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Real Fires: Open-sided car park fire resistance

Final report

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Quality Management

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Contents

1.	Introduction	6
2.	Summary of work packages	7
2.1	Overview	7
2.2	WP 1A – Review of vehicle fire spread in car parks	7
2.3	WP 1B – Quantitative assessment of fire spread in car parks.....	8
2.4	WP 2 – Monte Carlo fire severity assessment	9
2.5	WP 3A – Determination of occupant loads of car parks	9
2.6	WP 3B – Lifetime cost optimisation (LCO) study	10
3.	Conclusions and further work	11
3.1	Conclusions	11
3.2	Further work	11
4.	References.....	12
Appendix A	- WP 1A	
Appendix B	- WP 1B	
Appendix C	- WP 2	
Appendix D	- WP 3A	
Appendix E	- WP 3B	

List of Figures

Figure 1. Example output distributions from WP 1B showing number of bays ignited, maximum heat release rate and mean spread rate for 2.5 m floor-to-ceiling height and 80% space utilisation	8
Figure 2. Time equivalence vs cumulative probability in function of (left) space utilisation, (centre) floor-to-ceiling height, and (right) internal air speed	9

List of Tables

Table 1. Sample results from WP 3B – Lifetime optimal fire resistance ratings with and without sprinklers, assuming 100% utilisation	10

1. INTRODUCTION

OFR Consultants were engaged by the Department for Levelling Up, Housing and Communities (DLUHC) to deliver the “Real Fires” project (CPD/004/122/039) in support of fire safety technical policy, which commenced on 22nd of October 2021. The contract was subsequently novated to the Building Safety Regulator (BSR), formed within the Health & Safety Executive (HSE). As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations from real fires. Through this mechanism, OFR were engaged to undertake research on the structural fire resistance for purpose-built open-sided car parks.

The BSR stated that the research project was to be organised to generate data and evidence on the fire resistance ratings in car parks to support the BSR’s understanding of the level of safety in existing and new buildings, along with an analysis of options coupled with their respective supporting information to shape policy decisions. OFR proposed that this focus on above ground, purpose-built, open-sided multi-storey car parks.

To deliver on the requirements, OFR considered three sub work packages (WPs) to be necessary, which are summarised below:

- WP 1: Investigation of fire spread rates and extents in open sided car parks. This work package was split into two parts. The first involved a literature review of fire spread in car parks alongside the development of empirical fire spread models (WP 1A). The second concerned the development of a cellular automata model that generates fire spread scenarios for open-sided car parks (WP 1B).
- WP 2: Monte Carlo fire severity analysis to investigate the probability of failure of structural elements subject to different fire resistance / protection solutions.
- WP 3: Lifetime cost-optimisation analysis for different fire resistance / protection solutions to establish the optimal safety level considering sensitivity to life safety, property protection and business continuity goals. This work package was also split into two parts. The first determined car park occupant loads which are essential for estimating potential casualties in the event of fire induced structural failure (WP 3A). The second undertook the lifetime cost-optimisation (LCO) analysis to review which potential policy interventions provided the best return on investment (WP 3B).

This final report summarises the work carried out and describes how the various work packages are interlinked to generate the research findings. Each work package report is then separately appended.

2. SUMMARY OF WORK PACKAGES

2.1 Overview

The project comprises five deliverables in total, split across the three work packages outlined in Section 1. Each work package contributes towards the ultimate task of recommending fire resistance periods for purpose-built open-sided multi-storey car parks and was informed by OFR's investigations as to their historical origins [1]. Figure 1 shows the work packages, the associated deliverables and their interactions.

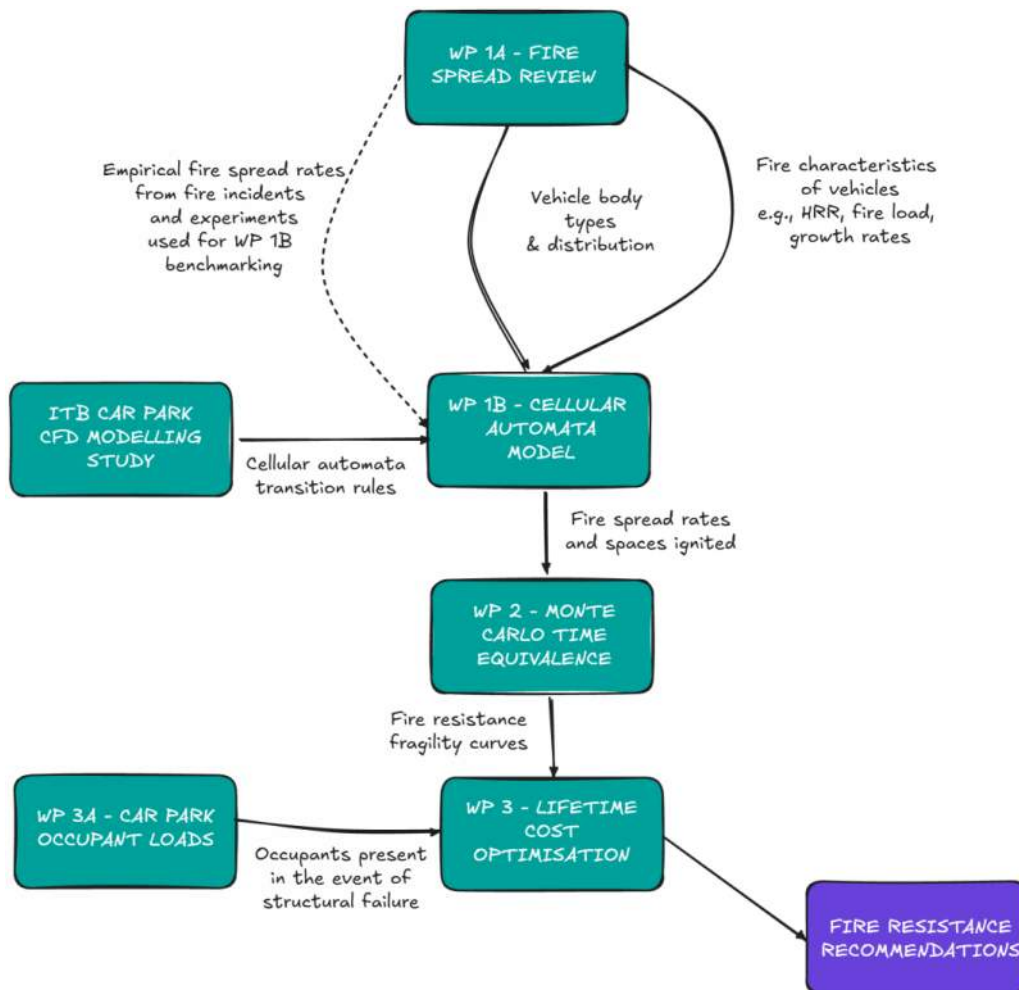


Figure 1. Project overview showing deliverables and their interactions

An overview of each work package is provided in the sections that follow.

2.2 WP 1A – Review of vehicle fire spread in car parks

Part A of WP 1 carried out an assessment of the types of private passenger vehicles (i.e. cars) on the road across the UK, using information on the history of vehicle registrations. This was followed up with a concise review of recent findings concerning the fire characteristics of passenger vehicles. This included studies by Miechówka and Węgrzyński [2] which included design fire parameters and their percentiles for both internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs). Subsequently, the report explores methods for quantifying fire spread within car parks by examining both laboratory test data and information gathered from real-world car park fires. Three empirical models are proposed to conservatively estimate the number of vehicles involved in a car park fire as a function of time.

Findings from WP 1A were used to inform the cellular automata (CA) modelling approach discussed in WP 2. WP 1A was also used to provide input data and benchmark the fire spread results from the CA simulations presented in WP 2. Although the empirical models generated some interesting results when compared to findings from selected incidents identified in the literature review the models were not used as part of the lifetime cost estimation presented in WP 3.

2.3 WP 1B – Quantitative assessment of fire spread in car parks

The work undertaken in WP 1B explored fire spread mechanisms in open-sided car parks through detailed computational fluid dynamics (CFD) modelling and a comprehensive cellular automata (CA) study, including both parametric and Monte Carlo simulations. The CFD analysis highlighted the significant role of ceiling geometry, demonstrating that structural bay effects can channel smoke and flames along beam spans, thereby extending ceiling jet lengths and promoting faster downstream spread. Variations in heat release rates, ceiling height, and internal air movement were shown to influence incident heat fluxes to adjacent vehicles, with increased ceiling heights and higher wind speeds generally reducing the likelihood of ignition downstream. These findings informed the development of transition rules used within the CA modelling.

The parametric CA study confirmed that vehicle heat release rates and car park utilisation were the dominant factors governing both the extent and rate of fire spread. High utilisation levels led to markedly higher spread rates, peak fire sizes, and numbers of vehicles involved. The initiating vehicle fire size also exerted an influence, although this effect diminished once variability in fire characteristics across the car park was introduced. Internal air velocities generated by external wind and ceiling height were found to have secondary yet measurable impacts, with higher air speeds and increased ceiling heights tending to reduce spread rates.

The Monte Carlo simulations provided a more representative assessment by incorporating uncertainty in vehicle fire characteristics (example outputs provided in Figure 2).

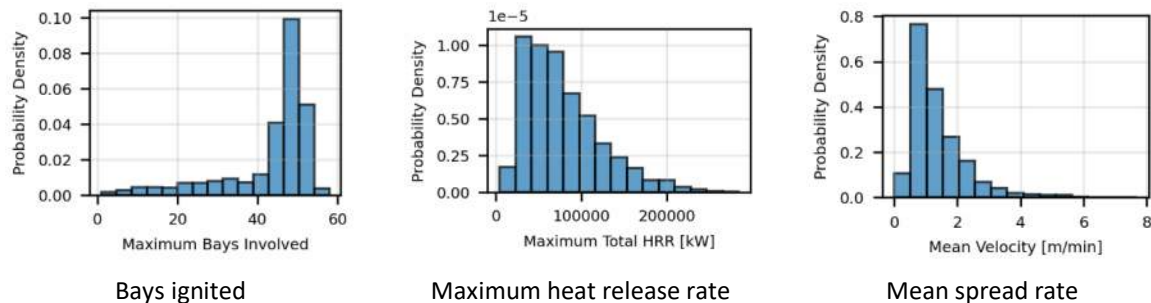


Figure 2. Example output distributions from WP 1B showing number of bays ignited, maximum heat release rate and mean spread rate for 2.5 m floor-to-ceiling height and 80% space utilisation

Utilisation again emerged as the principal driver of fire spread, with high-occupancy scenarios resulting in substantial proportions of vehicles becoming involved. Increased ceiling height and internal air speed reduced spread rates and peak fire sizes owing to the higher heat release rates required to achieve critical ignition thresholds under these conditions. The study also demonstrated the influence of unoccupied spaces in limiting fire propagation.

Comparison of modelled spread rates with data from experimental studies and real fire incidents showed good alignment, with predicted ranges corresponding well to documented events at locations such as Stavanger, Schiphol, Luton, and the Link apartments (discussed in WP 1A). This supports the validity of the modelling approach adopted.

The distributions derived for spread rates and number of cars ignited from WP 1B inform WP 2, where they are used within a probabilistic fire severity assessment framework to determine structural reliability under burnout conditions.

2.4 WP 2 – Monte Carlo fire severity assessment

Work Package 2 builds upon the fire dynamics established in WP 1B to assess the structural implications of fires in open-sided car parks. The work adopts a probabilistic, time-equivalence methodology to determine the likelihood of structural failure for a typical protected steel beam, taking account of uncertainties in fire spread, fire size, and car park operating conditions. A Monte Carlo simulation framework was used [3] to represent the full statistical range of input variables, including utilisation, ceiling height, and internal air speed.

Several assumptions underpin the analysis, including the use of a generic car park layout, the exclusion of active suppression systems, and the focus on a single structural element type. These allow a consistent basis for comparison, although they limit the direct applicability of the results to more complex layouts or alternative structural systems.

The findings (see Figure 3) demonstrate that ceiling height is an influential factor in determining fire severity, with modest increases resulting in reductions in the probability of extended fire spread and lower time-equivalence values. Car park utilisation also plays a significant role, with higher occupancies consistently associated with more onerous fire conditions. Internal air speed was found to exert a mitigating effect by inhibiting vehicle-to-vehicle spread. Across the parameter space considered, a fire resistance period of 90 minutes provides a high level of reliability, covering all but the most extreme fire intensity scenarios; however, such a specification must be viewed in the context of whole-life cost considerations, which were explored further in WP 3B.

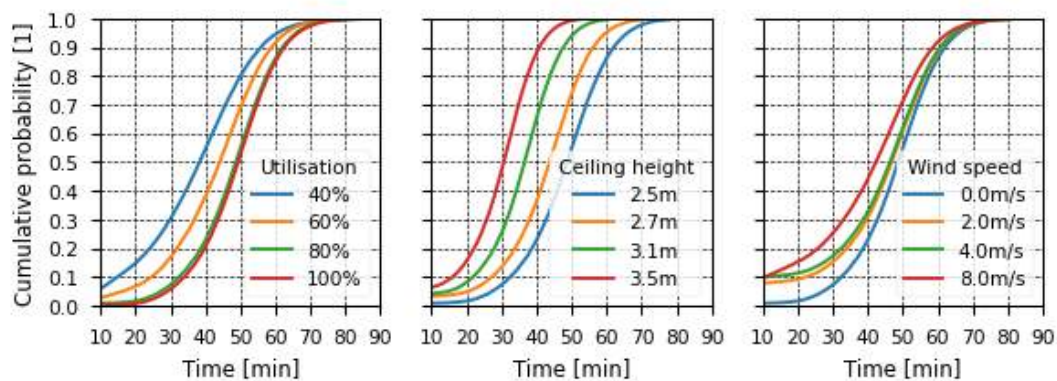


Figure 3. Time equivalence vs cumulative probability in function of (left) space utilisation, (centre) floor-to-ceiling height, and (right) internal air speed

The probabilistic distributions generated in WP 2 form the principal technical input to WP 3B, where they support a cost-benefit assessment of different fire resistance periods.

2.5 WP 3A – Determination of occupant loads of car parks

Work Package 3A explored the theoretical and empirical bases for determining occupant loads in car parks, highlighting methods recommended by international standards, as well as common practical approaches adopted in different jurisdictions. Calculations are presented for car park occupant load that consider situations in which all parked cars are occupied simultaneously (referred to as a static parking approach) or situations in which there is a flow of cars and people entering and leaving a car park (referred to as a dynamic parking approach). Design values for persons per bay have been determined for static and dynamic parking using 99th percentiles from distributions using Monte Carlo analysis.

The findings from WP 3A have been used to assess the number of people that would be in a car park at the time of a fire starting. The initial number of occupants was used to determine the number of people that might be subject to the hazard posed by a collapse of the building structure as part of the lifetime cost analysis undertaken in WP 3B.

2.6 WP 3B – Lifetime cost optimisation (LCO) study

Work Package 3B examines the lifetime cost-optimisation of fire safety measures for open-sided car parks, focusing on three reference cases broadly aligned with the layout and scale of Luton Airport's Terminal Car Park 1. These four-, eight- and twelve-storey cases represent large, purpose-built structures at the upper end of typical design practice, providing a conservative basis for evaluating the relative benefits of structural fire resistance and sprinkler protection. Current guidance would recommend 15 minutes of structural fire resistance for the lower-rise scenarios and 60 minutes for the twelve-storey case, with no recommendation for sprinklers.

The analysis draws on data from earlier project stages, including occupancy characteristics (WP 3A), fire spread behaviour (WP 1B) and structural failure probabilities (WP 2). The latter shows that highly utilised car parks can sustain severe fires capable of involving extensive areas, leading to relatively high failure probabilities at lower levels of fire resistance. As a result, meaningful reductions in failure likelihood generally require a minimum effective increase in passive protection. Cost inputs for intumescent coatings and Ordinary Hazard Group 2 sprinkler systems were used to assess the most viable interventions.

A simplified structural limit state was adopted in which an element is assumed to fail if exposed to thermal loading beyond its equivalent fire resistance rating. Failure probabilities were annualised over a 25-year design life using appropriate discounting, enabling the comparison of future uncertain losses with upfront intervention costs. Potential casualty impacts were incorporated using the life quality index and the Societal Capacity to Commit Resources (SCCR), with sensitivity studies undertaken to reflect uncertainties in occupancy at the point of failure. While the historical record indicates very few instances of fire-induced collapse and no known fatalities in UK car parks, the analysis recognises the potential for rare, high-consequence events.

For the base case of full utilisation, the lifetime optimisation results indicate high optimal structural fire resistance values driven primarily by the costs associated with reconstruction, loss of contents and disruption, rather than by casualty-related impacts alone (see Table 1). Sensitivity studies showed limited variation in the optimal fire resistance when utilisation or the SCCR were adjusted. When sprinklers were introduced, the combined strategy produced different optimal resistance values across the three building heights, and in some cases no optimum was identified where intervention costs outweighed the expected reduction in future losses.

Table 1. Sample results from WP 3B – Lifetime optimal fire resistance ratings with and without sprinklers, assuming 100% utilisation

Number of storeys	25-year optimal structural fire resistance [min]	
	Without sprinklers	With sprinklers
Four	65	18
Eight	69	51
Twelve	76	59

To complement the optimisation outputs, a J-Value assessment [4] compared the benefit-to-cost ratios of different interventions. Across all three building heights, increasing structural fire resistance to approximately 60 minutes provided the most favourable balance between safety benefit and cost, with ratios demonstrating significant returns relative to current policy expectations / recommendations. For the four- and eight-storey cases, sprinkler protection combined with 15 minutes of structural resistance offered a broadly comparable benefit-to-cost ratio, while the twelve-storey case also exhibited a positive return when sprinklers were included.

Several contextual considerations remain. Large car parks may benefit from economies of scale that improve the cost-effectiveness of sprinkler installation, whereas smaller or rural car parks may face proportionally higher installation and water supply costs. Steel-framed structures experience direct increases in cost when higher fire resistance is specified, whereas concrete frames may accommodate higher ratings with less financial impact. The potential loss of parking spaces due to sprinkler installation, and the associated revenue implications, has not been included but could influence overall feasibility.

3. CONCLUSIONS AND FURTHER WORK

3.1 Conclusions

The findings of this study highlight a broader question that falls outside the scope of this project to resolve: whether priority should be given to the option that is demonstrably optimal over the life of the building, or to the measures that deliver the greatest improvement in safety relative to their cost. As demonstrated in WP 3B, these two perspectives do not always coincide, particularly in the case of sprinklers. For the four- and eight-storey reference cases, sprinkler protection can achieve a comparable safety gain for its cost to that achieved by increasing structural fire resistance to 60 minutes when measured against current policy expectations. However, when considering the balance between upfront investment and the reduction in long-term damage costs, higher levels of passive protection may be justified alongside sprinkler protection.

A cautious alignment between the lifetime cost-optimisation analysis and the J-Value assessment in WP 3B suggests that enhanced passive fire protection represents a reasonable intervention, with an indicative range of approximately 60 to 75 minutes depending on the scale of the car park. This range strikes a balance between initial expenditure and lifetime damage reduction while also offering a favourable benefit-to-cost ratio relative to existing policy recommendations. It is additionally consistent with recent industry guidance published by the Institution of Structural Engineers [5].

3.2 Further work

The analysis makes certain assumptions regarding the fire load arising from the presence of the cars. WP 1A includes an assessment of the population of vehicles on UK roads in term of car body size but this has not been used to extend an analysis to the impact on fire load. Further work could be carried out to determine fire load similar to the work carried out by Spearpoint et al. [6] on New Zealand car parks. A revised study could investigate if and how the presence of electric vehicles has any measurable impact and could also consider how future changes in the car population of the UK might change the analysis.

The LCO study includes a measure of the potential benefit on installing a sprinkler system to OH2 classification. Partly in response to the changes in car park fire load and also the growth in the use of EVs, hazard classifications such OH3 and HHP3 are also recommended for car parks in guidance. Therefore, it would be informative to consider the potential costs and benefits of installing systems to these classifications. Work could include a review of the performance of sprinkler suppression in car parks. In addition OFR have previously proposed a series of full-scale sprinkler tests using a EV as the source to further understand the performance of sprinkler systems to OH3 and HHP3.

Finally, WP 3A has highlighted that current design occupancy figures for car parks in Approved Document B are highly conservative. A study could be undertaken to review the implications of WP 3A on means of escape provisions in car parks.

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Appendix A – WP 1A



CPD/004/122/039

Real Fires: Open-sided car park fire resistance

WP 1A: review of vehicle fire spread in car parks

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Quality Management

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Contents

1.	Introduction	7
1.1	Appointment	7
1.2	Overview of the deliverable	7
2.	Vehicles on UK roads and their fire characteristics	9
2.1	Car registrations in the UK by body type.....	9
2.2	Rationalisation of car body types for future analysis	12
2.3	Burning characteristics	12
2.4	Treatment of ICEV vs BEV drivetrains in this research project.....	13
3.	Method for assessing fire spread in car parks	15
3.1	Fire spread mechanisms	15
3.2	Fire spread in laboratory tests	17
3.3	Fire spread in real incidents.....	18
4.	Review of laboratory-based tests	20
4.1	BHP	20
4.2	Joyeux	21
4.3	Kitano et al.	22
4.4	Steinert	23
4.5	Building Research Establishment (BRE).....	24
4.6	Li et al.....	25
4.7	Park et al.	26
4.8	Tramoni et al.	26
4.9	Elbas project.....	27
4.10	Other work	28
5.	Review of specific fire incidents.....	29
5.1	Schiphol Airport, Netherlands, 2002.....	29
5.2	Lloydstraat, Netherlands, 2007.....	31
5.3	Kings Dock, England, 2017	33
5.4	Stavanger airport Sola, Norway, 2020	36
5.5	Open-air car park, China, 2020	37
5.6	London Luton Airport, England, 2023	38
5.7	Link apartments, USA, 2025.....	39
6.	Discussion and analysis of car park fire spread	43
6.1	Second vehicle ignition.....	43
6.1.1	Time analysis	43
6.1.2	Separation fire spread rate	44
6.1.3	Electric vehicles	45
6.2	Analysis of multiple vehicle spread	46

6.2.1	Key characteristics	46
6.2.2	External wind.....	48
6.2.3	Floor-to-ceiling height.....	50
6.2.4	Fire spread rate considering vehicle drivetrain	51
6.2.5	Transition to multi-dimensional spread	52
6.3	Fire spread models	53
6.3.1	Wind-aided spread	53
6.3.2	Burning area	53
6.3.3	Three stage model	54
6.3.4	Comparison	55
7.	Conclusions	60
8.	References.....	62

List of Figures

Figure 1.	Calculated distribution of car body type by the end of 2024.....	11
Figure 2.	Illustration of directional and dimensional fire spread along and between rows of vehicles.....	16
Figure 3.	Vehicle arrangement during the BHP open-deck car park ad-hoc tests.....	20
Figure 4.	Number of vehicles involved in the BHP tests based on estimated ignition times.....	21
Figure 5.	Arrangement of cars and ignition times, taken from Kitano et al.....	22
Figure 6.	Simplified spread rate model based on experimental observations of Kitano et al.	23
Figure 7.	Rig dimensions and car layout in BRE Tests 1, 2 and 3	24
Figure 8.	Number of vehicles involved in the BRE tests based on estimated times to ignition	25
Figure 9.	Photograph of the experiment involving two cars at around 500 s, taken from Park et al.	26
Figure 10.	Vehicle and experimental layout used by Tramoni et al.	26
Figure 11.	Test arrangement used in the ELBAS project	27
Figure 12.	Contemporary images of the elevation of the Schiphol Airport car park taken from Google Streetview	29
Figure 13.	Aerial views of the Schiphol Airport car park	30
Figure 14.	Estimated number of vehicles involved in the Schiphol Airport car park fire incident	31
Figure 15.	Google Streetview images of the Harbour Edge residential building from c. 2009 with the entrance to the car park shown on the right.....	31
Figure 16.	Arrangement of vehicles at the time of the Lloydstraat car park fire incident.....	32
Figure 17.	Estimated number of cars ignited / burning in the Lloydstraat car park fire incident	32
Figure 18.	Images taken from the presentation by Ged Knock (MFRS) to Engineers Ireland	33
Figure 19.	BA crew entry from stairwell, primary wind direction and estimated spread of fire at around 17:0834	
Figure 20.	Level 3 car park layout showing location of the initiating vehicle and estimated area of fire spread over 30 vehicles.....	35
Figure 21.	Estimated number of vehicles involved over time in the Kings Dock car park fire	36
Figure 22.	Photograph of the initial car alight showing vehicle parking arrangement in a double row	36
Figure 23.	Estimated number of vehicles involved in the incident over time in the Stavanger airport Sola car park fire.....	37
Figure 24.	Fire in an open-air car park	38
Figure 25.	Car park employee digital image of the first vehicle that ignited and spread to a neighbouring vehicle	38
Figure 26.	Estimated number of vehicles involved over time in the Luton Airport car park fire	39
Figure 27.	External view of the Link apartments car park.....	40
Figure 28.	Vehicles burning during the Link apartments parking garage fire	40
Figure 29.	Images from the fire in the Link apartments car park with vehicles numbered for identification	42

Figure 30. Time to second vehicle ignition as a function of separation distance	44
Figure 31. Separation fire spread rate as a function of separation distance	45
Figure 32. Still image taken from a security camera video of spread of fire to a neighbouring vehicle following thermal runaway of a battery	46
Figure 33. Number of vehicles involved in the car park fire tests and incidents	47
Figure 34. Fire spread rate with elapsed time of the fire (a) laboratory tests, (b) incidents	48
Figure 35. Variation in total vehicle spread exponent with external wind speed	49
Figure 36. Change in linear fire spread rate with external wind speed	49
Figure 37. Variation in vehicle spread exponent with car park floor-to-ceiling height	50
Figure 38. Variation in vehicle fire spread rate with car park floor-to-ceiling height	51
Figure 39. Illustration of a two-way fire spread scenario from a single vehicle within a row to neighbouring vehicles and adjoining rows	52
Figure 40. Comparison between test and incident data and the three vehicle-to-vehicle fire spread models at 0 m/s external wind speed	55
Figure 41. Comparison between test and incident data and the three vehicle-to-vehicle fire spread models at 4.3 m/s external wind speed	56
Figure 42. Comparison between test and incident data and the three vehicle-to-vehicle fire spread models at 12 m/s external wind speed	57
Figure 43. Estimated number of vehicles involved compared with the three empirical fire spread models for Stavanger airport	57
Figure 44. Estimated number of vehicles involved compared with the three empirical fire spread models for Lloydstraat car park	58
Figure 45. Estimated number of vehicles involved compared with the three empirical fire spread models for Luton Airport	58

List of Tables

Table 1. UK new car registrations by body type by year and total / SORN vehicles by year [ref]	10
Table 2. Estimated car body type number year-on-year from 2013 to 2024	12
Table 3. Proportion of cars on the road by rationalised size classification	12
Table 4. Comparison of key burning characteristics	13
Table 5. Summary of fire development characteristics for ICEV vs BEV drivetrains	14
Table 6. Typical modern vehicle sizes	17
Table 7. Chronological summary of multiple vehicle fire tests investigated in this study	18
Table 8. Chronological summary of multiple vehicle fire incidents investigated in this study	19
Table 9. Summary of experimental parameters	21
Table 10. Time for secondary ignition	22
Table 11. Summary of test parameters from Steinert	23
Table 12. Summary of experimental data from Tramoni et al.	27
Table 13. Estimated time of vehicle ignition and fire spread rate	32
Table 14. Summary of second vehicle characteristics	43
Table 15. Summary of key characteristics involving multiple vehicle fire spread	47

1. INTRODUCTION

1.1 Appointment

OFR Consultants were engaged by the Department for Levelling Up, Housing and Communities (DLUHC) to deliver the “Real Fires” project (CPD/004/122/039) in support of fire safety technical policy, which commenced on 22nd of October 2021, and will run until the 28th September 2025. The contract has since been novated to the Building Safety Regulator (BSR), formed within the Health & Safety Executive (HSE). As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations from real fires. Through this mechanism, OFR have been engaged to undertake research on the structural fire resistance for purpose-built open-sided car parks.

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To deliver on the requirements, OFR considered three sub work packages (WPs) to be necessary, which are summarised below:

- WP 1: Investigation of fire spread rates and extents in open sided car parks.
- WP 2: Monte Carlo fire severity analysis to investigate the probability of failure of structural elements subject to different fire resistance / protection solutions.
- WP 3: Lifetime cost-optimisation analysis for different fire resistance / protection solutions to establish the optimal safety level considering sensitivity to life safety, property protection and business continuity goals.

This report forms part of the deliverable for WP 1 (WP 1A), providing a literature review and analysis of fire spread rates in car parks based on real fire incidents and experiments reported in the literature.

1.2 Overview of the deliverable

The spread of fire within car parks is influenced by several factors, including the proportion of parking bays occupied by vehicles, the spacing between vehicles, and the fire growth characteristics of the cars themselves. Determining the number of vehicles likely to become involved in a fire and the speed of this involvement often requires modelling. The accuracy of such models, however, necessitates benchmarking against real-world data obtained from laboratory tests or actual fire incidents.

This report begins with an assessment of the types of private passenger vehicles (i.e. cars) on the road across the UK, using information on the history of vehicle registrations. This is followed up with a concise review of recent findings concerning the fire characteristics of passenger vehicles. Subsequently, the report explores methods for quantifying fire spread within car parks by examining both laboratory test data and information gathered from real-world car park fires. Three empirical models are proposed to conservatively estimate the number of vehicles involved in a car park fire as a function of time.

The data presented in this report supports the primary project objective of establishing appropriate fire resistance ratings for the structural elements of open-sided car parks. This consideration necessitates determining:

- The current and anticipated distribution of car body type and drivetrain categories on UK roads (and consequently in England). This understanding is important as different car types may exhibit varying fire behaviours due to differences in materials, design, and fuel load,
- The relevant characteristic burning parameters for these distinct car types. These parameters, such as heat release rate and total energy content, are essential inputs for fire modelling, and

- The appropriate fire spread rate to employ when modelling car park fires as travelling fires. This is particularly important for understanding how a fire might propagate across multiple vehicles.

For the purpose of this report, the terms 'car' and 'vehicle' are used interchangeably to refer to private passenger vehicles.

2. VEHICLES ON UK ROADS AND THEIR FIRE CHARACTERISTICS

2.1 Car registrations in the UK by body type

The UK Government does not appear to collate and publish consolidated statistics on the types of vehicles using UK roads and, thus, purpose-built car parks. Statistics are available in terms of the total numbers of cars registered through the tax system¹. In June 2024, there were ca. 33 million registered cars in the UK. This increased from ca. 30.5 million in 2014.

Each year, vehicles are declared as taken off the road, i.e., Statutory Off Road Notification (SORN). In 2024 this figure was ca. 3.6 million, which has progressively increased from ca. 1.6 million in 2014. Not all vehicles declared SORN, however, are removed from the roads in practice as some are driven without tax.

Statistics are collated by trade bodies in terms of new car sales, which for some sources are broken down by car body type. These are summarised by year in Table 1. For completeness the total number of UK car registrations and cars declared SORN are also shown by year.

The ca. 10-year trends suggest an increase in the use of SUV vehicles, which have progressively taken the market share previously occupied by large family hatchbacks/saloons, executive cars, luxury saloons and MPVs.

Table 1 gives some insight into the evolving UK car stock, with increasing emphasis on SUVs. However, the figures describe year on year new registrations and therefore cannot be taken in isolation to reflect the current distribution of car body types.

Noting that ca. 30.5 million private cars were registered in 2013 and that the accumulated vehicles declared SORN between 2014 to 2024 was ca. 31 million, it can be assumed that the typical service life of a UK vehicle is ca. 10 years. This makes the idealisation that vehicles SORN are typically those reaching the point of being scrapped when in practice vehicles may be SORN for other reasons, such as road traffic accidents, i.e., the typical service life of a vehicle is most likely greater.

¹ Vehicle licensing statistics data tables, www.gov.uk/government/statistical-data-sets/vehicle-licensing-statistics-data-tables#all-vehicles

Table 1. UK new car registrations by body type by year and total / SORN vehicles by year¹

Body type	Percentage of new registrations (%)											
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
A - Mini (city car)	3.60	3.40	2.70	2.90	2.70	2.40	1.80	0.80	1.00	0.80	0.70	0.8
B - Supermini	35.9	35.7	35.2	32.4	29.5	30.8	29.7	31.2	31.2	30.4	29.8	27.5
C - Lower medium (small family hatchback/saloon)	26.0	26.1	27.2	27.3	28.7	27.9	27.4	28.0	27.3	27.7	28.2	26.7
D - Upper medium (large family hatchback/saloon)	9.2	9.2	9.5	9.5	9.6	8.1	7.3	6.4	6.4	7.0	6.1	6.1
E - Executive	5.3	4.9	4.8	4.8	4.8	4.6	4.1	2.8	2.0	1.7	1.3	1.3
F - Luxury saloon	0.4	0.4	0.3	0.4	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0.2
G - Dual purpose (SUV)	11.0	11.8	13.5	16.3	18.1	21.2	24.3	25.4	26.9	27.0	28.6	32.6
H- MPV	6.7	6.7	5.0	4.7	4.4	3.1	3.2	2.4	1.6	3.8	3.6	3.9
I - Sports cars	2.1	1.7	1.9	1.9	1.9	1.6	1.9	2.9	3.4	1.4	1.6	0.9
Vehicles	Vehicles by year (millions)											
Total	30.5	30.5	31.2	31.8	32.2	32.5	32.9	32.7	32.9	33.2	33.6	33.9
SORN	NA	1.59	1.94	2.29	2.56	2.74	2.98	3.26	3.30	3.41	3.63	3.63

To develop an estimate of the distribution of car body types in 2025, several steps and associated assumptions are made:

1. That the 30.5 million vehicles registered in 2013 were distributed according to the body types newly registered in the same year.
2. That each year, an amount of the original 30.5 million vehicles registered in 2013 are removed from use and are replaced by new vehicles with distribution of body types new registered in that year. For example, in 2014, 1.59 million vehicles are removed from the 30.5 million on the road in 2013. These are replaced by 1.59 million vehicles distributed according to the 2014 body type sales figures. In

2015, a further 1.94 million vehicles are removed from the original 30.5 million on the road in 2013. These are replaced by a further 2.64 million vehicles distributed according to the 2015 body type sales figures, i.e., resulting in 31.2 million vehicles on the road in 2015. This procedure continues through to the end of 2024.

3. At the end of 2024, the distribution of vehicles by body type reflects the previous 10 years of sales, influenced by the year-on-year quantum of vehicles declared SORN.

Figure 1 shows the calculated distribution of car body types at the end of 2024, based on steps 1. to 3. above. Much like the sale trends, the increase in SUVs relative to 2013 figures is apparent. Table 2 shows the calculated year on year evolution of the number of cars by body type in the UK.

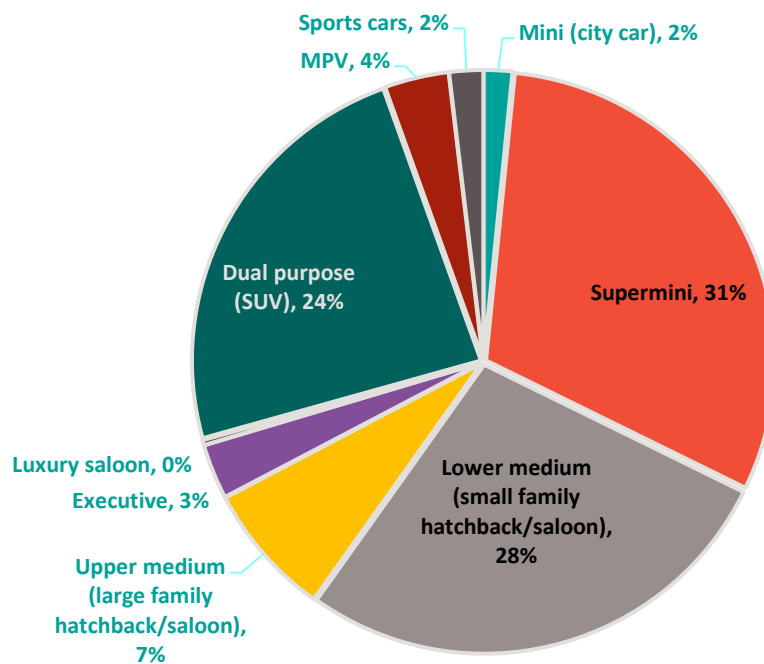


Figure 1. Calculated distribution of car body type by the end of 2024

Table 2. Estimated car body type number year-on-year from 2013 to 2024

	UK cars by body type (millions)											
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
A	1.10	1.10	1.10	1.10	1.08	1.06	1.01	0.92	0.84	0.74	0.64	0.54
B	10.9	11.0	11.2	11.3	11.2	11.2	11.1	10.9	10.8	10.7	10.6	10.4
C	7.93	7.94	8.14	8.34	8.51	8.66	8.81	8.82	8.91	9.05	9.24	9.37
D	2.81	2.81	2.88	2.94	2.99	2.98	2.96	2.85	2.77	2.72	2.63	2.54
E	1.62	1.61	1.63	1.65	1.66	1.65	1.63	1.55	1.44	1.32	1.18	1.04
F	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.12	0.11	0.11	0.10	0.09
G	3.36	3.37	3.51	3.73	3.98	4.33	4.82	5.24	5.82	6.44	7.19	8.10
H	2.04	2.04	2.04	2.03	1.98	1.90	1.80	1.66	1.49	1.41	1.31	1.22
I	0.64	0.63	0.64	0.65	0.65	0.64	0.64	0.67	0.72	0.70	0.68	0.64

2.2 Rationalisation of car body types for future analysis

Section 2.1 identifies nine car body type classifications and their proportions on UK roads. However, establishing fire development characteristics for each body type is not readily possible based upon the information available in the literature. Later Section 3.1 notes that cars can generally be grouped into the size classes of small, standard and large. Miechówka and Węgrzyński [2] in their systematic review use similar groupings of small, medium and big. Therefore, for the purpose of future analysis, the car body types presented are distilled into three size classes, as shown in Table 3. The final column shows the relative proportion.

Table 3. Proportion of cars on the road by rationalised size classification

Car size	Body types	Proportion in 2024 [%]
Small	A and B	33
Medium	C, D, F and I	36
Large	E, G and H	31

2.3 Burning characteristics

Three recent papers [1], [2], [3] have included systematic literature reviews and statistical analyses of fire experiments, focusing on key burning parameters, such as peak heat release rate (PHRR), time to peak heat release rate (TPHRR), and total heat released (THR). Since these papers have only recently been published there is no advantage in repeating a review of the burning characteristics of passenger vehicles herein, but instead a short summary is given below.

The study by Miechówka and Węgrzyński [2] examines how the key burning parameters relate to factors such as the type of drivetrain (internal combustion engine vehicles (ICEV), battery electric vehicles (BEV), hybrid vehicles, etc.), age of vehicle, ignition location, curb weight. Although the average HRR of an ICEV is found to be 4.15 MW, with a standard deviation of 2.35 MW, while the average HRR for BEVs is 5.96 MW, with a standard deviation of 1.48 MW, the 95th and 99th percentile data from ICEVs exceed BEVs. The paper notes the difficulty in assigning a single design fire to vehicles due to the uncertainty associated with events such as the failure of fuel tanks, the shattering of glass in windows, etc. The location of the ignition source also plays a significant role

in fire dynamics. Fires originating underneath the car tend to result in higher peak HRR and shorter times to peak HRR compared to fires starting at other locations. Finally, Miechówka and Węgrzyński paper observe that there is very little known about the fire behaviour of multiple car scenarios as most tests have been restricted to using a single vehicle.

Tohir and Martín-Gómez [3] place a focus on the development of design fire curves for ICEVs and BEVs without differentiating by vehicle age, curb weight, etc. This contrasts with the statement by Miechówka and Węgrzyński that it may be impractical to assign a single design fire curve. Tohir and Martín-Gómez report their PHRR, TPHRR, THR to derive design profiles for an EV and an ICEV that include characteristics for the growth and decay of the fire. They also investigate relationships between the sizes of batteries in BEVs with PHRR and fire growth coefficients.

Similar to Tohir and Martín-Gómez, Hodges et al. [1] have proposed design fires for ICEVs and BEVs based on a review of various tests reported in the literature. The authors propose a set of representative (and conservative) key burning parameters that vary by vehicle class (compact car, sports car, etc.). An interesting element to this work is that the contribution to the PHRR is separated by the fuel / battery and the vehicle body whereas in other work the PHRR is given as the combination of these elements.

Table 4 compares the PHRR, TPHRR and THR key burning characteristics expressed by Tohir and Martín-Gómez [3], Miechówka and Węgrzyński [2] and Hodges et al. [1]. The range given for Hodges et al. is between compact cars at the lower end and large SUVs at the upper end, with the median of their proposed values shown. The median PHRR and THR values from Hodges et al. exceed the maximum and 99th percentile values from Tohir and Martín-Gómez, and Miechówka and Węgrzyński. Both the median and the ranges of TPHRR from Hodges et al. are less than any of the values proposed by Tohir and Martín-Gómez, and Miechówka and Węgrzyński. Therefore, applying the design fire parameters from Hodges et al. result in heat release curves that achieve a higher PHRR at an earlier time from ignition, with a resulting greater THR than applying an equivalent approach from either Tohir and Martín-Gómez, or Miechówka and Węgrzyński.

Table 4. Comparison of key burning characteristics from Tohir and Martín-Gómez [3], Miechówka and Węgrzyński [2] and Hodges et al. [1]

Key burning parameter	Internal combustion engine vehicles (ICEV)			Battery electric vehicles (BEV)		
	Tohir and Martín-Gómez	Miechówka and Węgrzyński	Hodges et al.	Tohir and Martín-Gómez	Miechówka and Węgrzyński	Hodges et al.
	Median (maximum)	Median (99 th percentile)	Median (range)	Median (maximum)	Median (99 th percentile)	Median (range)
PHRR (kW)	4,103 (7,660)	3,700 (10,635)	14,200 (8,300 – 20,900)	6,346 (10,730)	6,100 (8,562)	13,900 (8,500 – 19,300)
TPHRR (min)	20.4 (62.0)	19.9 (64.9)	13.7 (10.5 – 16.7)	15.8 (40.9)	20.5 (44.8)	13.6 (10.6 – 16.0)
THR (GJ)	4.9 (8.1)	4.1 (10.2)	14.3 (8.4 – 20.6)	6.4 (9.0)	6.7 (9.0)	18.2 (9.8 – 30.2)

In addition to the parameters noted above, Tohir and Martín-Gómez [3], and Hodges et al. [1] also consider how long cars will burn for in which they provide ranges of the order of 45 to 60 min.

2.4 Treatment of ICEV vs BEV drivetrains in this research project

In a recent Government research briefing Tyers, et al., note that:

“The market for EVs is small yet growing. Just 3% of cars (931,000) were battery electric in the UK at the end of 2023, and 7% were hybrid electric (using an electric motor as well as petrol/diesel). Battery electric cars accounted for 16% of all new car registrations in 2023, an increase from 1% in 2018.

In its 2024 inquiry into EV strategy, the House of Lords Environment and Climate Change Committee said that demand for electric cars is being constrained due to their upfront cost, inadequate charging infrastructure and general consumer scepticism.”

As has been noted, the systematic review by Miechówka and Węgrzyński compared the fire development characteristic of ICEV vs BEV drivetrain vehicles, observing that:

“The average HRR of an ICEV was identified as 4.15 MW with a standard deviation of 2.35 MW. For BEV this value is 5.96 MW with a standard deviation of 1.48 MW. This does not necessarily mean that the BEV fires are more onerous than ICEV fires, as when the 95th and 99th percentile of data is compared for both types of cars, the reported ICEV fires were larger.”

Table 5 summaries the differences between ICEV and BEV drivetrain vehicles considering where the fire was initiated, i.e., either within the cabin or under the car. Results are presented for the peak HRR, time to peak HRR and total heat release rate. Values are shown for the mean and 95th percentile.

Table 5. Summary of fire development characteristics for ICEV vs BEV drivetrains

Parameter	Ignition in cabin		Ignition under car	
	ICEV	BEV	ICEV	BEV
Peak HRR – average [kW]	4238	5670	4569	6103
Peak HRR – 95 th percentile [kW]	8091	8140	9161	7498
Time to peak HRR – average [min]	24.3	28.4	15.6	17.8
Time to peak HRR - 95 th percentile [min]	44.75	38.0	38.5	36.6
Total heat release rate – average [MJ]	5969	6850	3346	7015
Total heat release rate – 95 th percentile [MJ]	10,023	8540	7162	8960

As the focus of the project is structural fire performance and, thus, higher consequence events, the parameters at higher percentiles, e.g., the 95th are likely more relevant. Comparing parameters across the 95th percentiles does not indicate that BEVs would produce more intense fires that might affect the structural integrity of a car park, i.e., the peak HRR, time to peak and total heat release rate (indicative of the fire load) are all comparable, with the ICEV parameters often the more onerous. Given this and the noted number of cars on the road at this time, no specific consideration will be given to BEVs when defining design fire scenarios for the purpose of evaluating the appropriate fire resistance periods for purpose-built open-sided car parks. However, there is potential utility in considering the impact of a fire originating in a BEV which could lead to more rapid fire spread to subsequent vehicles in the event of thermal runaway, see the discussion in Section 6.1.3.

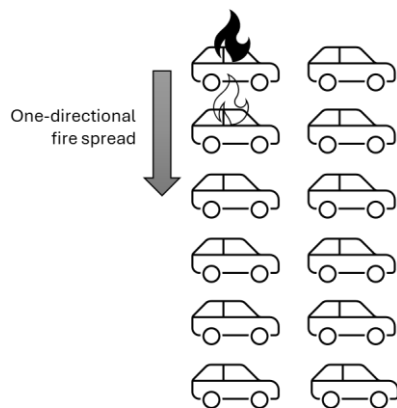
3. METHOD FOR ASSESSING FIRE SPREAD IN CAR PARKS

3.1 Fire spread mechanisms

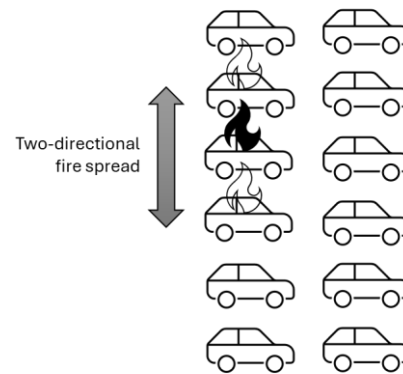
Fire spread in car parks can be through a combination of mechanisms. The accompanying report (WP 1B) on the CFD simulations discusses radiant heat transfer from fire plumes and flame extension under a ceiling which can lead to vehicle ignition. However, there may also be other processes that can lead to ignition either through heat transfer and/or direct flame contact such as closely parked vehicles, running hydrocarbon fuel fires, jet flames from venting hydrocarbon fuel tanks or energy storage systems such as lithium-ion batteries. An attempt to try to account for all these mechanisms is complex.

Although this review has identified several test programmes and incidents that involve fires in car parks, none of the associated reports provide a fully quantified measure of fire spread. Fire spread in car parks can be horizontal (i.e. from vehicle to vehicle on a floor plate) and vertical from one floor to another. Vertical spread can include via vehicles, fuel spills, and/or elements of combustible construction. However, this report is only focused on vehicle fire spread within a floor of a car parking building since the fire resistance required of elements forming a car park will mostly be affected by the fire dynamics in the 'enclosure' of origin and not the ability of the fire to spread vertically. Horizontal fire spread can be determined by various means:

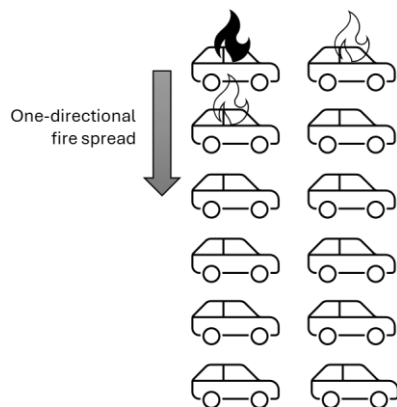
- A spread rate that assumes the fire spreads in a single dimension. In the context of a car park this would be like a fire moving along a single row of vehicles. The rate can be expressed as vehicles per unit time (e.g. vehicles per minute), or as a distance per unit time (e.g. m/min). The spread can either be in one direction down a row (such as where a car is at the end of a row), or in two directions both up and down a row (Figure 2(a) and (b)).
- An area spread rate that assumes a given area of fire increases with time. For car parks this could be the change in burning area over a single floor level (e.g. m^2/min) or the change in the number of vehicles burning (e.g. vehicles per minute). Spread rates in m/min can be combined to approximate an area of spread if it is assumed the fire spreads in two dimensions simultaneously – both along rows and between rows (Figure 2(c) to (f)), noting that spread between rows can also be in one or two directions. Using the number of vehicles is not as precise as using an area, but it can help to overcome the complexity associated with empty parking bays, the aisles between the parking bays, etc. As shown in other sections of this report, expressing the fire spread in terms of vehicles involved is often a practical measure of fire spread.



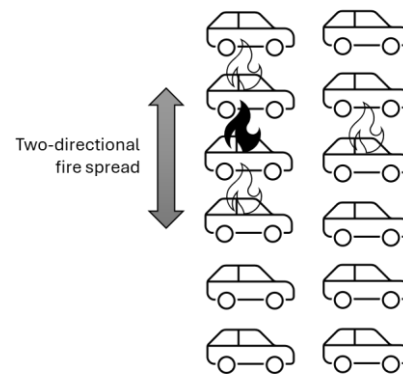
(a) One-directional fire spread only down a row of vehicles



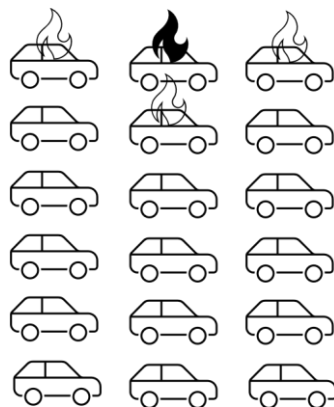
(b) Two-directional fire spread only up and down a row of vehicles



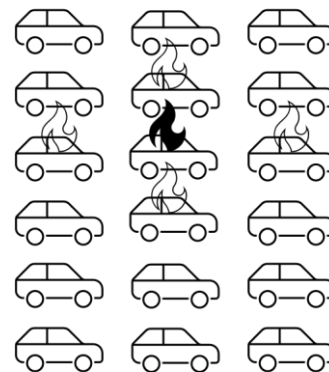
(c) One-directional fire spread down a row of vehicles but also spreading to an adjoining row in one direction



(d) Two-directional fire spread up and down a row of vehicles but also spreading to an adjoining row in one direction



(e) One-directional fire spread down a row of vehicles (direction arrow omitted) but also spreading to adjoining rows in two directions



(f) Two-directional fire spread up and down a row of vehicles (direction arrow omitted) but also spreading to adjoining rows in two directions

Figure 2. Illustration of directional and dimensional fire spread along and between rows of vehicles

To describe the spread in m/min where the development of the fire has been expressed as the number of vehicles burning in a row requires a measure of the distance. The distance may be determined where the size (i.e. its width and length) of the parking bays is documented, but this is not always the case. Alternatively, the distance can sometimes be estimated from the separation between vehicles and the footprint of the vehicles.

Some of the literature reviewed for this study gives the separation distance but not the vehicle footprint dimensions. If the exact vehicle manufacturer, model and year of production are given then it may be possible to locate the dimensions. Instead, estimated vehicle dimensions can be made from typical dimensions of the time. The 'Car park designers handbook' [4], published in 2005 suggests that the width of a car without wing mirrors is 1.8 m. However, Table 6 reproduces typical dimensions from the more recent guidance from the IStructE [5] in which 95% of standard modern vehicles have a width of 2.0 m. The 'Car park designers handbook' also notes that most cars are less than 1.5 m tall and that "*...it is unlikely that they [cars] will ever exceed a height of 1.950 m*", a statement which no longer appears to hold true.

Table 6. Typical modern vehicle sizes

Vehicle group ^a	Length (m)	Width ^b (m)	Height ^c (m)
Small ^d	≤3.95	≤1.75	≤1.75
Standard ^d	4.90	2.00	2.00
Large ^e	≥4.95	≥2.05	≥2.05
^a Includes electric and hybrid vehicles ^b Excluding wing mirrors ^c Excluding roof boxes, racks and roof bars ^d Includes 95% of vehicles on UK roads ^e Larger than 95% of vehicles on UK roads			

Any attempt to calculate fire spread using a linear distance can only be an approximation. As noted by Miechówka and Węgrzyński [2] "*...car fires undergo distinct transitions and phases connected to specific events such as the failure of gas tanks or batteries, shattering of windows or transitioning of the fire into the car interior. The randomness of these events underscores the challenge of applying a one-size-fits-all approach...*" The ignition of a neighbouring vehicle will depend on such random events, as well as factors such as the location and type of combustible materials on the target vehicle.

Furthermore, it is important to note that the fire spread analysis of the type described herein effectively assumes that once vehicles are ignited, they then continue burning indefinitely. In reality, burning vehicles will eventually consume much of their combustible material and effectively stop contributing to the fire environment. Therefore, when considering the number vehicles involved a car park fire at a given point in time this could include both those burning and those that have burned out (or those that have been extinguished by the emergency services or by automatic suppression systems). However, as noted in Section 2.3, times to vehicle burnout are of the order of 45 to 60 min which are comparable to the maximum times for fire spread identified in the tests and incidents discussed in Section 4 and Section 5, suggesting that most vehicles would still be burning by that point.

3.2 Fire spread in laboratory tests

Perhaps arising from the complexities (and costs) associated with fires involving multiple vehicles, a limited number of studies exist where fire spread between vehicles can be evaluated. A chronological list of the ad-hoc tests reviewed in this study is given in Table 7. Some of these studies were carried out in dedicated laboratory spaces and others within specifically constructed rigs.

Of the studies examined, measurements/observations relating to fire spread are not always reported. Where such data is reported, a fire spread rate has not been quantified by the respective authors but rather the propagation of fire from the vehicle of fire origin to adjacent vehicles is expressed relative to the time taken for this to occur. To determine an indicative fire spread rate from these observations, a simplified method is proposed on the assumption of a uniform spread rate between vehicles, predominately calculated based on the separation distance between them (as further discussed in Section 6.1) or the width of the parking bays (as discussed in Section 3.1).

Table 7. Chronological summary of multiple vehicle fire tests investigated in this study

Test identifier	Country / region	Year/s	Report section
BHP [9]	Australia	1980s	4.1
Joyeux [11]	France	1997	4.2
Kitano et al. [12]	Japan	2000	4.3
Steinert [13]	Germany	2000	4.4
BRE [8]	UK	2010	4.5
Li et al. [14]	China	2017	4.6
Park et al. [15]	South Korea	2019	4.7
Tramoni et al. [16]	France	2019	4.8
Elbas [17]	Denmark	2021	4.9

As noted in the following sections, the external wind speed may have an influence on the spread of fire in car parks. This is not always documented in laboratory-based tests, and this may simply be where the fires were conducted within an enclosed space then there were negligible wind effects. In such cases, this study has assumed the external wind speed was 0 m/s.

3.3 Fire spread in real incidents

A search of the media will disclose several fire incidents in car parks involving parked vehicles. In most cases only a single vehicle was involved since further fire spread was mitigated by factors such as the operation of automatic suppression systems, timely response by fire and rescue services, or the absence of other vehicles in proximity. In a previous review of the statistics of fires in car parks (albeit now over 20 years old), Joyeux [6] found that of 158 incidents there were only two cases involving 7 cars, one case with 5 cars, two cases with 4 cars and that 97.9% of incidents had less than 4 cars involved. Tohir and Spearpoint [7] compiled the statistics from Joyeux with data from what was then known as the New Zealand Fire Service to reach similar conclusions as Joyeux. Furthermore, in the study by BRE [8] it is stated that *“Most fires in car parks do not spread to a vehicle (from non-vehicle sources of ignition), or to another vehicle (from vehicle sources of ignition).”*

Notwithstanding the previous point that many fires in car parks will be limited to a few vehicles at most, to supplement the results from laboratory tests this study has investigated real world fire multi-vehicle incidents to estimate horizontal fire spread in car parks. To do this, information available in the public domain, such as witness reports (including pictures and videos) and incident reports from fire and rescue services has been sourced. Several incidents of interest have been identified, but in many of these cases there was insufficient information to proceed with a meaningful fire spread analysis. A list of incidents is provided in Table 8, highlighting those that were further evaluated. Clearly this is not an exhaustive list of every multi-vehicle fire that has occurred over the period of +20 years.

An advantage of incident data compared to laboratory tests is that there are cases in which a relatively large number of vehicles became involved in the fire. However, it is often a challenge to determine the exact time a fire started and when it spread to other vehicles. Therefore, the data presented is the best attempt at accuracy. It is important to recognise that the spread of vehicle fires is likely affected by the efforts of fire and rescue services to suppress the fires. It has been observed that external wind had a noticeable impact on fire spread, forcing it to follow a preferential direction. In such cases, this means that the fire did not spread equally in all directions from the vehicle that was first ignited.

