fire load”
EBSCO	(Car* or vehicle) and “heat release rate” and (carpark or “carpark”)
ScienceDirect	(car OR vehicle) AND ("fire load" OR "heat release rate")
ScienceDirect	hydrogen AND fire AND (car OR cars OR vehicle*)
EBSCO	hydrogen AND fire AND (car OR cars OR vehicle*)
ProQuest	hydrogen AND fire AND (car OR cars OR vehicle*)
Google Scholar	+hydrogen +fire +(car OR cars OR vehicle*)
ScienceDirect	Structural AND fire AND (carpark OR carpark)
ScienceDirect	Steel AND fire AND (carpark OR carpark)
EBSCO	Structural AND fire AND (carpark OR carpark)
EBSCO	Steel AND fire AND (carpark OR carpark)
Google Scholar	Structural AND fire AND (carpark OR carpark)
Google Scholar	Steel AND fire AND (carpark OR carpark)
Google Scholar	+"carpark" +fire +injury
Google Scholar	+"carpark" +fire +fatality
EBSCO	"carpark" AND fire AND (injur* OR fatal*)
ScienceDirect	"carpark" AND fire AND (injury OR injured OR injuries OR fatal OR fatality or fatalities)
ProQuest	Structural AND fire AND (carpark OR carpark)
ProQuest	Steel AND fire AND (carpark OR carpark)
ProQuest	Electric Vehicle + fire + chargepoint
ProQuest	Electric Vehicle + fire + carpark
ProQuest	Electric Vehicle + fire + charging
ProQuest	Vapour cloud explosion + electric vehicle + lithium + battery
ScienceDirect	Carpark + fire
ScienceDirect	Electric Vehicle + charging + carpark
ScienceDirect	Electric Vehicle + fire + charging + carpark
ScienceDirect	Vapour cloud explosion + electric vehicle + lithium + battery
World Electric Vehicle Journal	Fire
EBSCO	Electric Vehicle + fire
EBSCO	Vapour cloud explosion + electric vehicle + lithium + battery

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