Table 8. Chronological summary of multiple vehicle fire incidents investigated in this study

Incident name	Location	Date	Report section
Schiphol Airport	Netherlands	13 Oct 2002	5.1
Gretzenbach	Switzerland	27 Nov 2004	n/a
Monica Wills House	Bristol, England	20 Dec 2006	n/a
Lloydstraat	Rotterdam, Netherlands	1 Oct 2007	5.2
Brent Cross Shopping Centre	London, England	26 Dec 2007	n/a
Boulevard des Capucines	Paris, France	22 Oct 2014	n/a
Kings Dock (Echo Arena)	Liverpool, England	31 Dec 2017	5.3
17 East Adams Street	Chicago, IL, USA	10 Jun 2017	n/a
Kings Plaza	Brooklyn, NY, USA	17 Sept 2018	n/a
Newark Airport	Newark, NJ, USA	31 Jan 2019	n/a
Douglas Shopping Centre	Cork, Republic of Ireland	1 Sep 2019	n/a
Stavanger airport	Sola, Norway	7 Jan 2020	5.4
Open-air car park	China	8 May 2020	5.5
Somerville Assembly Row	Boston, MA, USA	24 Feb 2021	n/a
Märsta	Stockholm, Sweden	26 Aug 2021	n/a
London Luton Airport	Luton, England	10 Oct 2023	5.6
Velderwoude Castle apartments	Den Bosch, Netherlands	17 Jan 2024	n/a
Lisbon Airport	Lisbon, Portugal	16 Aug 2024	n/a
Windsor Yards	Windsor, England	22 Sept 2024	n/a
Rijsenhout	Netherlands	11 Nov 2024	n/a
Link Apartments	Charlotte, NC, USA	20 Feb 2025	5.7

4. REVIEW OF LABORATORY-BASED TESTS

4.1 BHP

In the mid-1980s BHP Australia carried out a series of ad-hoc tests on an open-deck car park arrangement. Details are published by Bennetts et al. [9]. Figure 3 shows the vehicle arrangement in which there are two parking bays per 5.2 m wide structural bay. The floor-to-ceiling height was 2.5 m.

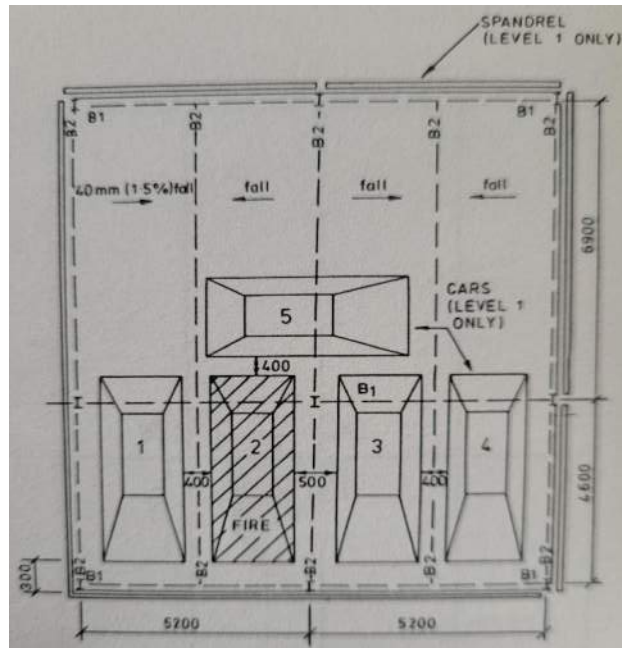


Figure 3. Vehicle arrangement during the BHP open-deck car park ad-hoc tests (taken from Bennetts et al. [9])

In the first of the two tests the fire did not spread from Car 2 to any of the other cars throughout the 70 min duration. In the second test, the fire spread to Car 1 at around 14 min and to Car 3 at 35 min. The wind during Test 1 was described as a “...gentle breeze blowing from the south...”, and in Test 2 as “...a constant breeze from the north.” It is reasonable to suggest that a ‘gentle breeze’ is between 8 mph and 12 mph, i.e. 3.6 – 5.4 m/s.

Further cases of vehicle-to-vehicle fire spread are described in a separate 1988 report [10] by Bennetts et al. in which the effectiveness of sprinklers was assessed. The arrangement of the vehicles was the same as in the 1985 work. However, the rig was fully enclosed. Therefore, there were no external wind effects. In two experiments the sprinklers were manually operated allowing spread to the two neighbouring vehicles to the one ignited, like the previous work. In the first experiment (referred to a Test 6) it appears that the two neighbouring cars ignited a few minutes after 20 min from the start. In a second experiment (referred to a Test 9) the fire had spread to the two neighbouring cars (Cars 1 and 3) and the rear car (Car 5) possibly after 28 min when the plastic fuel tank in Car 2 ruptured, spreading petrol over a wide area.

Since fire spread was only to the neighbouring vehicles any estimation of spread rate in terms of metres per minute are limited. Using the times noted above and a parking bay width of 2.6 m suggests values of between 0.1 m/min and 0.2 m/min. Collating the BHP test results in the form of number of vehicles is shown in Figure 4, with a best-fit exponential curve also included. The motivation for using an exponential curve is discussed as part of the investigation of the Kings Dock incident (see Section 5.3).

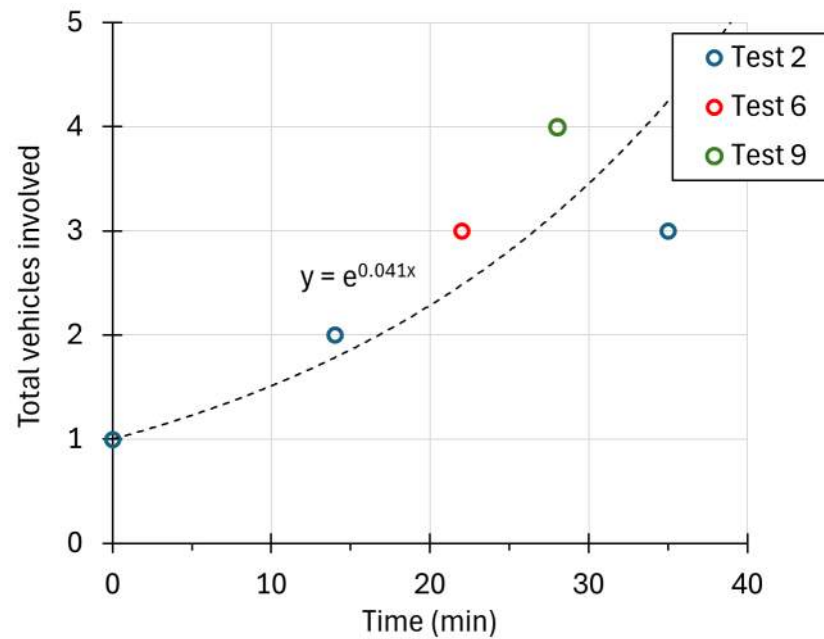


Figure 4. Number of vehicles involved in the BHP tests based on estimated ignition times

4.2 Joyeux

As part of a study conducted by the Centre Technique Industriel de la Construction Metallique (CTICM) investigating the impact of car fires on steel structures of closed car parks, Joyeux [11] conducted fire spread tests between two adjacent cars. A closed car park with plan area of 5 m × 5 m was simulated under a calorimetry hood intended to simulate two standard parking bays. A total of 10 tests were carried out, five of which involved two vehicles (referred to by Joyeux as Tests 1, 5, 6, 9, and 10). The vehicle type (categorised by mass), enclosure boundary conditions (closed or corner or open), and enclosure height were varied between tests. A summary of relevant parameters for experiments of interest is given in Table 9. The closed boundary condition refers to the complete enclosure of the vehicles, ventilated by an opening of 1.9 m × 0.55 m. Joyeux does not report any information on external wind speed.

Table 9. Summary of experimental parameters from Joyeux [11]

Test number	Mass of car 1 (kg)	Mass of car 2 (kg)	Enclosure height (m)	Boundary condition
1	820	Not measured	2.3	Corner
5	1150	736	2.6	Corner
6	870	1073	2.6	Closed
9	789	1306	2.6	Open
10	1306	790	2.6	Open

For Tests 1, 5, and 6, vehicles were fitted with 5 tyres (including the spare), filled with oil and the fuel tank was 2/3 full. For tests 9 and 10, all liquids were removed from the heavier car and the fuel tank of the lighter car was filled to ¼ of its capacity. A pool fire comprising 1.5 L of petrol placed under the left frontside seat was used as the ignition source for experiments 1, 5, and 6, whereas vehicles in experiments 9 and 10 were ignited by a 1 L petrol pool fire under the gear box. The separation distance between vehicles for all tests was 0.7 m, whereby spread from the car of fire origin to the adjacent car was observed in all cases. In all tests, the doors and windows of the second car were closed. The time taken for the fire to spread to the secondary vehicle was recorded during the experiment and is given in Table 10. Based on an assumed standard car width of 1.8 m [4], the spread is determined with an effective parking bay width of 1.8 + 0.7 = 2.5 m.

Table 10. Time for secondary ignition, adapted from Joyeux [11]

Test number	Time taken for secondary ignition (min)	Calculated spread rate (m/min)
1 ¹	12	0.20
5 ¹	9	0.27
6 ¹	12	0.20
9 ²	8	0.31
10 ^{2,3}	14	0.18

1. For Tests 1-7, left window fully open and right front window was half open
2. For Tests 9 and 10, the tank of the large car was empty, and small car was only ¼ full
3. For Test 10, windows and doors of both cars were closed

4.3 Kitano et al.

Kitano et. al [12] conducted large scale experiments involving the burning of 12 passenger vehicles in a four-storey car park. Vehicles were positioned in a thermally insulated corner of the first floor in two adjacent rows arranged longitudinally to the length of the car park. Parking bays were 2.5 m in width by 5 m in length, and the ceiling height was reported as 2.9 m. Structural columns and beams were arranged in a 7.5 m × 5 m grid such that vehicles were effectively divided into 4 groups, each of 3 vehicles. Neither the type/mass of the vehicles used nor the content of the vehicles (fuel contents, oil, tyres etc) were reported. A representative diagram of the layout is shown in Figure 5, whereby Vehicle 1 refers to the car of fire origin. The ignition source and location were not reported. Wind speed is quoted as being 3 m/s.

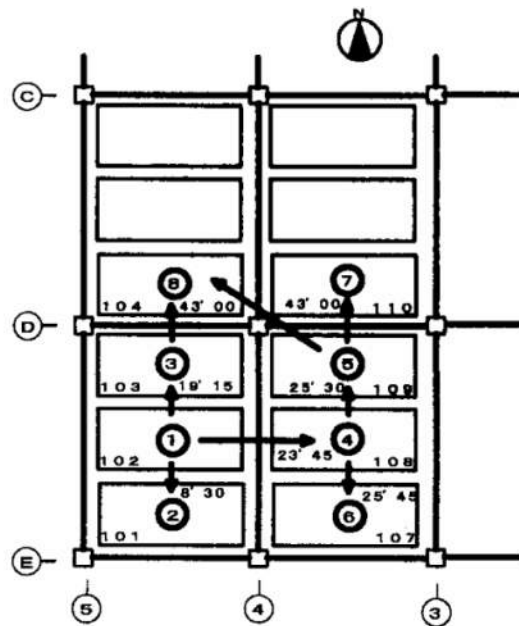


Figure 5. Arrangement of cars and ignition times, taken from Kitano et al. [12]

On the premise of a uniform and unidirectional spread rate from Vehicle 1 to 8 (the northern direction shown in Figure 5) and a distance of 2.5 m between vehicles, the spread rates to Vehicle 3 and 8 are calculated as 0.13 m/min and 0.12 m/min, respectively. It is of note that ignition of Vehicle 2 occurs earlier than that of Vehicle 3. Considering fire spread between Vehicles 1 and 2 in isolation, this yields a spread rate of 0.29 m/min. Alternatively, a spread rate can be determined based on a simplified model where vehicles are assumed to be in a singular row such that multidirectional effects are ignored. A graphical representation of this is shown in Figure 6, based on an 'effective' distance of 2 m between vehicles.

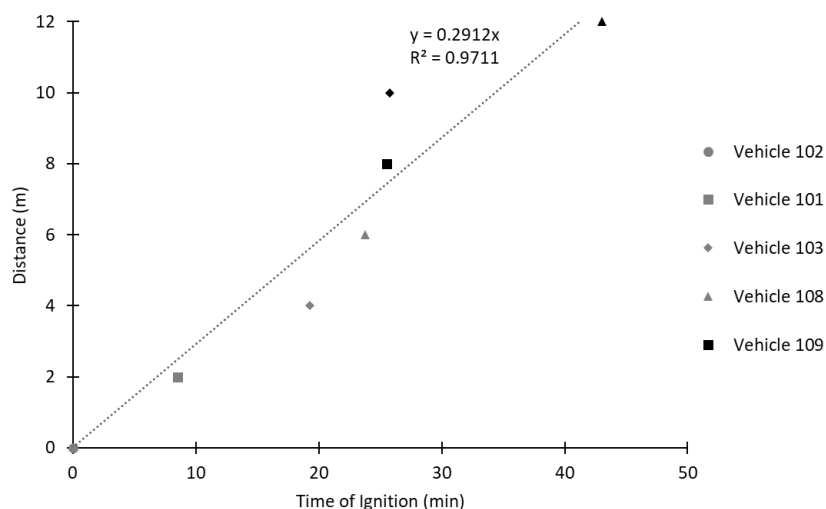


Figure 6: Simplified spread rate model based on experimental observations of Kitano et al. [12]

From the gradient of the graph, this method yields a spread rate of 0.29 m/min. It is interesting to note that ignition of Vehicle 8 and Vehicle 7 occur simultaneously. Considering the location of these vehicles in relation to the car of fire origin, it is suggested that this could be attributed to the presence of beam down stands effectively acting as smoke break. It is expected that radiation effects from the upper layer would have a non-negligible influence on the rate of fire spread. The simultaneous ignition of these vehicles is thought to be indicative of this. Potential re-radiation effects from the boundary walls are also suggested, indicated by the comparatively earlier ignition of vehicles in this direction.

4.4 Steinert

Steinert [13] carried out full scale testing to investigate fire spread and the burning behaviour of passenger vehicles. Ten fire tests were carried out in total, with 5 involving 2 vehicles and 1 comprising 3 vehicles. Tests were carried out in a purpose-built testing facility with floor dimensions 5 m × 7.5 m and a height of 4.5 m, noting that a floor-to-ceiling height of 4.5 m is not representative of a typical multi-storey car park. The fuel tank of both vehicles was emptied prior to the tests. Vehicles were ignited in the front passenger compartment. Vehicle mass was not reported; however, vehicles were described as mid-size and small. A summary of relevant parameters is given in Table 11.

Table 11. Summary of test parameters from Steinert [13]

Test number	Number of vehicles	Separation distance (m)	Time of secondary ignition (min)	Spread rate (m/min)
4	3	0.8	30, 32	0.08
5	2	0.4	35	0.06
6	2	0.8	22.5	0.12
7	2	0.8	12	0.22
8	2	0.8	52	0.05
9a	2	0.8	-	n/a
9b	2	0.8	28.5	0.09

For Test 4, vehicles were arranged in a row of 3 whereby the vehicle of fire origin was in the middle. The rate of fire spread has been calculated based on assumed standard car width of 1.8 m [4] and the stated separation distances based on an estimated bay width of 2.4 m. For Test 9a, the fire was not observed to spread to the adjacent vehicle.

4.5 Building Research Establishment (BRE)

The Building Research Establishment (BRE) carried out a study [8] on fire spread in car parks in 2010. The study included sprinklered and un-sprinklered full-scale ad-hoc tests in a specifically constructed 12 m by 6 m rig with a floor-to-ceiling height of 2.9 m. Generally, no specific mention is made on external wind speeds and given the enclosed nature of the rig it is assumed it was 0 m/s. More details are provided in [8].

Five of the 11 tests included multiple vehicles. Tests 1, 2 and 3 used three vehicles in each test, arranged as shown in Figure 7 such that there was an empty parking bay between Cars 2 and 3. Test 2 had a sprinkler system installed in which its operation prevented fire spread to the neighbouring cars. Tests 4 and 8 are described below, and Test 11 investigated the fire development in a car stacker arrangement, a scenario which is beyond the scope of this study. Vehicle manufacturers and models were recorded, although not their masses. Aside from the removal of air conditioning gas, the vehicles were in working order and contained 20 L of fuel.

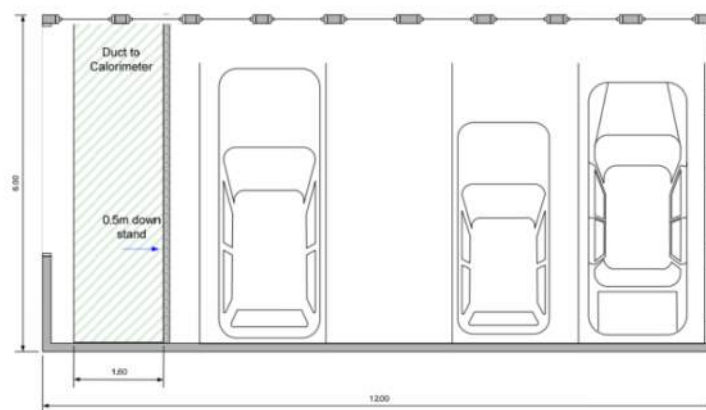


Figure 7. Rig dimensions and car layout in BRE Tests 1, 2 and 3

In Test 1, the fire spread to Car 2 at 20 min after Car 1 was ignited and then to Car 3 “...a few minutes later...” To be consistent with the analysis of the Stavanger airport incident (see Section 5.4), ‘a few minutes’ is assumed to be a period of 5 min. In Test 3 the fire spread from Car 1 to Car 2 after 9½ min. Thereafter the fire grew rapidly which resulted in fire Car 3 igniting. The time of ignition of Car 3 was not reported but given the test was terminated at 10½ min then ignition was likely around 60 s after Car 2.

Test 4 had four cars parked in a row with no empty bay between Car 1 and Car 2. Car 2 was converted to run on LPG. Due to the presence of the LPG and the possibility of explosion, Test 4 was carried out in a more exposed location than the other tests in which the effects of wind were limited by adopting the same rig. Car 2 ignited after 20 min 36 s, Car 3 at 23 min, 2 s and Car 4 at 23 min, 28 s.

In Test 8 a fire was started in the engine compartment of a ‘people carrier’ with another car located facing the people carrier with the two front bumpers positioned 0.5 m apart. The fire spread from the people carrier to the facing car reportedly after 5 min. However, there appears to be some discrepancy between this time and other parts of the description of the tests which would suggest ignition was much later.

Linear fire spread rates have been calculated for the above-described tests on the basis that the parking bays were 2.4 m wide. The maximum is around 0.7 m/min for the spread to Car 3 in Test 3, a minimum spread rate of 0.1 m/min is obtained for Test 8 while the spread rates to Car 2 in both Test 1 and Test 4 were a similar value of 0.12 m/min. Figure 8 shows the cumulative number of vehicles involved in each of the four BRE tests considered herein which includes the result from Test 8, noting the possible discrepancy. Consistent with the analysis throughout this review, an exponential trend line has been fitted to the results noting the scatter in the data.

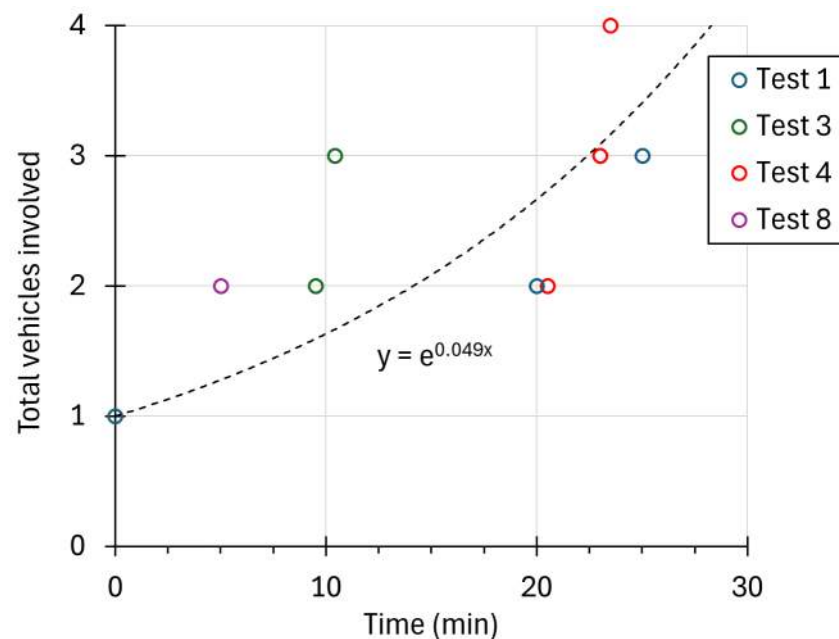


Figure 8. Number of vehicles involved in the BRE tests based on estimated times to ignition

4.6 Li et al.

In their study of flame spread and smoke temperatures in car fires, Li et al. [14] conducted full scale experiments involving fire spread between two adjacent vehicles. Experiments were carried out in a purpose-built testing facility with dimensions $L \times W \times H$ of $40 \text{ m} \times 12.87 \text{ m} \times 12 \text{ m}$ high, again noting as with the work by Steinert [13], that this exceeds a typical multistorey car park floor-to-ceiling height. Identical sedan-type vehicles with a mass of 1360 kg were positioned side-by-side such that the front of one car aligned with the rear of the other and were separated by 0.8 m. The primary vehicle was ignited by a sponge soaked in gasoline placed inside the engine compartment. The authors report the time at which the fire was considered to have spread to the secondary vehicle, in addition to observations of interest during the experiment.

The second car ignited at 20 min 10 s and based on an assumed standard car width of 1.8 m, a value for the spread of $(1.8 + 0.8) / 20.17 = 0.13 \text{ m/min}$ is determined. It is considered that ignition of the secondary vehicle is facilitated by the emergence of flames on the outside of the primary vehicle. When assessing fire spread rate between vehicles, it is therefore perhaps more useful to consider the period between the observation of external flaming and the ignition of the secondary ignition. From reported experimental events, this was observed to occur at 14 min 20 s, associated with the burning of the front left tyre. Considering the interval between this event and spread to the adjacent vehicle (5 min 50 s) provides a spread rate of 0.43 m/min.

Time Line (min:s)	Events
0:00	Car I Ignition at engine compartment Flame emerged from the cracks
9:24–10:10	Air leaked from the right rear tire
14:20	Left front tire began burning
19:00	Fire spread into car Cab
19:28	The flame reached the roof
20:00	Left rear glazing was blown out
20:10	Car II Right rear tire burst and burn; Fire spread to the second car
23:42	Car I The passenger compartment was enveloped in flame
25:50	Left rear tire began burning
25:52	Car II Rear passenger compartment started burning
26:23	Front passenger compartment started burning
29:00	Car I, Car II Fully-developed burning of two cars occurred
35:00	Car I, Car II The fire was put out by firemen

4.7 Park et al.

Park et al. [15] published their work on fire spread characteristics of burning vehicles in which they carried out a single experiment of spread from one vehicle to another. In addition, the work measured temperatures, heat release rate, and toxic gas concentrations. The height of the laboratory space was not stated but given the presence of the calorimeter hood above the vehicles, the height was effectively unrestricted.

The drivetrain of the vehicles was not specifically noted but given the paper discusses the ‘fuel tank’ it is likely they were petrol or diesel powered. The front, driver and passenger windows were fully open, and ignition was of the front passenger seat. The fire spread from the first to the second vehicle at 500 s (8.3 min). The separation distance between the two vehicles was stated to have been 50 cm and is illustrated in Figure 9. Park et al. did not report any external air movement and given the test appears to have been carried out in a laboratory then it is unlikely there would have been any influence of wind. Taking a vehicle width of 2 m then a vehicle-to-vehicle fire spread rate is $(2.0 + 0.5) / 8.3 = 0.30$ m/min, whereas the fire spread rate across the 50 cm separation is 0.06 m/min.



Figure 9. Photograph of the experiment involving two cars at around 500 s, taken from Park et al. [15]

4.8 Tramoni et al.

Tramoni et al. [16] conducted full scale experiments to investigate the thermal exposure of steel members for car park fires involving alternative fuel vehicles. The test apparatus comprised a 5.5 m × 5 m × 3 m open enclosure of unprotected steel columns and beams. Wind speed was not reported and is therefore assumed to be 0 m/s due to the testing facility being in an airport hangar. The experimental set up is shown in Figure 10. For Tests 2-5 (i.e. those involving alternative fuel vehicles), Vehicle 1 was located closer to the wall to increase the likelihood of thermal runaway.

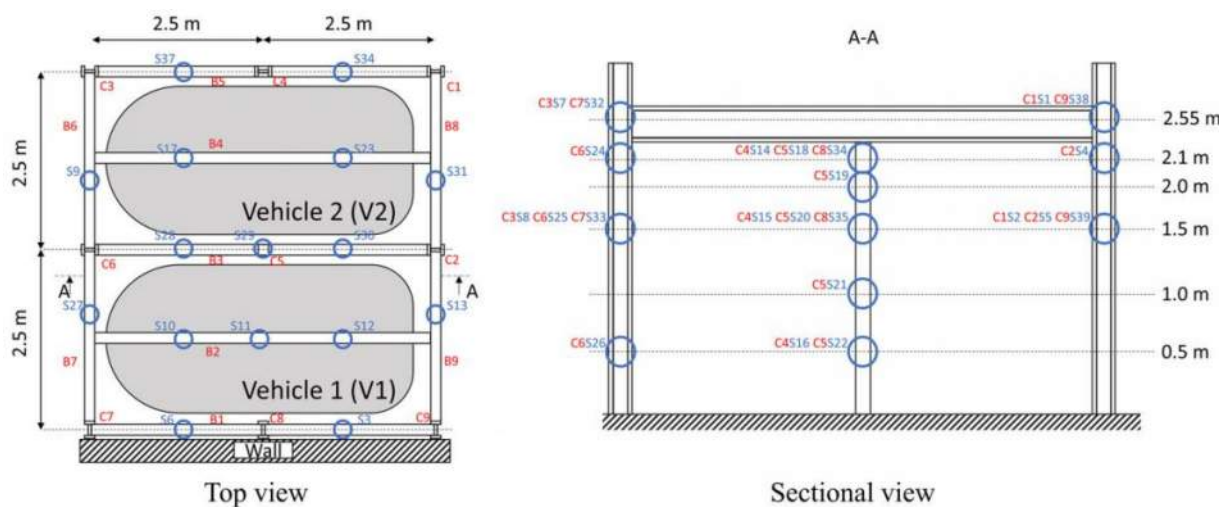


Figure 10. Vehicle and experimental layout used by Tramoni et al. [16]

Five experiments were carried out, each involving two vehicles. A summary of the vehicle types used for each test is given in Table 12. Vehicle 1 was ignited by 100 mL of liquid accelerant on the passenger seat for all tests.

A fire spread rate can be determined based on the time taken for secondary ignition and the width of the parking bays, reported as 2.5 m wide. The corresponding linear spread rates are given in Table 12. Tramoni et al. did not report the separation distance between the vehicles.

Table 12. Summary of experimental data from Tramoni et al. [16]

Test number	Vehicle 1 fuel type	Vehicle 2 fuel type	Ignition time of Vehicle 2 (min)	Ignition time of fuel tank in Vehicle 2 (min)	Spread rate (m/min)
1	Internal combustion engine	Internal combustion engine	26	43	0.10
2	Hydrogen cell		20	32	0.13
3	Natural gas		22	46	0.11
4	Electric (lithium metal polymer)		8	33	0.31
5	Liquefied petroleum gas		14	25	0.18

For Test 4, it was reported that a “*huge quantity*” of wooden pallets was added inside the electric vehicle. It is expected that this would have likely influenced both the fire size and the growth period, facilitating more rapid fire spread to the adjacent vehicle. Further, the comparatively decreased ignition time observed for Test 5 could also be attributed to the addition of “*...two wooden pallets and a tire*” within the LPG vehicle.

For all tests, Tramoni et al. report times associated with major events representative of a change in overall fire behaviour. As an alternative method of determining the rate of fire spread, the time to ignition of the fuel of the second vehicle is considered. Based on this interval, a spread rate of between 0.05 to 0.10 m/min is calculated. Tramoni et al. report that the battery in the electric vehicle did not enter thermal runaway. A second more onerous test was carried out on the electric vehicle in which more fuel was added to the vehicle but again there was no indication of thermal runaway after 2 hr of burning.

4.9 Elbas project

As part of a research project investigating electric vehicle fires at sea, the Danish Institute of Fire and Security Technology (DBI) carried out full scale experiments evaluating fire spread between multiple vehicles [17]. Tests were carried out in a test rig comprising two 40 ft ISO shipping containers with dimensions L × W × H of 12.2 m × 7.13 m × 2.4 m. Vehicles were arranged in three rows, each consisting of three vehicles with a 40 cm door-to-door separation, in which the electric vehicle was in the centre. All other vehicles had internal combustion engines which had been drained of all fluids, including fuel. A schematic of the test arrangement is shown in Figure 11. The test report does discuss wind effects on temperature recordings and smoke movement, but no speed is provided.

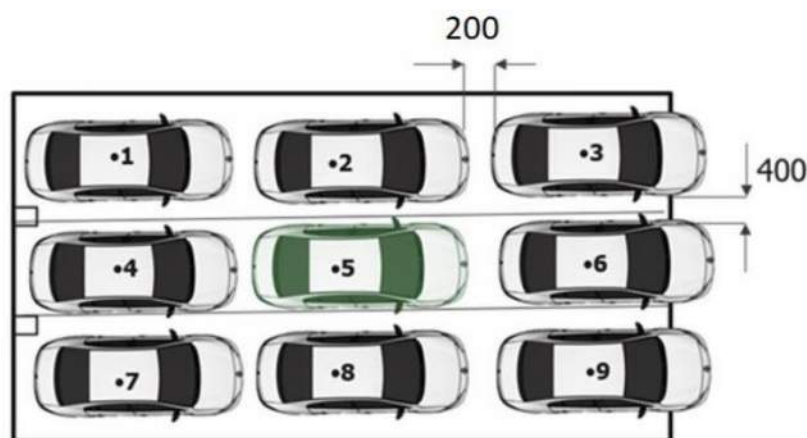


Figure 11. Test arrangement used in the ELBAS project [17]

Six tests were carried out to investigate the effectiveness of different suppression systems in restricting fire growth and spread. Ignition of the electric vehicle was caused by intentionally short circuiting the battery to initiate thermal runaway. Where ignition using this method did not occur, vehicles were ignited using pilot sources. The primary vehicle was allowed to burn for a maximum of 10 min prior to manual intervention by firefighters. Under these conditions, fire spread to adjacent vehicles was observed for Test 4 and Test 5. In Test 4, the battery was charged to 130% and the boot of the car was left open in attempt to accelerate thermal runaway of the battery. Fire spread to Vehicles 2 and 8 within 5 min. Test 5 utilised the same vehicle type. However, the battery was charged to 100% and the boot remained closed. Thermal runaway was not initiated by the short-circuit, and therefore Vehicle 5 was ignited by a diesel pool fire placed under the vehicle. It was reported that fire spread to Vehicles 2 and 8 occurred *“just before the [suppression] devices were placed”*. The water curtain suppression devices used in this test were deployed at 16 min 40 s. A time of 16 min for ignition of secondary vehicles has therefore been assumed. Flame spread in the parallel direction (i.e. to Vehicles 4 and 6) was not reported to occur. Based on an assumed standard modern car width of 2.0 m, the rate of fire spread is calculated as 0.48 m/min and 0.14 m/min for Tests 4 and 5, respectively. As individual ignition times for Vehicles 2 and 8 were not reported, it has been assumed that these occurred simultaneously and therefore have equal corresponding rates of fire spread.

4.10 Other work

Several other papers have been published in the literature in which multiple cars have been burned as part of the study. There are a few papers that merit commenting on herein but do not warrant their own separate sections.

Bürgi [18] reported on three tests carried out in a car park in Bern, Switzerland that was scheduled for demolition. The work included an assessment of the performance of automatic fire detection and fire suppression via sprinklers. The first test involved three cars parked in a row, in which the spread of fire was mitigated by the operation of the sprinklers. In the second test, water from the operation of the sprinkler directed burning petrol towards a second car leading to its ignition, although the time of ignition is not reported. In the third test, a simulated deliberate fire spread to a second vehicle parked 0.5 m next to the first after 3 min 30 s. The height of the space in the third test was 3.7 m, and Bürgi did not report any information about external wind.

Santangelo et al. [19] have carried out a series of seven full-scale laboratory tests of fire control and suppression in enclosed car parks using sprinklers and water-mist systems. The tests used three cars parked side-by-side 0.6 m apart within an enclosure in which the middle of the three vehicles was ignited. Unfortunately (for the purposes of this study) the fire did not spread to the two neighbouring vehicles and therefore no spread times were measured.

A full-scale study of fire spread behaviour of cars has been carried out by Jiang et al. [20]. In the second of two tests, fire spread from one car to another spaced 0.8 m apart at 20 min 30 s. The laboratory used in the tests was 10 m tall and described as having *“...good air ventilation”* but no specific wind speed was noted.

5. REVIEW OF SPECIFIC FIRE INCIDENTS

5.1 Schiphol Airport, Netherlands, 2002

The fire occurred on 13th Oct 2002 in a car park located on the Schiphol Airport site, close to Amsterdam, Netherlands. The car park was used by the Hertz car rental company as a vehicle storage area. Subsequent to the fire a report was published [21] on behalf of the Haarlemmermeer and Schiphol Fire Departments (hereafter referred to as the 'Schiphol fire report') which has been used as the primary source for this work. The report contains information about the incident and some analysis of the possible spread of fire that may have taken place.

The fire was determined to have been deliberately set in one of the cars on the second level in which flammable liquid was poured over the back seat. However, according to statements made by the person suspected of starting the fire *"...nothing happened for a long time after the arson, but eventually, smoke and flames appeared."* For this analysis, it is assumed it took 8 min before the flames appeared. The selection of 8 min is partly as a result of the discussion later presented in Section 6.1 and the spread of fire analysis presented in the Schiphol fire report.

At 04:47 the fire in the vehicle was reported by a passerby and 3 min later the Royal Military Police arrived at the scene by which there were *"...multiple cars on fire on the second floor."* On arrival of the first firefighter at 04:55 it was reported that *"...10 to 15 cars on fire on the second floor and exploding gas tanks."* At 05:22 the commanding fire officer reported there was approximately 30 cars on fire. Although this may have included vehicles on both the second and third storey, it is assumed here they were all on the second storey. The fire was almost extinguished by 05:53, 35 cars on the second floor and 16 on the third floor were destroyed by the end of the incident. It was reported in the Schiphol fire report that there was little wind during the fire.

Details of the car parking structure in the Schiphol fire report are limited. The parking structure still exists at the airport 23 years later and therefore Google Earth can be used to establish some key dimensions. The building is a three-storey open-sided structure in which the floor-to-ceiling height of the two covered levels is estimated to be 2.6 m per storey (Figure 12) based on the presence of a standard ISO shipping container next to the building.

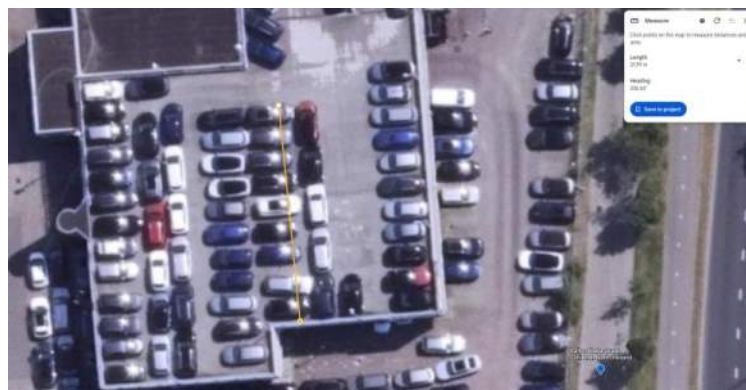


Figure 12. Contemporary images of the elevation of the Schiphol Airport car park taken from Google Streetview

The Schiphol fire report does not give the width of the parking bays but does note that *"In regular garages, average distances of 50 to 70 centimeters are common, compared to 40 centimeters for the Hertz setup."* Typically, cars around the 2000s would have been of the order of 1.8 m wide, so accounting for the parking spacing the vehicle-to-vehicle distance would have been 2.2 m. Using Google Earth, measuring the length of a row of cars in 2023 and assessing the original image of the arrangement of parked vehicles (Figure 13) would also suggest a parking bay spacing of around $22 \text{ m} / 10 \text{ cars} = 2.2 \text{ m}$. Assuming when the fire spread to 12 and 30 cars it was restricted to two parallel rows of parked cars, the fire spread rate is found to be 0.83 m/min and then 0.38 m/min. Note from the 2023 Google Earth image how the cars continue to be parked close together not to allow easy access for entering and exiting vehicles.



(a)



(b)

Figure 13. Aerial views of the Schiphol Airport car park (a) image extracted from Schiphol fire report [21], (b) contemporary view from Google Earth

As noted above, the Schiphol fire report also includes some analysis of the prospective times of fire progression between the cars in which it was suggested that:

- After 12 min, the first spread had occurred, and 3 cars were burning,
- After 24 min, the second spread had occurred, and 7 cars were burning, and
- After 36 minutes, the third spread had occurred, and 11 cars were burning.

Figure 14 shows the estimated number of cars ignited / burning over time along with the fire progression discussed in the Schiphol fire report. A best-fit exponential curve only through the reported times has been included.

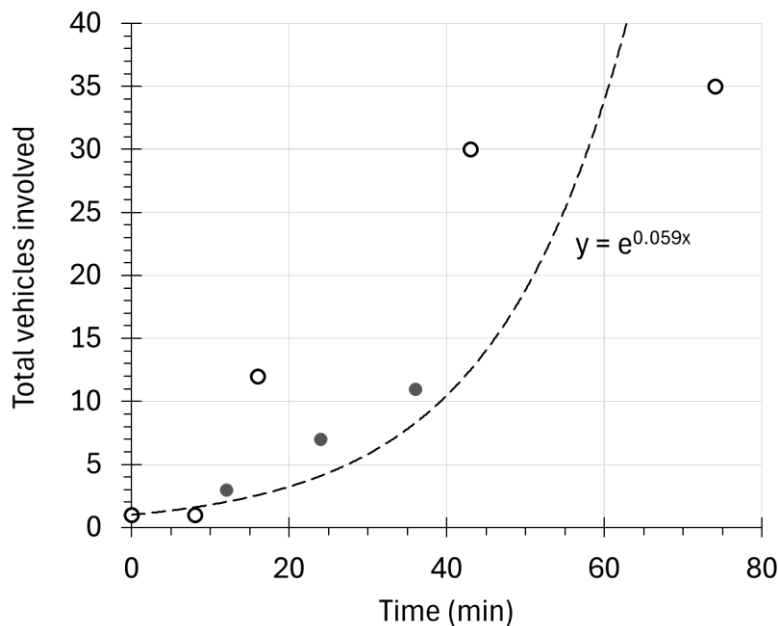


Figure 14. Estimated number of vehicles involved in the Schiphol Airport car park fire incident (open symbols are the reported times, closed symbols are the prospective times given in the Schiphol fire report [21]).

5.2 Lloydstraat, Netherlands, 2007

The Lloydstraat car park fire incident occurred on the 1st Oct 2007 under the Harbour Edge residential building (Figure 15) in Rotterdam, Netherlands. Following the fire, a report was published by de Feijter and Breunese [22], and further analysis by was later carried out by Tohir [23]. As far as can be determined from Google Streetview the building still exists in the same form as in 2007.



Figure 15. Google Streetview images of the Harbour Edge residential building from c. 2009 with the entrance to the car park shown on the right (note the images are date stamped 2022)

The fire involved seven cars (Figure 16) of which five were destroyed, one was 75% damaged and another had lesser damage. de Feijter and Breunese noted that the first two cars involved were parked less than 50 cm apart which likely contributed to a faster spread than if they were parked a typical 70 cm apart.

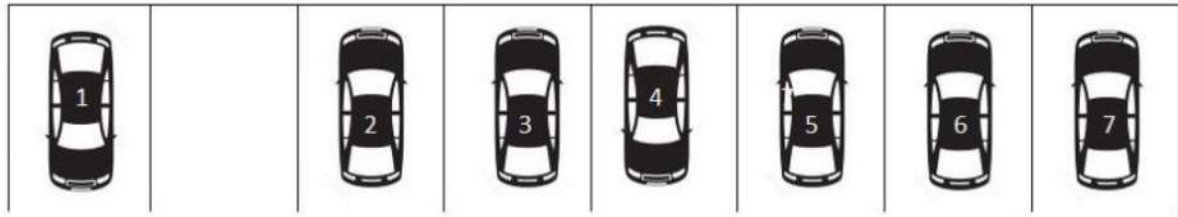


Figure 16. Arrangement of vehicles at the time of the Lloydstraat car park fire incident

Two fire spread scenarios were posited by de Feijter and Breunese of which one with a faster spread to the more remote cars was selected by Tohir in his analysis and is adopted herein (Table 13). The width of the parking bays was not reported by de Feijter and Breunese and so was assumed to be 2.2 m by Tohir and is also adopted herein. Thus, the linear fire spread is found to be between 0.18 and 0.22 m/min.

Table 13. Estimated time of vehicle ignition and fire spread rate, adapted from de Feijter and Breunese [22]

	Time (min)	Distance (m)	Linear fire spread rate (m/min)
Vehicle 4	0	0.0	0.00
Vehicle 3	10	2.2	0.22
Vehicle 5	12	2.2	0.18
Vehicle 2	22	4.4	0.20
Vehicle 6	24	4.4	0.18
Vehicle 7	36	6.6	0.18

de Feijter and Breunese state that the car park floor-to-ceiling height is 2.4 m high. No mention is made about the wind on the day but an online historical resource² for the weather for the Rotterdam region gives a speed of around 10 mph (~4.5 m/s) at the time.

Figure 17 shows the cumulative number of vehicles involved in the fire as a function of time with a best-fit exponential curve.

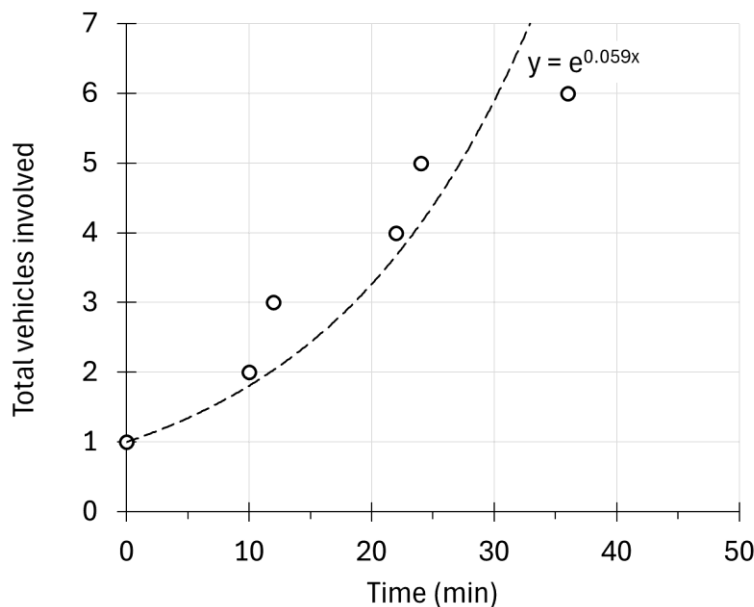


Figure 17. Estimated number of cars ignited / burning in the Lloydstraat car park fire incident

² www.wunderground.com/history/daily/nl/rotterdam

5.3 Kings Dock, England, 2017

The incident occurred on Sunday 31st Dec 2017. The fire started at around 16:26 in a Land Rover on Level 3 of the open-sided car park. The fire spread to multiple levels and eventually destroyed around 1200 vehicles. Merseyside Fire and Rescue Service (MFRS) have issued at least three reports on the incident: a Fire Investigation Report [24], a Significant Incident Report [25], and a Protection Report [26]. The building was an 8-level structure, less than 18 m tall, suggesting a floor-to-ceiling height of around 2.6 m since the top floor was open. The area of each floor was approximately 4,930 m². The car park was constructed of reinforced concrete beams and columns. Each structural bay was 7.2 m wide and spanned three parking bays, giving a width of 2.47 m each. The wind was cited as a factor during the incident. However, none of the MFRS reports give an indication of its speed. An online historical resource³ for the weather for the Merseyside region gives a speed of 20 km/h to 15 km/h (around 5 m/s) between 15:00 and 18:00, with gusts of 33-34 km/h.

Figure 18 shows CCTV camera images at the point when one of the first 999 calls was received and stated to be at around 16:52 in which the fire appears to still be primarily limited to the initiating vehicle. The MFRS Significant Incident Report [25] noted that after 35 min from ignition (at 17:01) a Watch Manager (WM) observed “...multiple cars on fire...” although no number is given.

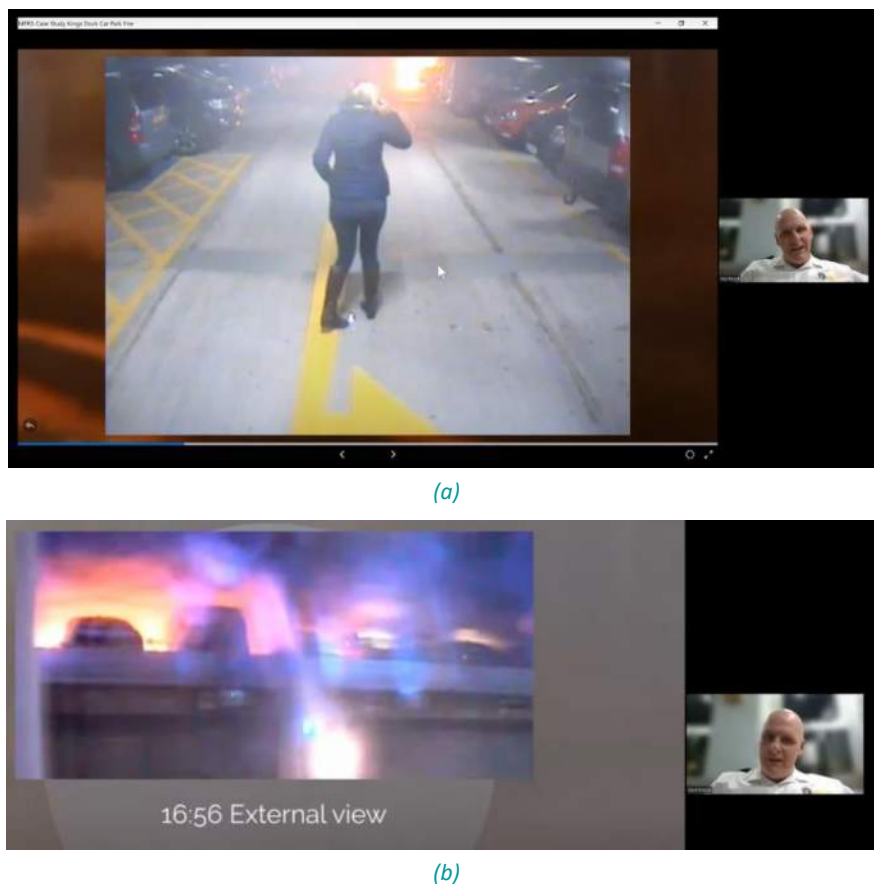


Figure 18. Images taken from the presentation by Ged Knock (MFRS) to Engineers Ireland⁴ (a) One of the first 999 calls, at 16:42 according to the MFRS Protection Report; (b) External view of the fire at 16:56 with some indication the extent of fire spread

³ www.worldweatheronline.com/liverpool-weather-history/merseyside

⁴ www.youtube.com/watch?v=Nvt_6D7ijs

At the time the first BA crews accessed the fire floor (at 17:08 according to the MFRS Protection Report, i.e. 42 min after ignition) it was estimated that “...upwards of 25 vehicles were involved with fire”. MFRS crews stated that the fire spread was affected by the wind and due to “...running fuel fire between rows of cars”. From Figure 19 the lateral spread in the windward direction is 6 parking bays, giving a spread rate of $(6 \times 2.47) / 42 = 0.35$ m/min and the spread is 5 bays, or 0.29 m/min against the wind.

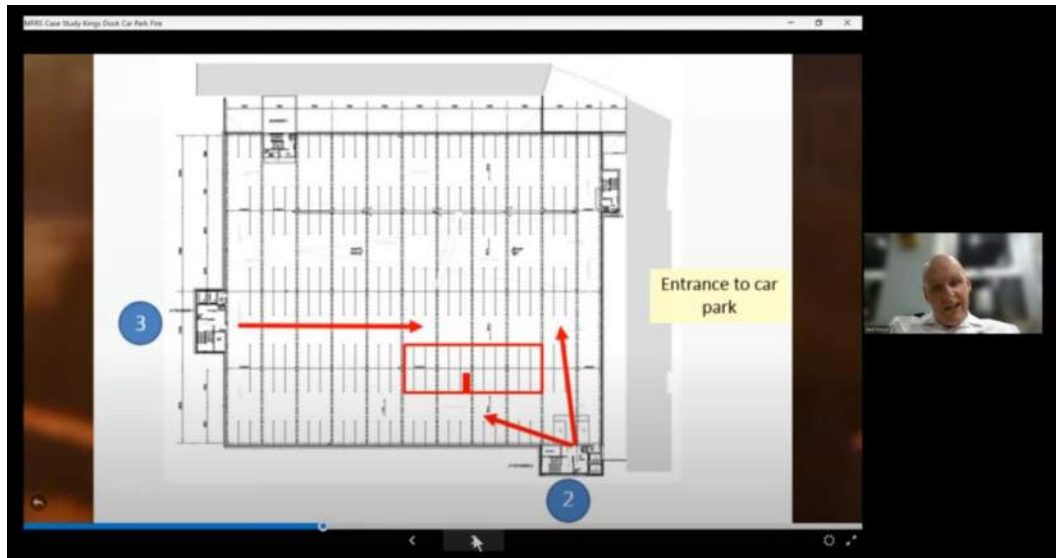


Figure 19. BA crew entry from stairwell, primary wind direction and estimated spread of fire at around 17:08 (taken from the presentation by Ged Knock)

Thus, using the spread rates calculated above, at 16:56 (i.e. after 30 min) it is estimated that 4 parking bays would be involved upwind and downwind, and assuming the two adjacent rows are burning leads to 16 vehicles alight. Similarly, at 17:01 (i.e. after 35 min) it is estimated that 4 parking bays would be involved against the wind direction and 5 in the windward direction, and therefore 18 vehicles were alight.

MFRS noted that after 74 min from ignition of the initiating vehicle (at 17:40) “...that possibly up to 30 cars were then involved...”. If it is assumed that the fire only spread in the two directions along the neighbouring parking bays (as indicated by the red area in Figure 20) then the spread rate is estimated to be between $(6 \times 2.47) / 74 = 0.20$ m/min against the wind and $(8 \times 2.47) / 74 = 0.27$ m/min windward.



Figure 20. Level 3 car park layout showing location of the initiating vehicle and estimated area of fire spread over 30 vehicles

The assumption that the fire was in the two rows at 17:40 is confirmed where the Significant Incident Report noted that at 18:07 “...the fire was confined to rows two and three and had not spread to row four.”

The MFRS Protection Report [26] noted that “...additional vehicles became involved ‘every 30 seconds’” which leads to an upper estimate of a spread rate of 2 vehicles per minute or a linear spread rate of 4.93 m/min. However, it is unclear when during the incident this was observed as the MFRS Protection Report states “The rate increased exponentially up to rapid fire development on level 4...”.

Thus, estimated linear spread rates from the Kings Dock incident range between 0.20 to 0.35 m/min depending on the wind orientation, up to a maximum of around 5 m/min. Figure 21 is a plot of the estimated number of vehicles burning as a function of time. The two points at 30 min and 35 min are those previously estimated. A best-fit exponential curve has been added through the data from the MFRS reports although there is noticeable scatter in the estimates. The number of estimated vehicles on fire at 30 min and 35 min would be 4 and 6 respectively using the exponential model.

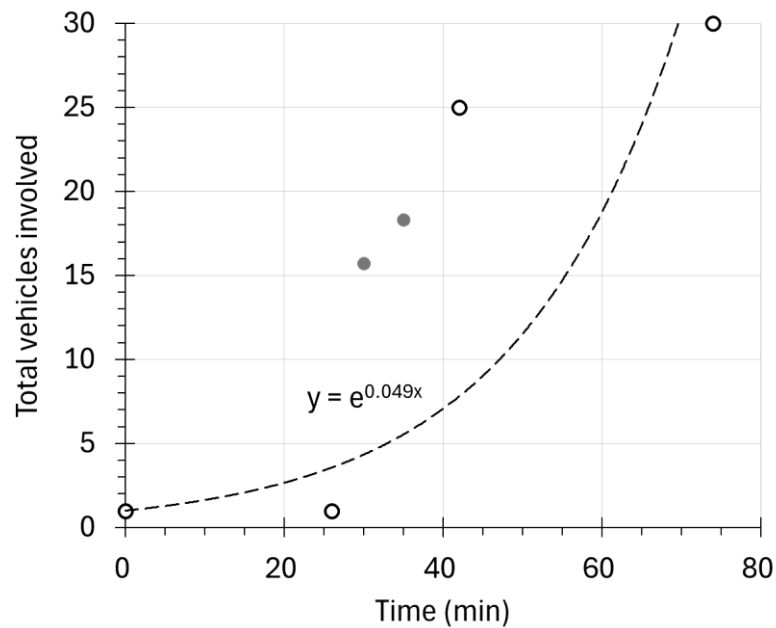


Figure 21. Estimated number of vehicles involved over time in the Kings Dock car park fire (open circles from MFRS reports, closed circles are by analysis)

5.4 Stavanger airport Sola, Norway, 2020

The incident occurred in Stavanger airport Sola car park on 7th Jan 2020 in which a car caught fire on the ground floor of the five-storey building. The airport and municipal fire and rescue services undertook firefighting operations. However, the fire resulted in partial collapse of the structure 2 hr from the start of the incident. Subsequent to the fire, RISE Research Institutes of Sweden published a report on the incident [27] which has been primarily used for the analysis in this study. The RISE report makes use of the incident report published by the municipal Rogaland Fire and Rescue IKS [28].

The RISE study reported that the floor-to-ceiling height was effectively 2.5 m. No information was given on the width of the parking bays in the Stavanger airport car park. However, Bergen airport has 2.3 m wide bays and therefore this dimension has been adopted herein. The wind speed at the start of fire was reported to be approximately 11-12 m/s.



Figure 22. Photograph of the initial car alight showing vehicle parking arrangement in a double row, taken from Rogaland fire and rescue IKS report [28]

The incident began at 15:25 and at 15:36 the first vehicle was described as being “...all aflame...”. At 15:40 the fire had progressed so that “...several vehicles on fire observed”, estimated to be around four cars⁵ and by 15:43 it is likely that the fire had spread to 10 vehicles. The RISE report thereafter notes that “...there were 10 cars, after only a few minutes, 30...”. In this analysis it is assumed that ‘a few minutes’ is equivalent to an additional 5 min. Given the arrangement of the parked vehicles, it would seem unlikely that the 30 would be burning in a single row so it is assumed the double row is involved, similar to Kings Dock (see Section 5.3), but in a single direction as a result of the strong wind. Figure 23 shows the estimated number of vehicles involved in the fire as a function of time.

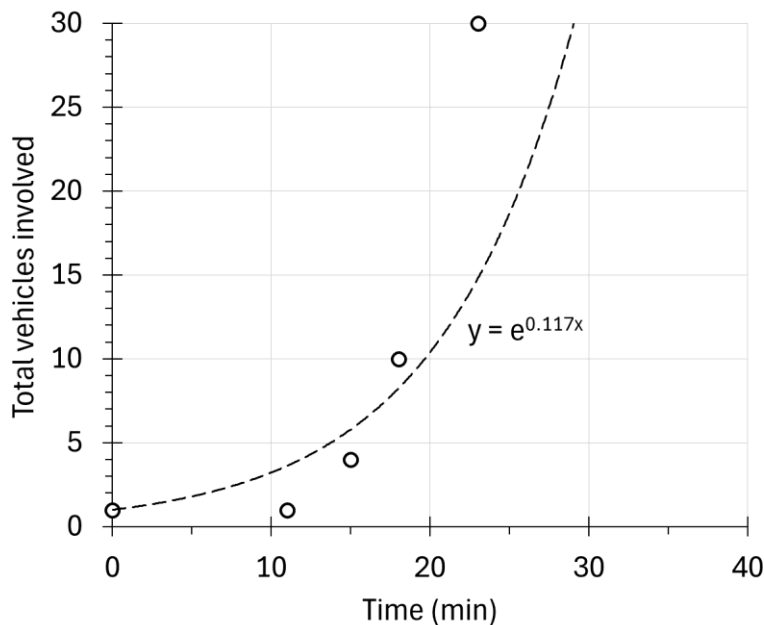


Figure 23. Estimated number of vehicles involved in the incident over time in the Stavanger airport Sola car park fire

Using an estimated parking bay width of 2.3 m results in linear fire spread rates of 0.21 m/min at 15:36, 0.61 m/min at 15:40 and 1.28 m/min at 15:43 if it is assumed that the fire spread along a line of parked vehicles in a single direction. By the time the fire involved 30 vehicles in a double row then the linear spread rate could have increased to 1.5 m/min.

5.5 Open-air car park, China, 2020

A fire occurred in an open-air car park likely in China in May 2020, the exact location has not been determined. Ignition was in a charging electric vehicle in which it appears that the battery went into thermal runaway. In a widely shared security camera video footage⁶ of the incident the timestamp indicates that following the thermal runaway that ignition of the neighbouring vehicle occurs in around 40 s (Figure 24(a)). Thereafter the second vehicle rolled out of its parking bay but continued burning until the fire spread to the third vehicle after around 1 min 50 s from the start of thermal runaway (Figure 24(b)). No further vehicle-to-vehicle spread was recorded.

⁵ www.youtube.com/watch?v=-6juEM8UTsc

⁶ www.bilibili.com/video/BV1wHPLeUEga/



Figure 24. Fire in an open-air car park (a) ignition of neighbouring vehicle's tyre at around 40 s after the initiation of thermal runaway of the battery in the charging EV, (b) ignition of the rear of the third vehicle in the row

Since this incident occurred in the open-air the findings from this incident have not been included in the fire spread analysis presented in Section 6 other than to illustrate the possible rapid time to ignition of second vehicle when exposed to a flame resulting from the thermal runaway of the battery in an electric vehicle.

5.6 London Luton Airport, England, 2023

The fire occurred on 10th Oct 2023, starting in a diesel-powered vehicle (Figure 25) on the third floor of the five-storey open-sided parking building (referred to as TCP2). The building had a footprint of approximately 12,000 m², with sufficient parking bays for 2,700 vehicles. It was reported that around 1,400 vehicles were destroyed in the incident. Bedfordshire Fire and Rescue Service (Bedfordshire FRS) released a Significant Incident Report [29] from which much of the analysis in this study is based.

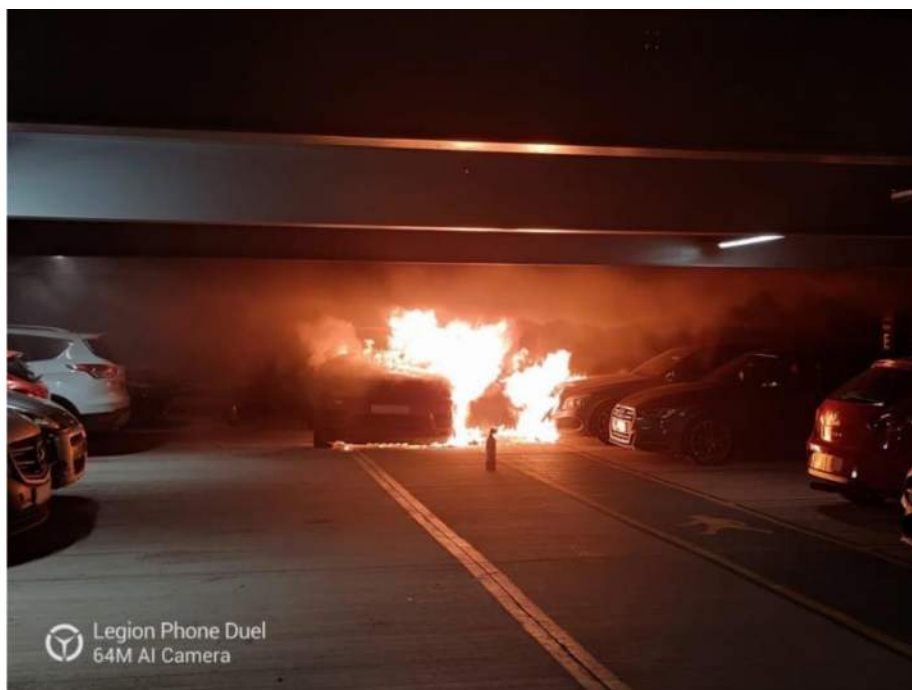


Figure 25. Car park employee digital image of the first vehicle that ignited and spread to a neighbouring vehicle (reproduced from ref. [29], no timestamp given)

The wind speed was reported to have been 10 mph (4.5 m/s) on the night of the incident and was noted by Bedfordshire FRS to have "...pushed the smoke through the car park" and "...enabled flames to be fanned and directed towards adjacent vehicles increasing the speed of fire development."

Bedfordshire FRS received a 999 call at 20:47, and by 20:52 reported that “...multiple cars involved in fire on the third floor (approximately three were visible from ground level).” Thereafter Bedfordshire FRS state that at 21:10 “... at least 6 on [the] 3rd floor were believed to be involved...” and then at 21:24 “...approx 25 cars involved in fire on third storey...”. By 21:37 it was reported that 80% of the third storey was involved. If it is assumed that the 1,400 destroyed vehicles were equally distributed over the five floors, this would suggest that $0.8 \times (1400/5) = 224$ were involved, noting that each floor had around $2700/5 = 540$ parking bays available. Figure 26 shows a graph of the estimated number of vehicles involved against time.

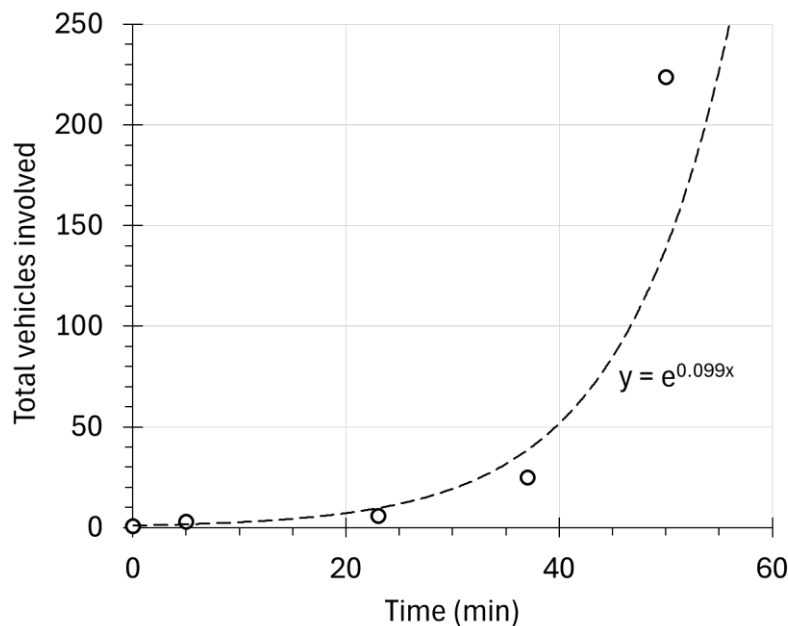


Figure 26. Estimated number of vehicles involved over time in the Luton Airport car park fire

No specific details on the width of the parking bays, nor the floor-to-ceiling height of the TCP2 car park have been identified. However the Luton Airport site also has another car park (TCP1) which OFR are aware that it has 2.4 m wide parking bays and a 3 m floor-to-ceiling height, so it is presumed these dimensions are representative of TCP2. Assuming fire spread in a single row of vehicles results in rates of 0.63 – 1.44 m/min up to 21:10. Where it was reported 25 vehicles were involved it is assumed this then involved two rows, giving a fire spread rate of 0.41 m/min. At the point 224 vehicles were involved it is unlikely spread was linear, so it is assumed that it was approximately equal in all directions. Using 80% of the 12,000 m² floor area suggests a spread distance of $\sqrt{0.8 \times 12000} = 98$ m in two directions to give a rate of 1.96 m/min at 21:37.

5.7 Link apartments, USA, 2025

The incident occurred on the 20th Feb 2025 on the North Davidson (NoDa) area of Charlotte, North Carolina. The fire started in the engine compartment of a BMW (not thought to be an electric vehicle by commentators on social media) on the third storey of six level car park (Figure 27).

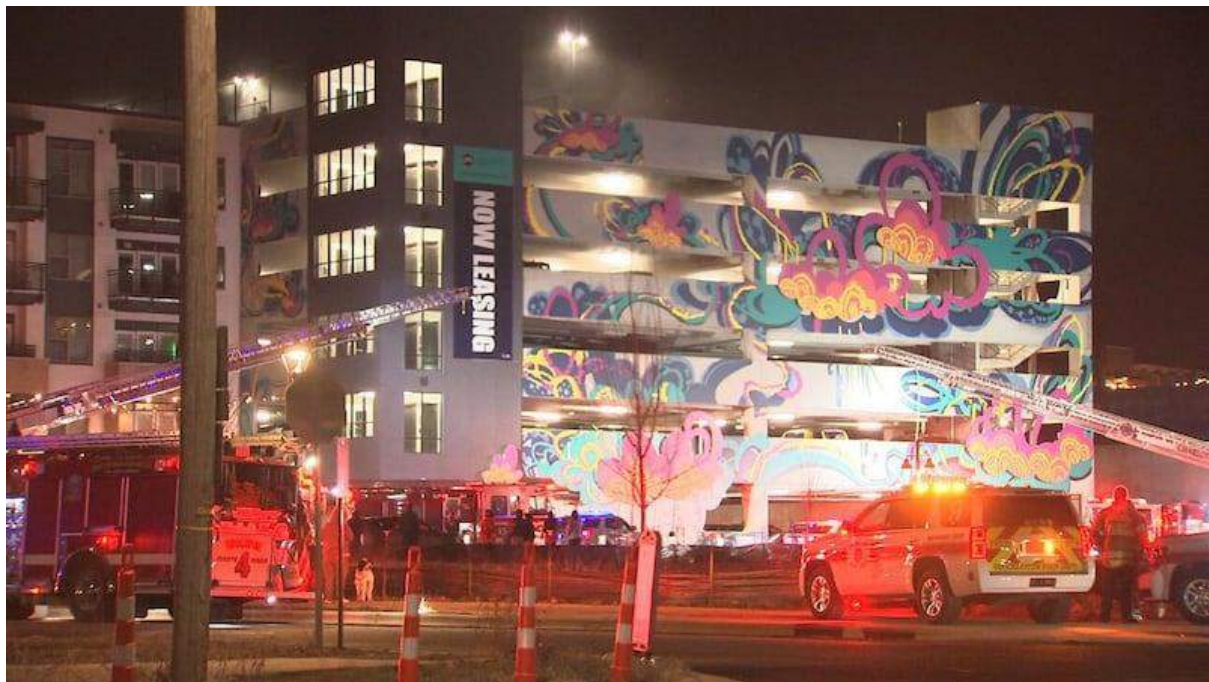


Figure 27. External view of the Link apartments car park

Multiple calls were received at 12:50 and when Engine 7 from Charlotte Fire Department arrived on scene at 12:54 it would appear that two vehicles were already burning (Figure 28). The fire was brought under control at 01:35. There is no mention of any influence from the wind on the fire spread and an online historical resource⁷ for the weather for Charlotte Airport notes still conditions at 12:52.



Figure 28. Vehicles burning during the Link apartments parking garage fire, numbers shown for identification (see Figure 29)

⁷ www.wunderground.com/history/daily/us/nc/charlotte/

A total of 14 cars were damaged in around 40 min, with a later article noting that “...at least six cars ruined by flames...” which appears to approximately tally with a video⁸ of the damaged row of cars (Figure 29). Examination of the video might suggest the logo on Vehicle 5 is Toyota which may point to Vehicle 4 being the first to ignite. However, the paucity of reliable information has meant it has not been possible to estimate the time at which each car ignited with great confidence.

No information on the width of the parking bays has been found but standard parking spaces in the USA appear to range from 8 ft up to 9 ft⁹. Assuming the parking bays to be 9 ft (2.74) m wide and that the fire travelled through six vehicles from end-to-end results in a spread rate of $(6 \times 2.74) / 40 = 0.41$ m/min. A lower bound estimate would be to use a parking bay width of 8 ft (2.44 m) for five cars assuming the fire started in Vehicle 4 to get a spread rate of $(5 \times 2.44) / 40 = 0.37$ m/min. Assuming the fire spread from the first to second vehicle in the four minutes between the calls and the arrival of the fire department would suggest spread rates of up to 1.37 m/min, although this does not account for the time between the vehicle likely igniting and the calls being made.

⁸ www.wbtv.com/2025/02/20/several-vehicles-caught-fire-inside-parking-deck-charlotte-apartments/

⁹ www.welovepaving.com/standard-parking-space-size-in-usa-a-complete-guide-to-dimensions-regulations-and-design-tips/

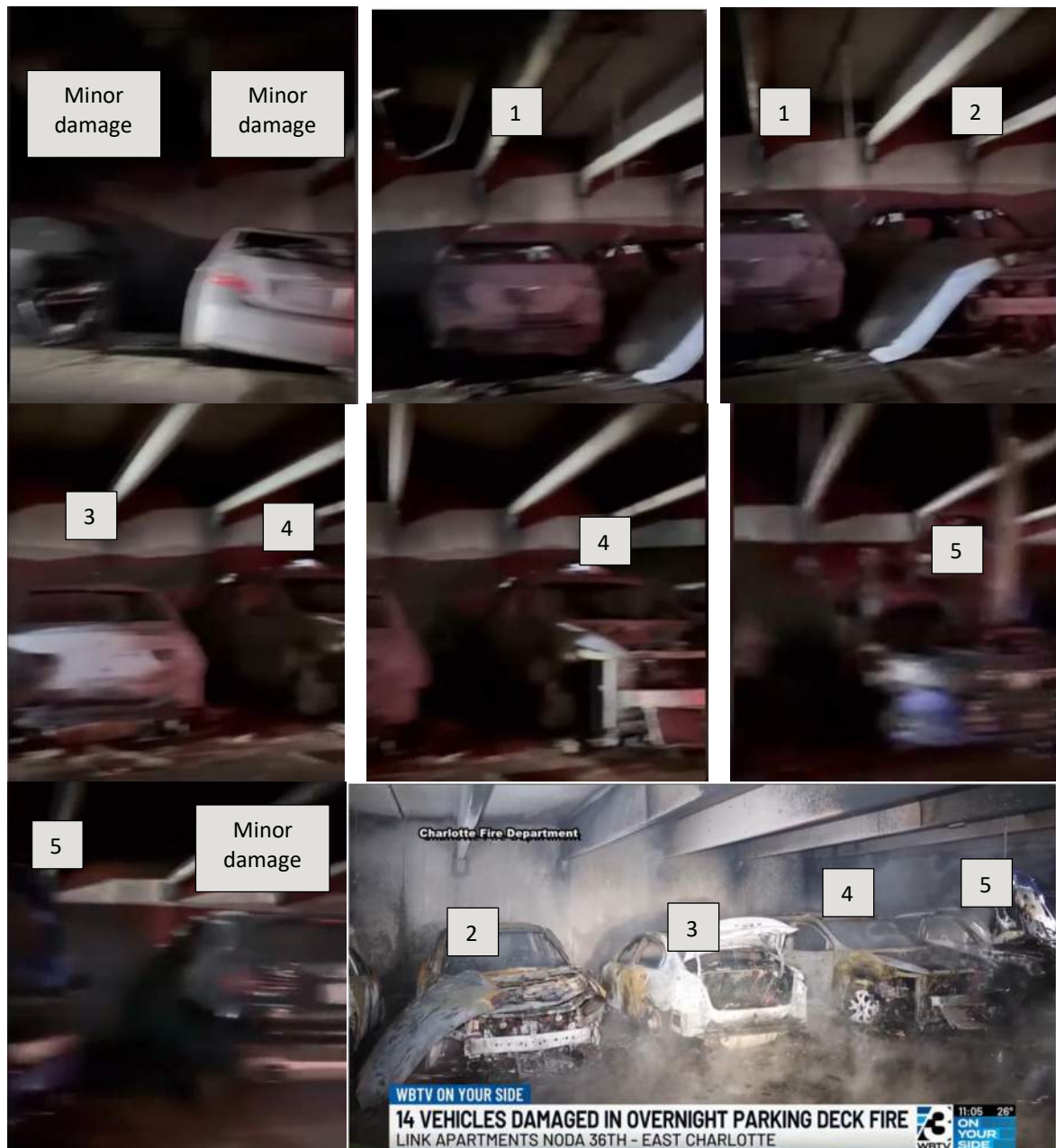


Figure 29. Images from the fire in the Link apartments car park with vehicles numbered for identification: (top) stills from a video of damage to the row of cars, (bottom) photograph of fire damaged cars

Details of floor-to-ceiling height have not been identified but the photographs suggest it was around 3 m. This estimate is supported by an examination of the height of the car park on Google Earth which the ground to the underside of the sixth storey height is around 15 m.

6. DISCUSSION AND ANALYSIS OF CAR PARK FIRE SPREAD

This section of the report discusses and analyses key events within the presented laboratory-based tests and real fire incidents shown in Sections 4 and 5. It focuses on the spread from the first vehicle ignited to the second, i.e., the onset of spread, the transition to multiple vehicles thereafter and then proposes / critiques potential models for evaluated car park fire spread.

6.1 Second vehicle ignition

6.1.1 Time analysis

Findings from the review of laboratory tests show that the time to fire spread from an initially burning vehicle to a second vehicle can vary over a wide range. The time is likely influenced by several factors including where the first vehicle is ignited, how fast the fire grows, the open or closed status of any of the passenger compartment windows, the proximity of the two vehicles, etc. Identifying the time to spread to a second vehicle in multiple car fire spread incidents has been more difficult to obtain. In the Lloydstraat car park incident the second vehicle was thought to have ignited after 10 min. The data from Steinert, Bürgi, Park et al., Li et al, Joyeux, ELBAS and the Lloydstraat incident (Table 14) gives a second vehicle ignition time of 17 ± 12 min, with a minimum value of 3.5 min.

Table 14. Summary of second vehicle characteristics

Test / incident	Ignition time (min)	Separation distance (m)	Separation spread rate (m/min)
Bürgi	3.5	0.5	0.14
Jaing et al.	20.5	0.8	0.04
Steinert	30	0.8	0.03
	35	0.4	0.01
	22.5	0.8	0.04
	12	0.8	0.07
	52	0.8	0.02
	28.5	0.8	0.03
Joyeux	12	0.7	0.06
	9	0.7	0.08
	12	0.7	0.06
	8	0.7	0.09
	14	0.7	0.05
Li et al.	20.2	0.8	0.04
Park et al.	8.3	0.5	0.06
ELBAS	5	0.4	0.08
	5	0.4	0.08
	16	0.4	0.03
Lloydstraat	10	0.5	0.05

A first-order approximation in which time to ignition via radiant heat flux is characterised with a point source would result in a $1/r^2$ relationship. The point source model for second vehicle ignition was used with some success by Tohir et al. [30] for the BRE test programme (see Section 4.5). Figure 30 shows a graph of time to ignition of the second vehicle versus vehicle separation distance (r) from the tests in which the distance was documented. Notwithstanding the multitude of factors that can affect the ignition time, a best-fit such that:

$$t_{ign,2} = 19.2 r^2 + 13r \quad (1)$$

where r is the separation distance in metres between the first and second vehicles, suggests there is a relationship between the separation distance and time to ignition, although the relationship is weak due to the scatter in the data. Care should be exercised extrapolating the relationship beyond the separation distances found in the literature, for example, at a (theoretical) separation distance of 0 m it is unlikely a second vehicle would immediately ignite.

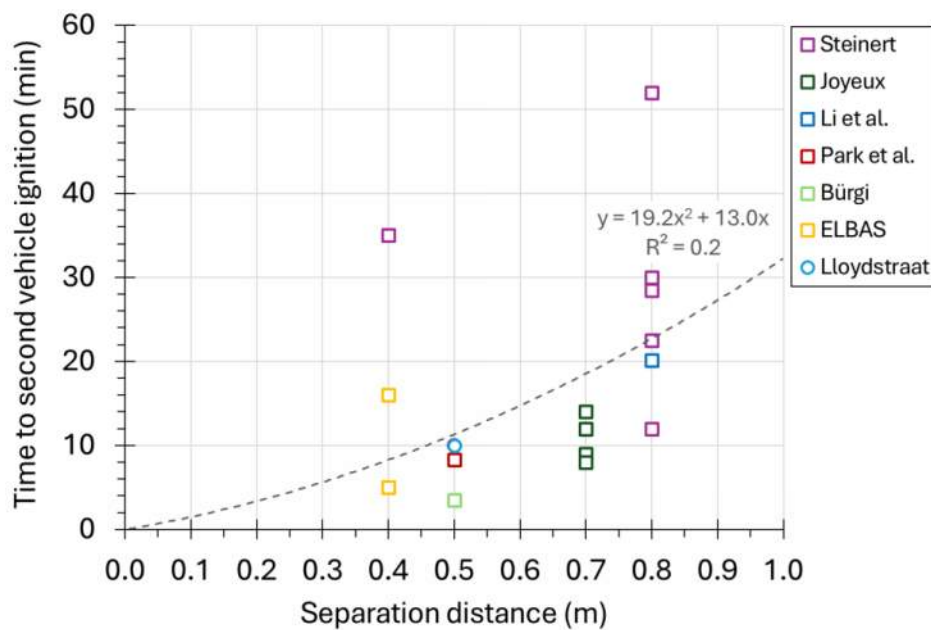


Figure 30. Time to second vehicle ignition as a function of separation distance

6.1.2 Separation fire spread rate

The separation fire spread rate is defined herein as the time taken for spread between two vehicles over their distance apart. This differs from the spread rate across parking bays in which the distance of interest is the dimension of the bay. Figure 31 shows a graph of separation spread rate as a function of separation distance in which there is no apparent relationship between the two parameters. However, the data suggests that an average spread rate of 0.054 m/min (shown by the dashed line) provides a representative value, again noting that at 0 m separation the time to second vehicle ignition is unlikely to be zero in most scenarios.

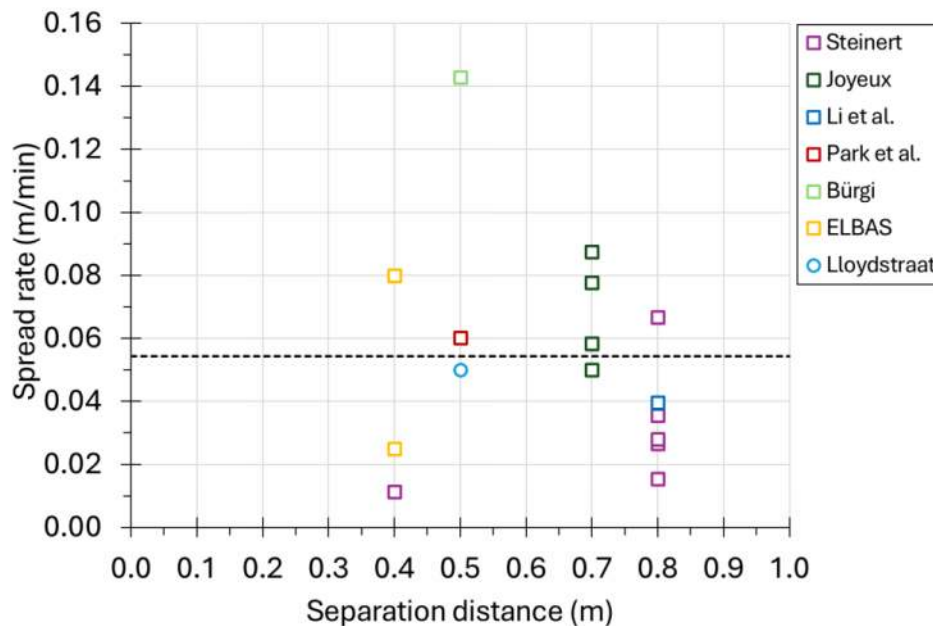


Figure 31. Separation fire spread rate as a function of separation distance, with average shown by the dashed line

As discussed in Section 6.2.2, the external wind has an influence on spread rate. However, in the case of ignition from the first to the second vehicle very few of the data have external wind speed reported and therefore any relationship between the two parameters cannot be ascertained.

Where the separation between vehicles is unknown then the time to second vehicle ignition can be estimated by using the parking bay width and vehicle width. Typical parking bay dimensions are noted in the WP 3A report where, for example, a medium-stay parking bay will be 2.60 m wide and 5 m long. Thus, for a modern vehicle with a width of 2 m (Table 6) the time to second vehicle ignition would be $(2.6 - 2.0) / 0.054 = 0.6 / 0.054 = 11$ min, or around 14 min from Equation (1). For a 2.4 m wide parking bay, the delay is 7 min 24 s. Clearly there is scatter in the spread rate data in Figure 31 such that times to second vehicle ignition could range from $0.6 / 0.14 = 4.5$ min up to around $0.6 / 0.01 = 60$ min.

6.1.3 Electric vehicles

With the current increase in electric vehicles (EVs) on the road there is considerable discussion in the literature regarding the thermal runaway of batteries and their potential impact on fires in car parks. In terms of fire spread to a second vehicle, the available information on whether the ignition time will be reduced when compared to internal combustion engine vehicles is limited.

The impact on second vehicle ignition time will partly depend on whether the fire starts in the energy storage system or within another part of the vehicle. As noted in Section 4.8, Tramoni et al. [16] were not able to achieve thermal runaway of the battery in an EV when the fire was started in the vehicle away from the battery. In the ELBAS tests (Section 4.9) the fire in the first vehicle was initiated in the battery of the EV and the ignition times of neighbouring vehicles were noted to be within 5 min in one test but likely to be around 16 min in a second case. Compared to other tests, the separation between vehicles in the ELBAS tests was at the lowest end of the range. However, there have been several videos of vehicle batteries apparently going into thermal runaway in which the time to ignition of neighbouring vehicles was relatively short. One such incident is discussed in Section 5.5, and another widely shared video¹⁰ from an incident from 2019 in a car park in Shanghai shows the ignition of a neighbouring vehicle within around 5 s from the indications of thermal runaway.

¹⁰ www.youtube.com/watch?v=uV2cwqdHuTA



Figure 32. Still image taken from a security camera video of spread of fire to a neighbouring vehicle following thermal runaway of a battery

Thus, where a fire starts in an electric vehicle due to the thermal runaway of a battery it might be reasonable to use a relatively short time for second vehicle ignition of the order of 5 – 40 s, say 20 s, or simply assume it is 0 s for conservatism.

6.2 Analysis of multiple vehicle spread

6.2.1 Key characteristics

This section provides a summary of the findings from the tests and incidents examined in Section 4 and Section 5 in which multiple cars were involved beyond a second vehicle ignition, as shown in Table 15. Examination of the maximum fire spread rate shows that the incidents generally have higher values than determined from the tests. There might be a multitude of reasons for this such as the influence of wind, the vehicle spacing, the height of the space in which the fire took place, and/or the effect of a larger number of simultaneously burning vehicles in the incidents.

Table 15. Summary of key characteristics involving multiple vehicle fire spread

Test / incident	External wind speed (m/s)	Floor-to-ceiling height (m)	Parking bay width (m)	Fire spread rate (m/min)		Vehicle involvement exponent
				Min	Max	
BHP	~5.5	2.5	2.60	0.10	0.20	0.041
Joyeux	n/a	2.3 or 2.6	~2.50	0.18	0.31	n/a
Kitano et al.	3	2.9	2.50	0.12	0.29	0.057
Steinert	n/a	4.5	~2.50	0.06	0.22	n/a
BRE	0	2.9	2.40	0.12	0.70	0.049
Li et al.	n/a	12	~2.40	0.13	0.43	n/a
Park et al.	0	n/a	~2.30	0.28		n/a
Tramoni et al.	0	3	2.50	0.09	0.31	n/a
ELBAS	n/a	2.40	~2.50	0.14	0.48	n/a
Schiphol	0	2.6	~2.20	0.38	0.83	0.059
Lloydstraat	~4.5	2.4	~2.20	0.18	0.22	0.059
Kings Dock	5	2.6	2.47	0.20	0.35*	0.049
Stavanger airport	12	2.5	2.30	0.21	1.50	0.117
Luton airport	4.5	3.0	~2.40	0.41	1.96	0.099
Link apartments	0	~3.0	~2.40	0.37	1.37	0.046

*4.95 m/min using 2 cars per minute

Figure 33 collates the number of vehicles involved with time showing a best-fit exponential curve along with the upper and lower bound curves. The fire at Stavanger airport showed the fastest fire spread.

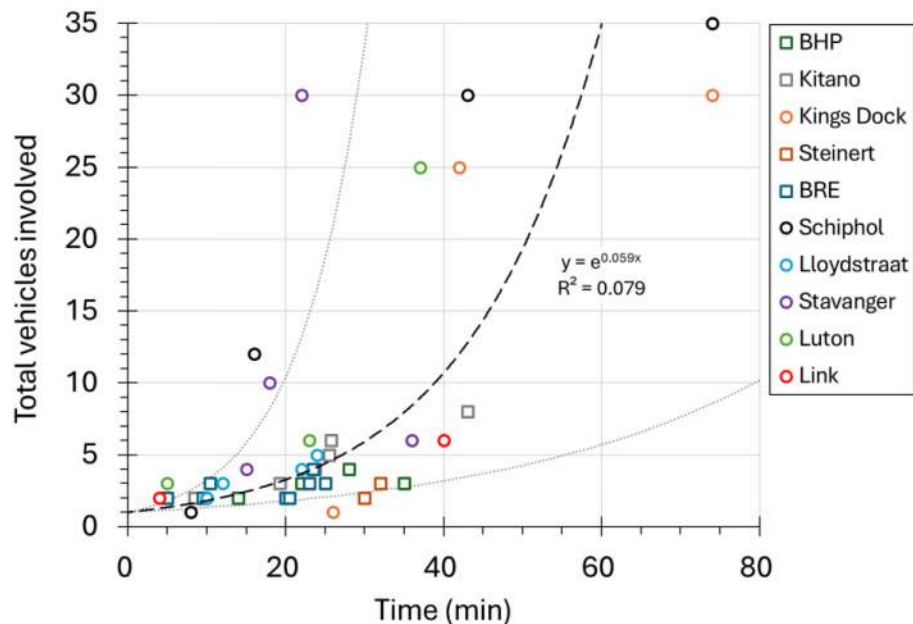


Figure 33. Number of vehicles involved in the car park fire tests and incidents

Figure 34 shows the collated fire spread findings where again the Stavanger airport fire stands out. Part of the objective of this graph is to investigate whether the rate of fire spread changes with time. However, there is considerable scatter in the data suggesting there is no relationship.

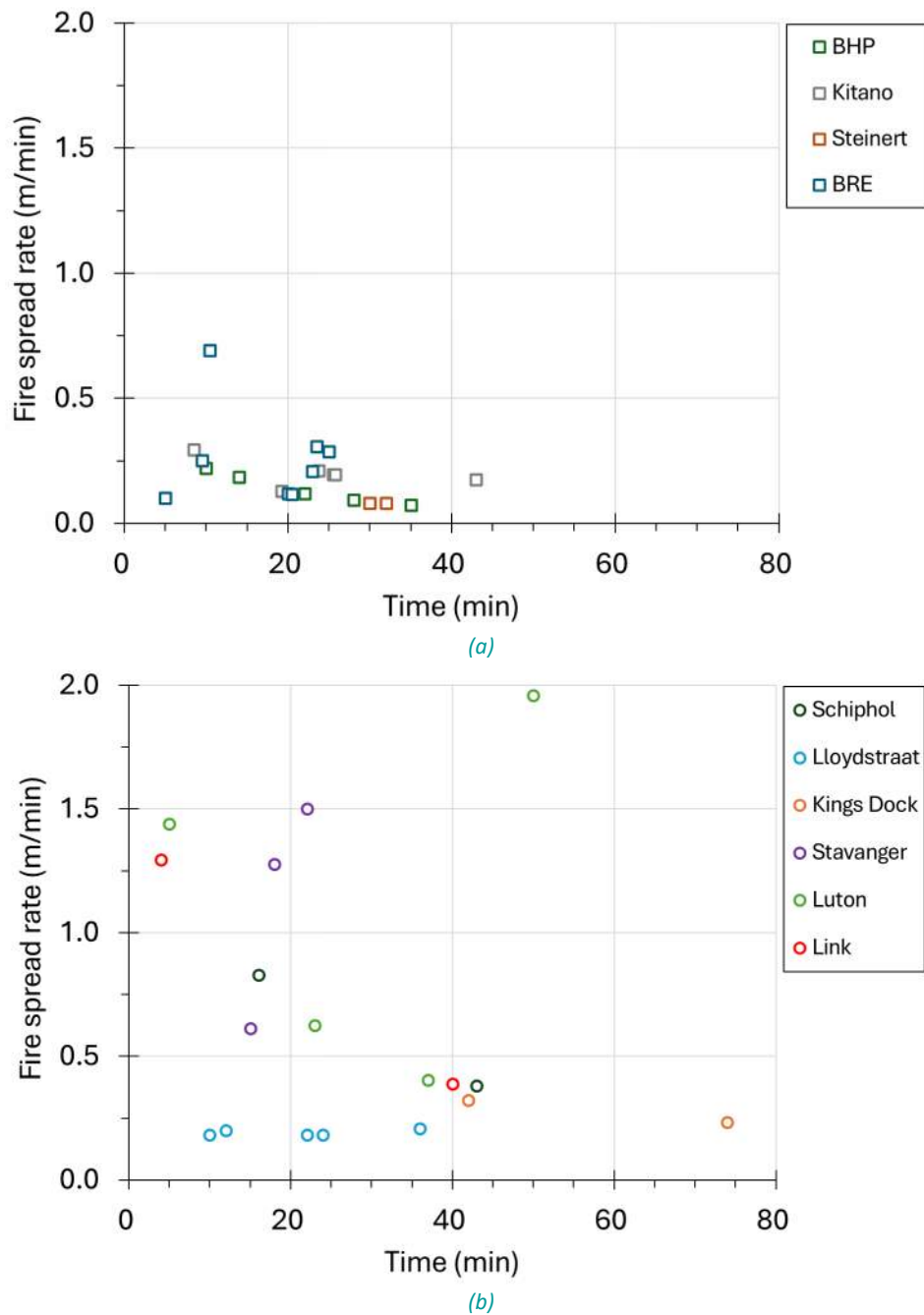


Figure 34. Fire spread rate with elapsed time of the fire (a) laboratory tests, (b) incidents

6.2.2 External wind

The effect of wind on fire spread is a complex topic with a number of important wind-fire interactions that occur as previously discussed by Pitts [31]. Although Pitts does not consider fire spread in car parks, it does include a discussion on urban fires, albeit where the flow of air is not constrained within a building structure. An examination of the findings from the individual tests and incidents suggests that the external wind can play an important role in the spread of fire between vehicles in a car park. This is particularly true for the incidents, in which there are several cases where the fire and rescue services noted the impact of the wind on fire and smoke spread. Figure 35 shows the exponent for the best-fit curves against the stated external wind speed, noting that not all the BHP tests included the effect of an external wind.

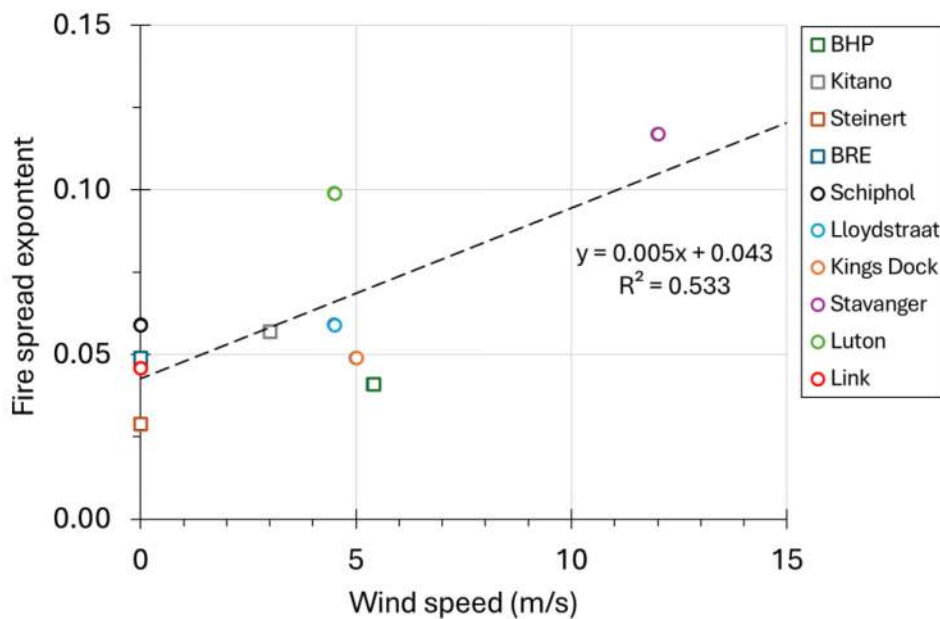


Figure 35. Variation in total vehicle spread exponent with external wind speed

Figure 35 also includes a best-fit straight line through the data which indicates there is likely to be a relationship between the number of vehicles involved over time with external wind speed. This is investigated further in Section 6.3.1.

An alternative approach for the impact of external wind speed on vehicle-to-vehicle fire development is to investigate the linear fire spread rate as a function of the external wind speed as shown in Figure 36. Here there is considerable scatter in the data across the range of external wind speeds, although much of the data is clustered below 0.5 m/min at external wind speeds between 3 m/s and 5.5 m/s. At an external wind speed of 0 m/s the spread rate is 0.33 ± 0.35 m/s (with lower and upper bounds of 0.08 m/min and 1.3 m/min respectively). The rationale for the indicated power law curve is discussed in Section 6.3.1

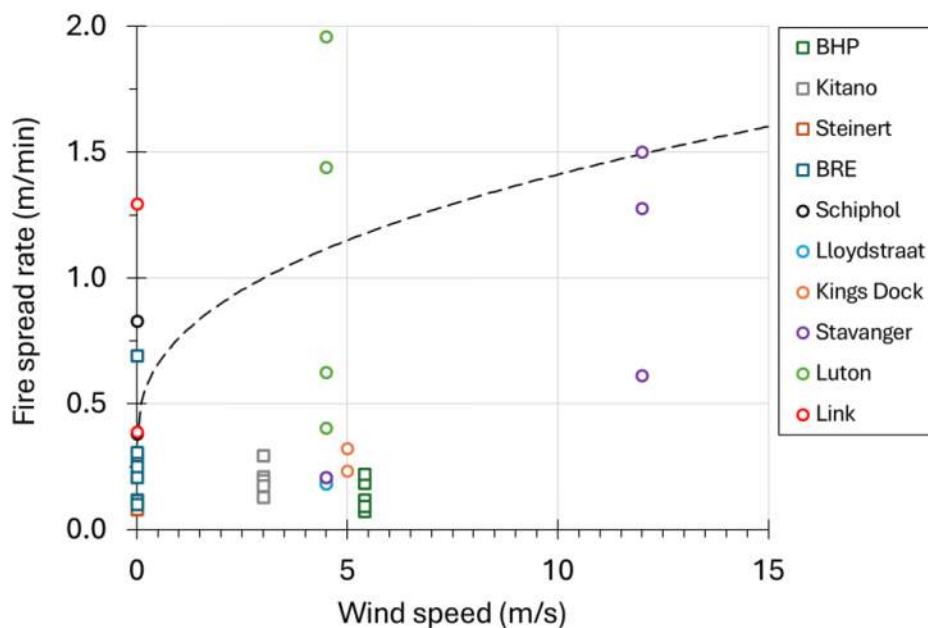


Figure 36. Change in linear fire spread rate with external wind speed

As well as accelerating the fire spread rate in the windward direction, the wind may also impact on the spread rate against the wind. Cheney and Sullivan [32] note that for grassfires that the “...backing rate of spread is largely unaffected by increasing wind speed...”. Clearly fire spread in car parks are not grassfires. The analysis of the Kings Dock fire (Section 5.3) illustrates this effect in which the spread rate is estimated to be 0.20 – 0.29 m/min against the wind and 0.27 – 0.35 m/min in the windward direction, i.e. the spread rate against the wind is 80% of the windward spread rate. This limited information suggests there may be some relative slowing of the fire spread against the wind, but the impact is not large.

6.2.3 Floor-to-ceiling height

Figure 37 shows the exponent for the best-fit curves against floor-to-ceiling height with objective to investigate whether the rate of spread changes with height. The CFD simulations carried out as part of WP 1B suggest that as the height increases then the rate decreases. Excluding the work of Steinert (who used a 4.5m floor to ceiling height), Li (with a 12 m floor to ceiling height), and Park (with a calorimeter hood above the vehicles) Figure 37 suggests there is no obvious influence, although the variation in constructed car park floor-to-ceiling heights is generally limited to 2.4 to 3 m.

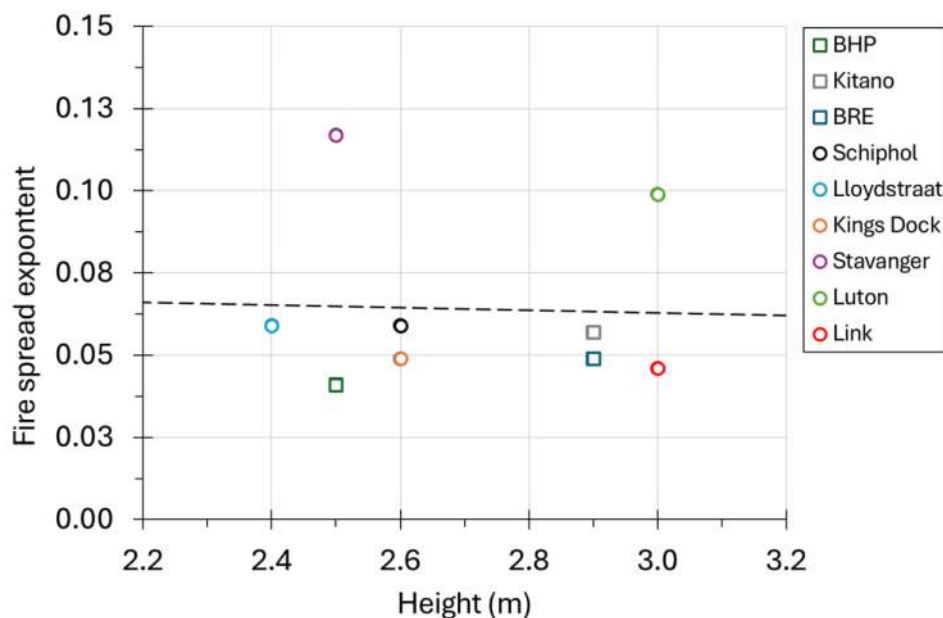


Figure 37. Variation in vehicle spread exponent with car park floor-to-ceiling height

A graph of fire spread rate against car park floor-to-ceiling height (Figure 38) also does not indicate any obvious relationship between the two parameters.

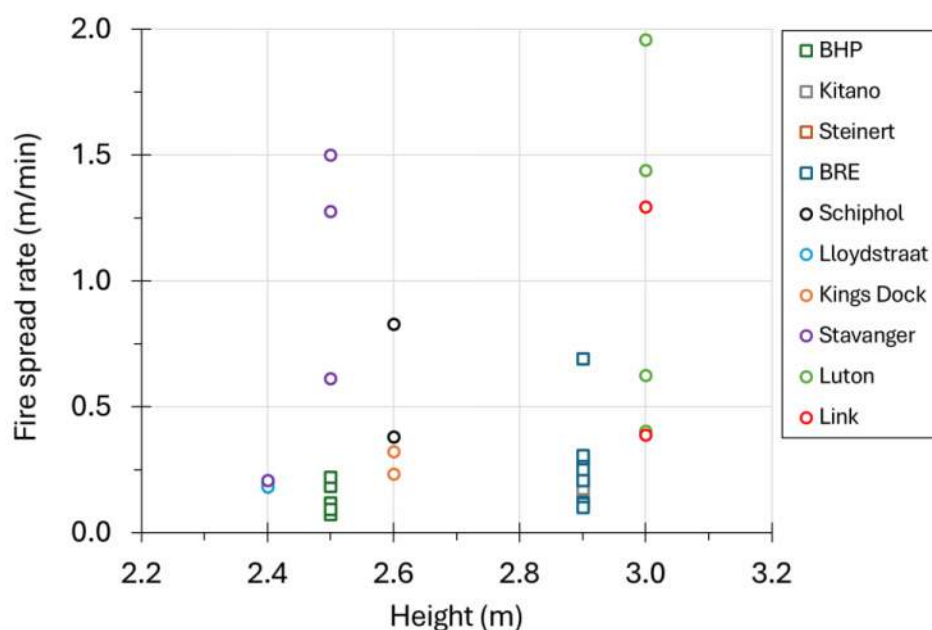


Figure 38. Variation in vehicle fire spread rate with car park floor-to-ceiling height

It is plausible that higher car park floor-to-ceiling heights provide a greater opportunity for external wind to influence fire spread. This could be through mechanisms that introduce fresh air into the combustion zone and direct the flames to lean towards yet to be ignited vehicles. An increased floor to ceiling height can also have positive effects, as discussed in WP 1B, in terms of reducing the incident heat flux from ceiling jets at the point fires become larger.

6.2.4 Fire spread rate considering vehicle drivetrain

Table 15 provides a summary of the minimum and maximum fire spread rates determined from the tests and incidents investigated in this study. It is useful to consider whether such vehicle-to-vehicle fire spread rate depends on vehicle drivetrains (i.e. petrol, diesel or battery).

Most of the vehicles used in the tests and involved in the incidents had internal combustion engines. This is partly due to modern electric vehicles being newer to the market. As observed in the Kings Dock incident (Section 5.3) and also by Bürgi [18], where internal combustion engine (ICE) vehicles are present then this may lead to running hydrocarbon fuel fires that will likely have an impact on further vehicle ignition; likely increasing the rate of fire spread. The likelihood of a fuel tank rupturing will depend on the construction materials, with more modern vehicles using plastic compared to metal in older vehicles. Running fuel fires may also be influenced by sloping floors, ramps, etc. that may be part of a car park structure. The tests and incidents investigated in this study do not provide sufficient information to place any modification on the fire spread rates as is the case for the influence of external wind discussed in Section 6.2.2.

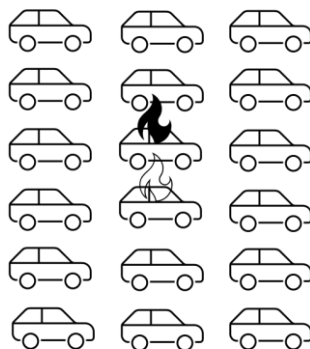
When considering electric vehicles, the possible impact on second vehicle ignition time when allowing for the thermal runaway of a battery is discussed in Section 6.1. However, it is useful to consider whether fire spread will also be impacted by the batteries in other electric vehicles. As already noted, in Tramonì et al.'s tests they were unable to get thermal runaway when their electric vehicles were ignited away from the battery. In the investigation report [27] of the Stavanger airport incident RISE concluded that "*Observations during the fire indicate that electric vehicles did not contribute to the fire development beyond what is expected from conventional vehicles*". Similarly, Siemon and Rupp [33] note that when discussing electric vehicles that "*when igniting the cars from the outside or at the seat, no significantly different fire progression can be detected compared to ICE cars*." Therefore, it seems reasonable to suggest that the presence of electric vehicles does not alter the rate of vehicle-to-vehicle fire spread beyond the impact of the vehicle first ignited compared with vehicles with internal combustion engines.

6.2.5 Transition to multi-dimensional spread

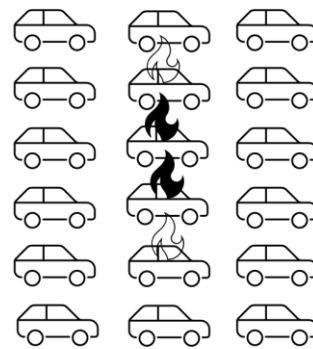
Section 3.1 discusses the general principles of likely fire spread between vehicles in car parks. This section investigates the transition from spread that is limited to a row of vehicles to spread that also occurs between rows. Several of the incidents investigated in this study had adjoining rows of parked vehicles (e.g. Kings Dock, Section 5.3) that became involved as the fire developed. Similarly, Kitano et al. (Section 4.3) had two rows of vehicles in their test which the fire eventually spread to. It is plausible to consider that after the fire spread from the initial vehicle to a second vehicle then further spread would be along the same row of parked vehicles as illustrated by Kitano et al.'s ignition times. However, at some point the fire transitions to include the adjoining row/s and therefore spreads in several dimensions.

At what point this transition takes place cannot be precisely determined. The Kings Dock incident indicates that once 25 cars were involved the transition to multiple row involvement had already occurred. Kitano et al. achieved spread to the second row after three vehicles had ignited, and similar results were obtained in one of the BHP tests (Section 4.1). In the analysis of fire spread carried out after the Schiphol Airport fire (Section 5.1) it was also assumed that fire would spread to an adjoining row after three cars had ignited.

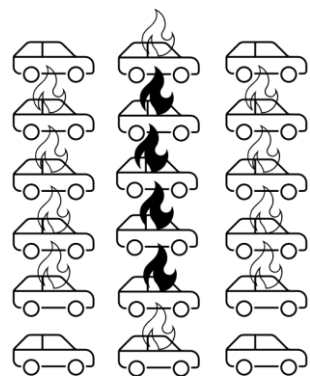
Figure 39 shows a scenario proposed herein in which fire spread is assumed to first to take place from an initial vehicle to a second one (Figure 39(a), as discussed in Section 6.1), and then spreads in two directions from those to vehicles to their neighbours along the same row such that four vehicles are then burning (Figure 39(b)). Thereafter, the spread transitions to include an adjoining row and spread occurs in two dimensions (Figure 39(c) and (d)). Fire could continue to spread along and across rows (not shown in the illustration). The scenario demonstrates how the rate of vehicle involvement increases as the transition occurs.



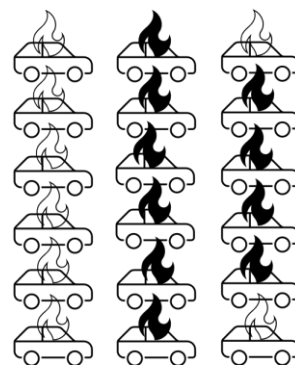
(a) One vehicle on fire. The initially burning vehicle heats a second vehicle



(b) Two vehicles on fire. Fire spread to the second vehicle. The two burning vehicles heat their neighbours



(c) Four vehicles on fire. Fire spreads to four vehicles. These vehicles heat up neighbours in the same row and across the adjoining rows



(d) Ten vehicles on fire. Vehicles in an adjoining row ignite as well as the neighbours in the original row.

Figure 39. Illustration of a two-way fire spread scenario from a single vehicle within a row to neighbouring vehicles and adjoining rows.

Where there is an external wind, it is plausible that the fire will spread further along the initial row of vehicles before transitioning to a spread to adjoining rows. However, it is not possible to verify this is the case from the limited information available from the incidents and laboratory tests.

6.3 Fire spread models

6.3.1 Wind-aided spread

The analysis in Section 6.2.2 suggests there is a relationship between vehicle-to-vehicle fire spread in car parks and the external wind speed. Using the linear best fit shown in Figure 35, an empirical equation for the cumulative number of vehicles (V_n) involved in the fire as a function of time (t) when accounting for the external wind speed (u) in m/s is:

$$V_n = \exp(t \times (0.005u + 0.043)) \quad (2)$$

An alternative approach is to consider the linear fire spread rate. Pitts [31] cites work that shows a non-linear relationship for the rate of fire spread as a function of wind velocity. He notes that best-fit correlations can be found in exponential or power law forms (albeit Pitts is discussing beds of pine needles and not parked cars). Figure 36 includes a tentative fit for wind-driven fire spread rate as a function of external wind speed (u) in the form of a power law such that:

$$v_f = v_0 + au^b$$

leading to

$$v_f = 0.33 + 0.43 \times u^{0.4} \quad (3)$$

The value for v_0 is the mean linear spread rate of 0.33 m/min when the external wind speed is 0 m/s as determined from the Steinert, BRE, Schiphol Airport and Link apartments data (see Sections 4.4, 4.5, 5.1 and 5.7). The constants a and b have been manually selected to allow the fit to give a velocity of 1.5 m/min for an external wind speed of 12 m/s to correspond to the findings discussed for Stavanger airport (see Section 5.4). When compared to the data that in many cases the fitting model gives a higher fire spread rate than determined by the analysis of tests and incidents. An application of the fire spread rate with external wind is presented in Section 6.3.3, and comparisons made with the data in Section 6.3.4.

6.3.2 Burning area

A simple analytical method to determine the increase in area of burning over time is to consider a fire as starting at a point and the spread occurs equally in all directions at a nominated flame front velocity. This approach forms the basis of the alpha t-squared (αt^2) fire growth equation found in many codes and standards around the world.

Since the increase in area depends on the flame velocity, then:

$$v_f = \frac{r}{t}$$

thus

$$r = v_f t$$

and

$$A = \pi(v_f t)^2$$

This can be written as

$$A = \beta t^2$$

where

$$\beta = \pi v_f^2$$

β is used here rather than α as alpha often has associated constants to represent 'ultra-fast', 'fast', 'medium' and 'slow' fires that include factors.

Values for v_f (in m/min) as a function of external wind speed can be derived from Equation (3), noting the previous comment regarding higher linear spread rates than found in the analysis of tests and incidents. Thus, β can be expressed as:

$$\beta = \pi(0.33 + 0.43 \times u^{0.4})^2$$

To determine the number of vehicles involved, the calculated area is divided by a parking efficiency which then allows for the parking bay area per vehicle plus the ancillary space that provides adequate room to allow vehicles to enter and exit the car park. In this study it is proposed that a parking efficiency of 35 m² is used, as adopted in the WP 3A report on occupant numbers.

This model assumes that fire spread occurs equally in all directions from the initiating vehicle and that any external wind effects have no directional factors. A more sophisticated calculation for wind directionality could be incorporated using approaches employed in wildfire analysis in which elliptical burning areas are established (e.g. as discussed in Cheney and Sullivan [32]).

6.3.3 Three stage model

The wind-aided and the burning area models are likely to have some utility simply because they are single-expression equations. However, neither model capture some of the nuances of vehicle-to-vehicle fire spread in car parks. Here a relatively simple analytical model is proposed that breaks the vehicle-to-vehicle fire spread into three stages, as described below.

- **Stage 1:** This represents the time taken for the fire to spread from the first vehicle to a second vehicle ($t_{ign,2}$). The discussion in Section 6.1 suggests this can be represented by applying the average separation fire spread rate of 0.054 m/min for the separation distance between the first two vehicles, but not allowing the calculated spread time to be less than 3.5 min. The model can be easily adjusted to alter the second vehicle ignition time to account for the fire in the first vehicle starting as the result of thermal runaway.
- **Stage 2:** The fire is assumed to spread along a single row of neighbouring vehicles at a specified spread rate, i.e. the spread is 'one-dimensional'. The spread continues until a critical number of burning vehicles is exceeded at which point the fire then starts to spread in the 'second' dimension. The model assumes that the fire spread in the second dimension immediately starts with the critical number of vehicles burning. The critical number is set to four vehicles as discussed in Section 6.2.5.
- **Stage 3:** The fire now spreads both along and between the rows of parked vehicles, i.e. the fire spread is 'two-dimensional'. The model assumes that spread between rows occurs in both directions (Figure 2(e) or (f)).

The model can be configured to have the fire spread to be either one-directional or two-directional, i.e. the fire can be assumed to start in a vehicle at the edge of the parking area and therefore spread is one-directional, or the fire can be considered as starting in the middle of a car park so that spread is two-directional (see Figure 39).

In Stages 2 and 3 the number of vehicles burning is determined by defining a parking bay width and length. The spread rate in a windward direction is calculated using Equation (3) and it is assumed herein that this spread occurs in the parking bay width direction. If the fire spread is assumed to be two-directional then the spread rate against the wind is taken as 80% the windward spread rate (see Section 6.2.2). The spread rate in the second dimension is taken to be that at a wind speed of 0 m/s, i.e. 0.33 m/min. The result of using this model is compared with the wind exponential and beta t-squared models in Section 6.3.4.

This model has several assumptions and limitations, some of which have already been discussed above. In addition, the model assumes that each vehicle has the same width which is parked in the centre of a parking bay such that the separation between each vehicle in a long row is uniform. In reality some vehicles will be closer together and others further apart, and where there are a larger number of vehicles present the differences in spacing will 'average out'. The model does not restrict the extent of spread in any direction as would be the case with a car park with a fixed floor area; the model assumes all the parking bays have a vehicle in place; the spread between rows of vehicles is assumed to be the length of a parking bay and does not account for the circulation

aisles etc. although this could be addressed by using an ‘effective’ parking bay length which is greater than just the bay dimension.

The model can easily be implemented in a spreadsheet or implemented in a programming environment such as Python. Although specific input parameters are used in this study, the model has flexibility that allows a user to adopt different values should they so wish to.

6.3.4 Comparison

Here a comparison is made of the three models developed in this section against the total number of vehicles involved in the tests and incidents presented in Section 4 and Section 5. For clarity the test and incident data are not identified by its specific name but is simply shown as a single dataset.

The parking bay width is chosen to be 2.32 m, which is the average of all the tests and incidents, and the parking bay length taken as 5 m. The separation distance between the first two vehicles is taken as 0.64 m, the average of those distances reported in the tests and incidents.

Three external wind speeds have been selected for the comparison, namely 0 m/s, 4.3 m/s (the mean external wind speed across the tests and incidents), and 12 m/s (the highest external wind speed reported during the Stavanger airport incident). Figure 40 to Figure 42 shows the comparison in which the test and incident data is shown by the solid circles. Fire spread in the rows in one direction and two directions is shown for the three stage model. In each case an inset graph shows the comparison for the first 45 min of the scenario (noting the aspect ratio of the image is taller and narrower than the main graph).

Figure 40 (inset) shows the transition from the single row of vehicles to several rows at the point four vehicles are considered to be involved by the jump at around 27 min in the two-directional spread. As expected, the transition occurs earlier as the external wind is increased as this means the four-vehicle threshold occurs sooner. Where there is data for early-stage fire development at which point only a few vehicles are involved it would appear that the three stage model gives its best predictions at an external wind speed of 0 m/s.

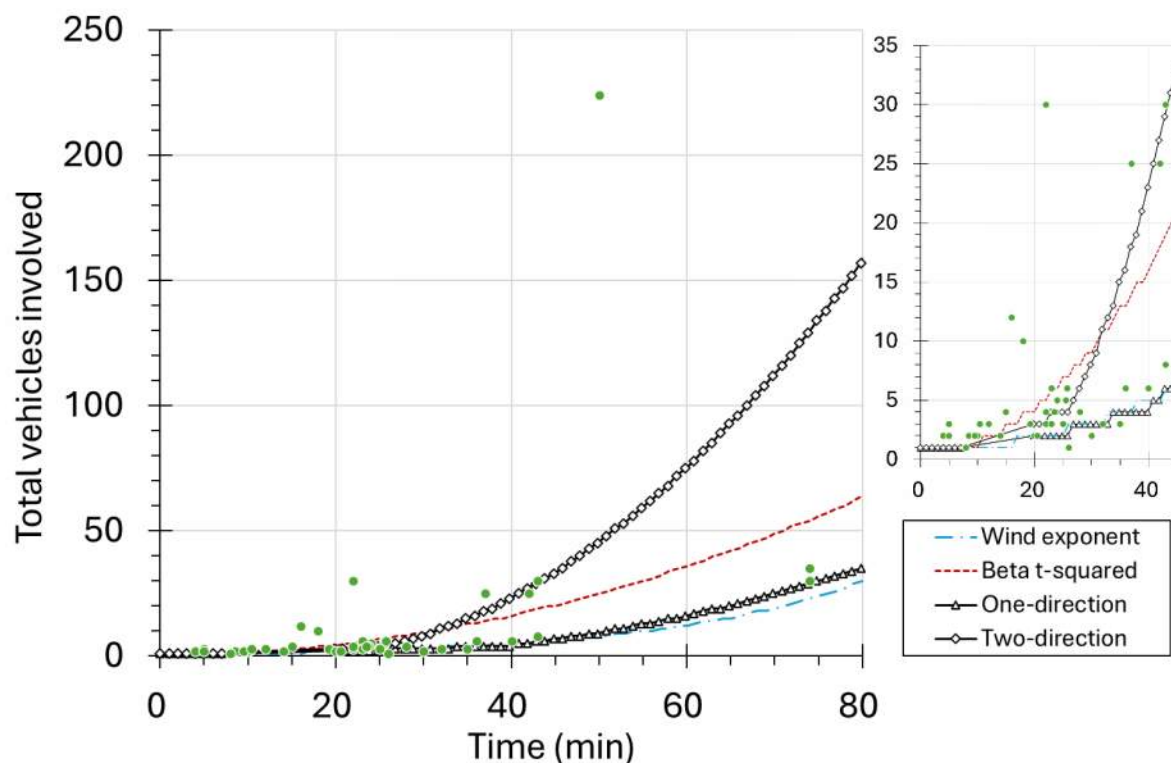


Figure 40. Comparison between test and incident data and the three vehicle-to-vehicle fire spread models at 0 m/s external wind speed

Figure 41 shows the comparison with an external wind speed of 4.3 m/s. It is seen that the three stage two-directional model fairly closely matches the time for the estimated 224 vehicles to become involved in the Luton Airport car park fire, particularly as also the estimated external wind speed during the incident was 4.5 m/s. The prediction made by the beta t-squared model is also reasonably close. The two-directional fire spread with an external wind speed of 12 m/s in Figure 42 shows a good correspondence to the observations made from the Stavanger airport fire at the point 30 vehicles were thought to have been burning. At external wind speeds of 4.3 m/s and 12 m/s the beta t-squared model shows a greater number of vehicles involved when compared to the test and incident data. A partial solution to this would be to offset the start of the curve along the time axis to account for the 'incipient' phase as the fire spreads from the first vehicle to the second one using the something akin to the 11 min discussed in Section 6.1.2.

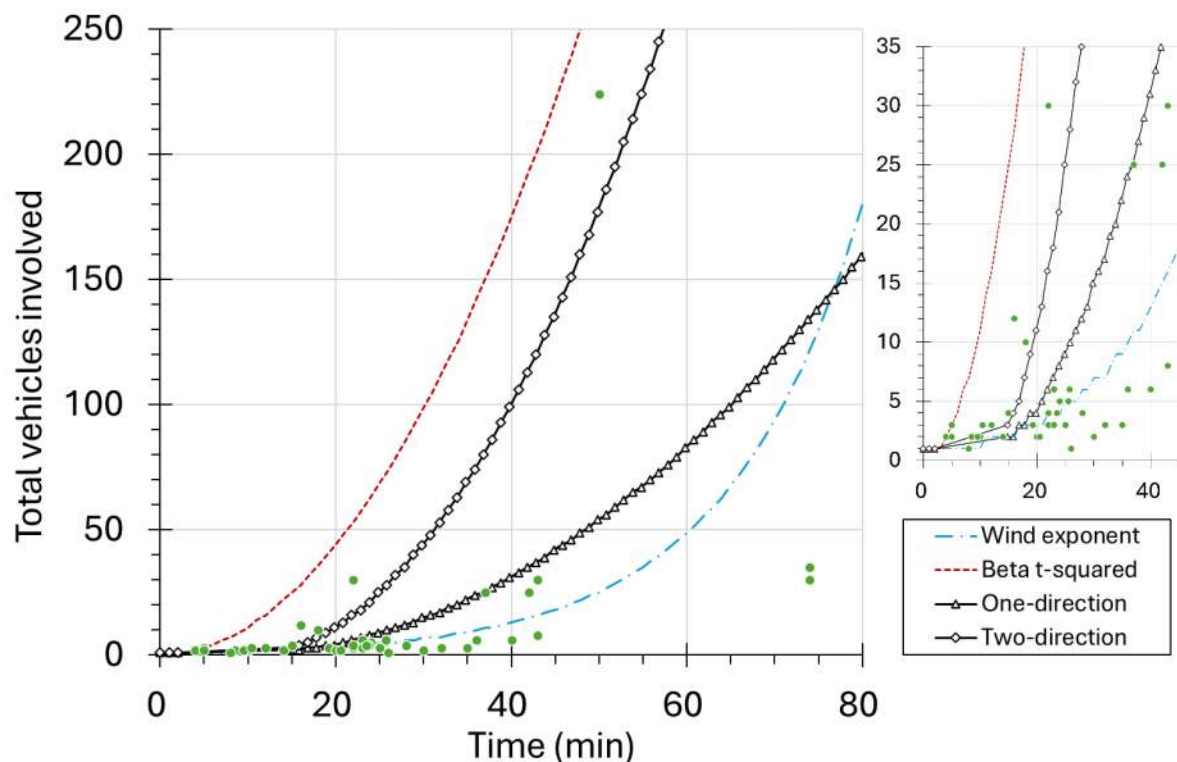


Figure 41. Comparison between test and incident data and the three vehicle-to-vehicle fire spread models at 4.3 m/s external wind speed

Of the three external wind speed cases examined, the wind exponent model appears to give its 'best' estimate at 4.3 m/s (i.e. with an exponent of 0.065) across most of the test and incident data. This should not be particularly surprising as the best fit through the data shown in Figure 33 has an exponent of 0.059.

Three of the previously examined incidents are revisited below to compare the three empirical models with the estimated number of vehicles involved with time. Here the wind speed and parking bay width are as stated in Table 15. In each comparison the beta t-squared model has have been offset by the second vehicle ignition time.

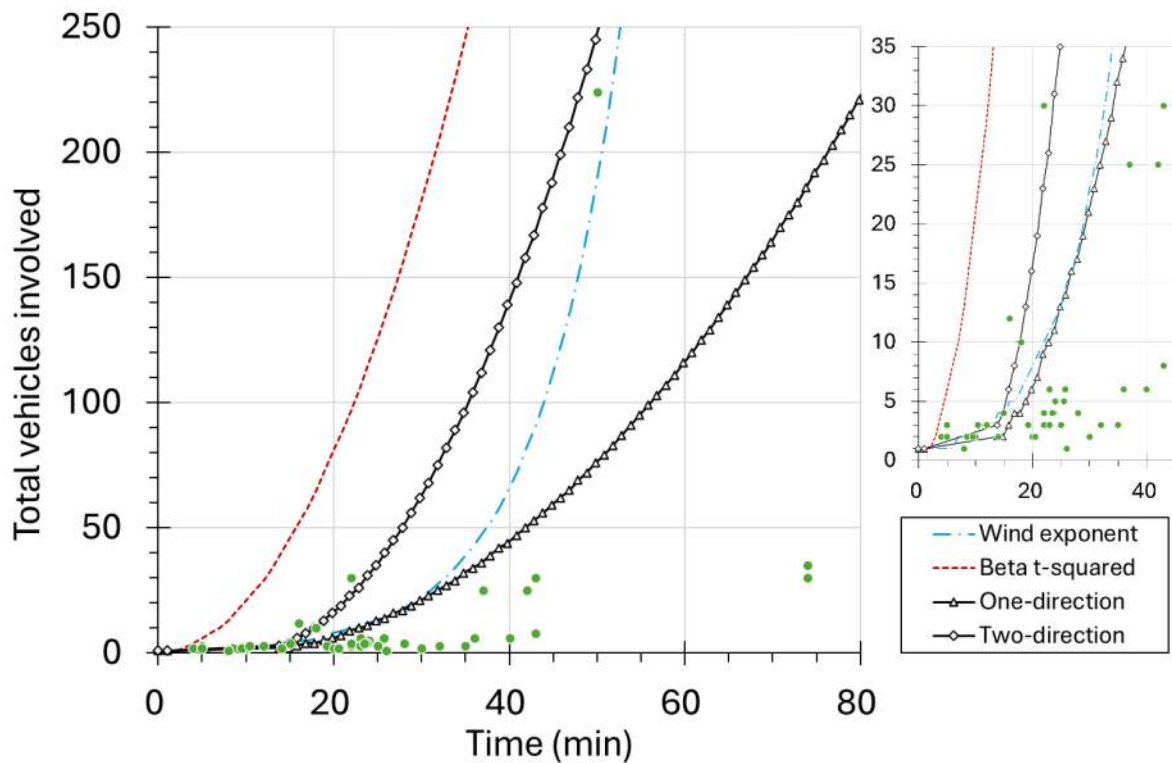


Figure 42. Comparison between test and incident data and the three vehicle-to-vehicle fire spread models at 12 m/s external wind speed

Figure 43(a) shows the Stavanger airport fire (Section 5.4) in which the two-direction three stage and beta t-squared models over-estimate the number of vehicles involved over time. The one-direction three stage model also provides an over-estimate other than at the point in which 30 vehicles were involved, where it then gives an under-estimate. If the second vehicle ignition time is shifted to 14 min (Figure 43(b)), then the two-direction three stage and beta t-squared models provide a good match.

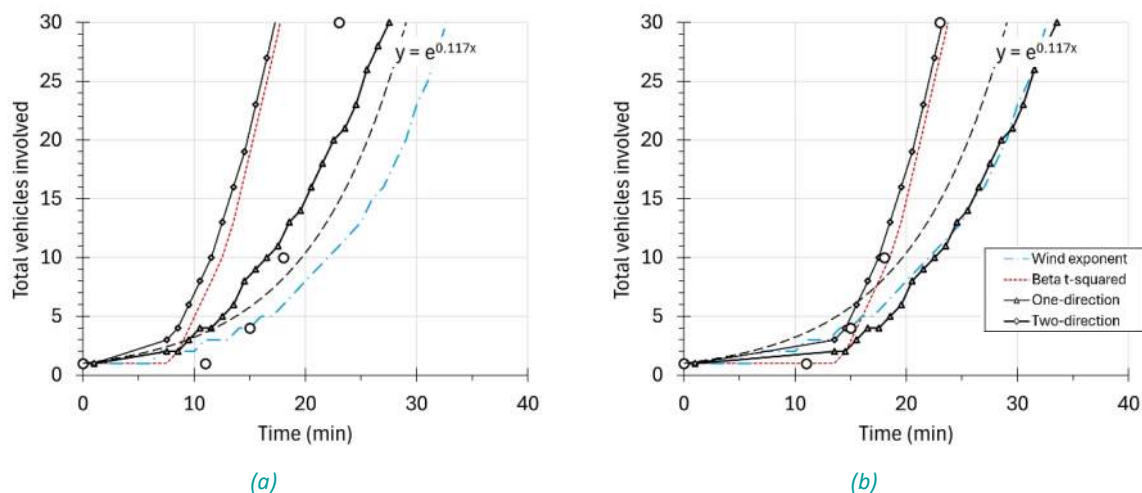


Figure 43. Estimated number of vehicles involved compared with the three empirical fire spread models for Stavanger airport (a) calculated second vehicle ignition using separation fire spread rate of 0.054 m/min, (b) second vehicle ignition manually set to 14 min

Comparison with the Lloydstraat car park incident (Section 5.2) is shown in Figure 44 using a separation distance of 0.5 m and no transition to two-dimensional spread as there was only a single row of cars. Of the two three

stage model estimates, the one-directional spread is the most representative to compare with the incident. The key limitation is that the time to second vehicle ignition is over-estimated, thereby shifting the involvement of subsequent vehicles later than thought to be what actually happened.

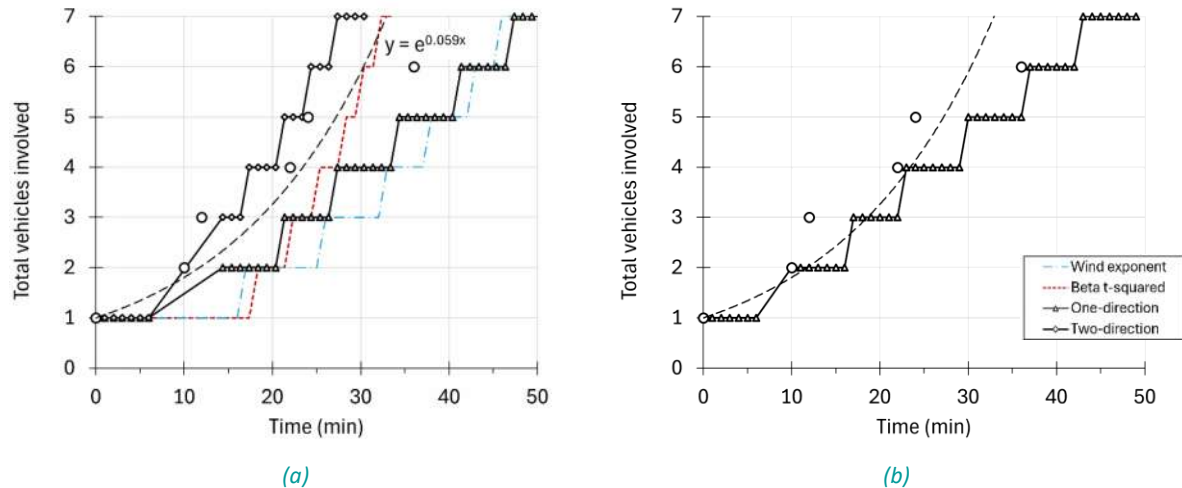


Figure 44. Estimated number of vehicles involved compared with the three empirical fire spread models for Lloydstraat car park (a) calculated second vehicle ignition using separation fire spread rate of 0.054 m/min, (b) second vehicle ignition set to 10 min compared to one-direction spread

Finally, Figure 45 shows the comparison with the Luton airport fire (see Section 5.6) with an assumed vehicle width of 2 m to give a separation distance of 0.4 m and thus a second vehicle ignition delay of 7 min 24 s. Using the preset model inputs (Figure 45(a)) then up until 37 min, when 25 vehicles were estimated to be involved, the one-direction, three stage model gives a close match, whereas the two-direction three stage and the beta t-squared models show a close match at the point the fire had reached 224 vehicles. Manually increasing the transition from one-dimensional fire spread to two-dimensional spread from 4 vehicles to 25 vehicles results in Figure 45(b) in which the estimated early fire spread between vehicles matches the observations, but later on the match is not as good. Further manual adjustments to the second vehicle ignition time and fire spread transition would improve the match in some places and not so in others.

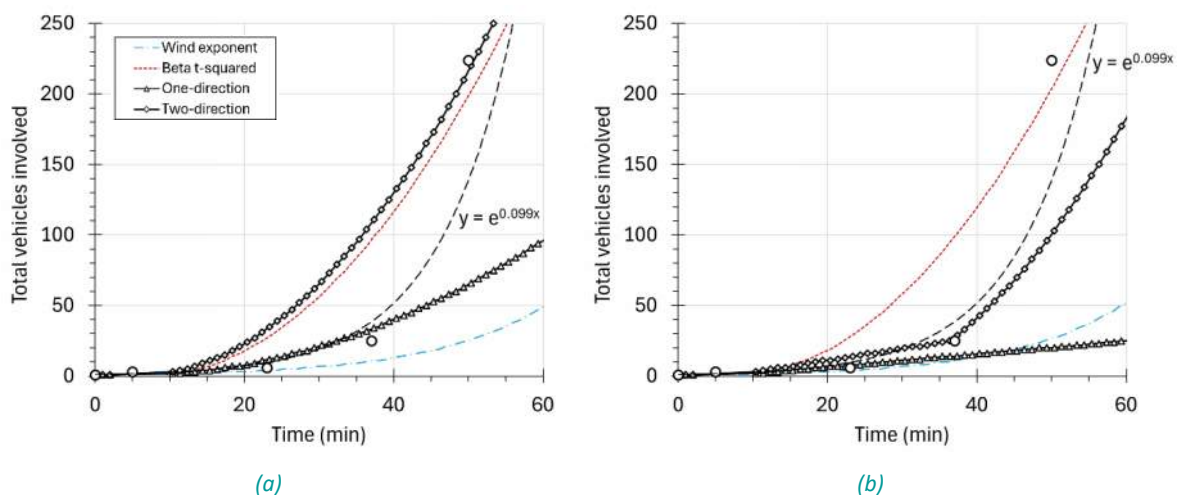


Figure 45. Estimated number of vehicles involved compared with the three empirical fire spread models for Luton Airport (a) four vehicle fire spread transition (b) 25 vehicle fire spread transition

The findings from the above comparisons lead to several conclusions about the empirical three models. The wind exponent model generally provides the poorest estimate of the number of vehicles involved. The two-directional three stage model and the offset beta t-squared models give similar estimates where a larger number

of vehicles are involved, and both will likely over-estimate vehicle numbers compared to incident numbers. All the model outputs are influenced by the estimated time to second vehicle ignition and when that time is manually adjusted then a closer match to the incident observations can be achieved. Similarly, the three stage model is influenced by the choice of when the fire spread transitions from one-dimensional to two-dimensional, another factor that is difficult to determine from the incidents. Increasing the transition from the preset of four vehicles will mean the estimates from the three stage model and the beta t-squared models will diverge.

7. CONCLUSIONS

Car sizes: Car statistics have been reviewed for the UK, going back to registrations in 2013 and considering year on year car sales / SORN vehicles. Based upon this, it has been possible to make an estimate of the distribution of car body types on the road in 2024 and, thus, likely occupying English car parks. This suggests a trend towards SUVs, albeit with significant market shares also for medium family cars and super-mini vehicles. For the purpose of mapping against test data, the car body types sold in the UK have been rationalised into the categories of small, medium and large vehicles. In 2024, it is estimated that these comprise 33, 36 and 31% respectively of cars on UK roads and, thus, likely occupying car parks in England.

Tests and incidents: This study has identified several multiple-vehicle laboratory-based test programmes and car park fire incidents over the past 40 years or so. For practical reasons the laboratory-based tests are only able to investigate fire spread between a relatively small number of vehicles. Incidents sometimes involved many vehicles under real-world conditions. Unfortunately, many of the incidents identified in media reports do not have sufficient information available to determine the times of vehicle-to-vehicle fire spread. Even where adequate information is available, it is often difficult to determine precise data on fire spread as the sources can require a considerable amount of interpretation.

Second vehicle ignition: The data suggests that a simple empirical quadratic equation indicative of a point source radiative ignition approximation gives an adequate estimate of the time to ignition of a second vehicle related to the door-to-door separation distance. Alternatively, the time to second vehicle ignition can be estimated using a representative fire spread rate of 0.054 m/min. Whether fires starting in electric vehicles lead to lesser second vehicle ignition times compared to fires starting in internal combustion engine vehicles likely depend on whether such fires are initiated in the battery or in another part of the vehicle. Evidence to support reducing the time to second vehicle ignition should the fire start with a battery undergoing thermal runaway is limited but suggests using a shorter time is a practical approach.

Floor-to-ceiling height: The findings from the review of tests and incidents suggest that the floor-to-ceiling height has little if any influence on the rate of vehicle-to-vehicle fire spread. The absence of impact may be partly due to the narrow range of floor-to-ceiling heights identified in the review.

Fire spread rate: Analysis of fire spread rates in the tests and incidents has identified as 0.41 ± 0.34 m/s (with lower and upper bounds of 0.1 m/min and 1.3 m/min respectively) as a practical range of values to use where there is no influence of external wind.

External wind: External wind appears to have an influence on vehicle-to-vehicle fire spread in car parks. As far as can be determined from the incidents investigated, the influence appears to manifest itself irrespective of whether vehicles are burning close to the perimeter of the car park or deeper within the structure. A tentative relationship for the increase in windward fire spread rate with external wind speed is proposed in this study. An 80% relative reduction in the fire spread rate against the direction of external wind is also suggested.

Transition to multi-dimensional fire spread: Findings suggest that a fire will initially spread along a row of parked vehicles before transitioning to spread across adjoining rows. Evidence to support the point at which the transition takes place is lacking and therefore it has been assumed to be at the point after four vehicles are involved. It is plausible that the number of vehicles involved prior to transition may increase with the influence of higher external wind speeds but there is insufficient evidence to determine if this is the case, and if so, how many vehicles.

Simple models: Three simple models for vehicle-to-vehicle fire spread in car parks have been developed: a 'wind exponent' model, a 'beta t-squared' model, and a 'three stage' model. All three models include the influence of external wind speed to some degree. The wind exponent and beta-squared models likely have some utility since they are single line equations that can be easily implemented. However, the 'three stage' model tries to capture some specific fire spread characteristics that are often observed in car park fires, and it also allows a user to consider factors such as parking bay dimensions. The models have been compared against the test and incident data and show encouraging results.

Car park design: A practical worst-case approach to obtain the time-based area of a car park fire is to apply the beta t-squared fire spread for an expected external wind speed with a 7 min offset to second vehicle ignition (i.e. similar to the beta t-squared curve in Figure 45(a)). If there is no information available on external wind speed, then use a wind speed of 4.3 m/s, i.e. a vehicle-to-vehicle fire spread rate of 1.1 m/min to give beta as 3.8. Where it is considered that an initial vehicle fire would be the result of thermal runaway in an electric vehicle then do not apply the 7 min offset (i.e. the beta t-squared curve in Figure 41). To obtain the number of vehicles involved, divide the area by the parking efficiency, for which a value of 35 m² is suggested.

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Appendix B – WP 1B



CPD/004/122/039

**Real Fires: Open-sided car park
fire resistance**

WP 1B: Quantitative assessment of fire spread in car parks

Revision: R00
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Contents

1.	Introduction	7
1.1	Appointment	7
1.2	Overview of the deliverable	7
2.	Development of a cellular automata model	9
2.1	Introduction to Cellular Automata models	9
2.2	Conceptual model for fire spread in a car park	9
2.3	Fire spread mechanisms in car parks	9
2.4	Primary features of the proposed automata	11
2.5	Stochastic parameters	11
2.5.1	Car park utilisation	12
2.5.2	Vehicle body types and heat release rates	13
2.6	CFD informed transition rules	15
2.6.1	Transition rules and the role of height	16
2.6.2	Role of wind	17
2.6.3	Implementation of the transition rules in the cellular automata model	19
2.7	Cellular Automata model workflow	20
2.7.1	Initialisation phase	20
2.7.2	Fire physics implementation	20
2.7.3	Fire spread mechanisms	20
2.7.4	Simulation execution	20
2.7.5	Data collection and analysis	21
2.7.6	Monte Carlo variation	21
2.8	Application to an experimental reference case	21
3.	Cellular automata parametric study	24
3.1	Variables	24
3.2	Impact of car park utilisation	25
3.3	Impact of vehicle HRR	28
3.3.1	Vehicle of origin	28
3.3.2	All vehicles	28
3.4	Impact of ceiling height	30
3.5	Impact of wind	30
4.	Cellular Automata MCS	33
4.1	Variables and constants	33
4.2	Results for different utilisations	33
4.3	Results for different ceiling heights	34
4.4	Results for different wind speeds	34
5.	Discussion & conclusions	38

5.1	CFD modelling of fire spread	38
5.2	Cellular automata parametric study	38
5.3	Cellular automata MCS.....	39
5.4	Comparison against real fire incidents.....	40
5.5	Next steps	40
6.	References.....	41
Appendix I – MCS output stats.....		42
	In function of utilisation of carpark.....	42
	In function of ceiling height.....	46
	In function of wind speed	49
Appendix II – ITB CFD Study		52

List of Figures

Figure 1.	Conceptual illustration of a car park fire spread cellular automata.....	10
Figure 2.	Car park fire spread mechanisms	10
Figure 3.	Parking space utilisation cumulative density functions from WP 1A	12
Figure 4.	Calculated distribution of car body type by the end of 2024.....	13
Figure 5.	Idealised design fire for a car from Tohir, et al.	14
Figure 6.	Idealised design fire curves for small, medium and large vehicles based on mean values from Miechówka and Węgrzyński	15
Figure 7.	CFD model geometry (left) and ignited plus target vehicles (right)	15
Figure 8.	Total heat release rate vs incident heat flux for six different ceiling heights (scenario 1).....	16
Figure 9.	Illustrative application of the fire spread transition rules for single or multiple burning vehicles.....	19
Figure 10.	BRE test one layout and instrumentation schematic	21
Figure 11.	Deterministic vehicle HRR curves adopted for benchmarking (green) initiating vehicle, and (red) subsequent vehicles, adapted from ref. [8].....	22
Figure 12.	CA output for BRE Experiment 1, time step = 1 min.....	23
Figure 13.	CA Heat release rate intensity map in function of time step (1 min)	23
Figure 14.	BRE experiment one, measured HRR with time	24
Figure 15.	Illustration of fire spread rate computation (S/N).....	26
Figure 16.	Parametric study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of car park utilisation (red dashed line indicates mean value).....	27
Figure 17.	Idealised design fire curves for small, medium and large vehicles for a combined 5 th time to peak HRR and 95 th percentile peak HRR based on values from Miechówka and Węgrzyński	28
Figure 18.	Parametric study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of car fire size (red dashed line indicates mean value)	29
Figure 19.	Parametric study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of ceiling height based on 95 th percentile vehicle fire size (red dashed line indicates mean value).....	31
Figure 20.	Parametric study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of ceiling height based on 95 th percentile vehicle fire size (red dashed line indicates mean value).....	32
Figure 21.	MCS study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of utilisation with distributed vehicle fire sizes (red dashed line indicates mean value)	35
Figure 22.	MCS study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of ceiling height with distributed vehicle fire sizes, 80% space utilisation (red dashed line indicates mean value)	36
Figure 23.	MCS study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of wind speed with distributed vehicle fire sizes, 80% space utilisation and 2.5 m ceiling (red dashed line indicates mean value).....	37

List of Tables

Table 1. Proportion of cars on the road by rationalised size classification	13
Table 2. Design fire characteristics of vehicles in function of size from Miechówka and Węgrzyński	14
Table 3. Critical heat release rate for car ignition in function of ceiling height (15 kW/m ²), 5 th percentile, still conditions.....	16
Table 4. Critical heat release rate for car ignition in function of ceiling height (15 kW/m ²), 5 th percentile, wind speeds of 2 to 8 m/s	17
Table 5. Impact of utilisation on mean spread rate, mean peak fire size and mean number of bays ignited.....	25
Table 6. Impact of initiating vehicle fire size on mean spread rate, mean peak fire size and mean number of bays ignited	28
Table 7. Impact of vehicle fire size on mean spread rate, mean peak fire size and mean number of bays ignited	28
Table 8. Impact of ceiling height on mean spread rate, mean peak fire size and mean number of bays ignited. Results for 95 th percentile vehicle sizes and 80% car park utilisation	30
Table 9. Impact of ceiling height on mean spread rate, mean peak fire size and mean number of bays ignited. Results for 95 th percentile vehicle sizes and 80% car park utilisation	30
Table 10. Summary statistics for MCS based on car park utilisation	33
Table 11. Summary statistics for MCS based on car park utilisation of 80% but varying ceiling heights.....	34
Table 12. Summary statistics for MCS based on car park utilisation of 80%, 2.5 m floor to ceiling but varying wind speeds	34
Table 13. Summary of key characteristics involving multiple vehicle fire spread, from WP 1A	40

1. INTRODUCTION

1.1 Appointment

OFR Consultants were engaged by the Department for Levelling Up, Housing and Communities (DLUHC) to deliver the “Real Fires” project (CPD/004/122/039) in support of fire safety technical policy, which commenced on 22nd of October 2021, and will run until the 28th September 2025. The contract has since been novated to the Building Safety Regulator (BSR), originally formed within the Health & Safety Executive (HSE) and now residing as part of the Ministry for Housing, Communities and Local Government (MHCLG). As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations from real fires. Through this mechanism, OFR have been engaged to undertake research on the structural fire resistance for purpose-built open-sided car parks.

The BSR stated that the research project is to be organised to generate data and evidence on the fire resistance ratings in car parks to support the BSR’s understanding of the level of safety in existing and new buildings, along with an analysis of options coupled with their respective supporting information to shape policy decisions. OFR proposed that this focus on above ground, purpose-built, open-sided multi-storey car parks.

To deliver on the requirements, OFR considered three sub work packages (WPs) to be necessary, which are summarised below:

- WP 1: Investigation of fire spread rates and extents in open sided car parks.
- WP 2: Monte Carlo fire severity analysis to investigate the probability of failure of structural elements subject to different fire resistance / protection solutions.
- WP 3: Lifetime cost-optimisation analysis for different fire resistance / protection solutions to establish the optimal safety level considering sensitivity to life safety, property protection and business continuity goals.

This report forms part of the deliverable for WP 1 (WP 1B), providing a quantitative assessment of spread rates in car parks through a combination of computational fluid dynamics (CFD) modelling and the application of a cellular automata (CA) with Monte Carlo simulation (MCS) functionality. The CA has been purpose-developed to deliver the project. This deliverable builds upon WP 1A, which looked at spread rates observed in either experimental studies or through a review of real fire incidents. The quantitative assessment outputs relevant statistics in terms of spread rates and extents of fire spread for the latter purpose (WP 2) which studies the implications for the structural fire resistance of purpose-built open-sided car parks.

1.2 Overview of the deliverable

The spread of fire within car parks is influenced by several factors, including the proportion of parking bays occupied by vehicles, the spacing between vehicles, and the fire growth characteristics of the cars themselves. Determining the number of vehicles likely to become involved in a fire and the speed of this involvement often requires modelling. The previous deliverable (WP 1A) provides data for the benchmarking of such models against real-world data obtained from laboratory tests or actual fire incidents. This report focusses on the development of models and their application to enhance understanding of the rate and extent of fire spread, in function of relevant parameters, such as the car park utilisation, the vehicle heat release rates (HRRs), the car park floor-to-ceiling height and external wind speeds.

This report begins with the steps involved in developing a model that can estimate spread rate and extent of spread efficiently, and in support of uncertainty quantification. The chosen model is a cellular automata model which describes spread from space to space using the concept of transition rules, which are informed by an extensive CFD parametric study by OFR’s sub-contractor ITB (Appendix II). The cellular automata is benchmarked against experimental data identified in WP 1A.

The report then applies the CA in a parametric study to identify the importance of variables on the rate and extent of fire spread. This generally adopts deterministic inputs with progressive variation in variables such as utilisation, floor to ceiling height, wind speed, etc.

Next, the full uncertainty quantification capabilities of the CA are utilised to generate random car park fire scenarios for different situations, such as differences in car park typology represented through changes in utilisation, geometrical interventions like floor-to-ceiling height and weather conditions like wind speed. The output of these MCS are distributions of spread rate and spread extent, which will be adopted in WP 2 for determining the thermal impact on structural elements and, therefore, the likely fire resistance requirements of car parks.

The report concludes with observations on the key parameters affecting fire spread in car parks and recommendations on how fire spread should be simulated when considering structural fire performance.

For this report, the terms 'car' and 'vehicle' are used interchangeably to refer to private passenger vehicles.

2. DEVELOPMENT OF A CELLULAR AUTOMATA MODEL

2.1 Introduction to Cellular Automata models

A cellular automata model is a discrete computational model consisting of a regular grid of cells, each occupying one of a finite number of states. The system evolves through discrete time steps according to a fixed set of rules that determine each cell's next state based on its current state and the states of its neighbouring cells [1], [2]. The fundamental components of a cellular automaton include the cellular space (typically a one- or two-dimensional lattice), the neighbourhood structure (defining which cells influence each other), the finite set of possible cell states, and the transition rules governing state changes. These rules are applied simultaneously to all cells, creating deterministic yet often complex emergent behaviour from simple local interactions.

2.2 Conceptual model for fire spread in a car park

In its most simple form, car park fire spread can be idealised as being in a linear pattern along a row of parked cars [3]. This is considered an adequate proxy for estimating vehicle fire spread rates as most conventional car parks will feature a row of parked vehicles, with a maximum of two successive rows, typically separated by roadways for the purpose of moving vehicles around the car park.

Figure 1 shows a conceptual illustration of a linear spread cellular automata for a car park. For such purposes, each car parking space can be considered a 'cell'. These cells can be occupied by vehicles or potentially empty. As a simulation moves through discrete time steps, the figure shows:

- At time step 0 there is an ignition (the car of origin) in a space.
- Once the vehicle of origin fire grows sufficiently, e.g., at time step N, the fire will likely ignite the proximal vehicle(s).
- At some point in time, e.g., time step N + 1, the compound fire size of two vehicles burning may be sufficient to ignite cars further away. This could be by igniting multiple vehicles simultaneously, including those that might be separated by empty spaces.

The bullet points above introduce the concept of transition rules, i.e., between time step 0 and N there is a condition whereby the vehicle of fire origin will produce sufficient heat to ignite those adjacent and, between time N and N+1, there is a condition where the fire size could be large enough to ignite multiple vehicles that are multiple spaces separated from the vehicle of origin. These transition rules can be thought of as fire spread mechanisms.

2.3 Fire spread mechanisms in car parks

Fire spread in car parks can often be attributed to one or a combination of three mechanisms. These are set out below:

- Direct heating / flame impingement, i.e., where vehicles are adjacent, sufficient heating can occur to ignite a vehicle in the next bay. This is depicted at time step N in Figure 1.
- Heating from the ceiling jet / smoke layer. This would occur once the fire size is large enough from single or multiple vehicles to result in hot smoke and/or flames to heat vehicles further away, leading to their ignition. This is depicted as time step N + 1 in Figure 1.
- Heating from running fuel fires. In some car park fires, fuel spillage, e.g., petrol can travel across multiple parking spaces and once ignited, propagate fire spread. This is not explicitly addressed in Figure 1.

The first two fire spread mechanisms are depicted in Figure 2 and are captured within the developed cellular automata.

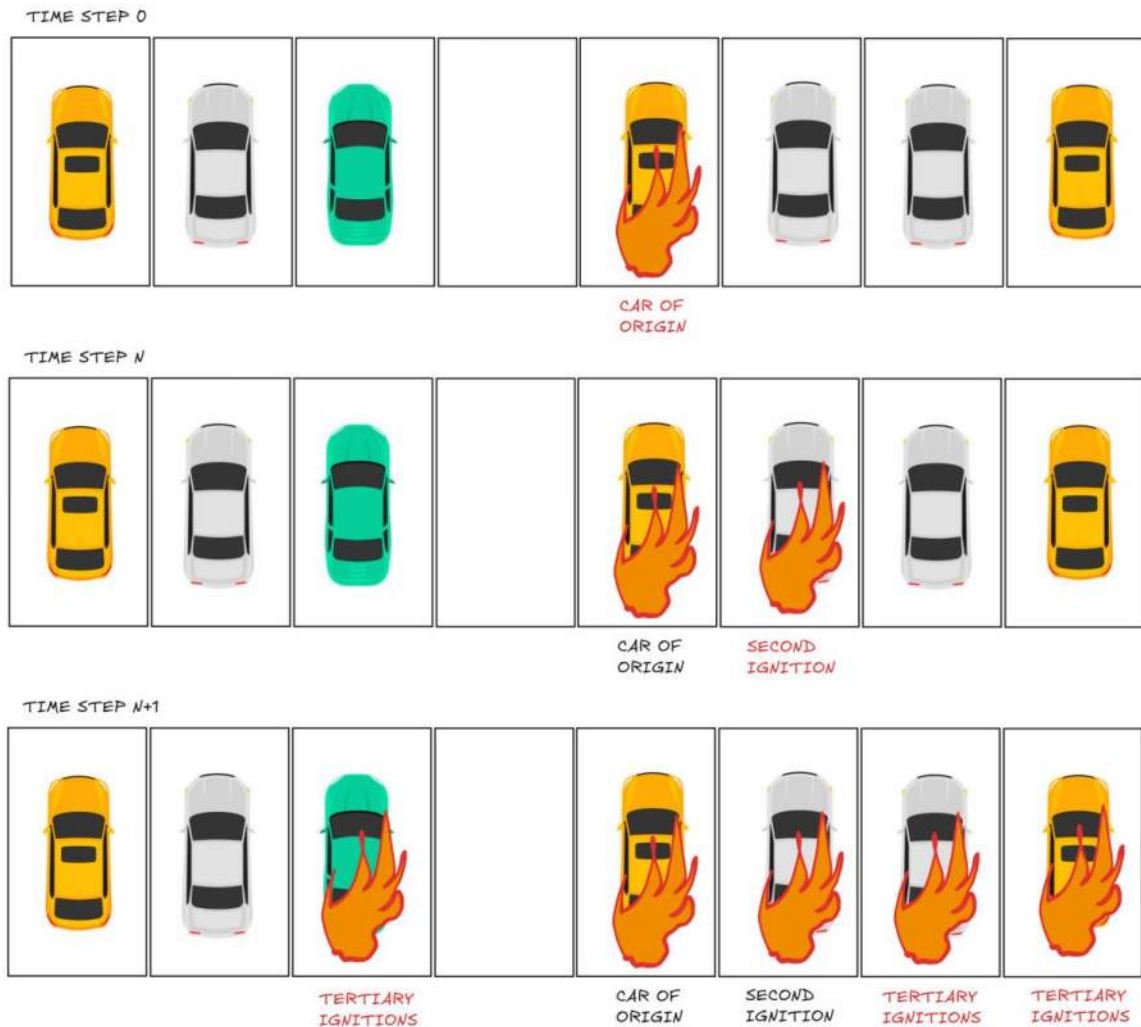


Figure 1. Conceptual illustration of a car park fire spread cellular automata

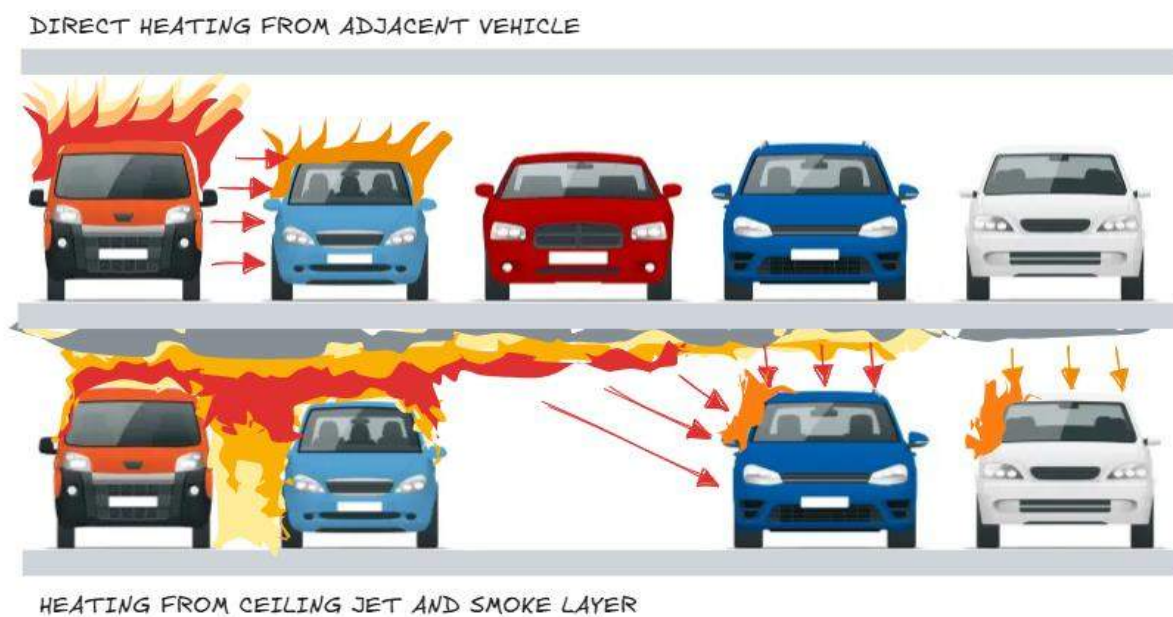


Figure 2. Car park fire spread mechanisms

2.4 Primary features of the proposed automata

The cellular automata has been developed in python to model linear spread. It assumes a single row of vehicles parked side-by-side, i.e., as per Figure 1. The primary features of the cellular automata are given below:

- The user may define any number of spaces that will simply increase the maximum linear length of parked vehicles.
- A fire may originate in any of the parking spaces with the assumption that space is occupied by a vehicle.
- Any parking space beyond that declared as the space of origin can be either occupied by a vehicle or empty.
- The arrangement of cars in spaces can either be user defined or randomly assigned. This includes both the space of fire origin and whether the remaining spaces are occupied by vehicles or empty.
- Each space may be occupied by one of four vehicle profiles. The vehicle profiles describe the relationship between heat release rate and time, $HRR(t)$. The vehicle of origin is afforded a profile so the user can test the sensitivity of different initiating scenarios. Three additional vehicle profiles can be applied to the remaining spaces occupied by a vehicle. These profiles can be user assigned on a space-by-space basis or randomly assigned with associated probabilities.
- Two transition rules are implemented that relate to the two fire spread mechanisms introduced in Section 2.3, i.e., direct heating and heating from the smoke layer / ceiling jet. Direct heating is addressed through a point source model, considering a user defined gap between parked cars. This gap extends to include any empty adjacent spaces. The ignition criteria is a user defined critical heat flux for ignition. Heating from the smoke / ceiling jet uses a critical heat release rate sufficient to bring about ignition up / down stream of a collection of burning vehicles. This critical heat release rate is informed by CFD simulations and is discussed in greater detail in Section 2.6.
- As a simulation progresses, spaces have one of four states: empty, unburnt (i.e., occupied and with the potential to ignite), burning or burned out. At each time step, the transition rules are evaluated both up and down stream to see if unburnt cars should transition to burning. Once a space has transitioned through its full $HRR(t)$, measured relative to the time of ignition of that space, the vehicle is considered “burned out”.
- A point can be reached where no transition rules are satisfied meaning that fires may not spread beyond the vehicle of origin or that fire spread is curtailed at some point. This is typically dictated by the spacing of vehicles, i.e., the allocation of empty spaces that require higher heat release rates for sufficient heating from the ceiling jet / plume to occur.
- The model assumes that fires are fuel controlled, i.e., there is no limit on the total heat release rate based on the ventilation conditions.
- The model can track the up and down stream burning fronts to give a profile of fire spread rate with time. It is also able to track the heat release rate with time and show the parking space states with time.
- The model can be run deterministically or in Monte Carlo Simulation (MCS) mode.
- Whilst the model does not explicitly consider the implications of wind or ceiling height, as is discussed in Section 2.6, transition rules relating to fire spread via the ceiling jet / smoke layer can be modified to implicitly capture such impacts. This is through a change in the critical heat release rate required to bring about up and down stream fire spread, that is a function of wind conditions and floor to ceiling height.

2.5 Stochastic parameters

Stochastic parameters are only relevant in cases where the cellular automata operates in Monte Carlo Simulation mode. In such an instance, the following variables can be assigned:

- Probability of a space being occupied by a car. This has been shown in WP 3A to be a distributed parameter that can depend on several factors, such as the type of car park and the facility it serves, e.g., an airport car park, venue car park, etc., the time of day, time of year and location. See Section 2.5.1.
- The bay of first vehicle ignition. That is, it is assumed that a fire originates in a parking space and not elsewhere in a car park. Furthermore, an ignition can only occur in a space that is occupied by a vehicle. In the cellular automata is assumed that there is an equal likelihood of a fire originating in any space in which a vehicle is present.
- The vehicle body types within occupied parking spaces. These are grouped by vehicle size and afforded likelihoods according to the estimated distribution of vehicle body types analysed in WP 1A. See Section 2.5.2.

2.5.1 Car park utilisation

Car park utilisation was the focus of some investigation in WP 1A. Figure 3 is reproduced from W3 1A and shows the cumulative density function (CDF) for car park utilisation based on five studies available in the literature.

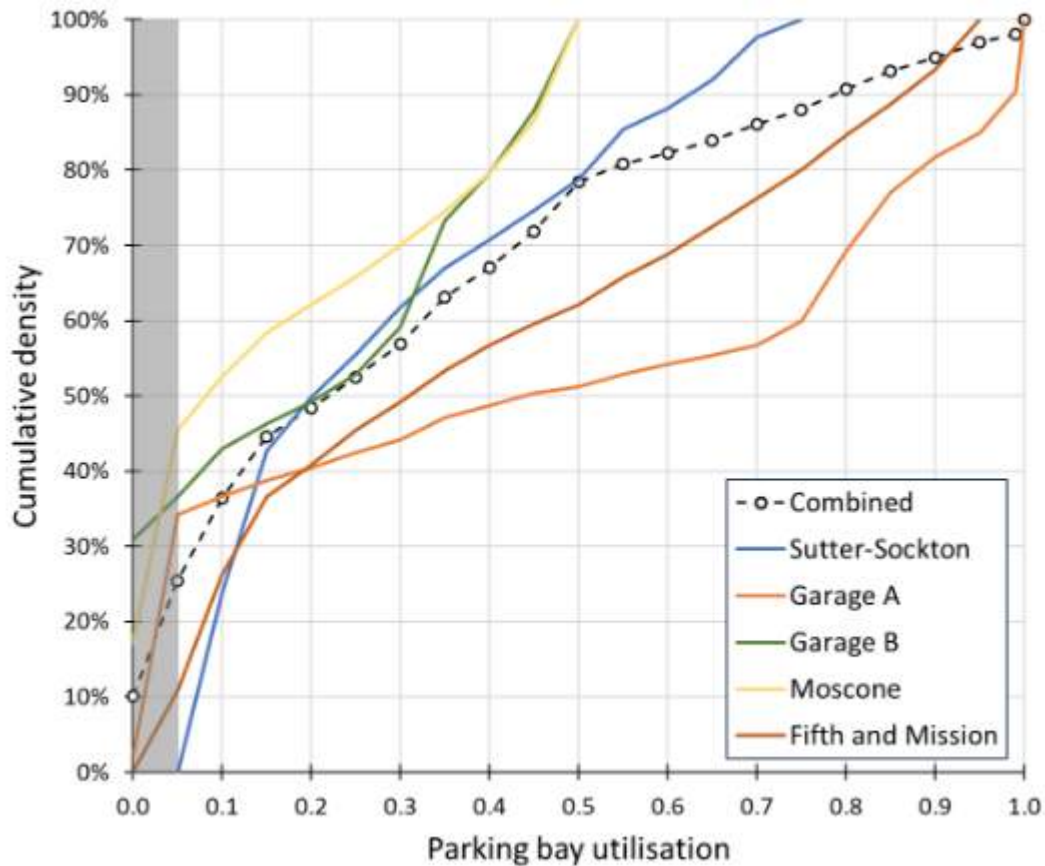


Figure 3. Parking space utilisation cumulative density functions from WP 1A

Based upon the combined data of these five studies, it is estimated that there is roughly a 10% probability that a car park is entirely empty. When considering the average utilisation of all spaces in a car park, the 50th percentile space utilisation is ca. 25%. This increases to ca 55% and 80% at the 80th and 90th percentiles, respectively,

2.5.2 Vehicle body types and heat release rates

WP 1A sought to estimate the distribution of vehicle types on the road in the UK at present. This looked at the vehicle registrations in 2013 and forecast forwards based on the vehicles declared off road vs. year-on-year new vehicle registrations. Based upon this, Figure 4 is reproduced from WP 1A below.

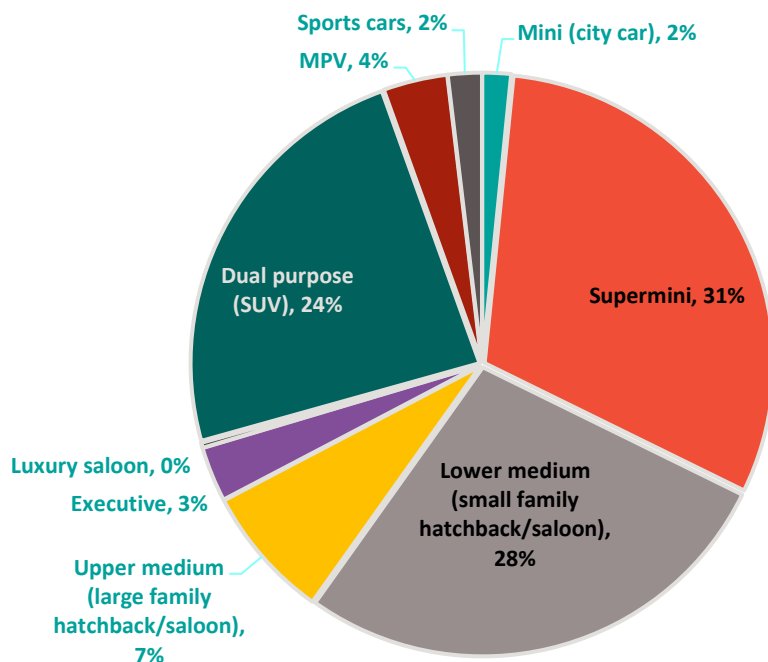


Figure 4. Calculated distribution of car body type by the end of 2024

The figure identifies nine vehicle body types that were subsequently further rationalised to more broadly represent common vehicle sizes, as grouped in Miechówka and Węgrzyński [4]. This created three car size classifications, as set out in Table 1.

Table 1. Proportion of cars on the road by rationalised size classification

Car size	Proportion in 2024 [%]
Small	33
Medium	36
Large	31

These three vehicle body types are adopted in the cellular automata, alongside a fourth to distinguish the vehicle of origin as a separate type that can be subject to sensitivity study.

Table 2 shows design fire characteristics for three different sizes of vehicles from Miechówka and Węgrzyński. This covers both internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs). The data groups all ignition scenarios, which covered within the cabin, on the chassis, within the engine compartment and from below the vehicle. The characteristics are therefore considered to cover a broad range of ignition possibilities and are adopted herein.

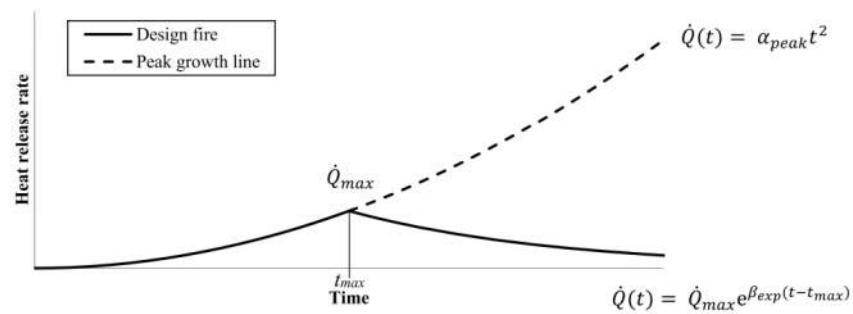


Figure 5. Idealised design fire for a car from Tohir, et al.

Tohir, et al. [5] note that most vehicle fires can be characterised through a t-squared relationship for the growth phase and an exponential decay phase. This is shown in Figure 5. For the average values in Table 2, assuming the area under the time vs. heat release rate curve must correspond to that of the total heat release rate (THR), Figure 6 shows idealised HRR(t) plots for the three vehicle sizes based on mean values.

Table 2. Design fire characteristics of vehicles in function of size from Miechówka and Węgrzyński

Parameter	Peak HRR [kW]	t _{PHRR} [min]	THR [MJ]
Small car			
Average	4232	25.22	4516
Median	3716	24.10	4217
5th percentile	1488	7.80	408
95th percentile	8521	48.25	8119
99th percentile	10580	65.63	8943
Standard deviation	2320	13.69	2149
Medium car			
Average	5296	21.64	6293
Median	5900	18.00	6670
5th percentile	1243	4.60	167
95th percentile	7860	52.36	10020
99th percentile	9690	63.33	10278
Standard deviation	2065	15.26	2953
Large car			
Average	3912	18.25	3730
Median	3618	16.00	3347
5th percentile	1239	2.45	346
95th percentile	7640	44.20	8763
99th percentile	8542	53.41	9065
Standard deviation	2208	15.39	3031

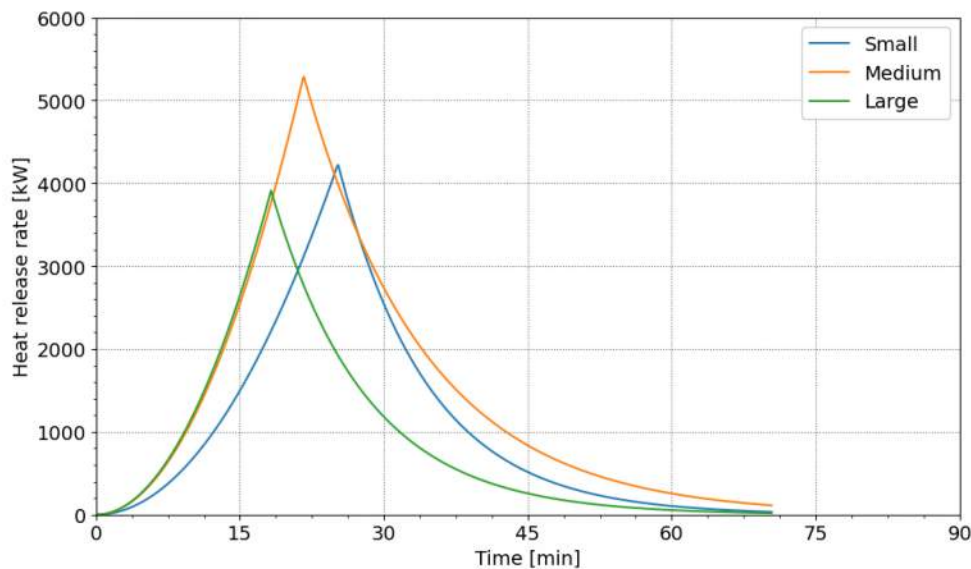


Figure 6. Idealised design fire curves for small, medium and large vehicles based on mean values from Miechówka and Węgrzyński

2.6 CFD informed transition rules

Appendix II documents a detailed computational fluid dynamics (CFD) study of fire spread in a representative car park structure. It notes the importance of a “bay effect” whereby the structural frame formed from beams and columns affects the shape of the flame extension that develops below a ceiling, thus influencing the mechanism and rate of fire spread. It concludes with the observation that flame extension below ceilings is likely the main driver of fire spread in car parks once the fire becomes sufficiently large. Sufficiently large can tentatively be considered the point at which two or more vehicles are involved.

After provisional benchmarking of the CFD modelling against experimental data, i.e., the BRE car park study [6], it is used to undertake studies on various permutations that help inform the CA spread transition rules. To recap, the transition rules describe the conditions under which the fire is considered to have spread from one parking space to next, inclusive of any gaps that may exist due to empty spaces.

Figure 7 shows the CFD model geometry (left) and the ignited plus target vehicles (right). Each modelling scenario ramps the heat release rate of the ignited vehicles (shown as A and B) and monitors the incident heat flux to the target vehicles (numbered 1 to 11). This is provisionally done through six different car park floor-to-ceiling heights, i.e., 2.50 m (fire 1), 2.70 m (fire 2), 2.90 m (fire 3), 3.10 m (fire 4), 3.30 m (fire 5) and 3.50 m (fire 6).

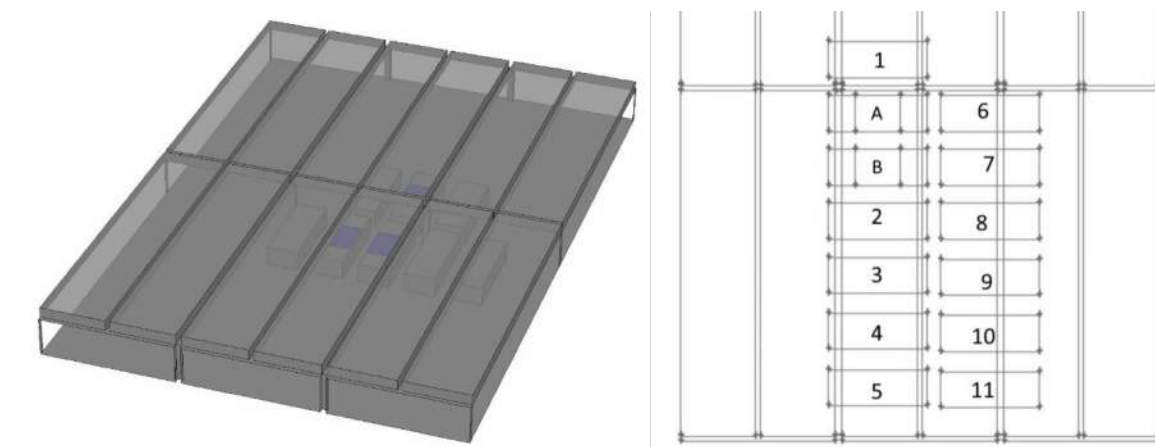


Figure 7. CFD model geometry (left) and ignited plus target vehicles (right)

The fire is modelled considering three scenarios as set out below:

- Scenario 1 – fire on both vehicles A and B start at 500 kW and the HRR is increased stepwise by 250 kW every 30 s, up to a maximum of 10 MW.
- Scenario 2 – fire on vehicle A is constant at 2000 kW and the HRR of vehicle B increases stepwise by 500 kW every 30 s, up to a maximum of 12 MW.
- Scenario 3 – fire on vehicle A is constant at 4000 kW and the HRR of vehicle B increases stepwise by 500 kW every 30 s, up to a maximum of 12 MW.

2.6.1 Transition rules and the role of height

Given the prevalence of the bay effect discussed in Appendix II, the cars of interest in terms of the dominant direction and rate of fire spread are vehicles 1 to 5. Figure 8 shows an extract from the results of the study, where the total heat release rate is plotted against the incident heat flux to car 1 for six different ceiling heights, under scenario 1. The incident heat flux is measured to all surfaces forming the car, i.e., top and sides, with the maximum value shown, typically occurring on the top / roof.

Appendix II references the work of Tohir [3], [7], with it shown that most car external car components, e.g., the mudflaps, rubber flaps, bumper trim and wheel arches, will ignite within two minutes when subject to an incident heat flux of 15 kW/m^2 . This also aligns with the BRE study from which Tohir sourced some of his data from.

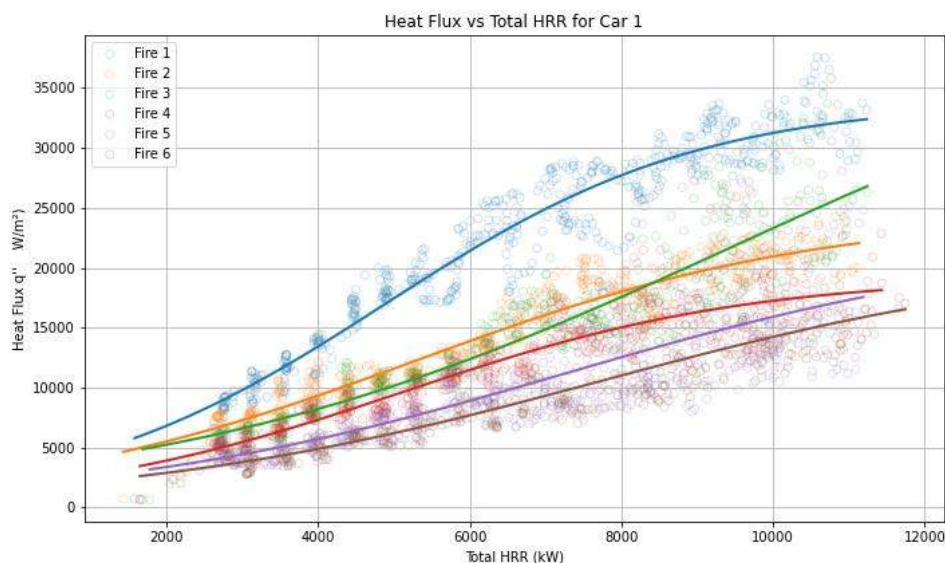


Figure 8. Total heat release rate vs incident heat flux for six different ceiling heights (scenario 1)

Applying the ignition criterion of 15 kW/m^2 across ceiling heights and scenarios yields the values in Table 3. Given each HRR was held for a period before being increased, the figures represent the 5th percentile, i.e., in 95% of cases the critical heat release rate to exceed 15 kW/m^2 would have been higher.

Table 3. Critical heat release rate for car ignition in function of ceiling height (15 kW/m^2), 5th percentile, still conditions

Car pos.	Range of critical heat release rate [MW] in function of ceiling height for scenarios 1 to 3 (5 th percentile)					
	2.5 m	2.7 m	2.9 m	3.1 m	3.3 m	3.5 m
1	3.61-4.82	3.74-6.67	3.68-6.59	4.03-7.21	4.46-7.56	4.88-7.78
2	3.04-4.84	3.28-5.29	3.88-5.73	4.42-5.72	5.06-5.84	5.25-6.44
3	3.41-5.85	3.74-6.17	4.32-7.13	4.57-7.15	5.69-7.10	6.07-7.45
4	4.21-6.19	4.23-6.69	4.75-8.00	5.60-7.29	6.15-8.05	6.30-8.12

5	5.37-6.80	5.55-7.17	5.33-8.58	6.10-8.19	6.32-8.51	7.09-9.02
6	4.59-5.38	5.25-6.28	5.42-5.91	6.23-6.58	5.19-8.82	5.82-8.02
7	5.22-5.80	5.27-5.96	5.72-5.96	5.83-6.58	5.68-6.43	6.19-6.94
8	6.24-6.72	6.18-6.67	5.80-6.57	6.26-7.18	6.44-7.28	6.27-7.51
9	6.89-7.78	6.65-7.61	7.08-7.94	7.51-8.10	7.18-8.31	7.28-8.56
10	7.16-8.52	7.49-8.45	7.31-8.53	8.14-8.88	8.34-8.99	8.24-9.57
11	7.17-10.23	8.14-9.26	7.60-9.43	8.71-9.50	8.58-9.36	9.56-10.63

2.6.2 Role of wind

The CFD study presented in Appendix II also looked at the role of wind speed on the relationship between vehicle HRR and the incident heat flux received to nearby vehicles. Applying an ignition criterion of 15 kW/m² incident heat flux results in Table 4 for the 5th percentile vehicle HRR, i.e., in 95% of cases the critical heat release rate to exceed 15 kW/m² would have been higher. It should be noted that the speed given corresponds with the air velocity within the car park, with higher external wind speeds likely necessary to deliver the noted internal velocities.

Unlike the static case, the wind transition rules produce cases where upwind fire spread is prevented, noted as “not observed” in Table 4. That is, the CFD results suggest that internal air speed can have a role in limiting the extent of fire spread depending on the location of origin. The CFD results also suggest typically air speed increases the critical heat release rate for downstream ignition when applying the 15 kW/m² criterion.

Table 4. Critical heat release rate for car ignition in function of ceiling height (15 kW/m²), 5th percentile, wind speeds of 2 to 8 m/s

Air vel.	Car position	Critical heat release rate [MW] in function of ceiling height					
		2.5 m	2.7 m	2.9 m	3.1 m	3.3 m	3.5 m
2 m/s	Car 1	Not observed	6.65	9.51	9.12	10.06	12.10
	Car 2	4.59	5.18	5.30	6.16	6.60	7.10
	Car 3	5.22	5.63	6.66	6.69	7.95	8.80
	Car 4	5.71	5.83	7.52	7.41	9.11	9.66
	Car 5	6.21	7.04	7.89	7.81	9.67	9.94
	Car 6	8.84	4.87	5.70	7.79	8.34	9.46
	Car 7	6.26	4.87	5.91	7.53	7.10	8.46
	Car 8	6.26	6.15	6.59	7.61	7.64	8.58
	Car 9	6.73	7.31	7.84	8.72	8.88	9.79
	Car 10	7.58	8.16	8.70	10.02	10.44	11.58
	Car 11	7.89	9.52	9.54	10.41	10.84	Not observed
4 m/s	Car 1	Not observed	Not observed	Not observed	Not observed	Not observed	Not observed
	Car 2	4.75	5.20	5.45	5.32	6.38	5.85
	Car 3	5.70	7.05	6.32	6.01	7.69	7.59
	Car 4	6.17	7.79	6.75	6.20	8.51	9.01
	Car 5	7.57	8.44	7.67	6.27	8.82	9.77
	Car 6	Not observed	Not observed	10.73	10.73	Not observed	11.89
	Car 7	Not observed	12.56	6.76	7.62	11.45	9.65
	Car 8	Not observed	9.89	6.33	7.29	9.05	8.38
	Car 9	9.86	9.41	7.11	7.30	9.03	8.85
	Car 10	9.44	10.77	7.77	7.44	9.98	9.79
	Car 11	9.43	11.26	8.63	8.00	10.80	11.25

8 m/s	Car 1	Not observed	Not observed	Not observed	Not observed	Not observed	Not observed
	Car 2	5.89	5.49	5.04	5.28	4.91	6.88
	Car 3	7.79	7.79	8.12	6.85	6.39	8.20
	Car 4	10.49	10.61	11.39	9.13	9.43	10.18
	Car 5	11.46	13.01	Not observed	9.67	11.17	11.04
	Car 6	Not observed	Not observed	Not observed	Not observed	Not observed	Not observed
	Car 7	Not observed	Not observed	Not observed	Not observed	Not observed	9.70
	Car 8	Not observed	Not observed	Not observed	Not observed	Not observed	8.30
	Car 9	Not observed	Not observed	Not observed	13.21	12.93	8.75
	Car 10	Not observed	Not observed	Not observed	13.21	13.47	11.02
	Car 11	Not observed	Not observed	Not observed	13.19	Not observed	11.87

2.6.3 Implementation of the transition rules in the cellular automata model

Sections 2.6.1 and 2.6.2 propose critical upstream heat release rates for ignition of downstream vehicles in function of ceiling height and wind speed, respectively. These critical heat release rates result in an incident heat of 15 kW/m² or more, in 5% of cases to downstream target vehicles. These critical heat release rates form the fire spread transition rules as illustrated in Figure 9.

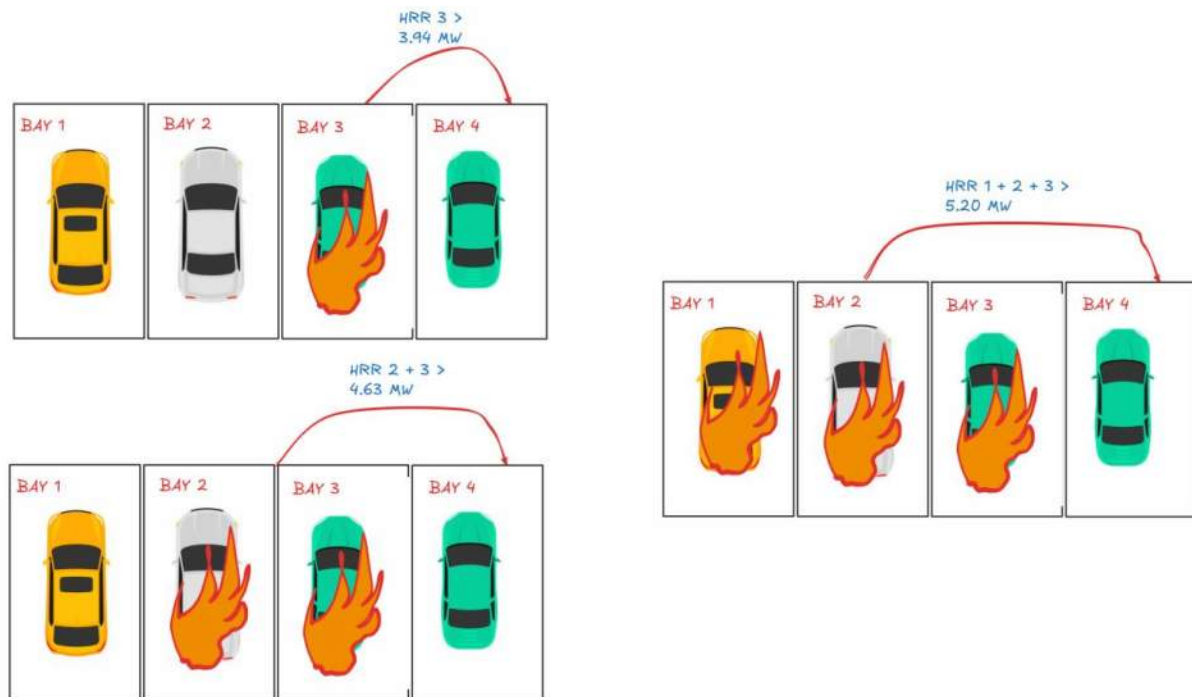


Figure 9. Illustrative application of the fire spread transition rules for single or multiple burning vehicles

The figure communicates a form of countback or upstream sum. The critical heat release rates for spread come from Table 3, using the central value in each range. By way of an example, for a ceiling height of 2.5 m and still conditions, if the ignition status of Bay 4 is being considered, three conditions can bring about its transition to “burning”:

- 1) Bay 3 reaches a HRR > 3.94 MW (see mid-range value for car position 2 in Table 3, 2.5 m ceiling height),
- 2) The sum of the heat release rate from Bays 2 and 3 reach a HRR > 4.63 MW, or
- 3) The sum of the heat release rate from Bays 1 to 3 reach 5.2 MW.

This countback sum is flexible as it allows for spaces to be empty or occupied. For example, remaining with Bay 4 and in the event Bay 3 were empty, two conditions can bring about spread: Bay 2’s HRR > 4.63 MW or the sum of Bay 1 and Bay 2 exceeding a HRR of 5.2 MW. This logic is then extended through further countbacks with increasingly larger HRRs required to spread fire further downstream.

Where wind is considered, the same principle applies, albeit using the critical HRRs from Table 4.

2.7 Cellular Automata model workflow

2.7.1 Initialisation phase

The simulation begins by establishing the parking configuration. The user specifies three key parameters: the total number of parking bays, the initial ignition point, and the probability of empty spaces. Each occupied bay is assigned one of four possible heat release rate (HRR) profiles, which determine the fire's intensity characteristics over time. These profiles represent different vehicle types or fire loads, with weightings according to Section 2.5.2.

The initially ignited bay receives a 'first' profile to represent the primary ignition source. All other occupied bays begin in an unburnt state, whilst empty bays remain permanently vacant throughout the simulation. This stochastic element introduces realistic variability in parking occupancy patterns.

2.7.2 Fire physics implementation

The simulation incorporates established fire engineering principles through several key mechanisms. Heat release rates follow predefined temporal profiles, as shown in Figure 5. These profiles reflect empirical data for vehicle fires.

Radiative heat transfer calculations employ the point source approximation, where incident heat flux decreases with the square of distance from the burning source. The radiative fraction (χ) is user defined representing the proportion of total heat release transferred via radiation. The critical heat flux threshold for ignition is established at 15 kW/m², bringing about ignition after 2 min of exposure, based on automotive fire research [7]. This assumes piloted ignition which is generally the more conservative threshold and likely in enclosure fires where embers and flames may contact un-burnt vehicles in proximity to those ignited.

2.7.3 Fire spread mechanisms

The simulation implements two distinct fire spread mechanisms operating simultaneously. The primary mechanism involves direct radiative heating between adjacent vehicles. When a burning bay's heat flux exceeds the ignition threshold at a neighbouring unburnt bay, ignition occurs. The effective distance calculation accounts for empty bays between burning and target vehicles, as fire can 'jump' across vacant spaces. The user defines both the parking space width (for cases where spaces may be empty) and the space between parked vehicles (when spaces are occupied). Both are deterministic in the current implementation of the model.

The secondary mechanism models ceiling jet effects, representing hot gas layers that develop beneath parking facility ceilings. This is as set out in section 2.6.3.

2.7.4 Simulation execution

During each time step, the simulation performs several sequential operations. First, it updates all currently burning bays by incrementing their burn duration and calculating current heat release rates according to their assigned profiles. Bays that have completed their burn cycle, i.e., their HRR returns to zero, transition to the 'burnt' state.

Next, the simulation evaluates potential ignitions through direct radiation. For each unburnt bay, it calculates the heat flux received from adjacent vehicles with a direct line-of-sight to the unburnt space, accounting for intervening empty spaces. If this flux exceeds the 15 kW/m² ignition threshold, the bay ignites and begins following its pre-assigned HRR profile.

Finally, the algorithm assesses ceiling jet conditions. It identifies groups of burning bays whose combined heat release exceeds the relevant thresholds and triggers ignition in eligible unburnt bays within the affected zones. This two-stage approach ensures that both local (radiative) and global (ceiling jet) fire spread mechanisms operate appropriately.

2.7.5 Data collection and analysis

Throughout the simulation, the system continuously records multiple data streams. Visual state histories track each bay's condition over time, enabling animated visualisation of fire progression. Heat release rate data captures the temporal evolution of fire intensity for individual bays and the overall car park.

The simulation calculates fire spread rates by measuring the time intervals between ignitions and the distances involved. This enables quantification of fire front velocities and spread characteristics.

2.7.6 Monte Carlo variation

The model can operate semi-deterministically or in a probabilistic format, using a simple Monte Carlo simulation approach. For each fire scenario, the model:

- Randomly places vehicles in the car park (some spaces may be empty)
- Starts a fire at a specified location
- Calculates heat transfer to nearby vehicles each time step
- Determines if adjacent vehicles ignite based on heat exposure
- Tracks the fire's progression until it either burns out or stops spreading
- Records key metrics like spread rate, maximum fire size, and total vehicles ignited

2.8 Application to an experimental reference case

BRE test one [6] is used as a reference case for the developed CA, like Tohir [7]. This involved a four parking space configuration, in which three spaces were occupied by cars. The cars were a 2002 Renault Laguna, a 1998 Renault Clio and a 2003 Ford Mondeo. The initiating vehicle was the Laguna, shown as the far right car in Figure 10.

The test rig was 12 m long by 6 m wide. The floor to ceiling height was 2.9 m. The fire initiation simulated an arson attack. Car 1 driver's window and offside passenger window were open (i.e. on the side furthest from Cars 2 and 3). All other car windows were closed. The fire was started using a small wood crib on the Car 1 driver's seat.

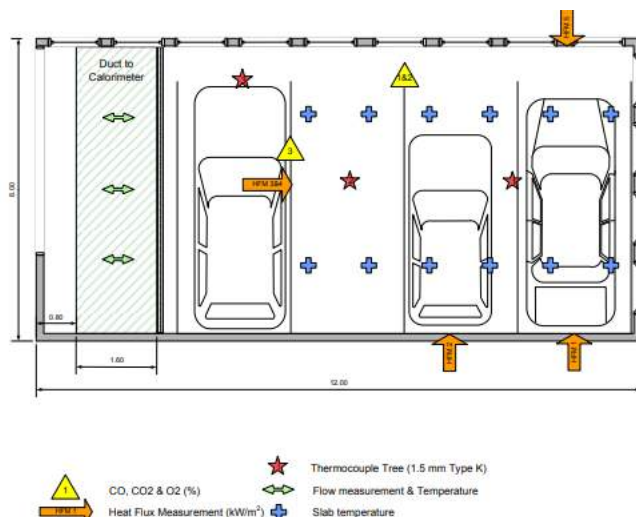


Figure 10. BRE test one layout and instrumentation schematic

For simplicity, the design fire input curves, HRR(t) are taken from the previous work of TNO [8]. The initiating vehicle is distinguished from subsequent involved vehicles by an incipient phase, typically associated with the development of a fire either beneath the engine or within the cabin. Once a fully developed fire has developed

within / on one vehicle, it is assumed that the same incipient behaviour would not be present in subsequent vehicles due to the high heat flux exposures expected.

The adopted design fire curves are shown in green and red, respectively, in Figure 11, i.e., all vehicles have the same peak heat release rate.

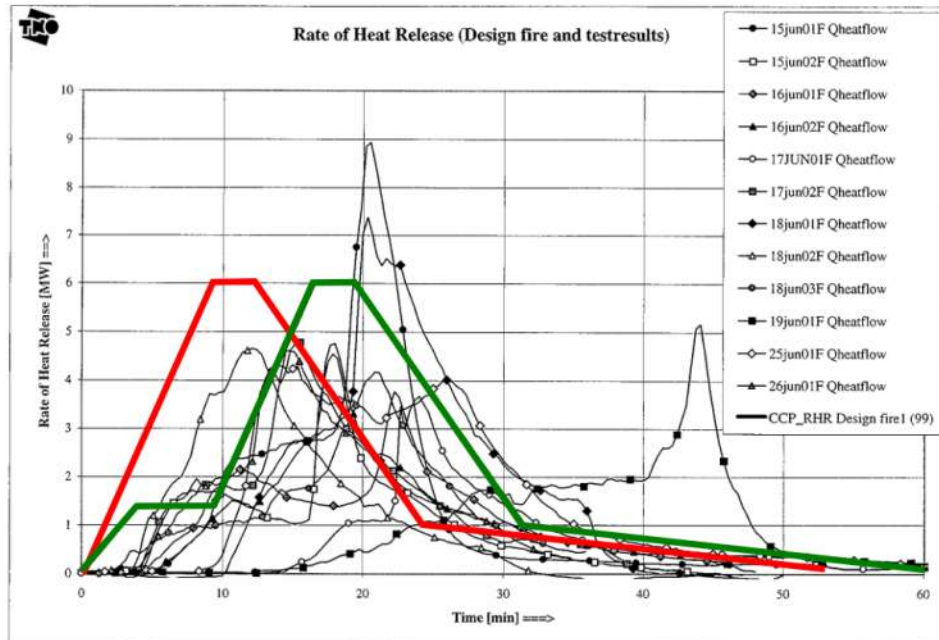


Figure 11. Deterministic vehicle HRR curves adopted for benchmarking (green) initiating vehicle, and (red) subsequent vehicles, adapted from ref. [8].

The transition rules for fire spread are taken from Section 2.6.1, using the applicable ceiling height (2.9 m). The median value in each presented range is chosen. A standard parking bay dimension of 2.4 x 4.8 m is adopted in the simulations.

Figure 1 shows the CA output for the simulation of BRE experiment 1. The top plot shows the HRR with time. The bottom plot shows the cell state with time. The time step in each instance corresponds to one minute.

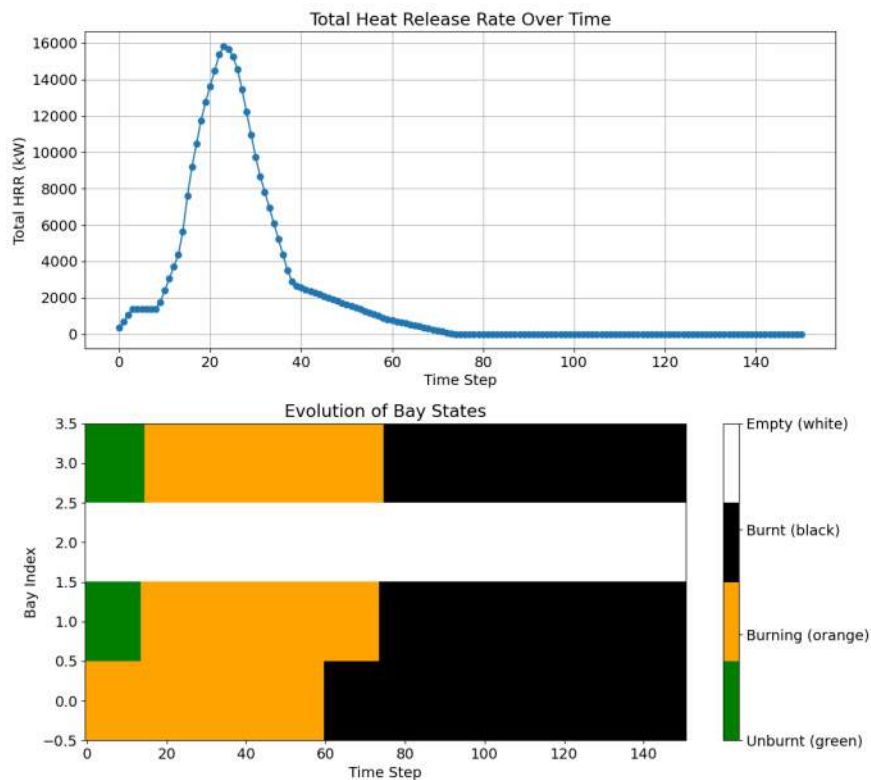


Figure 12. CA output for BRE Experiment 1, time step = 1 min

Figure 13 shows the heat release rate intensity in function of time step. The peak heat release rate predicted by the CA is ca. 15.8 MW, with this occurring after ca. 25 min. Ignition of vehicle two is seen to occur after ca. 14 min and vehicle three after ca. 16 min. For comparison, Figure 14 shows the measured HRR(t) from BRE experiment one. It should be noted that the test was terminated after ca. 25 min, with water applied to the compartment. In advance of this, it is seen that the CA peak HRR aligns well with the experiment. However, the time to peak is more conservatively estimated. This could be for several reasons, such as the implicit conservatism built into the transition rules of the CA (using a 5% threshold) or the adoption of generalised design fire curves from TNO that might not accurately represent the burning behaviour of the specific vehicles in the conditions of the experiments. Nevertheless, the correlation is sufficient.

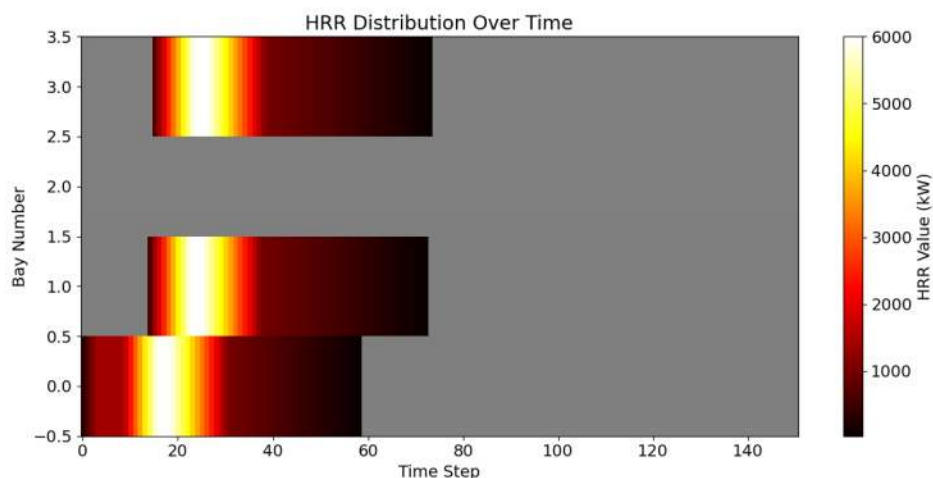


Figure 13. CA Heat release rate intensity map in function of time step (1 min)

In the description of test one, BRE note that: “Following ignition, the fire grew involving Car 1 and burned for 20 minutes at around 2 MW. At this time, the exterior combustible trim and paint on Car 2 ignited. This was

followed, a few minutes later, by the breaking of Car 2 windows and immediate full involvement of Car 2, the interior of which had become pre-heated prior to local ignition. During this stage the fire rapidly increased in intensity, reaching a momentary peak of around 16 MW, with air temperatures in the top of the rig (i.e. beneath the ceiling) reaching 1100°C. Heat fluxes at all measuring locations exceeded 25 kW/m² (i.e. in excess of critical irradiance of most combustible materials). The severity of the fire, and in particular the temperature of the smoke/ceiling jet, ignited Car 3, which then continued to burn.”

Much like the CA simulation, this would suggest that the significant involvement of cars two and three occurred together and that significant fire spread was not observed until 20 min from ignition. The CA simulation places these events ca. 3-4 min earlier than those observed.

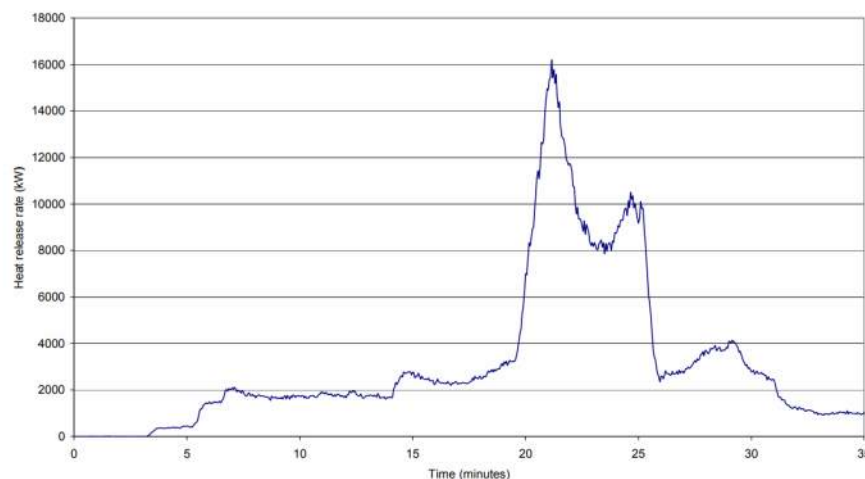


Figure 14. BRE experiment one, measured HRR with time

3. CELLULAR AUTOMATA PARAMETRIC STUDY

3.1 Variables

The parametric study adopts the cellular automata in a semi-probabilistic mode to isolate the sensitivity of fire spread to parameters. Namely, the car park space utilisation probability, the burning characteristics of the vehicles, the ceiling height and the wind speed. Stochastic parameters are included in respect of: (a) selecting the bay of ignition, and (b) assigning vehicle body types to the remaining occupied spaces. The model assumes a continuous row of 60 vehicles and runs 1000 Monte Carlo simulations for each parameter in all cases. 1000 simulations is considered sufficient to understand the sensitivity of the fire spread outcomes to the limited number of variables changed in each parametric study.

Where the mean spread rate is expressed, this is computed as follows:

- The mean spread rate to the left of the vehicle of origin is taken as the number of bays ignited to the left-hand side / time for the last left-hand side vehicle to ignite.
- The mean spread rate to the right of the vehicle of origin is taken as the number of bays ignited to the right-hand side / time for the last right-hand side vehicle to ignite.
- The iteration spread rate is taken as the maximum of mean spread rate to the left or right of the vehicle of origin.

For the computation of linear distance travelled, each bay is taken as 2.4 m wide. The calculation procedure means that spread rates will be computed if a minimum of 2 vehicles are ignited up to a maximum of 60. In some instances, this may yield fast vehicle-to-vehicle fire spread but small overall fire sizes or bays ignited if cars are randomly allocated into clusters with spaces in-between. This is as shown in Figure 15, where the right-hand side spread rate would be expressed as fire spread distance (S) / time (N).

3.2 Impact of car park utilisation

The first study adopts the mean fire sizes for each body type, time to peak HRR and THR per Section 2.5.2. The first vehicle ignited is assumed to be a small car in all cases. The ceiling height is fixed at 2.5 m.

Table 5 summarises key statistics relating to the rate and extent of fire spread in function of the car park utilisation. Where the percentile is expressed, this relates to Figure 3 in Section 2.5.1.

Table 5. Impact of utilisation on mean spread rate, mean peak fire size and mean number of bays ignited

Percentile	Utilisation	Mean spread rate [m/min]	Mean peak fire size [kW]	Mean number of bays ignited [-]
50 th	25%	0.19	6087	2.5
80 th	55%	0.28	13405	9.2
90 th	80%	0.43	27269	35.3
∞	100%	0.54	38250	60.0

Figure 16 provides histograms for the mean spread rate, mean peak fire size and mean number of bays ignited in function of the car park space utilisation probability.

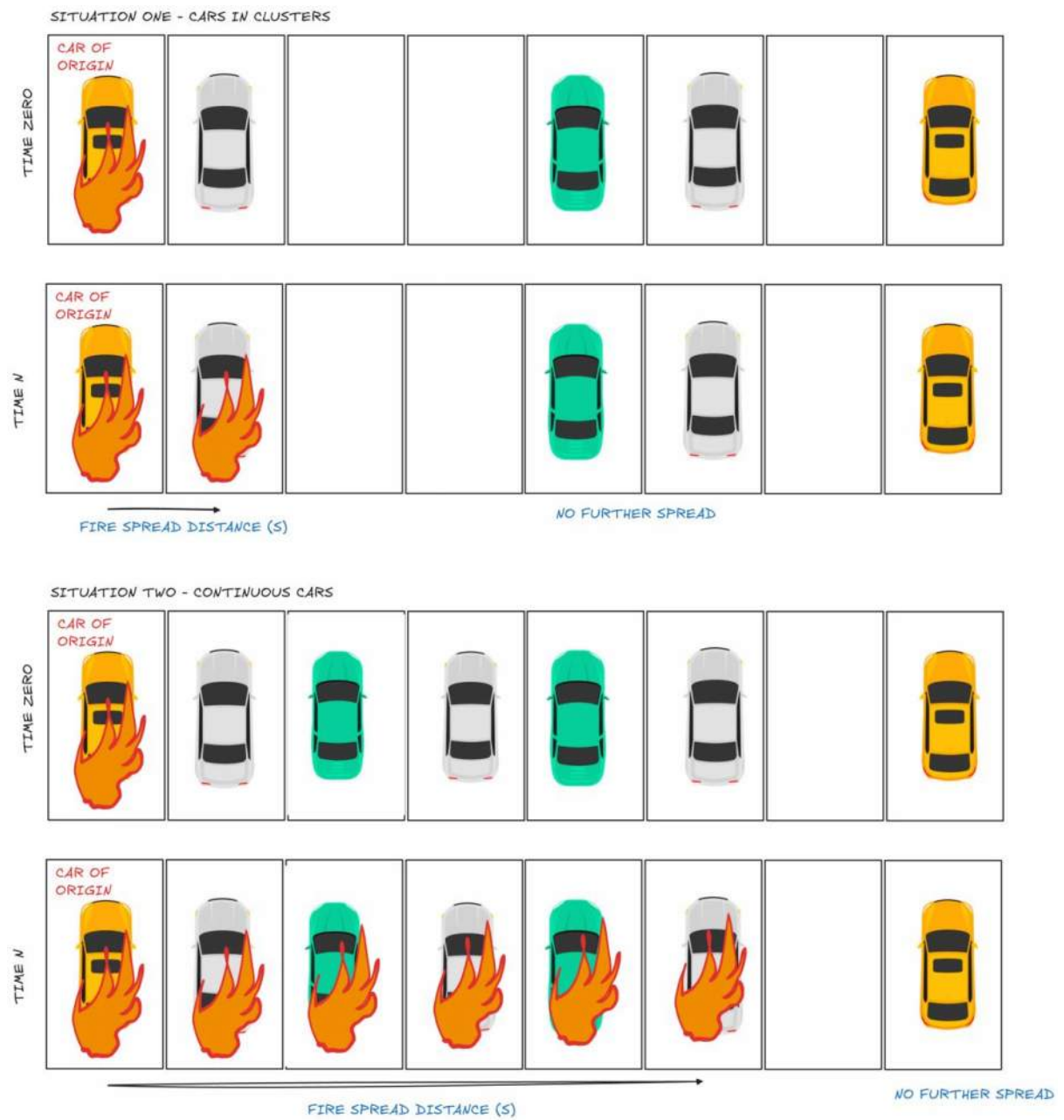


Figure 15. Illustration of fire spread rate computation (S/N)

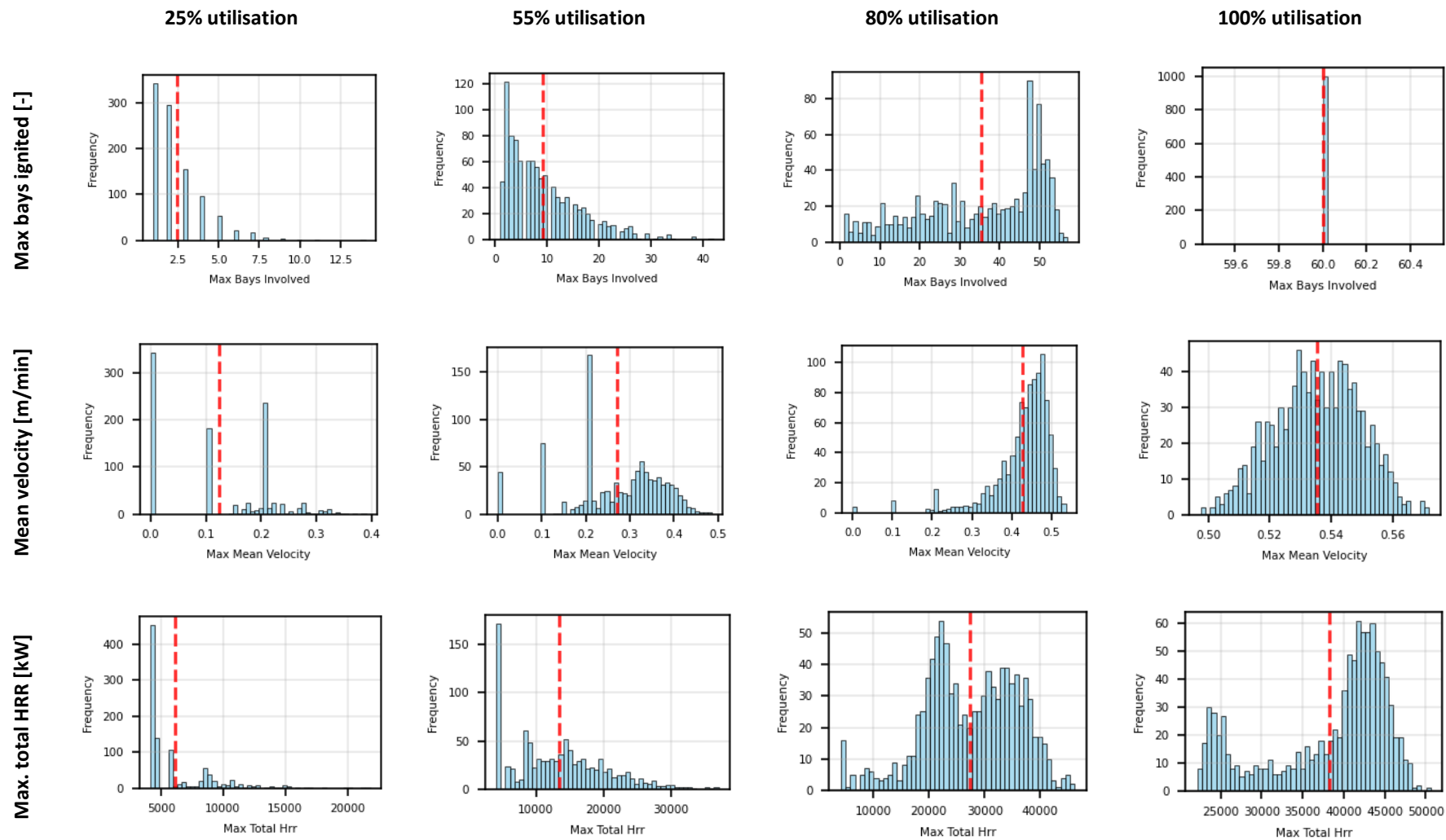


Figure 16. Parametric study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of car park utilisation (red dashed line indicates mean value)

3.3 Impact of vehicle HRR

3.3.1 Vehicle of origin

For this study, the car park utilisation is fixed at 80%, the floor to ceiling height is 2.5 m and the peak fire size of all vehicles except that of origin adopts the mean values for relevant size. The vehicle of origin adopts the small vehicle size, but varies the peak HRR, THR and growth rate to align with the 5th/95th percentiles. These are as given Table 2, with the resulting HRR(t) shown in Figure 17. The aim is to isolate the impact of the vehicle of origin on the extent and rate of subsequent fire spread. This could be considered to represent a severe initiating event, such as that arising from the thermal runaway of an electric vehicle. The intent is to observe if such an initiating event promotes rapid fire spread through the car park.

Table 6 summarises key statistics relating to the rate and extent of fire spread in function of the initiating vehicle fire size. Figure 18 provides histograms for the mean spread rate, mean peak fire size and mean number of bays ignited in function of the vehicle heat release rates (initiating and all).

Table 6. Impact of initiating vehicle fire size on mean spread rate, mean peak fire size and mean number of bays ignited

Initiating vehicle fire size	Mean spread rate [m/min]	Mean peak fire size [kW]	Mean number of bays ignited [-]
Mean	0.43	27269	35.3
95 th	0.79	31389	37.7

3.3.2 All vehicles

The impact of peak vehicle heat release rate is considered by adopting the same parameters as Section 3.2, albeit with a fixed space utilisation of 80%. The design fire curve corresponded to each vehicle size of small, medium and large, is modified to represent the 95th percentile peak HRR and THR, alongside the 5th percentile time to peak HRR. The resulting HRR(t) is shown in Figure 17. This represents a somewhat arbitrary high severity event as it is unlikely that the 95th percentile peak HRR would coincide with the 5th percentile time to peak HRR, i.e., the fire is both intense and fast growing.

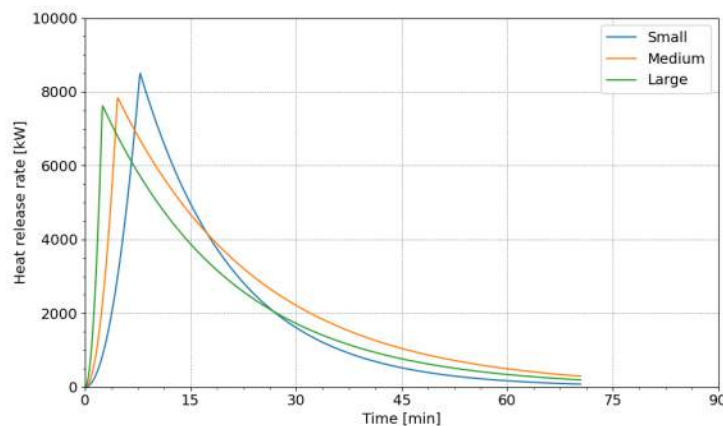


Figure 17. Idealised design fire curves for small, medium and large vehicles for a combined 5th time to peak HRR and 95th percentile peak HRR based on values from Miechówka and Węgrzyński

Table 7 summarises key statistics relating to the rate and extent of fire spread in function of the vehicle fire size. Figure 18 provides histograms for the mean spread rate, mean peak fire size and mean number of bays ignited in function of the vehicle heat release rates (initiating and all).

Table 7. Impact of vehicle fire size on mean spread rate, mean peak fire size and mean number of bays ignited

Fire size	Mean spread rate [m/min]	Mean peak fire size [kW]	Mean number of bays ignited [-]
Mean	0.43	27269	35.3
95 th	3.82	202979	47.2

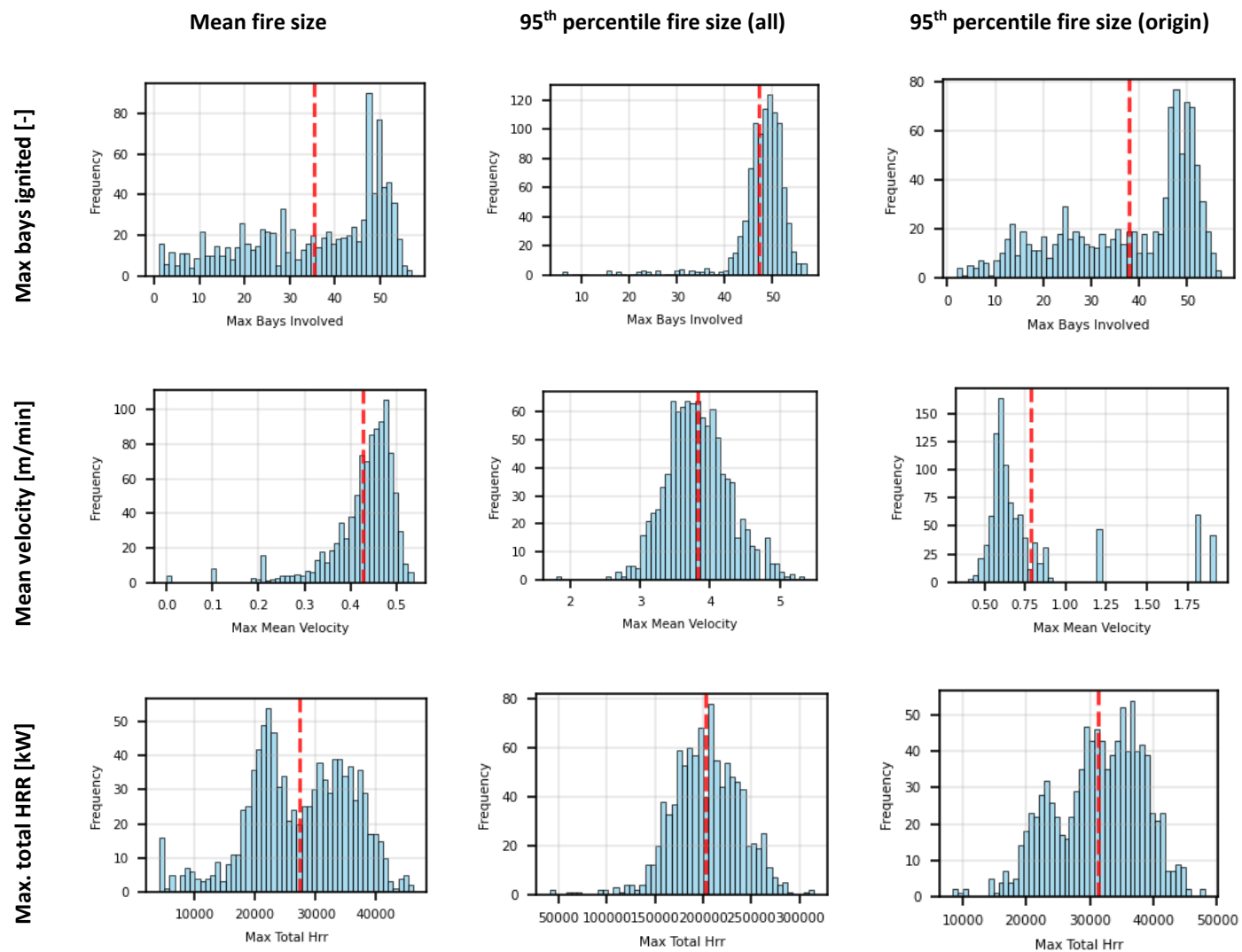


Figure 18. Parametric study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of car fire size (red dashed line indicates mean value)

3.4 Impact of ceiling height

The impact of ceiling height is considered through a change in the transition rules. Specifically, the critical heat release rate to deliver an incident heat flux exceeding 15 kW/m^2 , as set out in Section 3.4. By inspection of Table 3, it is seen that the critical heat release rate for spread often exceeds the mean peak heat release rate of vehicles noted in Table 2¹. Given this, the decision was made to use high vehicle design fires, corresponding to the 95th percentile peak HRR, 95th percentile THR and 5th percentile time to peak HRR. The car park utilisation is fixed at 80%, with all other parameters as described in Section 3.2.

Table 8 summarises key statistics relating to the rate and extent of fire spread in function of the ceiling height.

Table 8. Impact of ceiling height on mean spread rate, mean peak fire size and mean number of bays ignited. Results for 95th percentile vehicle sizes and 80% car park utilisation

Ceiling height [m]	Mean spread rate [m/min]	Mean peak fire size [kW]	Mean number of bays ignited [-]
2.5	3.82	202979	47.2
2.7	3.79	200541	47.3
2.9	3.37	189798	47.1
3.1	3.35	189994	47.1
3.3	3.09	183607	47.4
3.5	3.04	181827	47.3

Figure 19 provides histograms for the mean spread rate, mean peak fire size and mean number of bays ignited in function of the floor-to-ceiling height. Three select ceiling heights are shown, 2.7, 3.1 and 3.5 m.

3.5 Impact of wind

The impact of ceiling height is also considered through a change in the transition rules. Section 2.6.2 describes the relationship between the critical heat release rate to deliver an incident heat flux exceeding 15 kW/m^2 , and the windspeed. This considered windspeeds of 2, 4 and 8 m/s. Much like the impact of ceiling height, it is seen that the critical heat release rate for spread often exceeds the mean peak heat release rate of vehicles noted in Table 2. For this reason, the higher vehicle fire intensities were adopted as in Section 3.4. The car park utilisation is also fixed at 80%, with all other parameters as described in Section 3.2, e.g., a fixed floor-to-ceiling height of 2.5 m.

Table 9 summarises key statistics relating to the rate and extent of fire spread in function of the wind speed.

Table 9. Impact of ceiling height on mean spread rate, mean peak fire size and mean number of bays ignited. Results for 95th percentile vehicle sizes and 80% car park utilisation

Wind speed [m/s]	Mean spread rate [m/min]	Mean peak fire size [kW]	Mean number of bays ignited [-]
0	3.82	202,979	47.2
2	3.98	177,875	46.7
4	3.82	175,526	47.0
8	2.66	121,232	37.6

Figure 20 provides histograms for the mean spread rate, mean peak fire size and mean number of bays ignited in function of the wind speed.

¹ When the ceiling heights get larger, the HRR required to observe spread must also be larger. If the impact of ceiling height on spread is to be observed, fire sizes large enough to induce spread need to be imposed.

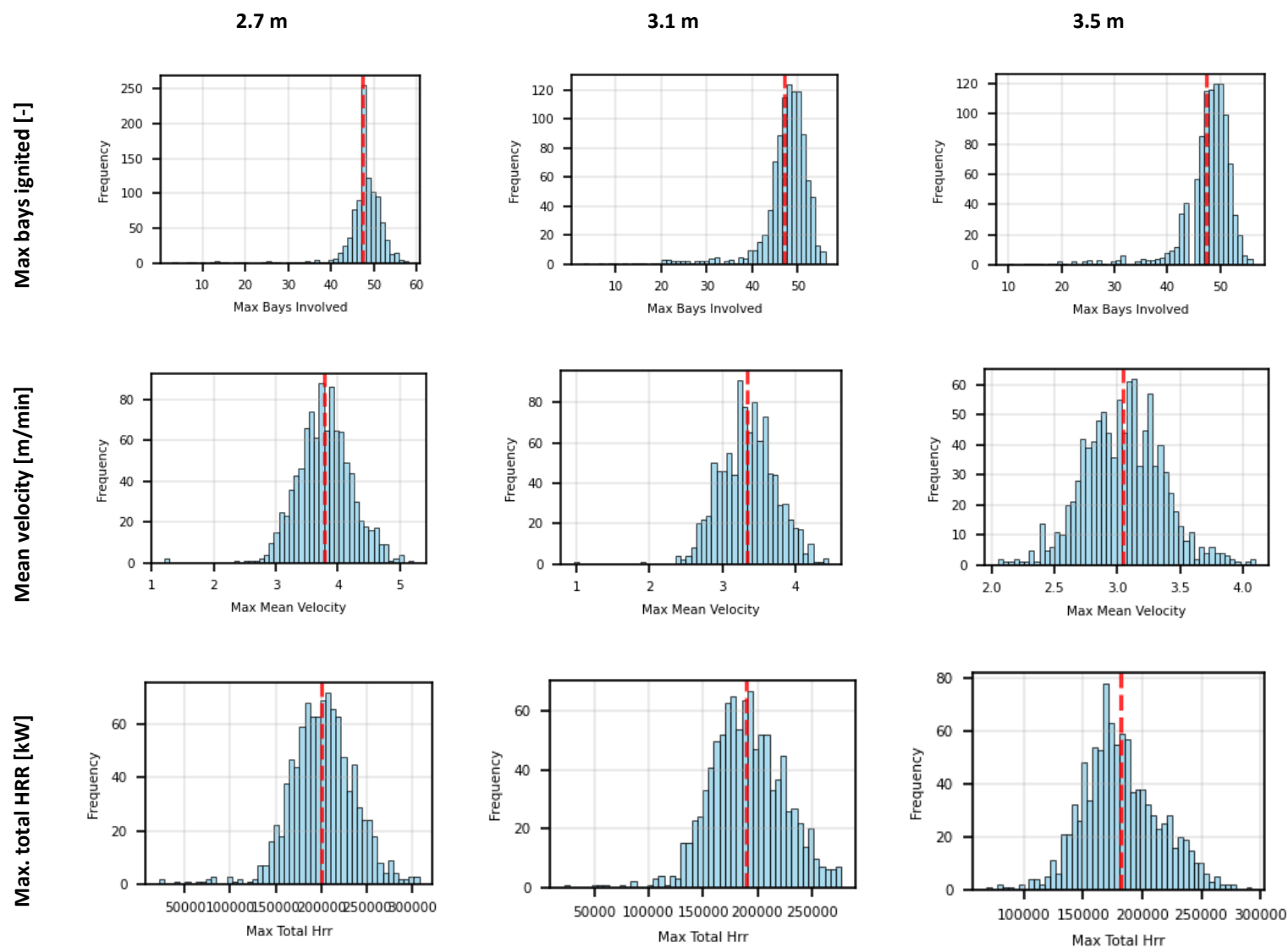


Figure 19. Parametric study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of ceiling height based on 95th percentile vehicle fire size (red dashed line indicates mean value)

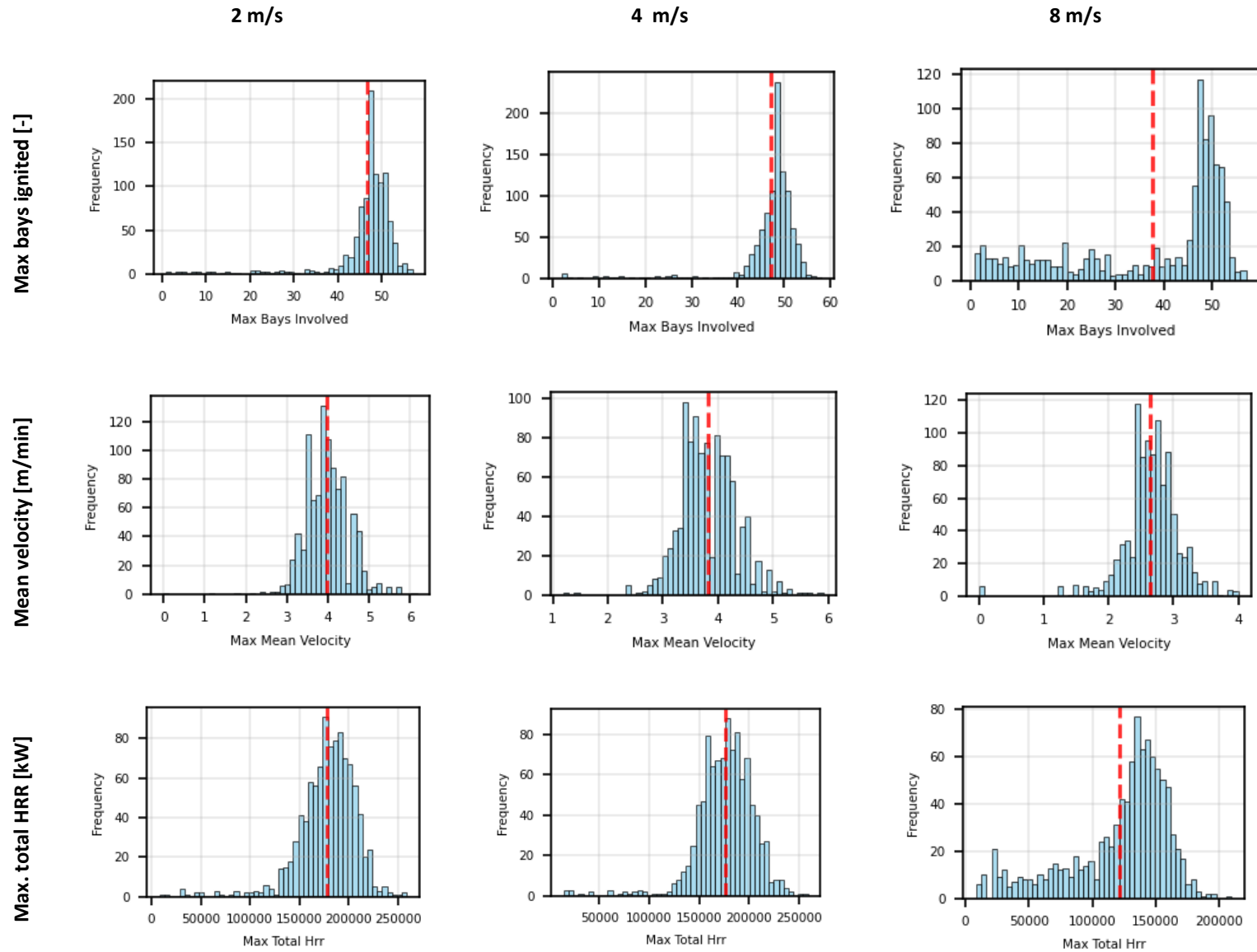


Figure 20. Parametric study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of ceiling height based on 95th percentile vehicle fire size (red dashed line indicates mean value)

4. CELLULAR AUTOMATA MCS

4.1 Variables and constants

The Monte Carlo Simulation (MCS) procedure introduces several sources of uncertainty simultaneously, whilst varying fixed parameters, i.e., the car park utilisation, the floor-to-ceiling height and the wind speed. Procedurally, the location of the car of origin is randomly assigned to one of 60 spaces that are linearly arranged. The first vehicle body type is sampled as being either small, medium or large according to Section 2.5.2. Each remaining space is assigned a probability of being occupied. This is fixed at 80% unless the car park space utilisation is a variable. In spaces occupied by a vehicle, the vehicle body type is sampled again according to Section 2.5.2. For each occupied space and according to their body type, heat release rate parameters are sampled according to Table 2. This defines the severity of the fire originating from each vehicle, expressed in terms of its peak heat release rate, time to peak heat release rate and total heat release rate. Discrete weightings are applied to each design fire percentile as follows: 50% for 50th percentile, 25% for the 75th percentile, 1% for the 99th percentile and the remaining 24% assigned to the 95th percentile. In practice, the design fire intensities exist on a continuum, but the sampling procedure introduces a slight bias towards more severe individual vehicle fires.

One iteration of the MCS (i.e., one run of the cellular automata model) will have randomly assigned (i) space of origin, (ii) vehicle body type of origin, (iii) distribution of vehicles in remaining spaces according to utilisation, (iv) body types of vehicles and, finally, (v) their design fire curve. This set of parameters leads to one iteration of the cellular automata where fire spread parameters are recorded, i.e., the mean spread rate, the peak fire size and the number of bays ignited. This is repeated 5,000 times (based on the guidance in PD 7974-7 [9] when seeking convergence at higher percentiles), with each iteration yielding a new random assignment of the parameters (i to v) noted. Transition rules, as discussed in Section 2.6 are used to distinguish between different ceiling heights or wind speeds.

4.2 Results for different utilisations

The first MCS adopts the stochastic parameters (i to v) alongside deterministic space utilisation probabilities of 40, 60, 80 and 100%. A summary of key spread statistics is given in Table 10.

Table 10. Summary statistics for MCS based on car park utilisation

Car park space utilisation	Mean spread rate [m/min]	Mean peak fire size [kW]	Mean number of bays ignited [-]
Low (40%)	0.96	23,474	7.8
Medium (60%)	1.17	46,299	20.7
High (80%)	1.38	78,581	43.1
Full (100%)	1.67	113,123	60.0

Figure 21 provides histograms for the mean spread rate, mean peak fire size and mean number of bays ignited in function of the car park space utilisation probability. Appendix I fits distributions to the mean spread rate and mean number of bays ignited parameters.

4.3 Results for different ceiling heights

The second MCS has uncertainty in the parameters (i to v). However, the space utilisation probability is fixed at 80%, indicative of a high average occupancy for a car park year-round. The impact of ceiling height is varied according to the transition rules in Section 2.6.1. Table 11 provides a summary of key fire spread statistics.

Table 11. Summary statistics for MCS based on car park utilisation of 80% but varying ceiling heights

Ceiling height	Mean spread rate [m/min]	Mean peak fire size [kW]	Mean number of bays ignited [-]
2.5 m	1.36	78,893	42.9
2.7 m	1.32	75,246	40.9
3.1 m	1.21	69,362	37.3
3.5 m	1.11	63,612	33.8

Figure 22 provides histograms for the mean spread rate, mean peak fire size and mean number of bays ignited in function of the ceiling height. Appendix I fits distributions to the mean spread rate and mean number of bays ignited parameters.

4.4 Results for different wind speeds

The final MCS retains uncertainty in the parameters (i to v). However, the space utilisation probability is fixed at 80% and the floor to ceiling height of the car park is fixed at 2.5 m. The wind speed is varied according to the transition rules in Section 2.6.2. As Table 4, even low wind speeds at 2 m/s retard upwind fire spread. Therefore, the cellular automata fixes the ignition bay to index 0 (space 1) to impose a condition of downwind spread only.

Table 12. Summary statistics for MCS based on car park utilisation of 80%, 2.5 m floor to ceiling but varying wind speeds

Wind speed [m/s]	Mean spread rate [m/min]	Mean peak fire size [kW]	Mean number of bays ignited [-]
0	1.22	62,449	40.4
2	1.05	53,699	33.9
4	0.99	51,113	32.0
8	0.66	31,040	16.8

Figure 23 provides histograms for the mean spread rate, mean peak fire size and mean number of bays ignited in function of the ceiling height. Appendix I fits distributions to the mean spread rate and mean number of bays ignited parameters.

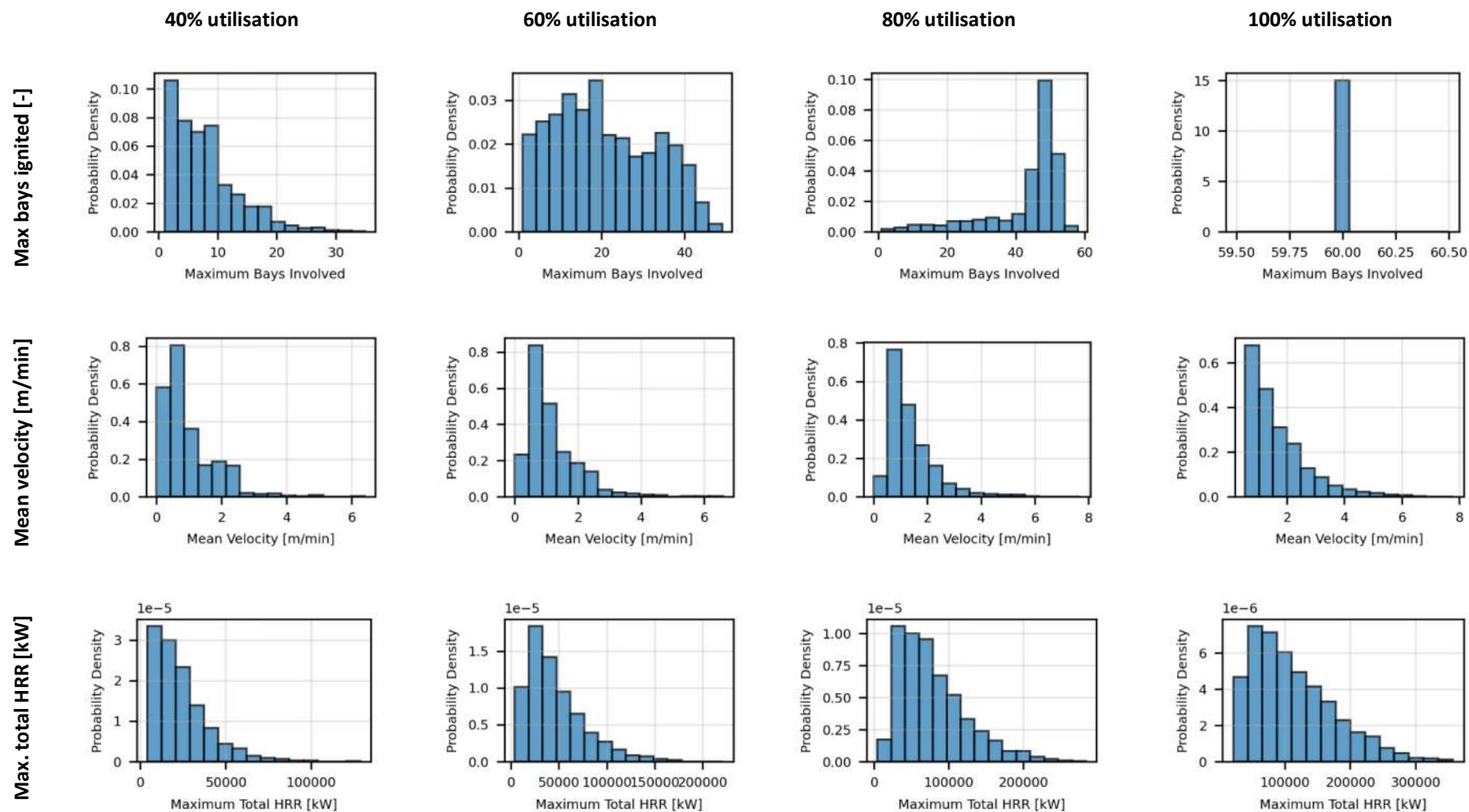


Figure 21. MCS study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of utilisation with distributed vehicle fire sizes (red dashed line indicates mean value)

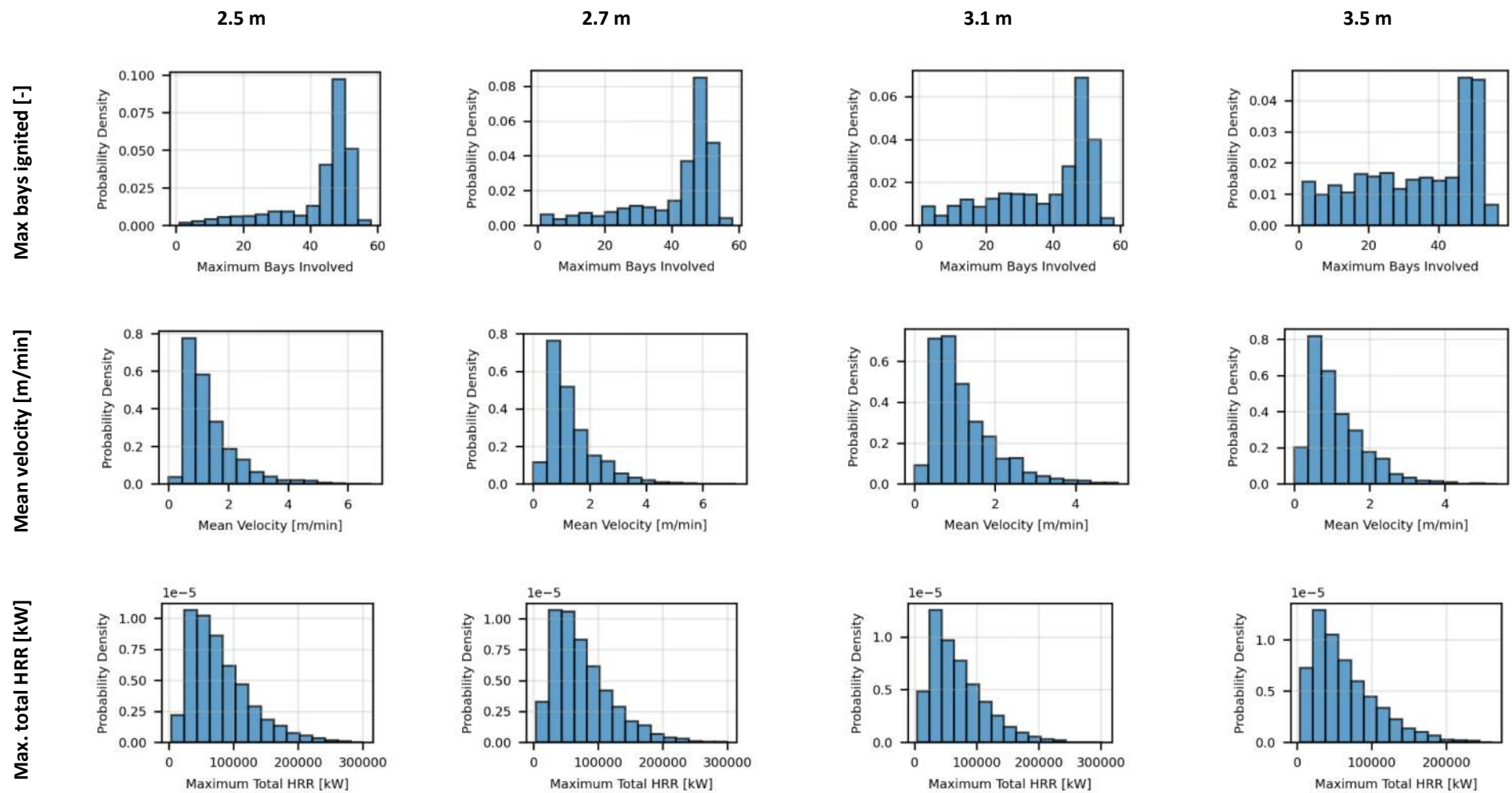


Figure 22. MCS study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of ceiling height with distributed vehicle fire sizes, 80% space utilisation (red dashed line indicates mean value)

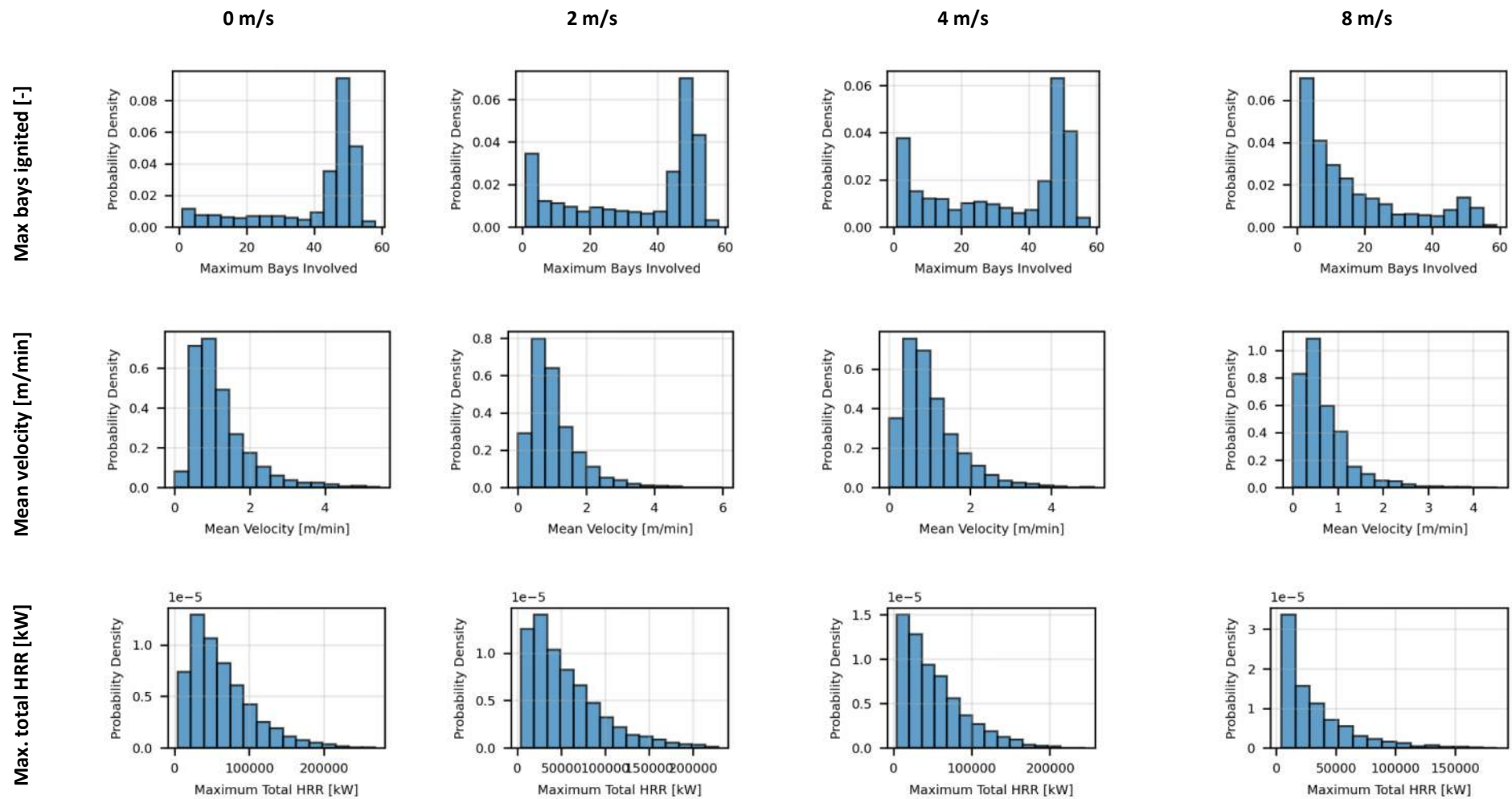


Figure 23. MCS study - PDFs for max. bays ignited, mean fire spread velocity and max. total HRR, in function of wind speed with distributed vehicle fire sizes, 80% space utilisation and 2.5 m ceiling (red dashed line indicates mean value)

5. DISCUSSION & CONCLUSIONS

5.1 CFD modelling of fire spread

Appendix II presents the CFD study undertaken by ITB. Most crucially, the CFD modelling of car parks identifies a strong influence of ceiling geometry, whereby structural bay effects are observed. This bay effect constrains smoke and flames between structural elements, such as beams, which then channels the flow in the direction of the span. This has the effect of increasing ceiling jet lengths as they are no longer unconstrained. Thus, having the potential to promote faster downstream spread and, ultimately, a greater extent of spread. As a general observation, there may be some utility in ensuring car parking spaces are aligned perpendicular to the spans of primary beams to mitigate any such bay effects.

The CFD modelling has systematically observed the impact of heat release rate on incident heat flux to vehicles away from those burning, considering variables such as ceiling height and wind speed. In the case of ceiling height, the CFD results indicate that increasing ceiling height typically reduces the incident heat flux to downstream vehicles and, thus, has the potential as a mitigation measure when seeking to reduce the rate and extent of fire spread. Wind effects were seen to retard upstream fire spread at relatively low velocities, i.e., > 2 m/s. Increased wind speed reduced incident heat flux to downstream vehicles regardless of ceiling height, suggesting that air movement could also be an effective mitigation measure for fire spread, e.g., through the inclusion of smoke control. However, empirical evidence from WP 1A indicates that many larger car park fires have been wind driven.

Ultimately, the CFD modelling served to provide transition rules for fire spread for the cellular automata, as presented in Table 3 and Table 4.

5.2 Cellular automata parametric study

The parametric study systematically varied parameters that included: the car park utilisation, the initiating vehicle fire size, all vehicle HRRs, ceiling height and wind speed. The dominant parameters affecting the extent and rate of fire spread, in order of influence, were:

- 1) Vehicle HRRs, i.e., when all vehicles were afforded the 95th percentile peak HRR and THR, combined with the 5th percentile growth rates, the spread rate (mean of 0.43 to 3.82 m/min), peak fire size (mean of 27 to 203 MW) and number of spaces ignited (mean of 35 to 47) substantially increased.
- 2) Car park utilisation, i.e., fuller car parks generally produced much higher peak heat release rates, spread rates and number of cars ignited. When car parks were full, simulations generally showed that the fire would spread to involve all cars without intervention. The mean spread rate increased from 0.19 to 0.54 m/min across a utilisation range of 25 to 100%. This led to an increase in mean peak fire size from 6 to 38 MW.
- 3) Initiating vehicle fire size, i.e., when the first vehicle was afforded the 95th percentile peak HRR and THR, combined with the 5th percentile growth rates the spread rate (mean of 0.43 to 0.79 m/min), peak fire size (mean of 27 to 31 MW) and number of spaces ignited (mean of 35 to 38) increased. This could indicate that were an EV to be the initiating vehicle through thermal runaway, the subsequent extent of fire spread could be more onerous. However, this is less apparent when uncertainty is introduced for fire sizes across all occupied spaces, as discussed in section 5.3.
- 4) Wind, i.e., high internal air speeds were generally seen to reduce the extent (mean from 47 to 38 vehicles as air speed increased from 0 to 8 m/s) and rate of fire spread (mean from 3.82 to 2.66 m/min as air speed increased from 0 to 8 m/s) as the HRR required to induce sufficient downstream heat fluxes for ignition was substantially higher. It should be noted that the burning rate of the cars in the CFD models was decoupled from the windspeed. It is possible that higher windspeeds might result in higher HRRs, which in turn could promote fire spread.
- 5) Ceiling height, i.e., varying the ceiling height from 2.5 m through to 3.5 m did have an impact on the spread rate and extent of fire spread. However, this was the least significant of the parameters in the

study undertaken. That is, across a range of 2.5 to 3.5 m, mean spread rate dropped from 3.8 to 3.0 m/min. The mean peak fire size dropped by 20 MW as a consequence of a 1 m change in ceiling height.

5.3 Cellular automata MCS

The cellular automata MCS study randomly assigned vehicles and their HRRs to spaces according to the relevant distributions presented. Car parks were studied considering different utilisations and adopting transition rules to represent different floor to ceiling heights and wind speeds. This is considered a more representative series of scenarios than the parametric studies as uncertainty in how vehicles may burn is inherently captured. The key metrics observed were the distribution of spread rate and number of bays ignited (up to a maximum of 60). Again, utilisation, which can be considered proxy for fire load, was the dominant parameter. For high utilisations, e.g. 80% to 100% the mean spread rates for a 2.5 m floor to ceiling height ranged from 1.38 to 1.67 m / min, involving on average 43 to 60 cars (ca. 2/3s or all of the car park spaces). It is noteworthy that the average number of spaces ignited for an 80% utilisation, i.e., 43, is below the average number occupied at the start of each simulation (80% x 60 = 48). This suggests that empty spaces between vehicles have a role in curtailing fire spread.

Ceiling height had an impact in terms of reducing spread rate, fire size and number of vehicles ignited. This is due to the transition rules, where higher HRRs are required to reach a critical heat flux of 15 kW/m² downstream from the fire. A change in ceiling height from 2.5 m to 3.5 m resulted in a ca. 20% reduction in spread rate, peak fire size and number of vehicles ignited.

Increasing internal air speed generally had the impact of reducing the rate of spread, number of bays ignited and peak heat release rate. The reason is evident from the transition rules, where higher heat release rates are required to promote downstream spread due to disruption of the plume and ceiling jet. This is coupled with the retarding of upstream fire spread. This might suggest interventions such as smoke control and jet fans could be effective in reducing fire severity in car parks. This finding is inconsistent with WP 1A, where empirical evidence from real fire incidents suggests wind may promote more rapid downstream spread. However, as is noted in WP 1A, determining spread rates retrospectively from fire incidents is challenging and introduces several sources of uncertainty.

The outputs of the Monte Carlo simulations are presented as distributions in Appendix . Distribution types and relevant statistics have been fit to the MCS outputs for sampling during WP 2. The fitting process uses various goodness of fit tests, that include:

- **Kolmogorov-Smirnov Test:** Compares empirical vs theoretical cumulative distribution
- **Anderson-Darling Test:** More sensitive to tail differences (for normal distribution)
- **RMSE (Root Mean Square Error):** Measures CDF differences
- **AIC/BIC (Information Criteria):** Balance goodness-of-fit with model complexity

The method trials the following distributions:

- **Normal (Gaussian)** - bell curve distribution
- **Log-Normal** - for right-skewed data that becomes normal when log-transformed
- **Gamma** - flexible shape for positive data
- **Beta** - bounded between 0 and 1
- **Weibull** - reliability/survival analysis
- **Exponential** - for processes with constant failure rates
- **Uniform** - equal probability across a range
- **Chi-Square** - for squared normal variables
- **Pareto** - power law distributions ("80/20 rule")

- **Rayleigh** - for vector magnitudes
- **Logistic** - S-shaped curve similar to normal
- **Generalized Extreme Value** - for modelling extremes

5.4 Comparison against real fire incidents

Section 6.2 of the WP 1A deliverable summarises a range of car park spread rates from both experiments and real fire incidents. The summary is reproduced in Table 13. Considering the results presented in Section 4.2, the mean spread rates ranged from 0.78 to 1.31 m/min for a 2.5 m ceiling height. This aligns with the Stavanger and Schiphol fires but is more conservative than Lloydstraat. Reviewing the sensitivity to floor to ceiling height in Section 4.3, the mean spread rate for a 3.1 m ceiling was 1.37 m/min, compared to ranges of 0.41 to 1.96 and 0.37 to 1.37 m/min observed at Luton and the Link apartments, respectively. Therefore, there is agreement between the outcomes of the CA MCS and the empirical reference incidents.

Table 13. Summary of key characteristics involving multiple vehicle fire spread, from WP 1A

Test / incident	External wind speed (m/s)	Floor-to-ceiling height (m)	Parking bay width (m)	Fire spread rate (m/min)	
				Min	Max
BHP	~5.5	2.5	2.60	0.10	0.20
Joyeux	n/a	2.3 or 2.6	~2.50	0.18	0.31
Kitano et al.	3	2.9	2.50	0.12	0.29
Steinert	n/a	4.5	~2.50	0.06	0.22
BRE	0	2.9	2.40	0.12	0.70
Li et al.	n/a	12	~2.40	0.13	0.43
Park et al.	0	n/a	~2.30	0.28	
Tramoni et al.	0	3	2.50	0.09	0.31
ELBAS	n/a	2.40	~2.50	0.14	0.48
Schiphol	0	2.6	~2.20	0.38	0.83
Lloydstraat	~4.5	2.4	~2.20	0.18	0.22
Kings Dock	5	2.6	2.47	0.20	0.35*
Stavanger airport	12	2.5	2.30	0.21	1.50
Luton airport	4.5	3.0	~2.40	0.41	1.96
Link apartments	0	~3.0	~2.40	0.37	1.37
*4.95 m/min using 2 cars per minute					

5.5 Next steps

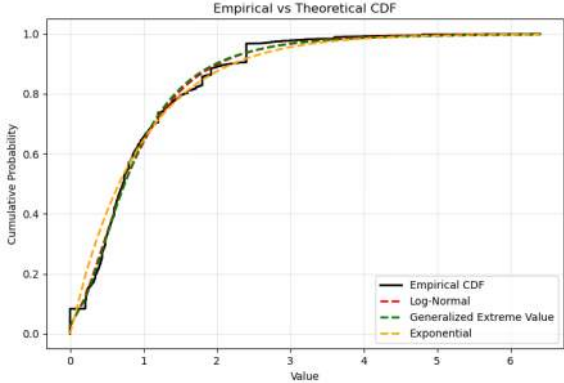
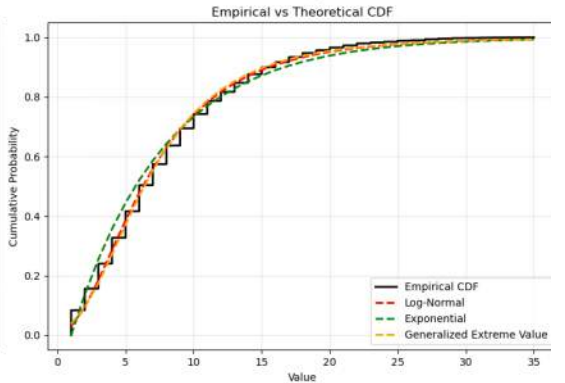
The distributions in Appendix I will be carried into WP 2 when undertaking probabilistic fire severity assessments using OFR's SFEpra.py tool [10], [11]. The probabilistic fire severity assessment uses the time equivalence methodology within a Monte Carlo simulation framework to produce relationships between the probability of surviving burnout (reliability) and the structural fire resistance of structural elements. The tool is thermally based and equates the thermal exposure in real fires to equivalent durations of ISO 834 heating [12]. This deliverable provides spread rate and extent of fire spread data in function of key variables that is integral to estimating the thermal exposure to structural elements forming purpose-built open-sided car parks.

6. REFERENCES

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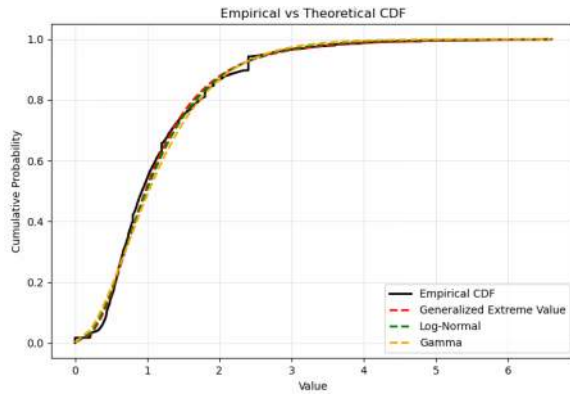
APPENDIX I – MCS OUTPUT STATS

In function of utilisation of carpark

Low utilisation (40%)	
Spread rate [m/min]	Bays ignited [-]
 LOG-NORMAL ===== PARAMETERS: s (σ) = shape parameter: 0.620485 loc = location shift: -0.304456 scale = scale factor: 1.048013 INTERPRETATION: s = shape parameter (σ of underlying normal), loc = location shift, scale = scale factor Formula: $\ln(X) \sim N(\ln(\text{scale}), s^2)$ SCIPY USAGE: stats.lognorm.rvs(s=0.6205, loc=-0.3045, scale=1.0480, size=n)	 LOG-NORMAL ===== PARAMETERS: s (σ) = shape parameter: 0.621958 loc = location shift: -1.351537 scale = scale factor: 7.612224 INTERPRETATION: s = shape parameter (σ of underlying normal), loc = location shift, scale = scale factor Formula: $\ln(X) \sim N(\ln(\text{scale}), s^2)$ SCIPY USAGE: stats.lognorm.rvs(s=0.6220, loc=-1.3515, scale=7.6122, size=n)

Medium utilisation (60%)

Spread rate [m/min]



GENERALIZED EXTREME VALUE

=====

PARAMETERS:

c (ξ) = shape parameter: -0.165061

loc (μ) = location: 0.782966

scale (σ) = scale: 0.501387

INTERPRETATION:

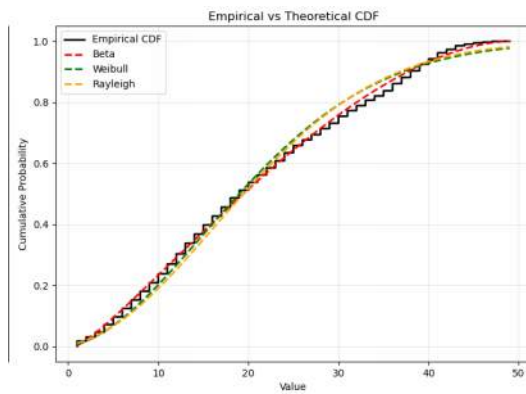
c = shape parameter (ξ), loc = location (μ), scale = scale (σ)

Formula: $X \sim \text{GEV}(\xi, \mu, \sigma)$

SCIPY USAGE:

`stats.genextreme.rvs(c=-0.1651, loc=0.7830, scale=0.5014, size=n)`

Bays ignited [-]



BETA

=====

PARAMETERS:

a (α) = first shape parameter: 1.215541

b (β) = second shape parameter: 1.757283

loc = location: 0.825535

scale = scale: 48.216114

INTERPRETATION:

a = first shape parameter (α), b = second shape parameter (β)

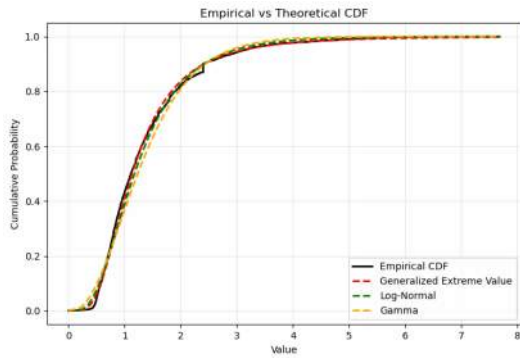
Formula: $X \sim \text{Beta}(\alpha, \beta)$

SCIPY USAGE:

`stats.beta.rvs(a=1.2155, b=1.7573, loc=0.8255, scale=48.2161, size=n)`

High utilisation (80%)

Spread rate [m/min]



GENERALIZED EXTREME VALUE

=====

PARAMETERS:

$c(\xi)$ = shape parameter: -0.246227

$loc(\mu)$ = location: 0.944418

scale (σ) = scale: 0.489356

INTERPRETATION:

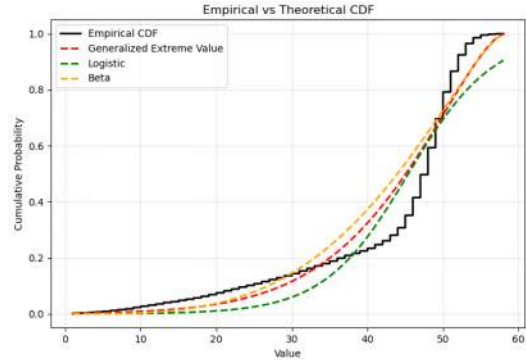
c = shape parameter (ξ), loc = location (μ), scale = scale (σ)

Formula: $X \sim \text{GEV}(\xi, \mu, \sigma)$

SCIPY USAGE:

`stats.genextreme.rvs(c=-0.2462, loc=0.9444, scale=0.4894, size=n)`

Bays ignited [-]



GENERALIZED EXTREME VALUE

=====

PARAMETERS:

$c(\xi)$ = shape parameter: 0.681215

$loc(\mu)$ = location: 41.399754

scale (σ) = scale: 11.312362

INTERPRETATION:

c = shape parameter (ξ), loc = location (μ), scale = scale (σ)

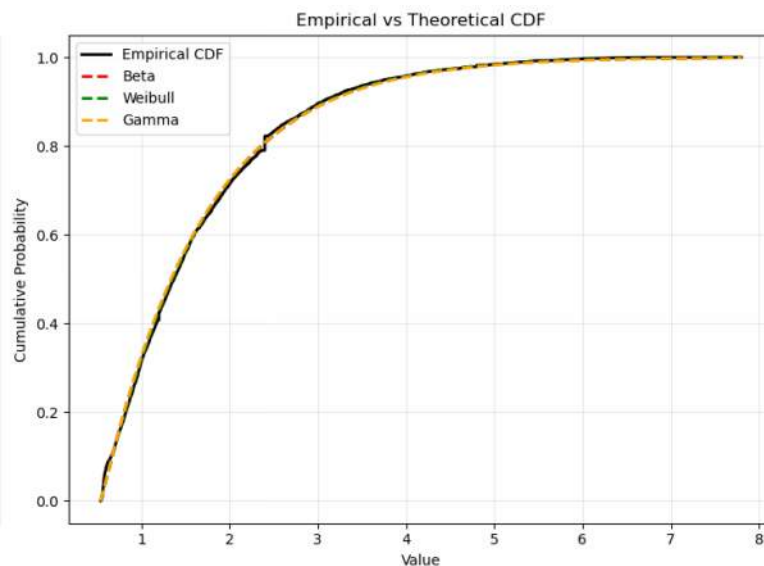
Formula: $X \sim \text{GEV}(\xi, \mu, \sigma)$

SCIPY USAGE:

`stats.genextreme.rvs(c=0.6812, loc=41.3998, scale=11.3124, size=n)`

Full utilisation (100%)

Spread rate [m/min]



BETA

=====

PARAMETERS:

a (α) = first shape parameter: 1.020355

b (β) = second shape parameter: 33.737090

loc = location: 0.540654

scale = scale: 38.453255

INTERPRETATION:

a = first shape parameter (α), b = second shape parameter (β)

Formula: $X \sim \text{Beta}(\alpha, \beta)$

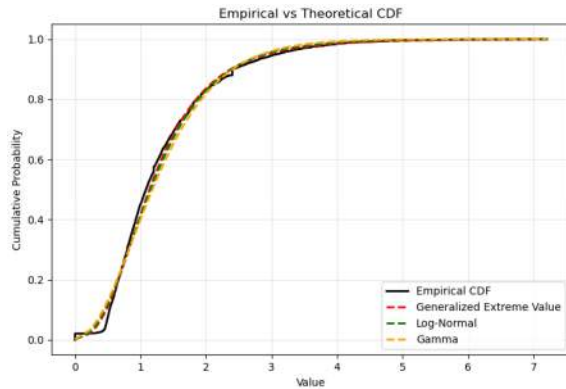
SCIPY USAGE:

`stats.beta.rvs(a=1.0204, b=33.7371, loc=0.5407, scale=38.4533, size=n)`

In function of ceiling height

2.7 m ceiling height

Spread rate [m/min]



GENERALIZED EXTREME VALUE

=====

PARAMETERS:

$c(\xi)$ = shape parameter: -0.121232

$loc(\mu)$ = location: 0.923073

scale (σ) = scale: 0.561918

INTERPRETATION:

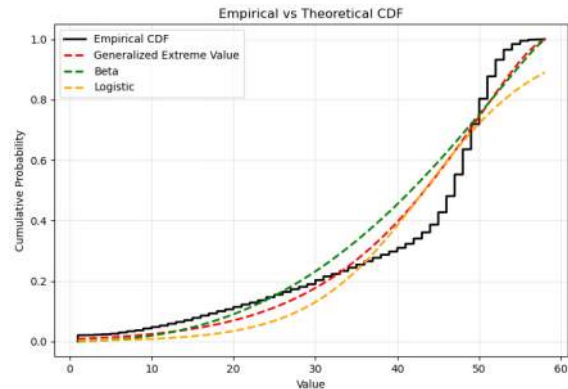
c = shape parameter (ξ), loc = location (μ), scale = scale (σ)

Formula: $X \sim \text{GEV}(\xi, \mu, \sigma)$

SCIPY USAGE:

`stats.genextreme.rvs(c=-0.1212, loc=0.9231, scale=0.5619, size=n)`

Bays ignited [-]



GENERALIZED EXTREME VALUE

=====

PARAMETERS:

$c(\xi)$ = shape parameter: 0.708154

$loc(\mu)$ = location: 39.010257

scale (σ) = scale: 13.453943

INTERPRETATION:

c = shape parameter (ξ), loc = location (μ), scale = scale (σ)

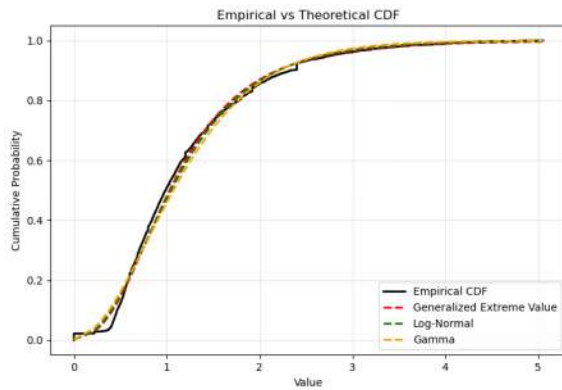
Formula: $X \sim \text{GEV}(\xi, \mu, \sigma)$

SCIPY USAGE:

`stats.genextreme.rvs(c=0.7082, loc=39.0103, scale=13.4539, size=n)`

3.1 m ceiling height

Spread rate [m/min]



GENERALIZED EXTREME VALUE

PARAMETERS:

$c(\xi)$ = shape parameter: -0.121463
 $loc(\mu)$ = location: 0.833530
 $scale(\sigma)$ = scale: 0.524241

INTERPRETATION:

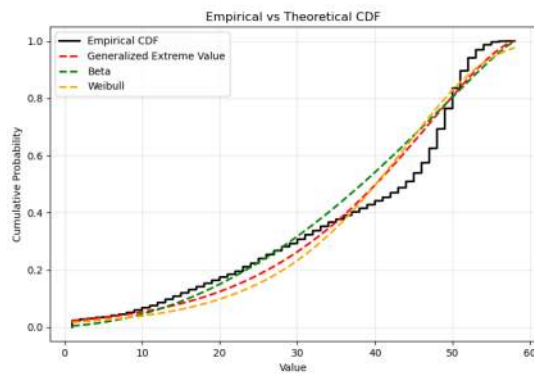
c = shape parameter (ξ), loc = location (μ), $scale$ = scale (σ)

Formula: $X \sim \text{GEV}(\xi, \mu, \sigma)$

SCIPY USAGE:

`stats.genextreme.rvs(c=-0.1215, loc=0.8335, scale=0.5242, size=n)`

Bays ignited [-]



GENERALIZED EXTREME VALUE

PARAMETERS:

$c(\xi)$ = shape parameter: 0.684096
 $loc(\mu)$ = location: 35.014812
 $scale(\sigma)$ = scale: 15.727509

INTERPRETATION:

c = shape parameter (ξ), loc = location (μ), $scale$ = scale (σ)

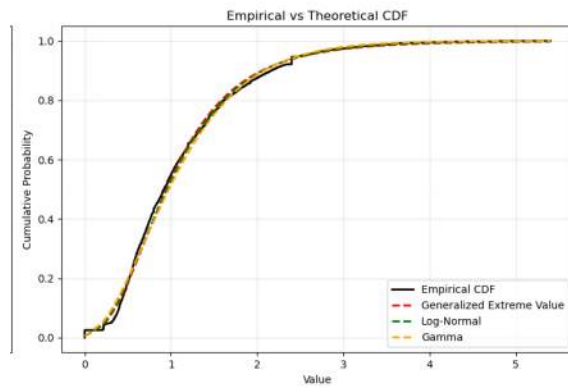
Formula: $X \sim \text{GEV}(\xi, \mu, \sigma)$

SCIPY USAGE:

`stats.genextreme.rvs(c=0.6841, loc=35.0148, scale=15.7275, size=n)`

3.5 m ceiling height

Spread rate [m/min]



GENERALIZED EXTREME VALUE

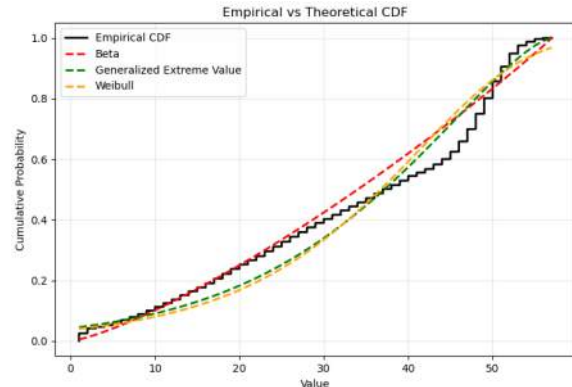
=====

PARAMETERS:
 c (ξ) = shape parameter: -0.116222
 loc (μ) = location: 0.755361
 $scale$ (σ) = scale: 0.505236

INTERPRETATION:
 c = shape parameter (ξ), loc = location (μ), $scale$ = scale (σ)
 Formula: $X \sim GEV(\xi, \mu, \sigma)$

SCIPY USAGE:
`stats.genextreme.rvs(c=-0.1162, loc=0.7554, scale=0.5052, size=n)`

Bays ignited [-]



BETA

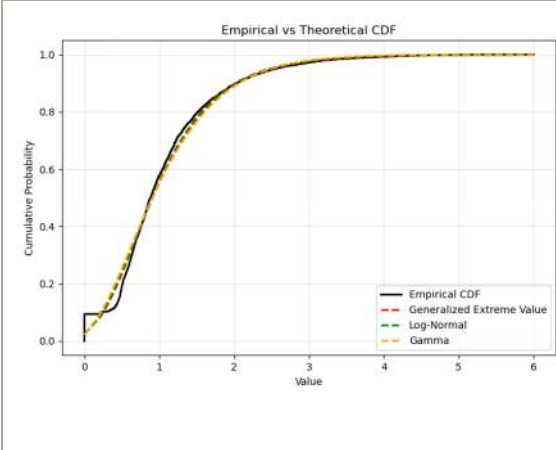
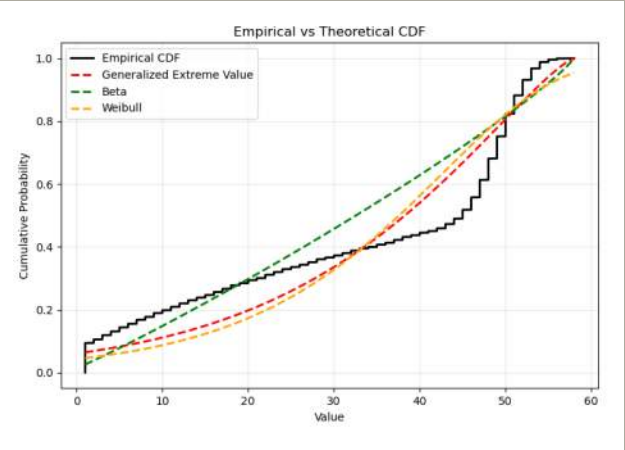
=====

PARAMETERS:
 a (α) = first shape parameter: 1.290015
 b (β) = second shape parameter: 0.964493
 loc = location: 0.027940
 $scale$ = scale: 56.972060

INTERPRETATION:
 a = first shape parameter (α), b = second shape parameter (β)
 Formula: $X \sim Beta(\alpha, \beta)$

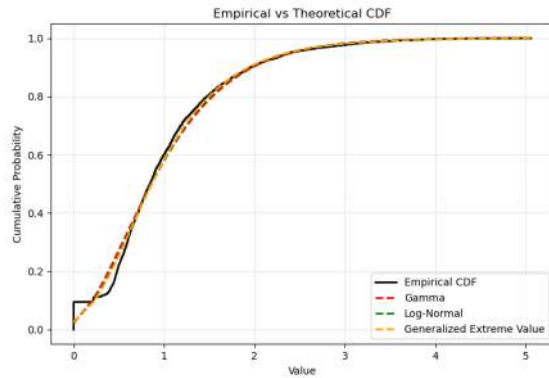
SCIPY USAGE:
`stats.beta.rvs(a=1.2900, b=0.9645, loc=0.0279, scale=56.9721, size=n)`

In function of wind speed

2 m/s wind speed	
Spread rate [m/min]	Bays ignited [-]
 GENERALIZED EXTREME VALUE ===== PARAMETERS: c (ξ) = shape parameter: -0.051416 loc (μ) = location: 0.702914 scale (σ) = scale: 0.552826 INTERPRETATION: c = shape parameter (ξ), loc = location (μ), scale = scale (σ) Formula: $X \sim \text{GEV}(\xi, \mu, \sigma)$ SCIPY USAGE: stats.genextreme.rvs(c=-0.0514, loc=0.7029, scale=0.5528, size=n)	 GENERALIZED EXTREME VALUE ===== PARAMETERS: c (ξ) = shape parameter: 0.771769 loc (μ) = location: 31.812677 scale (σ) = scale: 20.212768 INTERPRETATION: c = shape parameter (ξ), loc = location (μ), scale = scale (σ) Formula: $X \sim \text{GEV}(\xi, \mu, \sigma)$ SCIPY USAGE: stats.genextreme.rvs(c=0.7718, loc=31.8127, scale=20.2128, size=n)

4 m/s wind speed

Spread rate [m/min]



GAMMA

PARAMETERS:

a (α) = shape parameter: 2.793484
 loc = location: -0.219245
 scale (β) = scale parameter: 0.436459

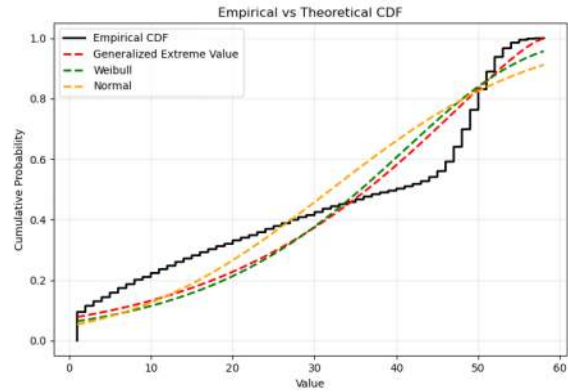
INTERPRETATION:

a = shape parameter (α), scale = scale parameter (β)
 Formula: $X \sim \text{Gamma}(\alpha, \beta)$

SCIPY USAGE:

`stats.gamma.rvs(a=2.7935, loc=-0.2192, scale=0.4365, size=n)`

Bays ignited [-]



GENERALIZED EXTREME VALUE

PARAMETERS:

c (ξ) = shape parameter: 0.745979
 loc (μ) = location: 29.631492
 scale (σ) = scale: 21.168709

INTERPRETATION:

c = shape parameter (ξ), loc = location (μ), scale = scale (σ)

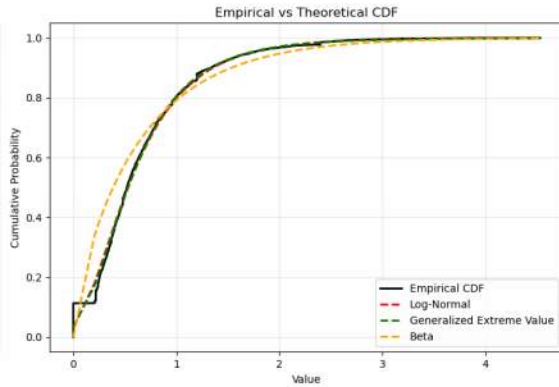
Formula: $X \sim \text{GEV}(\xi, \mu, \sigma)$

SCIPY USAGE:

`stats.genextreme.rvs(c=0.7460, loc=29.6315, scale=21.1687, size=n)`

8 m/s wind speed

Spread rate [m/min]



LOG-NORMAL

=====

PARAMETERS:

s (σ) = shape parameter: 0.534368
 loc = location shift: -0.307721
 scale = scale factor: 0.838192

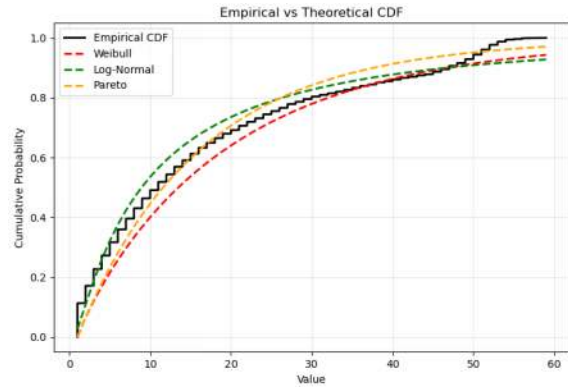
INTERPRETATION:

s = shape parameter (σ of underlying normal), loc = location shift, scale = scale factor
 Formula: $\ln(X) \sim N(\ln(\text{scale}), s^2)$

SCIPY USAGE:

`stats.lognorm.rvs(s=0.5344, loc=-0.3077, scale=0.8382, size=n)`

Bays ignited [-]



WEIBULL

=====

PARAMETERS:

c (k) = shape parameter: 0.925648
 loc = location: 1.000000
 scale (λ) = scale parameter: 18.550380

INTERPRETATION:

c = shape parameter (k), scale = scale parameter (λ)

Formula: $X \sim \text{Weibull}(k, \lambda)$

SCIPY USAGE:

`stats.weibull_min.rvs(c=0.9256, loc=1.0000, scale=18.5504, size=n)`

APPENDIX II – ITB CFD STUDY



Instytut Techniki Budowlanej

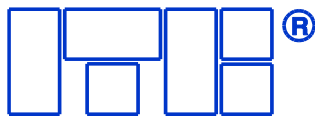
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Jednostka notyfikowana nr 1488 | Członek EOTA | Certyfikowane systemy zarządzania ISO 9001, ISO 27001

TECHNICAL EXPERTISE

on the multiparmetric CFD analysis of fires in open car parks

01768/25/Z00NZP

Warszawa, June 2025



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Contents

1	CFD approach description	2
2	Preliminary studies and calibration.....	4
3	Sensitivity studies	10
3.1	Study definition	10
3.2	General fire spread considerations	12
3.3	CFD results and observations – the bay effect.....	17
3.4	CFD results and observations – car park height.....	21
3.5	CFD results and observations – multiple vehicle fires.....	29
3.6	CFD results and observations – vehicle parking orientation within the car park	33
4	CFD for calibration of simplified model - heat flux on target vehicles at different HRR.....	38
4.1	Assumptions for the investigation	38
4.2	Results of the calibration study.....	41
4.3	Investigation of potential implications of wind on the case-study	55
5	Conclusions.....	64
6	Cited literature	66

1 CFD approach description

Numerical fluid flow simulation involves solving systems of differential equations describing the analysed phenomena. Basic equations solved for all tasks are the equations describing the velocity and pressure field (continuity equation) and Navier–Stokes movement equations. Additional equations of energy and radiation conservation and smoke transport are solved for the smoke and heat spread calculations. McGrattan [1] and Merci [2][2] described the CFD method used in fire safety engineering. Theoretical foundations of the CFD method are described [3]. The most common tool used in modelling fires is the Fire Dynamics Simulator (FDS). In the current study, due to limitations in parallelisation of simulations with FDS and a preference to use RANS turbulence modelling approach, ANSYS Fluent was used for this study. The core set of equations used in FDS presented by McGrattan is fundamentally the same, as the mathematical model of ANSYS Fluent software [4]. Applications of CFD in ANSYS Fluent for fire problems have been demonstrated in eg.: [5], [6], [7].

CFD modelling is a widespread engineering tool that enables the prediction of the distribution of flow parameters, i.e. velocity, pressure, species mass concentration, and temperature, which is important for forecasting fire development and smoke spread in actual facilities. This is particularly valuable for car parks, given the severity of typical vehicle fires, hazards for humans, and potential structural damage. In this study, ANSYS Fluent 19R1 CFD code was used. It is a commercial software based on the finite volume method (FVM) for general use in simulating fluid flow with chemical reactions and heat transfer. CFD modelling involves numerical solving governing partial differential equations (PDE) of fluid motion in 1-dimensional space. One of the principles is the continuity conservation equation, which defines that the fluid is treated as a continuous medium:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{u}) = S_m \quad (1)$$

In equation (1), S_m is the mass added to the fluid volume, such as combustible gas, into the burner area's surface. Chemical species transport in fluid motion is calculated using equation (2).

$$\frac{\partial \rho}{\partial t}(\rho Y_i) + \nabla(\rho \vec{u} Y_i) = -\nabla \vec{J}_i + R_i \quad (2)$$

In the equation (2), $\vec{J}_i$ is mass diffusion flux of species i and differently calculated for laminar and turbulent flows, R_i is the net rate of production of species i by chemical reaction calculated using the Eddy-Dissipation Model (EDM) proposed by Magnussen and Hjertager [8].

Conservation of momentum is the implementation of the Navier-Stokes equation expressed as follows:

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla(\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot \vec{\tau} + \rho \vec{g} + \vec{F} \quad (3)$$

In equation p is static pressure, $\vec{\tau}$ is the stress tensor, $\rho \vec{g}$ are the gravitational body, $\vec{F}$ represents external body forces. The energy conservation follows:

$$\frac{\partial}{\partial t} \left(\rho \left(e + \frac{u^2}{2} \right) \right) + \nabla \left(\rho v \left(h + \frac{u^2}{2} \right) \right) = \nabla \left(k_{\text{eff}} \nabla T - \sum_j h_j \vec{J}_j + \vec{\tau} \vec{v} \right) + S_h \quad (4)$$

The energy source due to chemical reaction is defined as:

$$S_h = - \sum_j \frac{h_j^0}{M_j} R_j \quad (5)$$

In eq. h_j^0 is the enthalpy of the formation of species j , M_j is the molecular mass of species j , R_j is the volumetric rate of creation of species j .

The simulations were performed in a transient mode with a fixed time step. The realizable k- ϵ model was used for turbulence modelling, classified as an Unsteady Reynolds-Averaged Navies Stokes (URANS) model. The fire phenomenon was simulated as a reacting fluid flow controlled by mixing using the Eddy-Dissipation Model (EDM) for turbulence-chemistry interaction and the Moss-Brookes model for soot (smoke) production.

The heat flow in the system was modelled using the energy conservation equation (6), which identifies that the enthalpy (7) in any point changes according to the stream of energy flowing into the control volume. The equation also considers the possibility of heat generation directly in the finite element ($\dot{q}'''$), which in this case amounts to 0. Heat can also be delivered as a result of the fluid kinetic energy dissipation as a result of friction ($\mathcal{E}$), the impact of pressure ($\frac{Dp}{Dt}$) or heat radiation. In fire-safety related applications, the term responsible for the pressure field impact or kinematic energy dissipation is usually neglected.

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho h \vec{u}) = \frac{Dp}{Dt} + \dot{q}''' - \nabla \cdot \vec{q} + \mathcal{E} \quad (6)$$

$$h = \int_{T_0}^T c_p dT \quad (7)$$

A change in the density can be sufficiently described by a perfect gas equation (8). M_{avg} (9) in equation (2) stands for the averaged molecular weight of the gas mixture ingredients, whose concentration can be identified in any volume using (2).

$$p = \frac{\rho \mathcal{R} T}{M_{avg}} \quad (8)$$

$$M_{avg} = \frac{1}{\sum \frac{Y_i}{M_i}} \quad (9)$$

where: p —pressure, $\mathcal{R}$ —gas constant, T —temperature, Y_i —vol. concentration of i -th species, M_i —molar mass of the i -th species.

A list of general models and initial conditions is presented in Table 1.

Table 1. Numerical simulations setup

Feature	Value
Solver	Pressure-based, double-precision
Turbulent flow and sub-models	Unsteady RANS, Reliazble $k-\epsilon$
Time step	Fixed, 0.5 s
Radiation heat transfer	Discrete ordinates, WSGGM model
Convective heat transfer	Tunnel walls: forced convection,
Conductive heat transfer	Based on the Fourier law
Combustion model	Species transport with EDM, 1-step chemical reaction
Computational scheme	Coupled
Gradient discretization	Green-Gauss Node Based
Pressure discretization	Body Force Weighted
Under-relaxation factors	ANSYS Fluent defaults
Initial and boundary conditions	
Fluid material	Air, ideal gas
Air viscosity	$1.789 \cdot 10^{-5}$ [kg/m·s]
Operating pressure	101325 Pa with hydrostatic profile
Wall roughness	natural, 0.003 m
Combustion model	Eddy-Dissipation Model (EDM)
Fire curve	Mass flow rate-based, prescribed from fire test

2 Preliminary studies and calibration

While CFD is a recognised method for studying fire problems in enclosed spaces, we have conducted a preliminary study to verify our ability to model heat flux distribution on surfaces from a vehicle fire. For this purpose, we have referred to the BRE testing programme for fire spread in car parks, and in particular the Experiment 1 from this programme [9]. A representative geometry was built following the design provided by the BRE, considering the changes to the design visible on photographs. Vehicles' shapes were simplified to boxes, and for the first two vehicles, the top and window surfaces were maintained as open.

Walls were modelled as solids, a third type boundary condition, built out of concrete with a 2200 kg/m^3 density, and thermal conductivity of $1.2 \text{ W/m}\cdot\text{K}$. Emissivity of the surfaces was chosen as 1, and the conductive heat transfer coefficient of $35 \text{ W/m}^2\text{K}$.

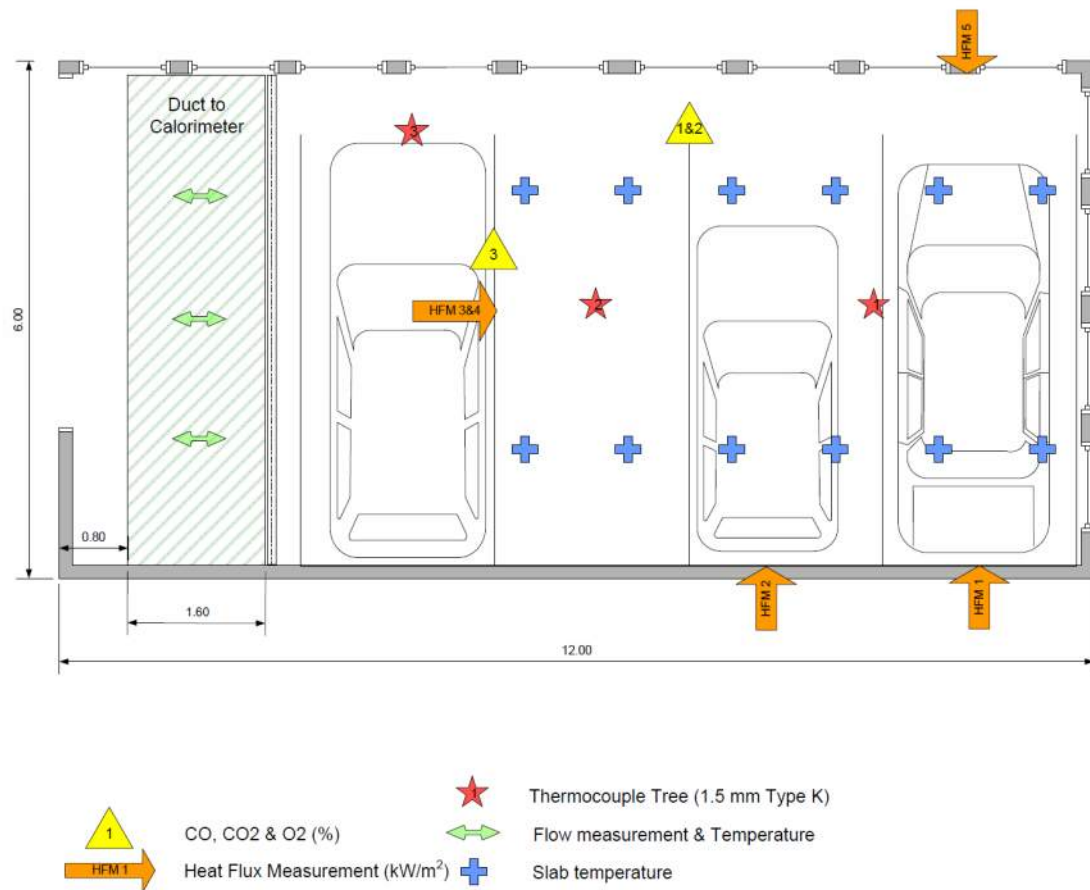


Fig. 1. BRE test rig design [9]

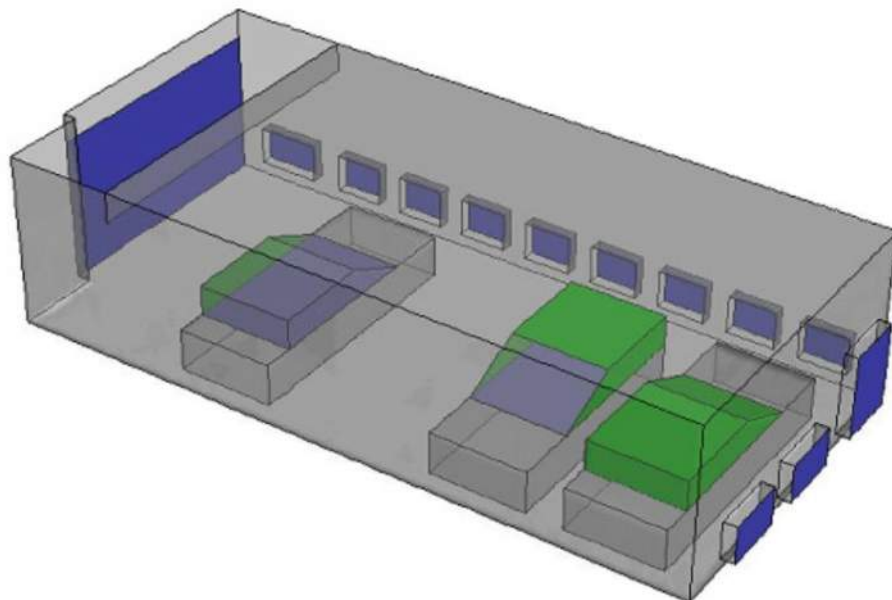


Fig. 2. Numerical representation of the BRE rig

A comparison of the experiment HRR curve and simplified HRR curve used in the study is given in Fig. 3. The BRE results provide one compound plot for all vehicles, while input to numerical analysis requires separate fire definition for each vehicle. Therefore, we have defined a HRR with peak value of 8 MW for the first vehicle, 6 MW for second vehicle and 2 MW for the third vehicle. The ignition time is based on observations in the test (20th minute for car 2 and 21st minute for car 3). Please note that the simulation starts at the 3rd minute (incipient period is skipped). The sum of fires represents the BRE study, but the chosen values of HRR for individual vehicles are to some extent arbitrarily, and no further sensitivity was carried, neither a precise numerical representation of the fires in BRE is possible. We have carried the study up to the peak value reached in 20th minute of our analysis, as due to uncertainties in the description of the fire there is no possibility to prescribe the HRR after the peak is reached for 3 vehicles.

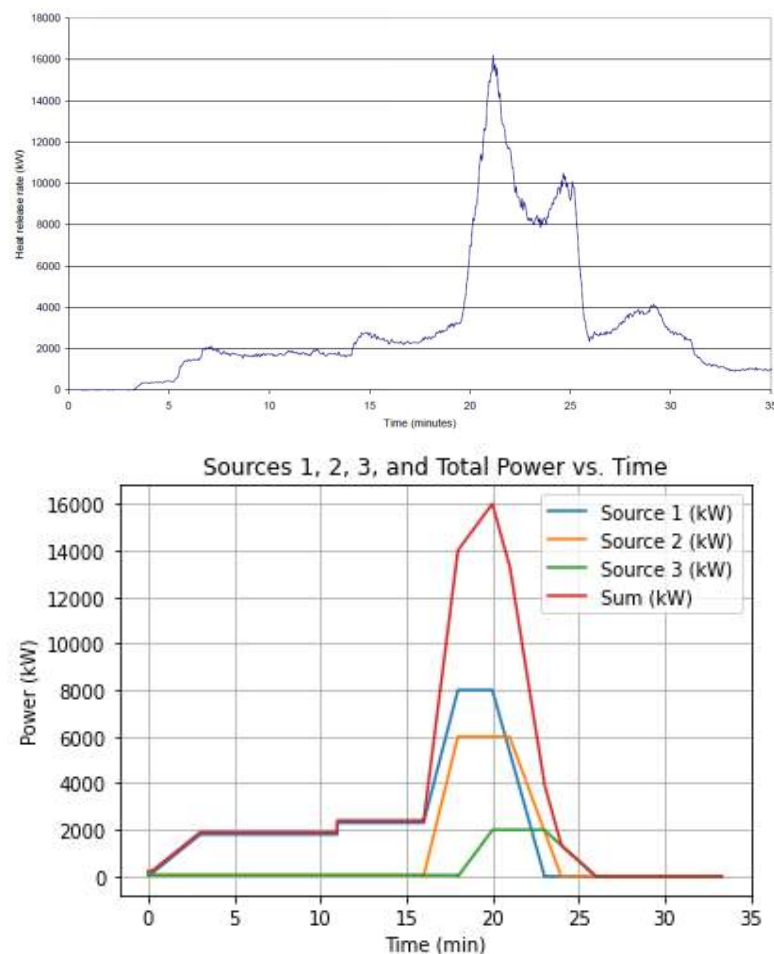


Fig. 3. HRR measured in the experiment, and as introduced in the CFD

Figure 4 presents a comparison between measured heat flux in experiment and in CFD. For HFM1 measurements, in the early stage of the fire the measured heat flux is lower than in experiment, likely due to differences in spatial arrangement of fire (breakage of windshields, presence of roof). In fully developed fires, the peak measured at HRM1 in experiment is at approx. 100 kW/m² and in CFD at 115 kW/m². For HRM 4 and 5 the values at the early stage of the fire are relatively close between the experiment and CFD, whereas in late stage of fire almost whole compartment shows similar heat flux at walls, while at the experiment some gradient was observed. Three dimensional aspects of the flames and radiation are discussed further.

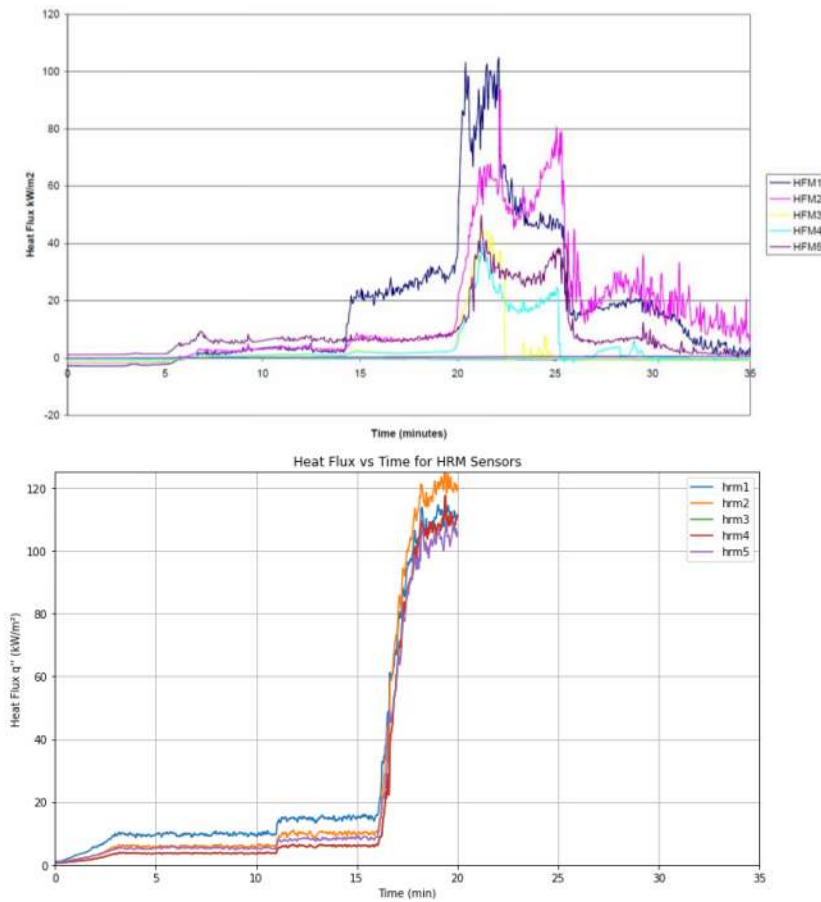


Fig. 4. Heat flux measurements in the BRE experiments [9] and in the current simulations.

As shown on Fig. 5, in the early phase of the experiment, the fire has broken through the windshield and is almost reaching the rig ceiling. In the case of CFD, there is no barrier above the fire (roof), and combustion happens on the whole burner surface. Therefore, the flame is present in the middle of the vehicle, and is approx. 30 cm lower than in the experiment. Regarding heat flux distribution – a direct comparison is challenging due to the uncertainty of the height of the HF meters in the experiments. In the plane of vehicles around the first vehicle (likely location of the HFM 1 & 5) we have observed heat flux of approx. 5 kW/m^2 , which is in the range observed in the experiment. The heat flux at the likely location of HFM 2 (wall near the adjacent vehicle) is approx. half of the value visible at the HFM 1, as in the experiment.



Fig. 5. Flame shape at 180 s of the analysis (6th minute of the experiment)

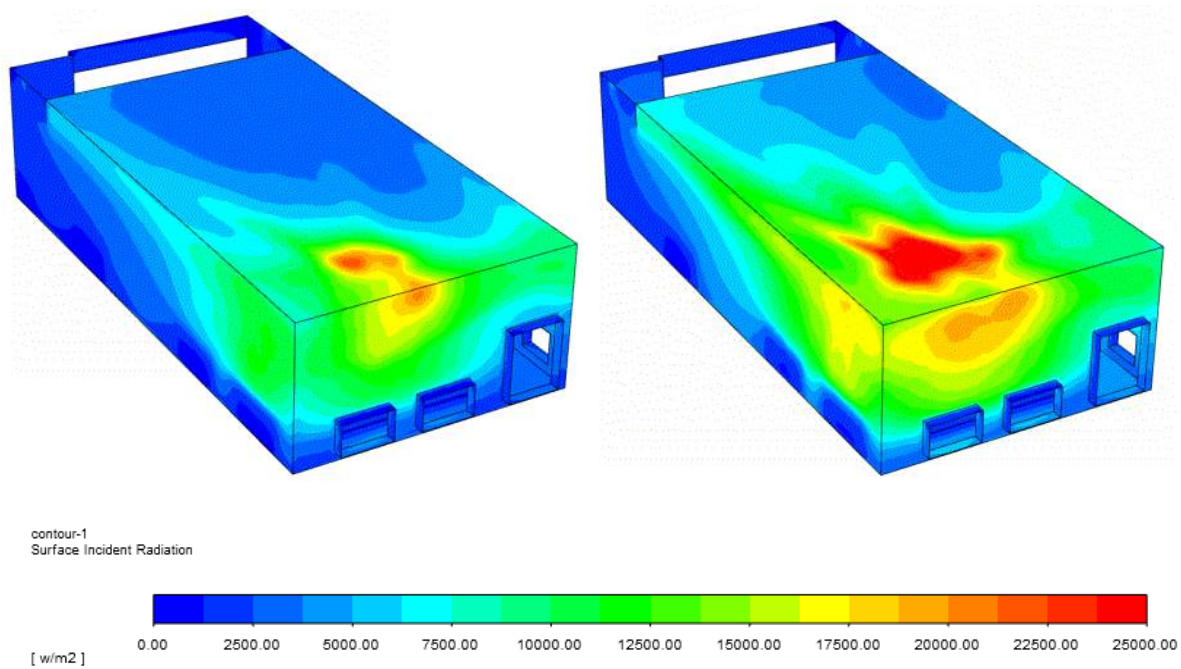
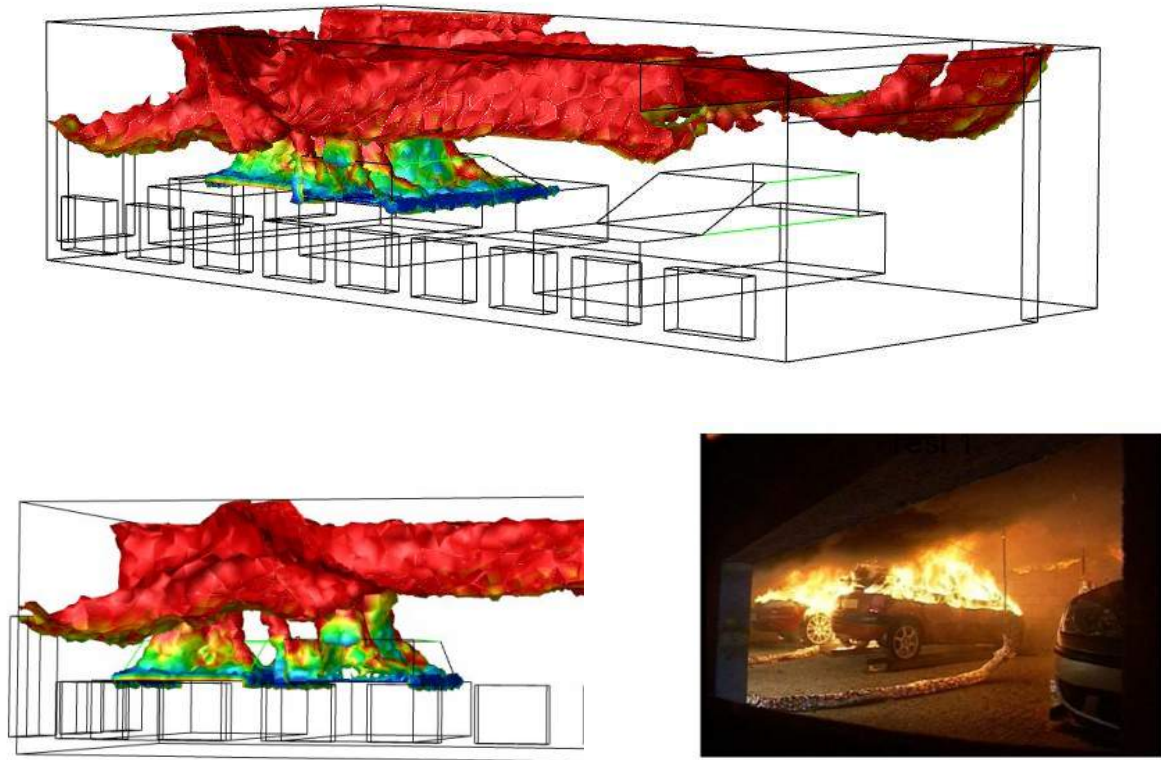


Fig. 6. Incident surface radiation in the CFD, 360 s of the analysis (1.8MW, left) and at 720 s (2.3 MW, right)

In the fully grown fire (1200 s, Fig. 7), we observe flame extension under the ceiling and two fire plumes from two vehicles. The flame shape (iso-surface shown at Fig. 7) observed resembles observations in the experiments, however, the flame extension appears to be larger in the CFD. At the time of spread of the fire to second vehicle (20th minute of the experiment, 17th minute of the simulation), the gradient of heat flux across the height of the compartment is visible, and the heat flux at vehicle 2 is close to 50 kW/m².

At the peak HRR in 20th minute of the CFD the observed incident surface radiation at the likely location of HFM 1 is approx. 115 kW/m², slightly more than the experiment. At the location HFM 2, we observe a significant gradient over a height of ~30 cm, from 80 kW/m² to 125 kW/m² again. Given that we do not have a separate HRR measurement for the secondary vehicle, it is hard to confirm when this vehicle HRR peaked. A likely assumption is that this peak is present in the 25th minute of the experiment, at which a peak heat flux at HFM 2 reached 80 kW/m². Heat flux at further targets is higher than measured in experiments, with values of 50 kW/m² - 90 kW/m² reached in the CFD and up to 50 kW/m² in the experiment. This may be related to the overestimation of the flame extension region.



Photograph 2.9.3: Test 1, 21 minutes after ignition

Fig. 7. Flame shape at 1080 s of the analysis (refers to 21st minute of experiment)

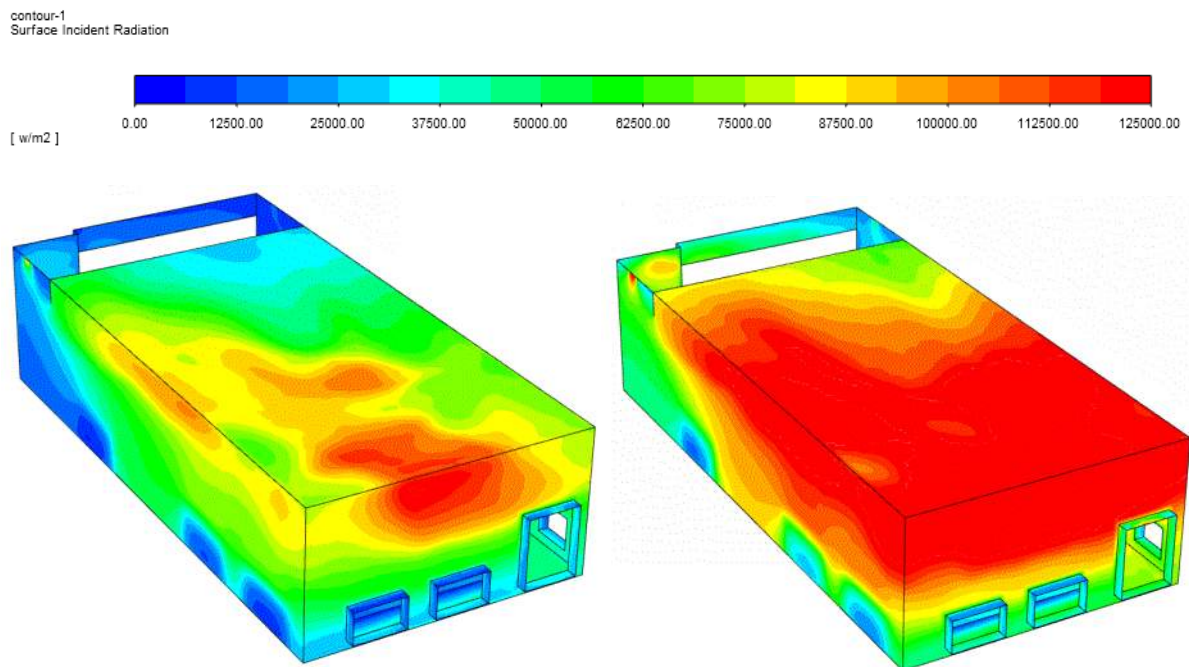


Fig. 8. Incident surface radiation in the CFD, 1020 s of the analysis (the moment fire spread to car 2, left) and at 1080 s ((the moment fire spread to car 2, right)

Summarizing the recreation of the BRE study we have concluded that:

- Results related to heat flux distribution, especially at the early stage of the fire, are sufficiently accurate for further studies;
- CFD approach used here allows for significant simplification of the CFD models of vehicles into boxes with surfaces emitting fuel, therefore streamlining the CFD process;
- The uncertainties associated with the CFD are not possible to be precisely estimated, due to the unknown heat release rate of the vehicles used in BRE study (only total HRR is known).
- Simulated values of the heat flux are higher than measured, likely indicating conservative results in relation to the fire spread.

3 Sensitivity studies

3.1 Study definition

A car park geometry was built based on Luton Airport MSCP Level 1 design, Fig. 9. The clean floor height was at 2.50 m, but two more models were created in which this height was increased to 2.90 m and 3.30 m. The car park structure followed the original design, Fig. 10. A numerical model of three car parks differing in height is shown on Fig. 11. For sensitivity studies, a part of the model was extracted, spanning overall 12 structural bays, Fig. 12. All side walls were maintained as “open” (pressure-inlet boundary condition), and all other solver settings were as described above.

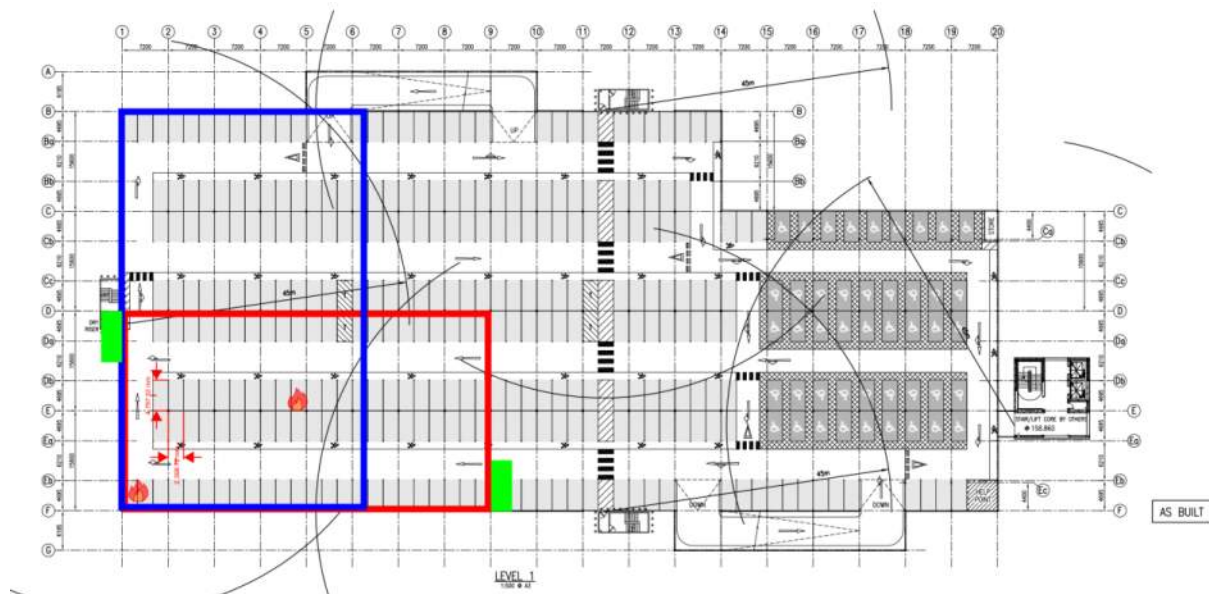


Fig. 9. Overview of Luton Airport MSCP car park level 1, with indication of parts of the car park undergoing investigation

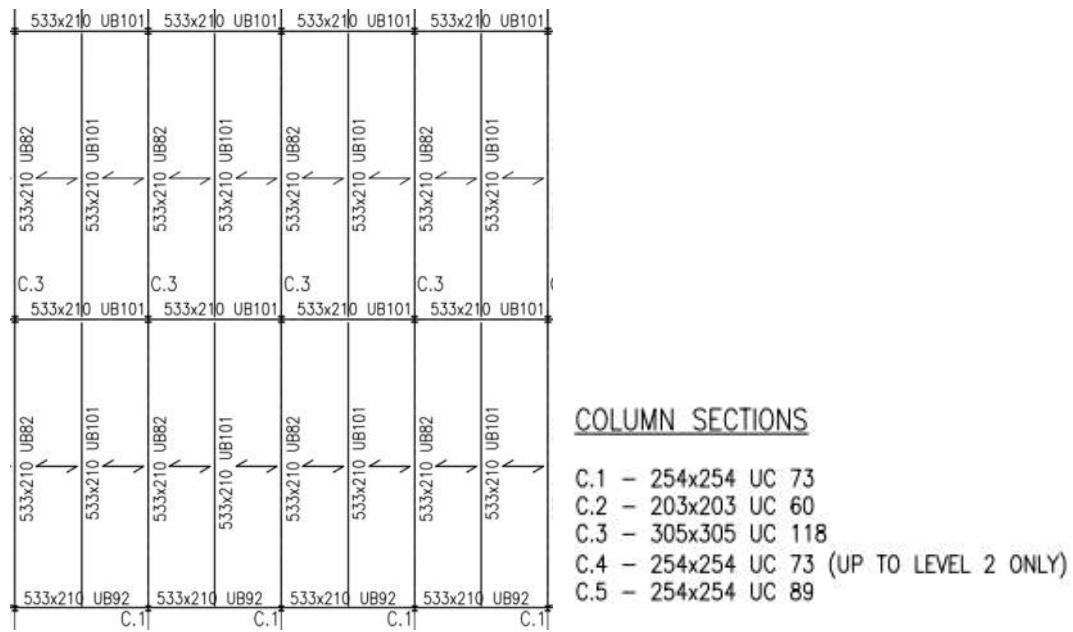


Fig. 10. Structural design of the floor including description of the beams that form the “structural bays”

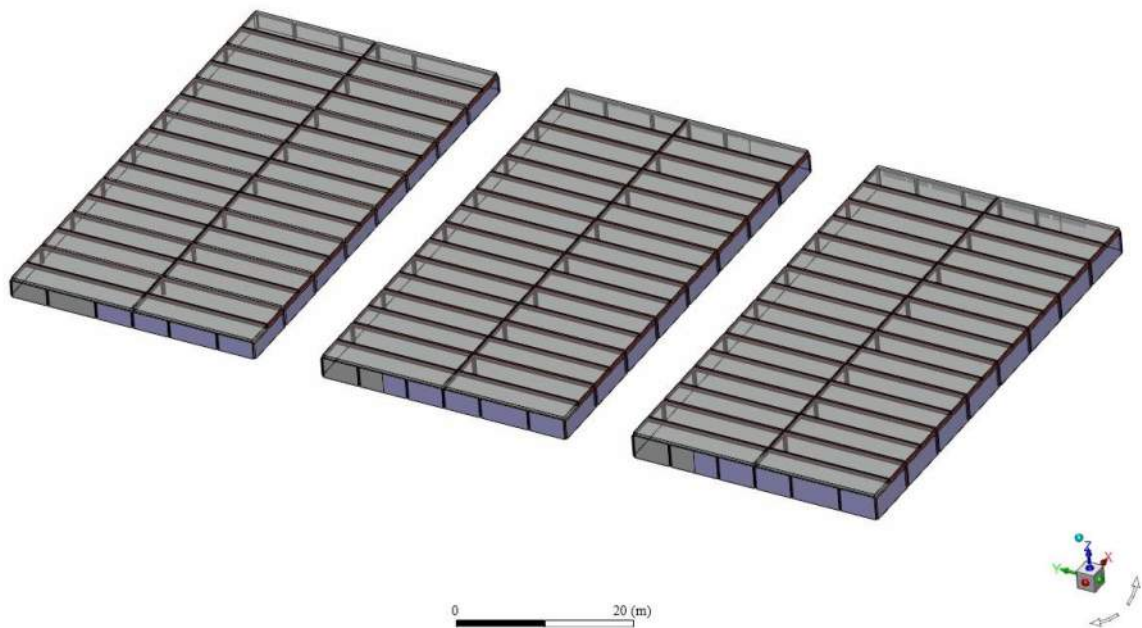


Fig. 11. Three car park models built for the study, with heights of 2.50 m, 2.90 m and 3.30 m

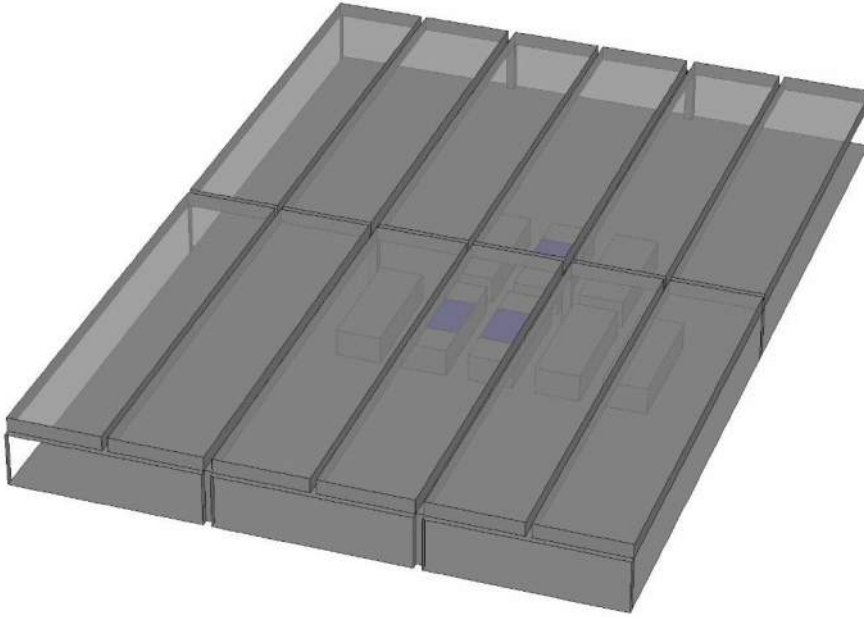


Fig. 12. Simplified numerical model for the sensitivity studies

For the sensitivity analysis overall of 31 CFD multi-parametric simulations were performed, considering the following variables:

- Location of the initial vehicle versus the structural bay (4 different settings)
- Presence of structural elements
- Combustion of 1 vehicle, 2 vehicles or 3 vehicles
- Car park height of 2.50 m, 2.90 m and 3.30 m
- Orientation of vehicles related to the structural bay (parallel, perpendicular).

Each of the simulations was carried out in transient mode, with HRR increasing linearly to 15 MW over 15 minutes (increase rate of 1 MW/min or 16 kW/s). If multiple vehicles were present in the scenario, the total HRR was split between the sources (ie. two vehicles with each having $\frac{1}{2}$ of the total HRR, or three vehicles with each having $\frac{1}{3}$ rd of the total HRR).

Chapter 3.2 includes general conclusions from the parametric study, and chapters 3.3 – 3.7 detailed results.

3.2 General fire spread considerations

Determining fire spread between vehicles is possible with the use of Flux-time product (FTP) ignition criterion, as adopted by Tohir et al. [10] This concept assumes that the time to ignition is proportional to the heat flux at a material surface, which exceeds a critical value under which the ignition will never occur.

$$FTP = t_{ig}(\dot{q}'' - \dot{q}_{crit}'')^n \quad (10)$$

Where t_{ig} is the time for combustible material to ignite, $\dot{q}''$ is the incident heat flux and $\dot{q}_{crit}''$ is the critical heat flux, both fluxes expressed in kW/m². n is the power law index (usually between $1 \leq n \leq 2$). For transient state, the FTP may be integrated over time. If FTP exceeds a critical value for a material, one can consider that ignition has occurred. Based on previous research and material properties, Zahir

has provided values of the power law index, FTP and $\dot{q}_{crit}$ for relevant vehicle components, as shown in Table 2.

Table 2. Values used in FTP model for vehicle components [10], values obtained through cone calorimeter tests

Component	Power law index	FTP [(kW/m ²)s]	$\dot{q}_{crit}$ [kW/ m ²]
Mudflap	1.5	3258	5.7
Rubber tyre	1.5	9828	8.0
Bumper trim	2.0	21 862	3.1
Wheel arch	2.0	50 234	0.0

Using values from Table 2 and the FTP model, time to ignition of a car component can be plotted in function of $\dot{q}$, Fig. 13. While this model may be directly applied in CFD, for the sensitivity studies and preliminary findings we have established values, at which the ignition happens within 2 minutes (corresponding heat flux of approx. 15 kW/m²) and in less than 1 minute (later considered as immediate flame spread, 25 kW/m² and more). These conditions have been used as qualitative metrics to indicate whether in a given scenario fire spread to another vehicle is delayed, likely or imminent.

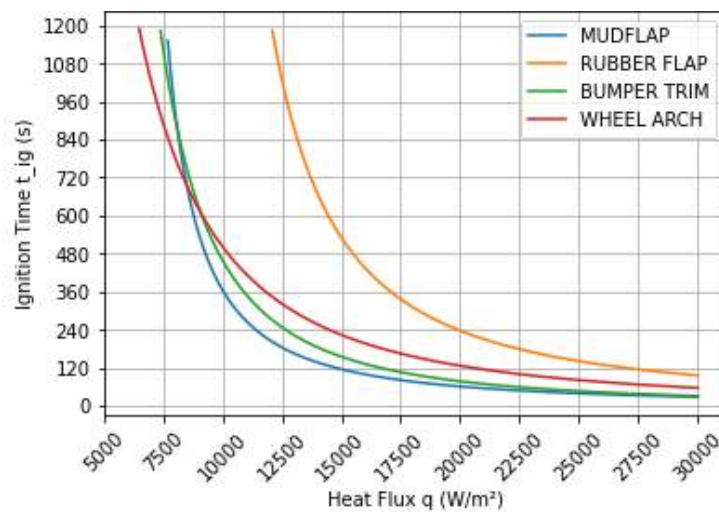


Fig. 13. Time to ignition in function of incident heat flux

Prior to the research carried out herein, the effect of structural bays on fire spread was not considered as an important factor. After sensitivity analysis (as shown in next section), we have formulated working hypotheses for the influence of the structural bays on the fire spread. The hypotheses are presented here, and the CFD study supporting their formulation are shown in further sub-chapters.

If one considers an enclosed car park, the flame spread between the vehicles may occur through direct flame contact with neighbouring vehicles (e.g.: spill of fuel, battery vent fire) or indirectly through flame/smoke layer radiation, Fig. 14. In case of the car park design, the designer has limited influence on the direct flame contact, other than introduction of sloped floor and drainage (to remove spillage) or providing ample separation between vehicles. In contrast, the indirect flame spread modes will largely depend on the car park structural layout and variables such as height, or the presence of

structural bays. If the flame does not reach the ceiling, the dominant source of radiation in the car park is the fire plume, and the radiation from the smoke may be considered secondary, Fig.14.

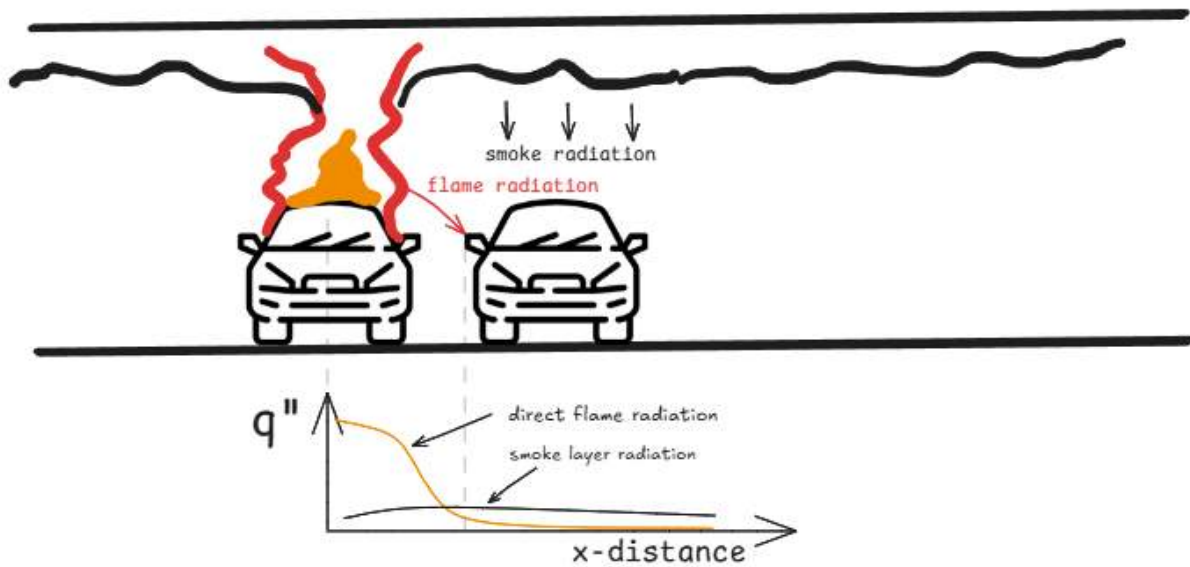


Fig. 14. Heat transfer considerations through radiation from fire plume in the car park

To determine whether the fire may reach the ceiling height, once again consider a vehicle fire in a car park, as in Fig. 15. The fire forms a buoyant convective plume that may reach the ceiling. The height of the flame is generally related to the fire power (heat release rate, HRR), and can be approximated for a specified fire using e.g. the Heskestad's model [11]:

$$L_f = 0.235 Q^{\frac{2}{5}} - 1.02 D \quad (11)$$

Where:

- L_f = average flame height (m)
- Q = heat release rate (kW)
- D = burner/fuel diameter (m)

If one assumes D as the width of the vehicle (1,6 m), Equation 11 can be used to illustrate the potential flame heights, and thus approximate at what HRR the flame will reach the ceiling, Fig. 15. If the flame does reach the ceiling, a lateral flame extension forms.

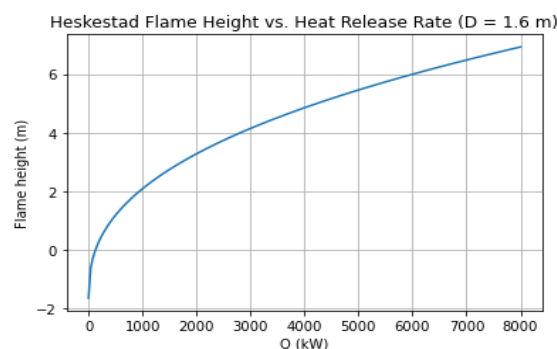


Fig. 15. Approximation of the flame height in function of Q for a fixed D

In the presence of the flame extension in a ceiling jet, the heat transfer in the car park changes. The fire plume still emits a similar amount of heat, but now the flame extension underneath the ceiling significantly contributes to surface incident radiation at the target. As the flames may extend for a large distance, this elevated radiant heat flux can be observed at a considerable distance from the initiating fire, Fig. 16.

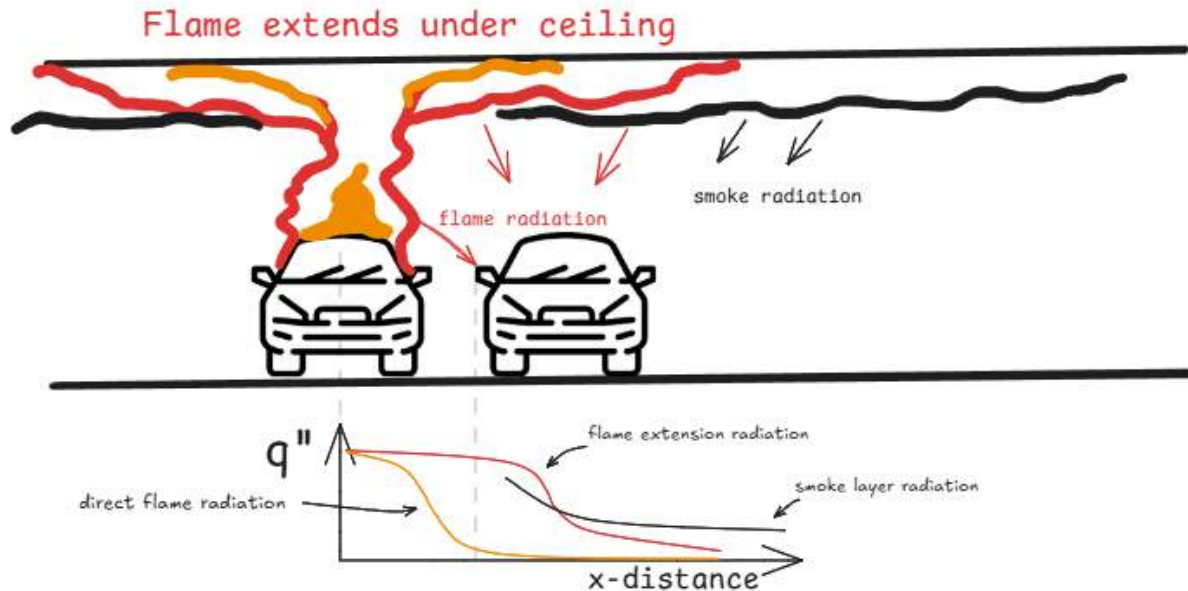


Fig. 16. Heat transfer considerations in car park with flame extension (ceiling jet)

This observation led to formulation of the first working hypothesis:

Working Hypothesis 1 – as the height between the vehicle and the ceiling is known for a structural design, only a certain amount of heat can be released within the fire plume, and if the fire size exceeds that size, the additional fuel will burn in a flame extension in a ceiling jet below the ceiling.

This hypothesis is explained graphically in Fig. 17. Practical consequences are that for a single vehicle fire, the HRR is likely to be sufficient to create a flaming region that extends into the ceiling, creating conditions in which the radiation from the flame extension becomes a strong contributor to the fire's spread.

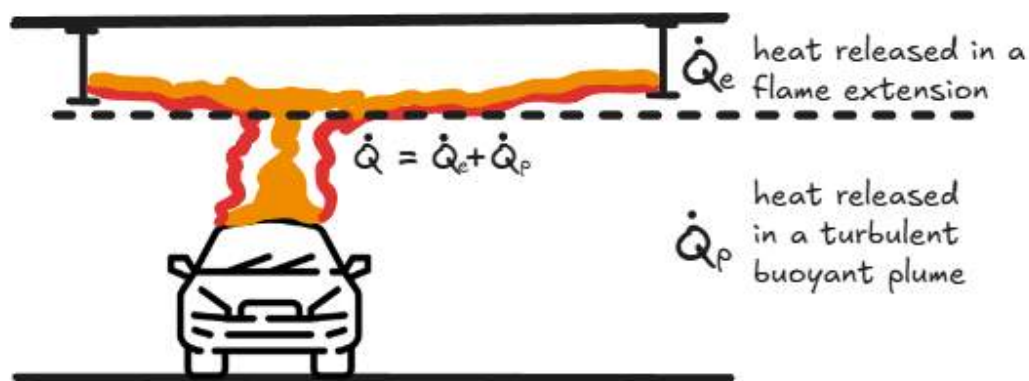


Fig. 17. Heat generation in the fire plume and in the flame extension underneath the ceiling. Total heat released is a sum.

Working Hypothesis 2 – in sufficiently high car parks the flame extensions are less likely to happen, therefore the likelihood of fire spread between vehicles is reduced.

This is a direct consequence of hypothesis 1 – if a car park is sufficiently high not to exhibit formation of the flame extension in the ceiling jet, the heat transfer is only through the radiation from the fire plume and smoke layer.

If the ceiling jet is formed but is constrained by the structure of the car park, we observe formation of flame extensions that fill the structural bays, creating effect as in Fig. 18. A practical consequence of this is that the heat flux measured within the structural bay is significantly higher than into the adjacent bays. Therefore, presence of the structural bays promotes the fire spread inside the bays, which leads us to the third working hypothesis:

Working Hypothesis 3 – if structural elements constrain the flame extension, the fire spread between vehicles parked within the structural bay is more likely than a fire spread to vehicles in adjacent bays.

Which directly leads to the fourth working hypothesis:

Working Hypothesis 4 – a structural bay can be considered a unit in which the fire severity is somewhat uniform.

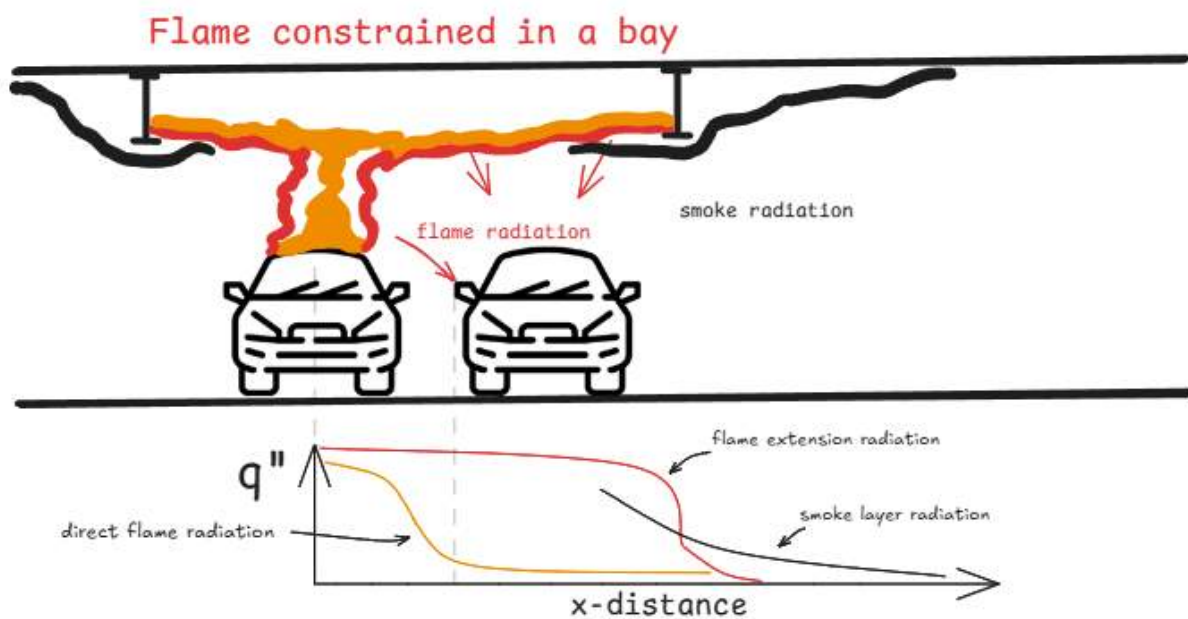


Fig. 18. Heat transfer considerations in car park with flame extension in a presence of a structural bay

Based on this hypothesis, we propose considering the fire spread in a car park separately within and between structural bays. In such a setting, the fire severity can be considered as a function of car park height, structural bay size, amount of fuel within the bays and the probability of the fire spread between the vehicles within the initial structural bay. The spread between the bays will depend on the view factor considered for the flame extension and the target fuel in adjacent structural bay, as well as the distance from the fire plume, Fig. 19. This is the basis of the further work in the project.

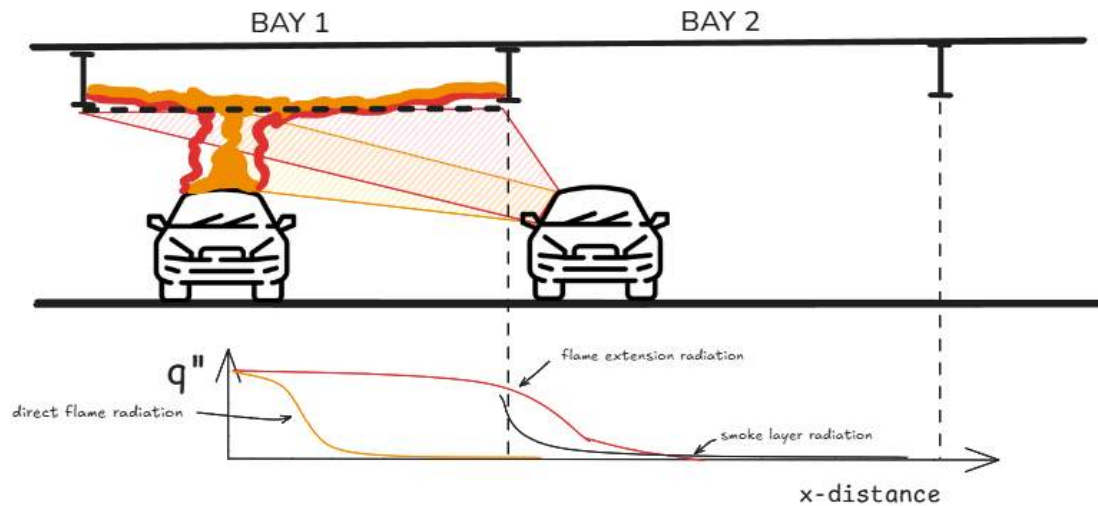


Fig. 19. Heat transfer considerations between two structural bays

3.3 CFD results and observations – the bay effect

The CFD simulations have revealed a significant impact of the structural bays on the accumulation of heat in the smoke layer, creation of flame extension underneath the ceiling, and in consequence the heat flux at the floor of the car park. An example is provided on Fig. 20, where the flame shape, ceiling temperature and incident heat flux at the floor are shown for a fire of single vehicle at 8 MW. The flame is constrained within the structural bay and extends along the beams. It is observed that the temperature in this bay is considerably higher than at the adjacent bays, and so is the heat flux towards the car park floor. It can be also observed that the heat flux in adjacent bays is significantly lower than in the bay in which the car is burning, indicating significant likelihood of fire spread within the bay, rather than into adjacent bay.

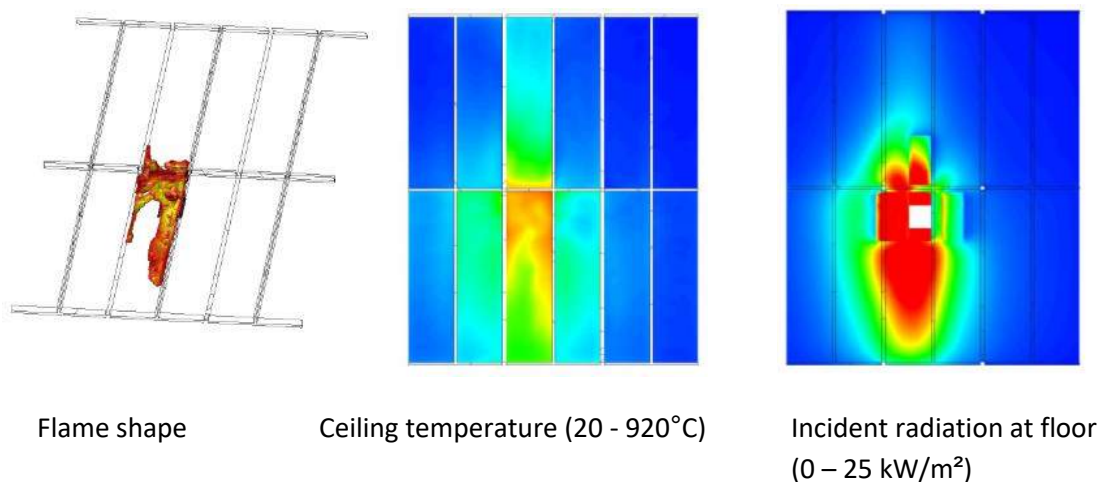


Fig. 20. Results of the single vehicle fire with HRR of 8 MW for car park with height 2,50 m – the shape of flame above the source, distribution of temperature under the ceiling and incident radiation on the floor and adjacent vehicles

If the structural elements are removed (the car park has a flat ceiling without beams), the flame shape takes more a circular form, the ceiling temperatures are lower and the radiation towards the floor is significantly lower, Fig. 21.

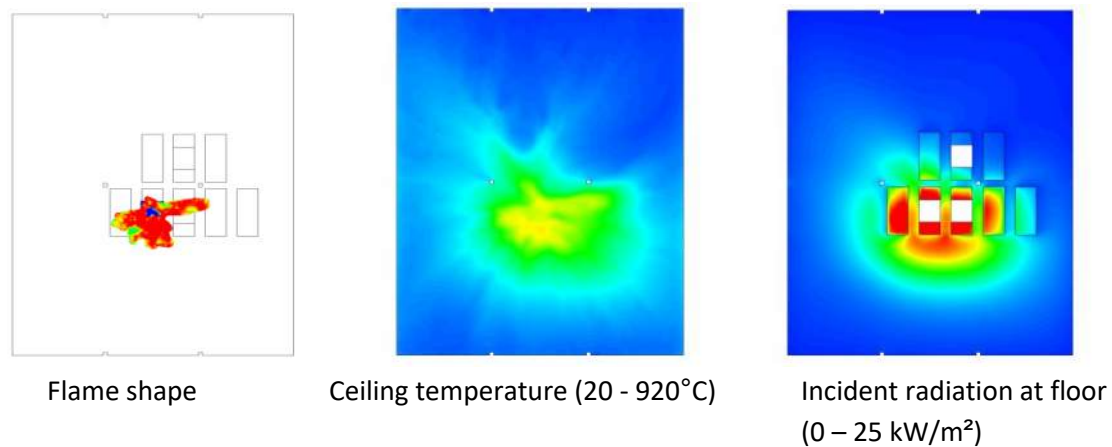


Fig. 21. Results of the single vehicle fire with HRR of 8 MW without structural elements (flat ceiling) for car park with height 2.50 m – the shape of flame above the source, distribution of temperature under the ceiling and incident radiation on the floor and adjacent vehicles,

The location of the vehicle versus structural bay also influences the bay effect. Fig. 22 shows the results of three simulations with vehicle placement changed slightly (by 80 cm per case), towards the beam. Case 1 has fire underneath the beam, between two bays, Case 2 has fire in the middle of the bay, and Case 3 has fire adjacent to the bay. For a vehicle under the beam, the fire enters two bays, and in consequence its severity is lower than when the flame is constrained within a single bay.

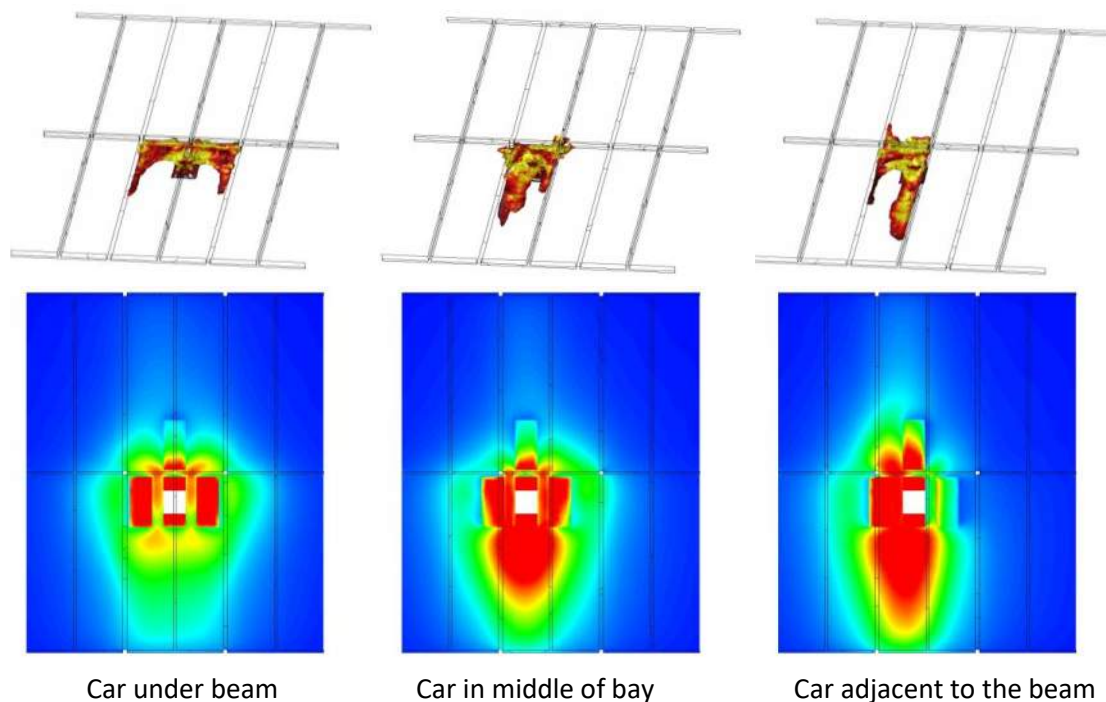


Fig. 22. Results of the single vehicle fire with HRR of 8 MW with structural elements for car park with height of 2.50 m, for three vehicle locations against the structural elements. Upper plots show the flame shape, bottom plot Incident radiation at floor (0 – 25 kW/m²)

Table 3 contains a summary of simulations (incident radiation towards the floor) for different HRR values, indicating the effect of the vehicle placement, and in a comparison with a car park with a flat ceiling. Table 4 presents results of temperature of the structure, for the same cases.

Table 3. Summary of results – incident heat flux to the floor for different locations of vehicle versus the structural bay, for different values of HRR, and also in comparison with case with a flat ceiling (0 – 25 kW/m²)

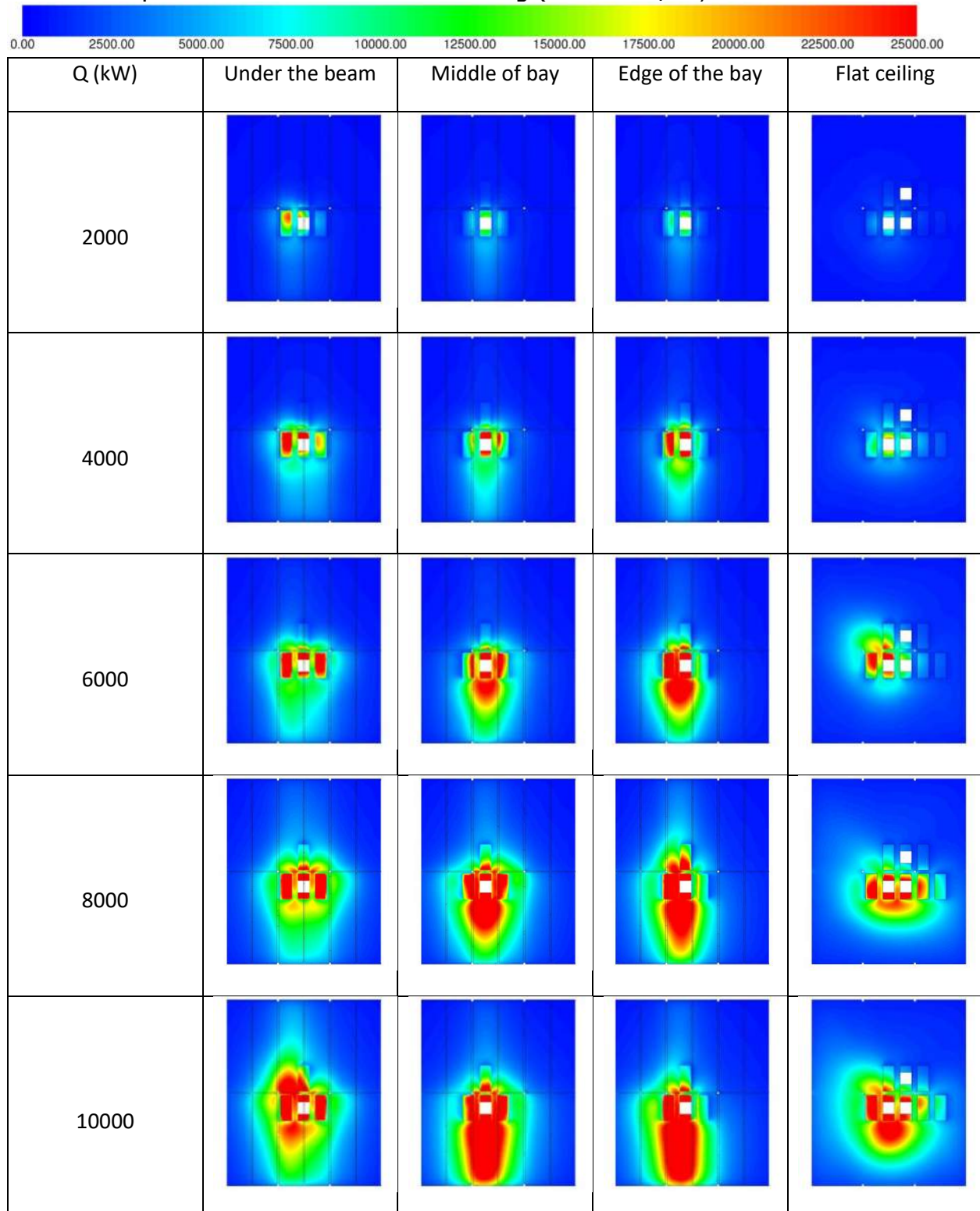


Table 4. Summary of results – temperature of the exposed structure surface for different locations of vehicle versus the structural bay, for different values of HRR, and also in comparison with case with a flat ceiling. (20 – 920°C)



Q (kW)	Under the beam	Middle of bay	Edge of the bay	Flat ceiling
2000				
4000				
6000				
8000				
10000				

3.4 CFD results and observations – car park height

CFD simulations have revealed the impact of car park height on the formation of the flame extension underneath the ceiling and, consequently, the heat flux towards the car park floor. As shown in Fig. 23, with increasing car park height, the ceiling flame extension is smaller, resulting in a significant reduction of the heat flux emitted towards the car park floor, hence reducing the probability of the fire spreading. A complete overview of the incident heat flux emitted to the car park floor for three heights of the car park, for a fire of a single vehicle is given in Table 5.

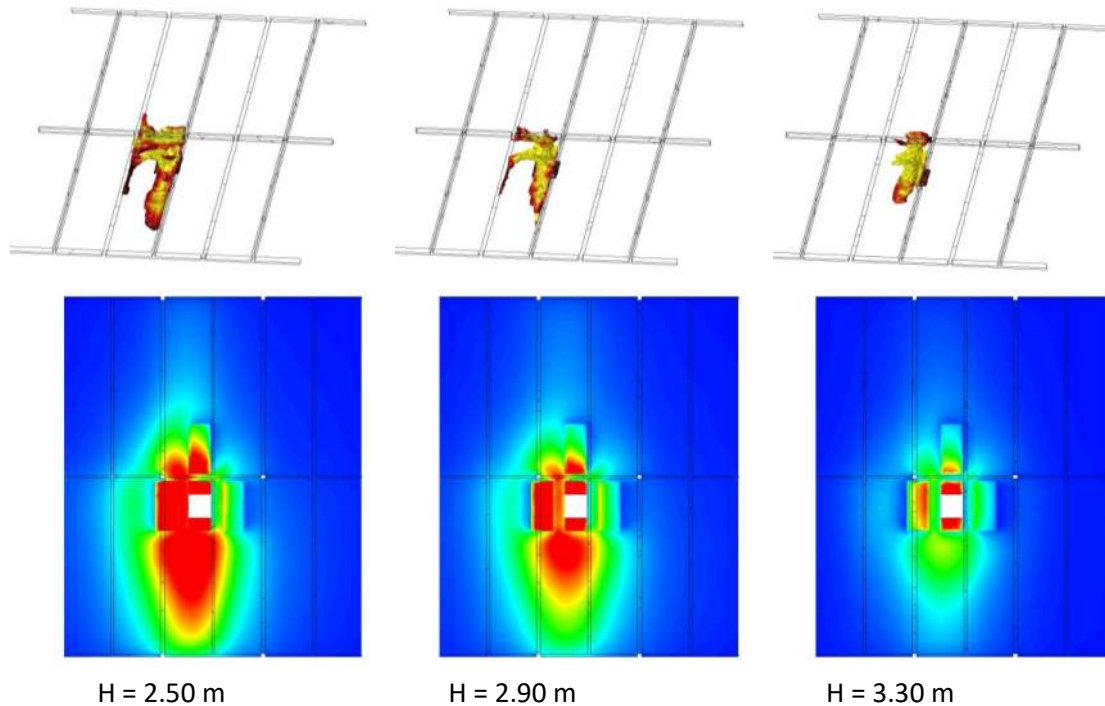


Fig. 23. Results of the single vehicle fire with HRR of 8 MW with structural elements for car park with height of 2.50 m, 2.90 m and 3.30 m. Upper plots show the flame shape, bottom plot: Incident radiation at floor (0 – 25 kW/m²)

The decrease in flame extension is likely to be explained by a larger portion of the total HRR emitted within the fire plume. When flames do not reach the ceiling, the effect of the height of the car park is smaller. Fig. 24 shows the same scenario as Fig. 23, but the fire power is split among three vehicles (9 MW, split into three sources of 3 MW each, note: the effect of multiple vehicles burning is considered in Section 3.6). In this case, a small flame extension forms above the fire in the car park with a height of 2.50 m, but no flame extensions are present at 2.90 m and 3.30 m. In this case, there is a little difference between the two latter cases regarding heat flux emitted to the car park floor. The same effect is observed for car parks without structural bays, Fig. 25. A complete overview of the incident heat flux emitted to the car park floor for three heights of the car park, for three burning vehicles in a car park with structural bays is given in Table 6, and in a car park without structural bays is given in Table 7.

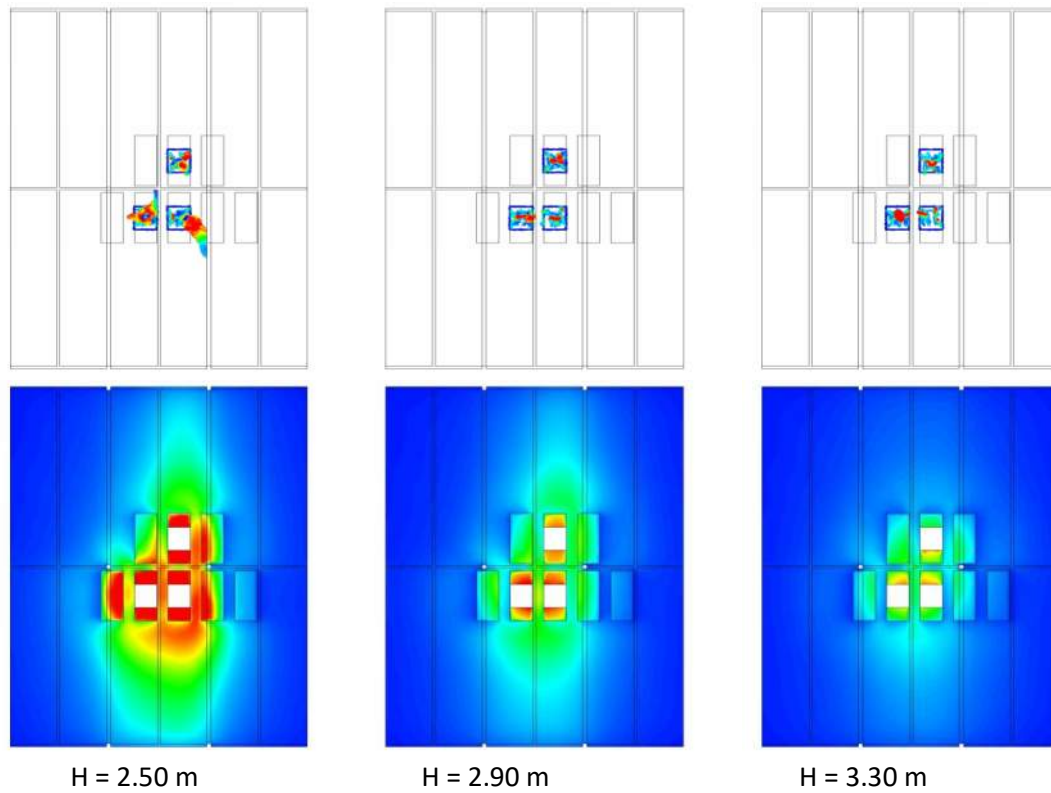


Fig. 24. Results of three vehicle fire with HRR of 9 MW (3 x 3 MW) with structural elements for car park with height of 2.50 m, 2.90 m and 3.30 m. Upper plots show the flame shape, bottom plot: Incident radiation at floor (0 – 25 kW/m²)

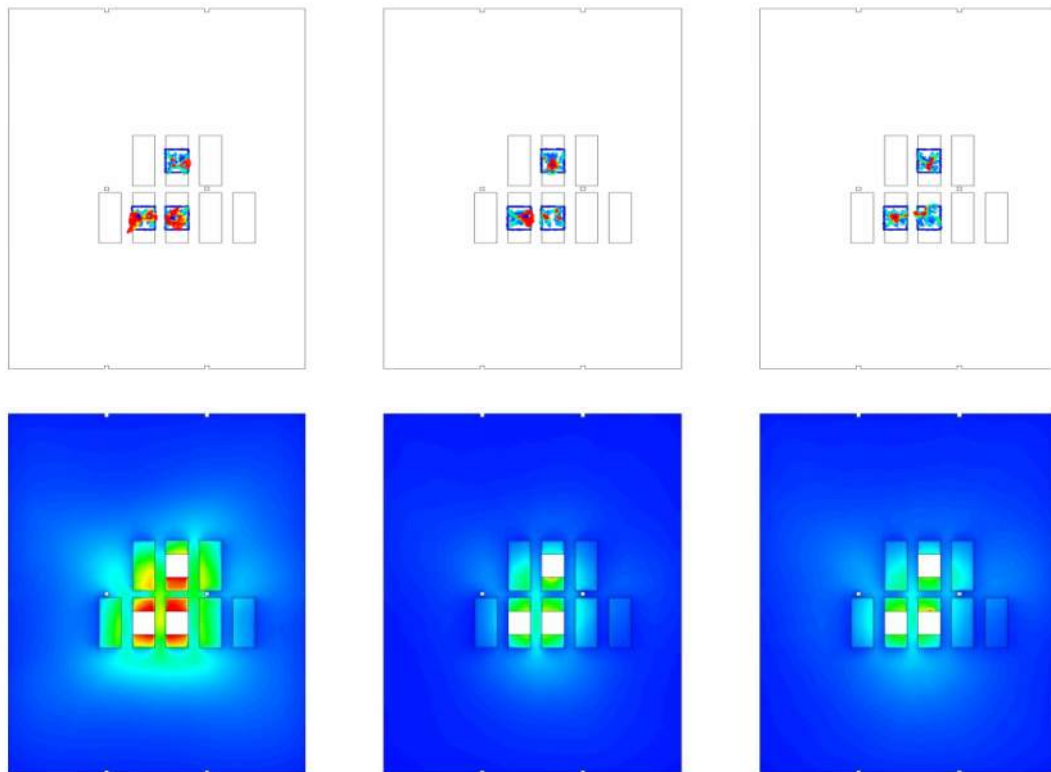


Fig. 25. Results of three vehicle fire with HRR of 9 MW (3 x 3 MW) without structural elements for car park with height of 2.50 m, 2.90 m and 3.30 m. Upper plots show the flame shape, bottom plot: Incident radiation at floor (0 – 25 kW/m²)

Table 5. Summary of results – incident heat flux to the floor for different heights of the car park, for cases with one vehicle burning (0 – 25 kW/m²)

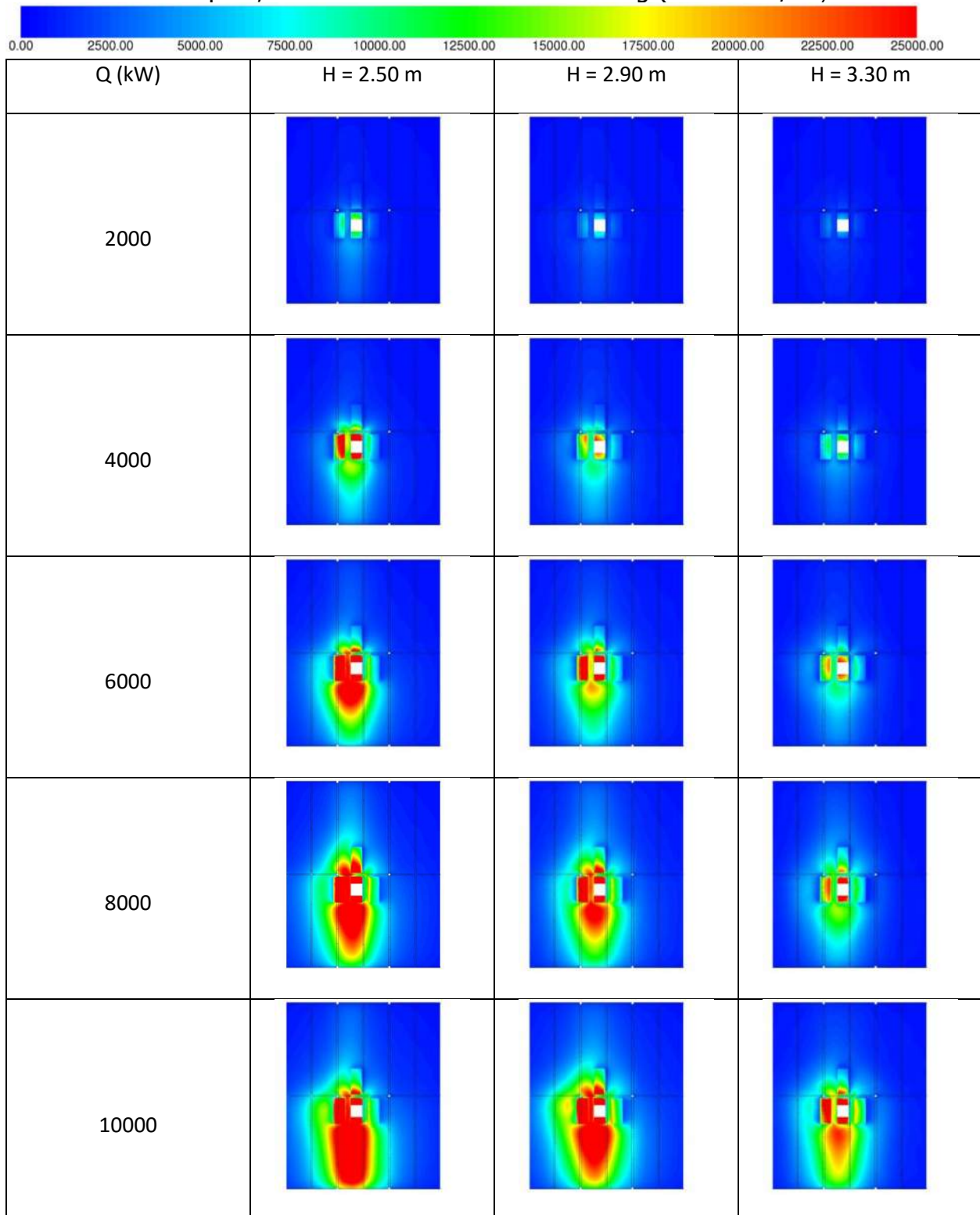
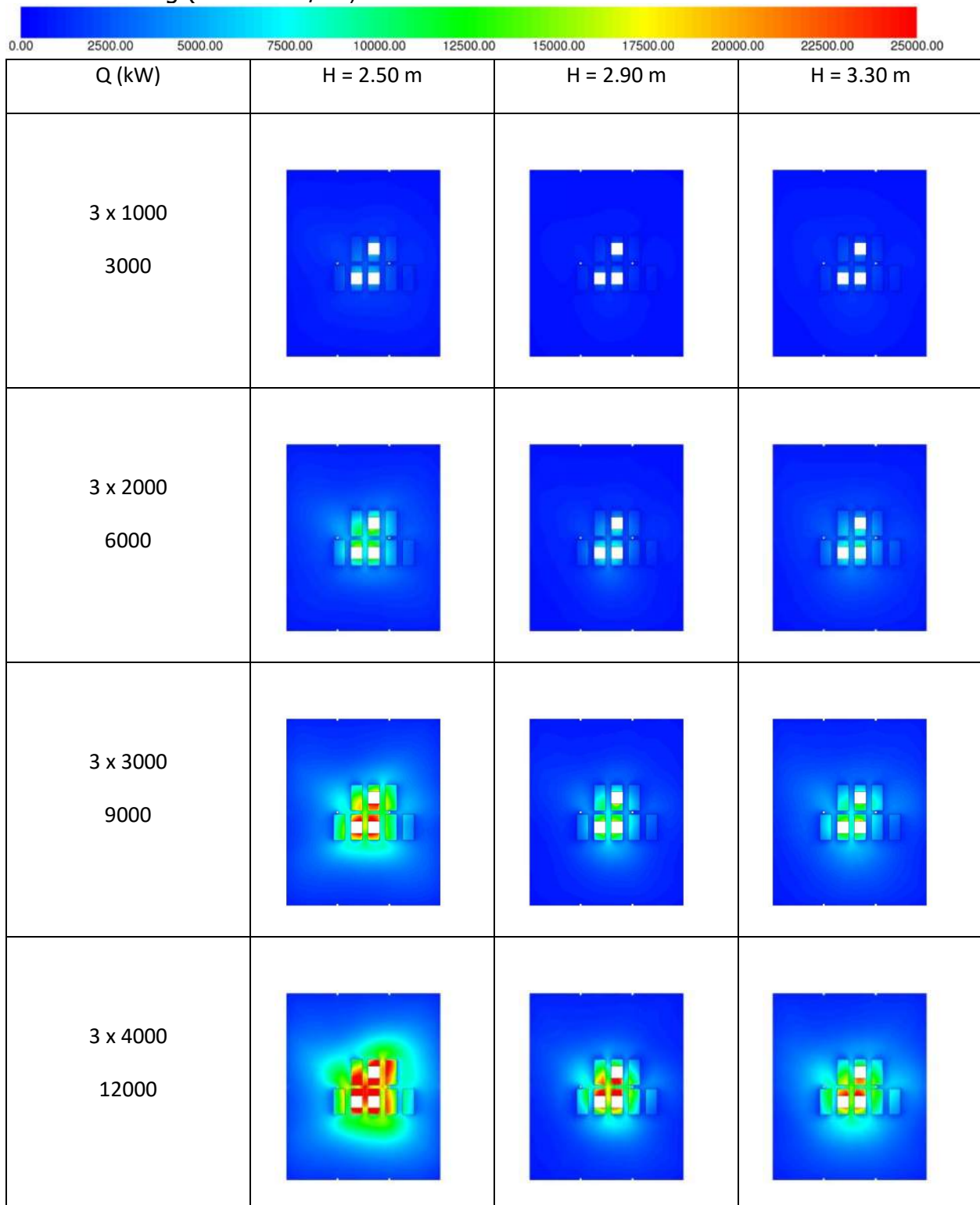


Table 6. Summary of results – incident heat flux to the floor for different heights of the car park, for cases with three vehicles burning (0 – 25 kW/m²)



Q (kW)	H = 2.50 m	H = 2.90 m	H = 3.30 m
3 x 1000 3000			
3 x 2000 6000			
3 x 3000 9000			
3 x 4000 12000			

Table 7. Summary of results – incident heat flux to the floor for different heights of the car park in car park without structural bays, for cases with three vehicles burning (0 – 25 kW/m²)



The heat flux directly to adjacent vehicles was studied in more detail for a case with structural bays, and three burning vehicles. Four target vehicles were positioned surrounding the three burning vehicles, Fig. 26. Cars 1 and 3 were in structural bays where the fire was present, and Cars 2 and 4 were in adjacent bays. The maximum incident heat flux was recorded on every surface of each vehicle in every simulation time-step, and a maximum value found on any of the surfaces is reported. The values

of maximum incident heat flux were then correlated with the HRR of the fire, to give a $q'' = f(Q)$ plots, Fig. 27. Given earlier considerations presented in Section 3.2, if the $q'' < 10 \text{ kW/m}^2$ the fire spread is unlikely (without direct flame contact), and if $q'' > 20 \text{ kW/m}^2$, the fire spread may be rapid. It can be observed that for nearest vehicles in a car park with 2.50 m height, at a total HRR of less than 6MW the incident heat flux exceeds 20 kW/m^2 , possibly leading to a rapid fire spread. In the car park with a height of 3.30 m, this value is never obtained. The same analysis performed for the car park without structural bays reveals lower incident heat fluxes for the corresponding HRR, fig. 28. Interestingly, we observe almost no qualitative difference between 2.90 m and 3.30 m car parks (in both cases there was no flame extension under the ceiling).

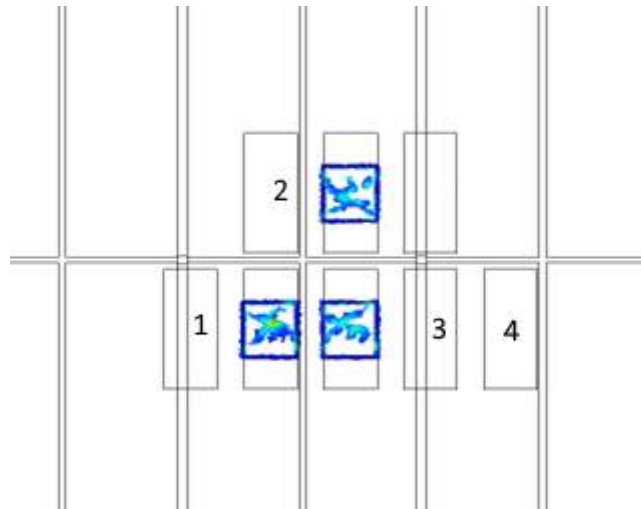


Fig. 26. Location of target vehicles in further considerations

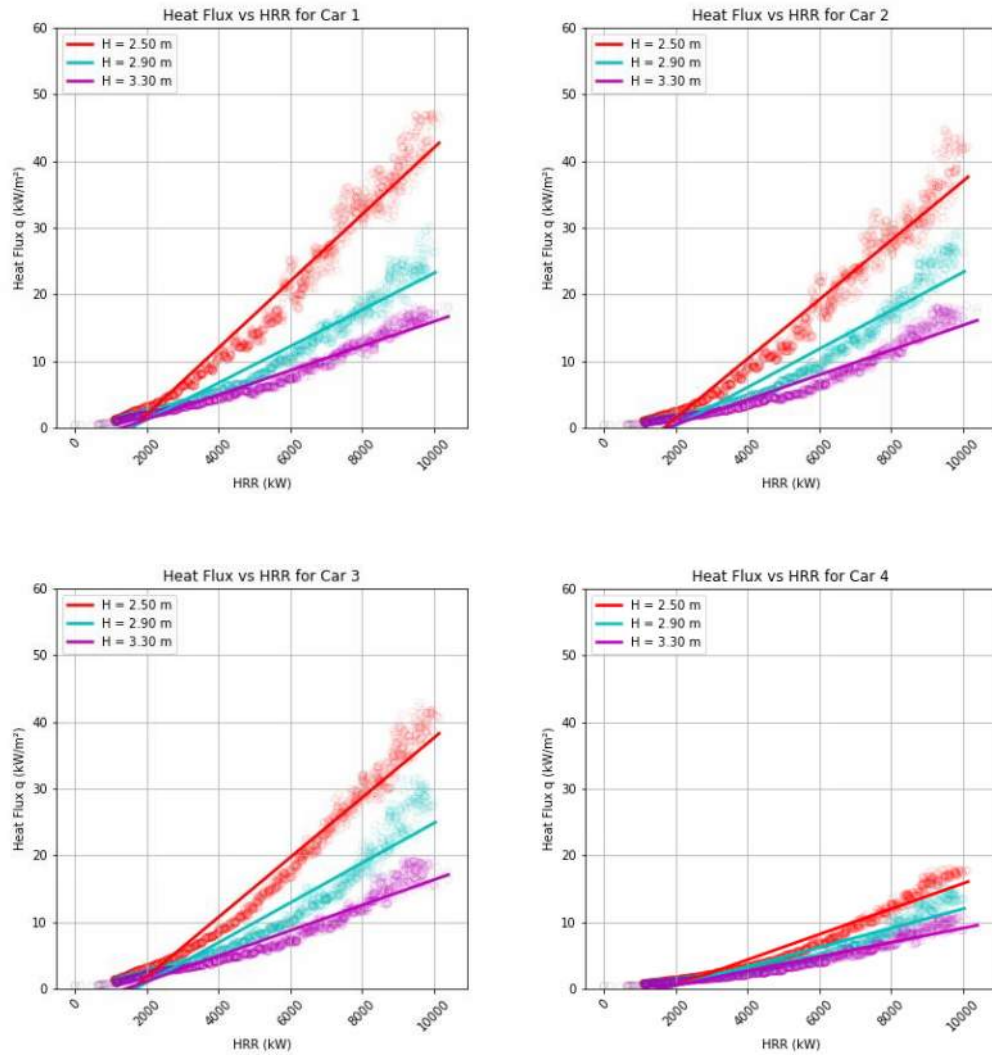


Fig. 27. Maximum incident heat flux measured at four adjacent vehicles, in function of growing HRR, car park with structural bays, 3 vehicles burning

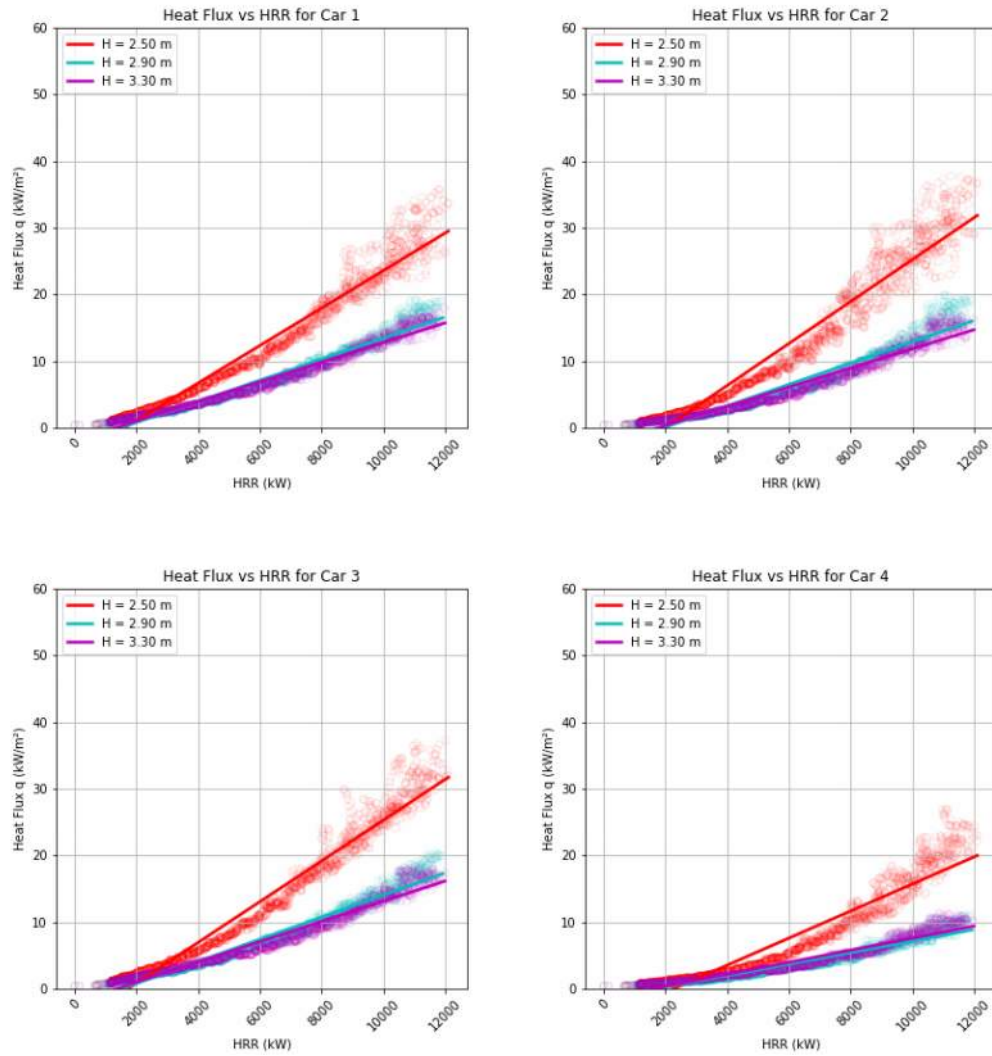


Fig. 28. Maximum incident heat flux measured at four adjacent vehicles, in function of growing HRR, car park without structural bays, 3 vehicles burning

3.5 CFD results and observations – multiple vehicle fires

As indicated earlier, the HRR in the car park is produced in two volumes – the volume of fire plume above the burning vehicle, and within the flame extension under the car park ceiling. Therefore, when considering the fire size within the car park, it is essential to understand individual contributions of each vehicle. The differences between fires of the same size of 12 MW, but involving one, two or three vehicles are shown on Fig. 29-31. A comparison of results for the car park with height of 2.50 m, 2.90 m and 3.30 m is given in Tables 8 – 10, respectively.

The effects observed are interpreted as a compound effect of the reduction of the flame extension volume, and the spread of fire beyond the first structural bay. Therefore, another set of cases was investigated, in which the burning vehicles were positioned in a way, that multiple plumes merge within one structural bay, as further discussed in Section 3.6.

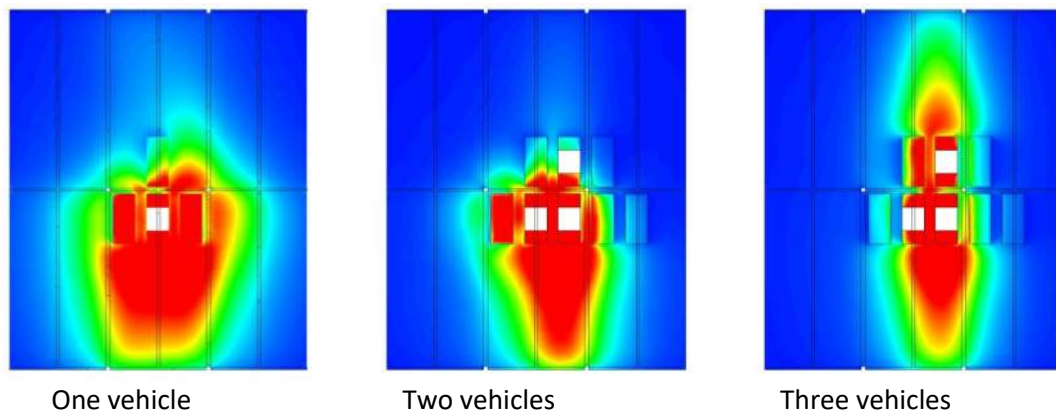


Fig. 29. Results of one, two or three vehicle fire with HRR of 12 MW with structural elements for car park with height of 2.50 m. Incident radiation at floor (0 – 25 kW/m²)

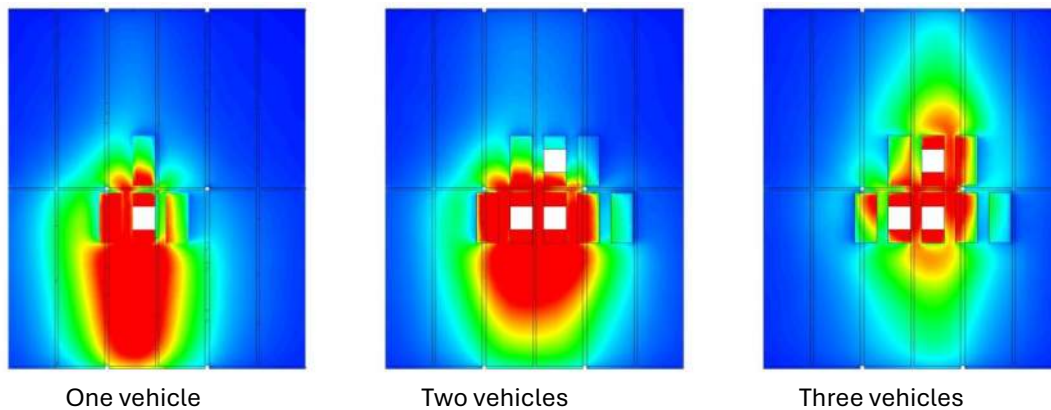


Fig. 30. Results of one, two or three vehicle fire with HRR of 12 MW with structural elements for car park with height of 2.90 m. Incident radiation at floor (0 – 25 kW/m²)

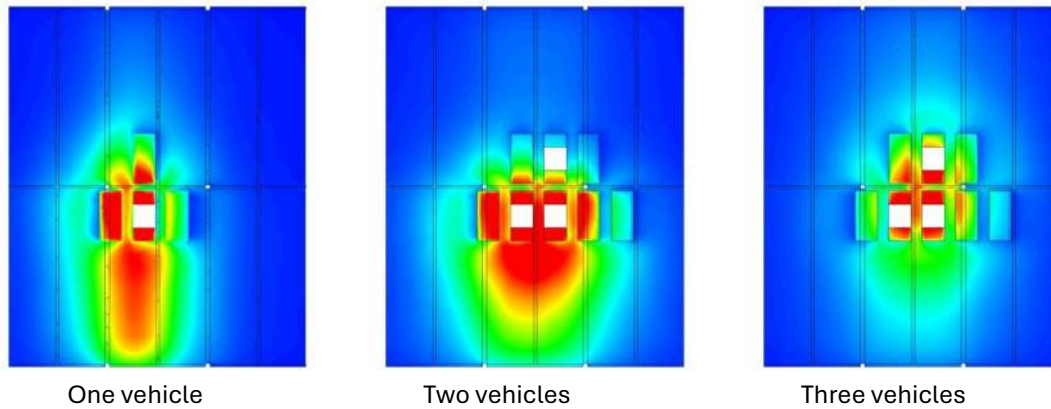
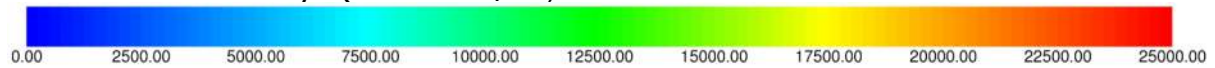


Fig. 31. Results of one, two or three vehicle fire with HRR of 12 MW with structural elements for car park with height of 3.30 m. Incident radiation at floor (0 – 25 kW/m²)

Table 8. Summary of results – incident heat flux to the floor for car parks with height of 2.50 m, with one, two or three vehicles burning, for car park with structural bays (0 – 25 kW/m²)



Q (kW)	One vehicle	Two vehicles	Three vehicles
3000			
6000			
9000			
12000			

Table 9. Summary of results – incident heat flux to the floor for car parks with height of 2.90 m, with one, two or three vehicles burning, for car park with structural bays (0 – 25 kW/m²)



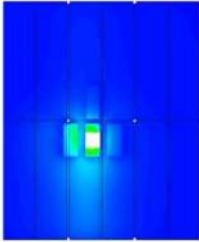
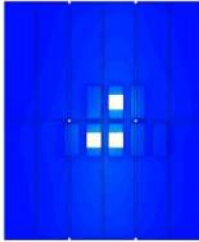
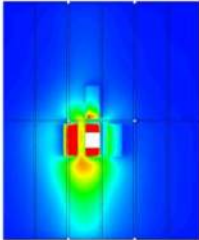
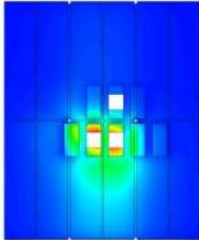
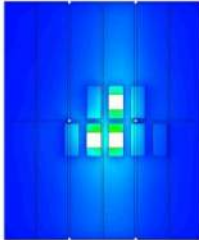
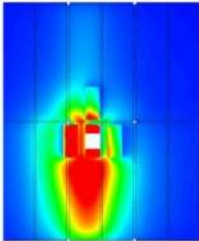
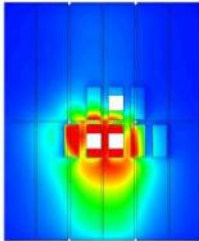
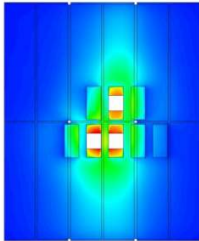
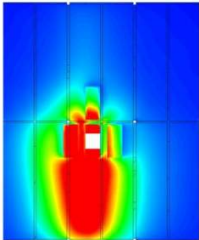
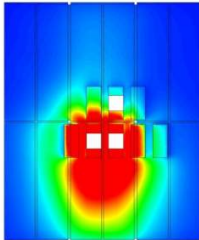
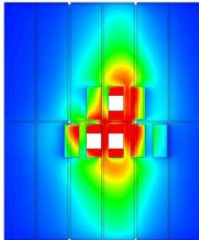
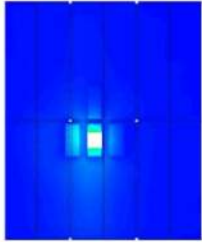
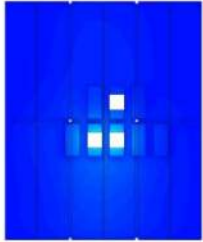
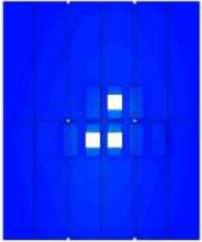
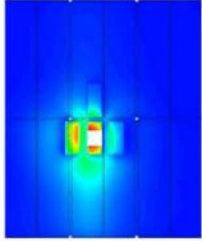
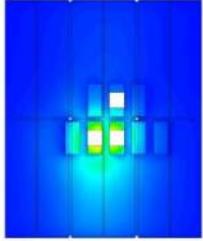
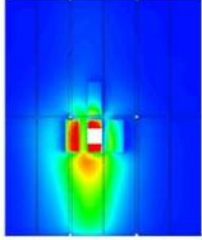
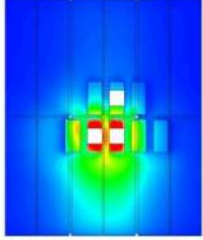
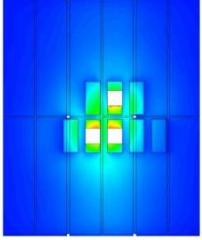
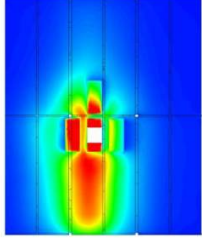
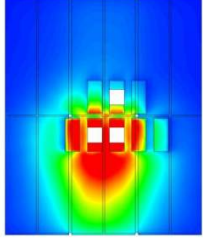
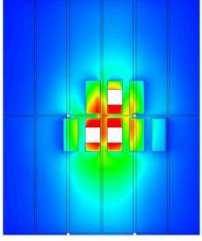
Q (kW)	One vehicle	Two vehicles	Three vehicles
3000			
6000			
9000			
12000			

Table 10. Summary of results – incident heat flux to the floor for car parks with height of 3.30 m, with one, two or three vehicles burning, for car park with structural bays (0 – 25 kW/m²)



Q (kW)	One vehicle	Two vehicles	Three vehicles
3000			
6000			
9000			
12000			

3.6 CFD results and observations – vehicle parking orientation within the car park

As mentioned in the previous section, the vehicle arrangement in the car park may influence how multiple fire plumes merge within a structural bay. Therefore, we have performed an additional analysis with cars filling the bay in a different direction (Fig. 32).

The differences are not profound for a single vehicle fire within the bay, as shown in Table 11. Small observed deviations may be an outcome of the shielding effect of vehicles. For 2 and 3 vehicle fires, rotated arrangement results in significantly worse incident heat flux, Tables 12 and 13.

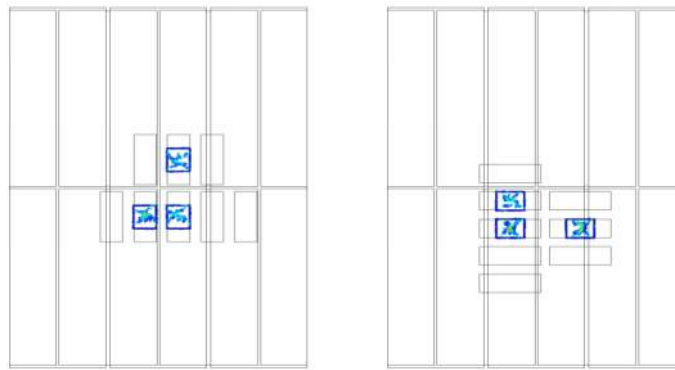


Fig. 32. Arrangement of cars in the car park, left is the previous arrangement (Sections 3.3 – 3.5), right is the rotated arrangement

Table 11. Results comparison of results – incident heat flux to the floor for the previous and rotated vehicle arrangements, car parks with a height of 2.50 m, with one vehicle burning in a car park with structural bays (0 – 25 kW/m²)



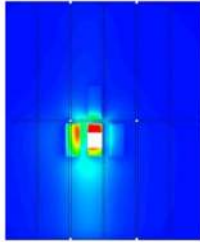
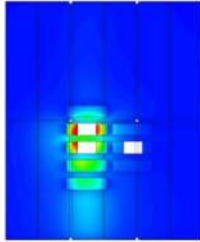
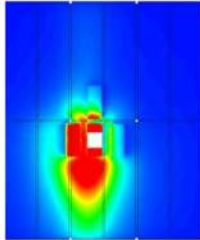
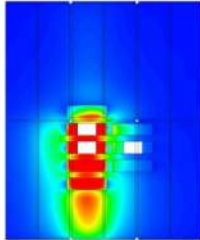
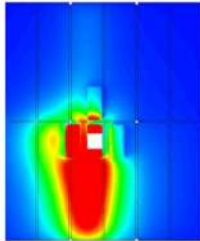
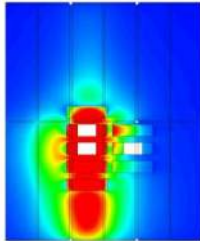
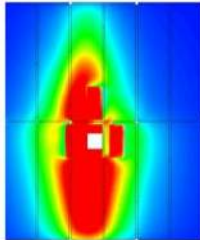
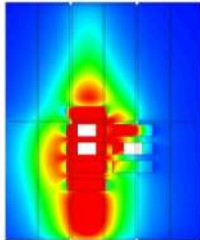
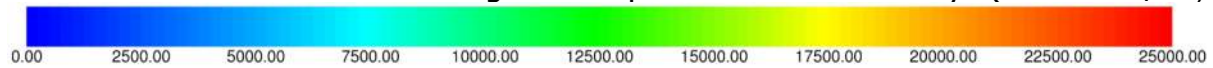
Q (kW)	Previous arrangement	Rotated arrangement
3000		
6000		
9000		
12000		

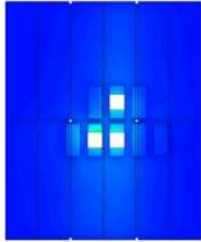
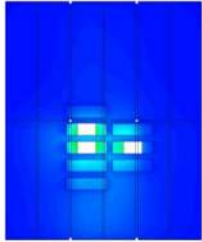
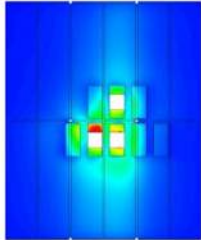
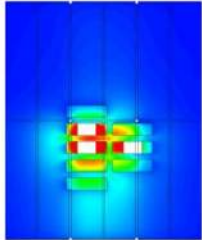
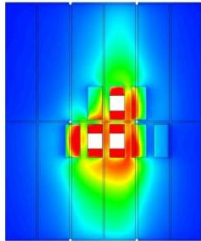
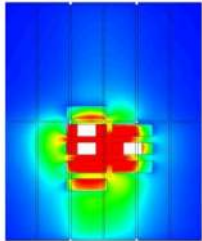
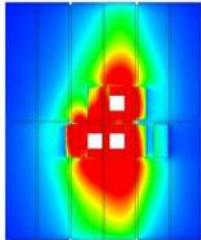
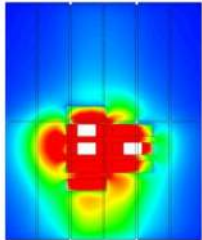
Table 12. Results comparison of results – incident heat flux to the floor for the previous and rotated vehicle arrangements, car parks with a height of 2.50 m, with two vehicles burning in a car park with structural bays (0 – 25 kW/m²)



Q (kW)	Previous arrangement	Rotated arrangement
3000		
6000		
9000		
12000		

Table 13. Results comparison of results – incident heat flux to the floor for the previous and rotated vehicle arrangements, car parks with a height of 2.50 m, with three vehicles burning in a car park with structural bays (0 – 25 kW/m²)



Q (kW)	Previous arrangement	Rotated arrangement
3000		
6000		
9000		
12000		

An interesting comparison may be done for the maximum heat flux measured at the target vehicles, as on Fig. 27 – see new Fig. 33. For car parks with 2.50 m and 2.90 m height, in the rotated arrangement all the vehicles are experiencing higher incident heat fluxes, especially car 4. This vehicle was previously located in an adjacent structural bay, far from the fire. Now it is within the bay in which the fire is happening, under a flame extension. In case of the car park with a height of 3.30 m, no significant differences were observed.

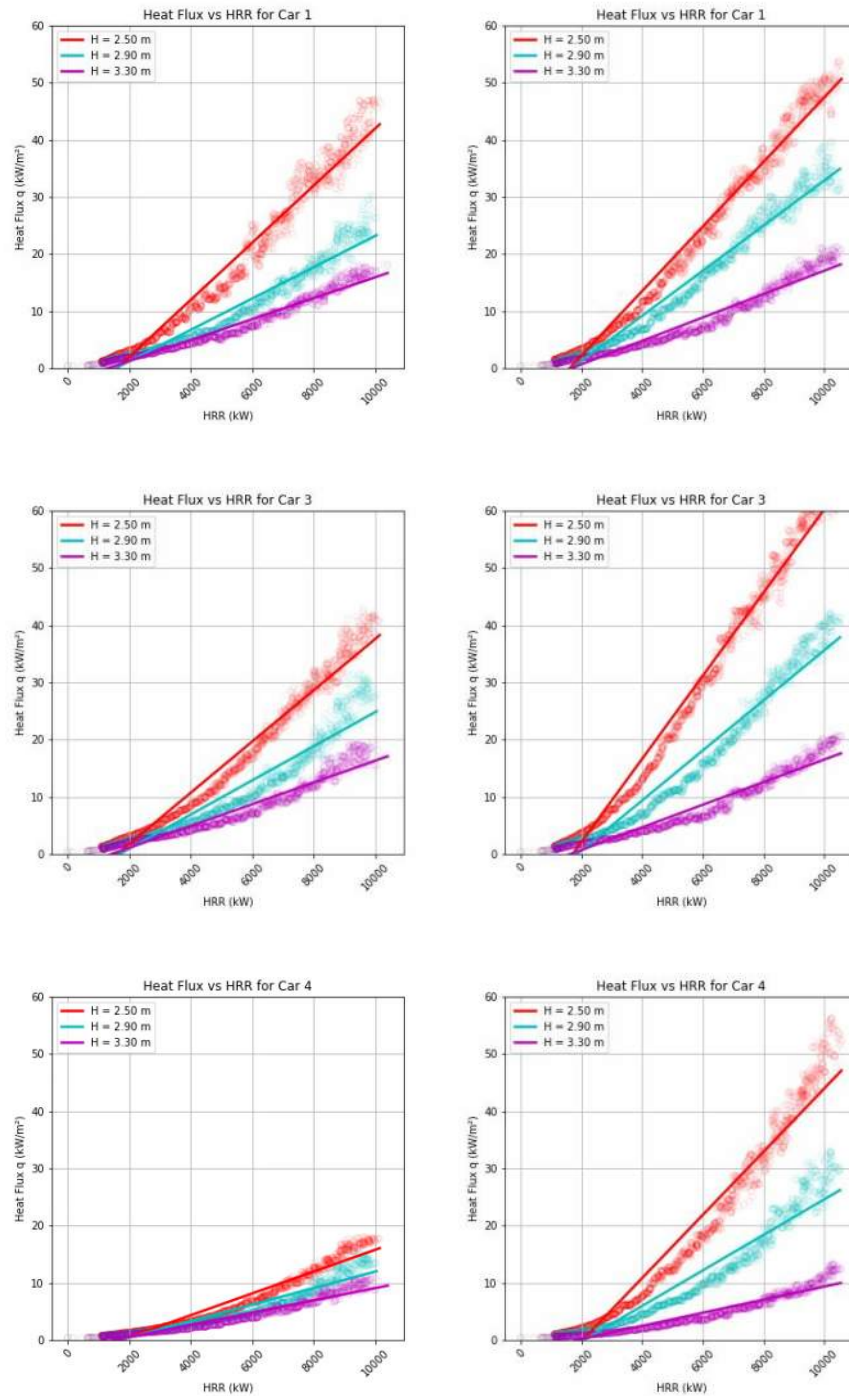


Fig. 33. Maximum incident heat flux measured at adjacent cars 1, 3 and 4, in function of growing HRR, car park without structural bays, 3 vehicles burning. Left hand side plots show previous arrangement (see Fig. 27), right hand side plots present rotated arrangement

4 CFD for calibration of simplified model - heat flux on target vehicles at different HRR

4.1 Assumptions for the investigation

To further inform the development of simplified fire spread models, a calibration study was done with the use of the CFD model. Three different fire scenarios were considered, and each was performed in six carparks with different heights (2.50 m, 2.70 m, 2.90 m, 3.10 m, 3.30 m and 3.50 m). Fire was considered on two vehicles (here named A and B), with the following assumptions:

- Scenario 1 – fire on both vehicles A and B start at 500kW and the HRR is increased stepwise by 250 kW every 30 s, until the end of simulation.
- Scenario 2 – fire on vehicle A is constant at 2 000 kW and the HRR of vehicle B increases stepwise by 500 kW every 30 s, until the end of simulation.
- Scenario 3 – fire on vehicle A is constant at 4 000 kW and the HRR of vehicle B increases stepwise by 500 kW every 30 s, until the end of simulation.

The fire growth progressed up to the end of simulation, which was approx. 480 s after the initiation, which means each scenario went through 16 increases. In some cases, the simulations were continued for exploratory reasons, but due to an unstable combustion regime in the upper layer, an increase of the fuel had a limited impact on the chemical release in the car park. Whenever results are correlated, instantaneous chemical energy release (HRR) and not the burner fuel emission are taken.

Vehicles A and B are surrounded by 11 target vehicles, such as (fig. 34):

- Vehicle 1 is in a neighbouring bay to the side of vehicle A;
- Vehicles 2 – 5 are within the same structural bay as vehicles A and B;
- Vehicles 6 – 11 are in an adjacent structural bay.

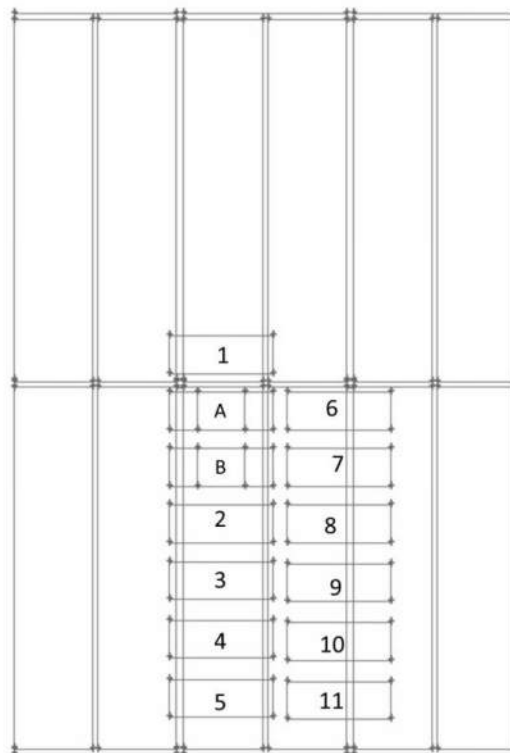


Fig. 34. Locations of the fire and target vehicles in simulations

Figures 35 – 37 illustrate the HRR of the fires simulated in car parks of different heights. In each car park we have considered the energy generated in fire plumes and in flame extensions separately (for this purpose, the volume between the beams of the structural bay was considered the “flame extension” region, and the remaining volume of the car park was considered as the “plume region”). It can be observed that at the total HRR higher than 5 MW, the combustion process starts to be driven by large-scale turbulence, and so-called “puffing behaviour” is observed. However, time averaging was not introduced to allow for comparison between momentary values Q and q'' . It can also be observed that the energy generated in the flame extension is significantly lower for taller car parks. The energy generated within the plume reaches some maximum value dependent on the car park height, and then the rest of the energy is produced in flame extension. However, this value differs from approx. 2 MW in the car park with 2.50 m height to above 4 MW in the car park with 3.50 m height. The same trend is observed for Scenarios 2 and 3.

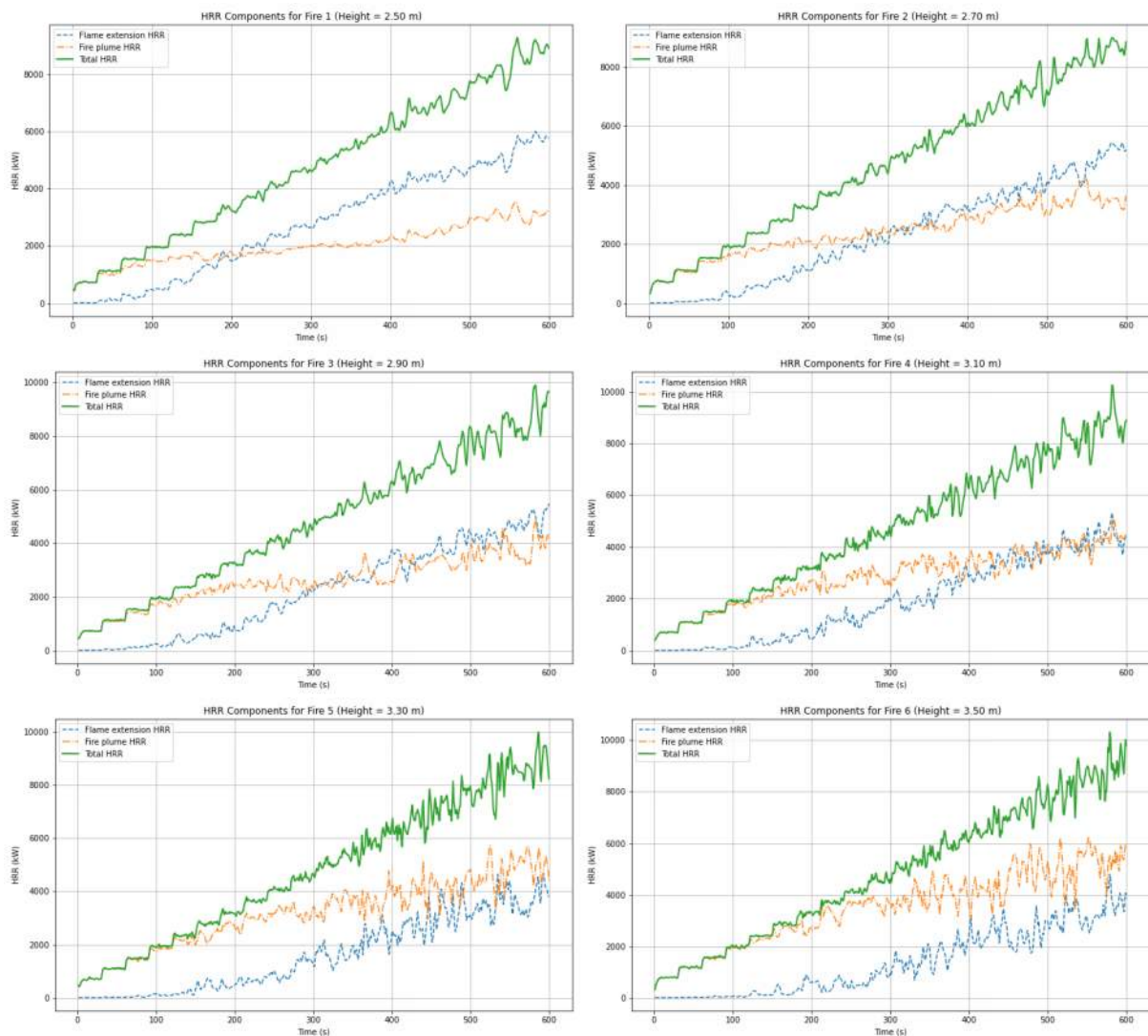


Fig. 35. HRR plots for fires in six different car park heights, for scenario 1.

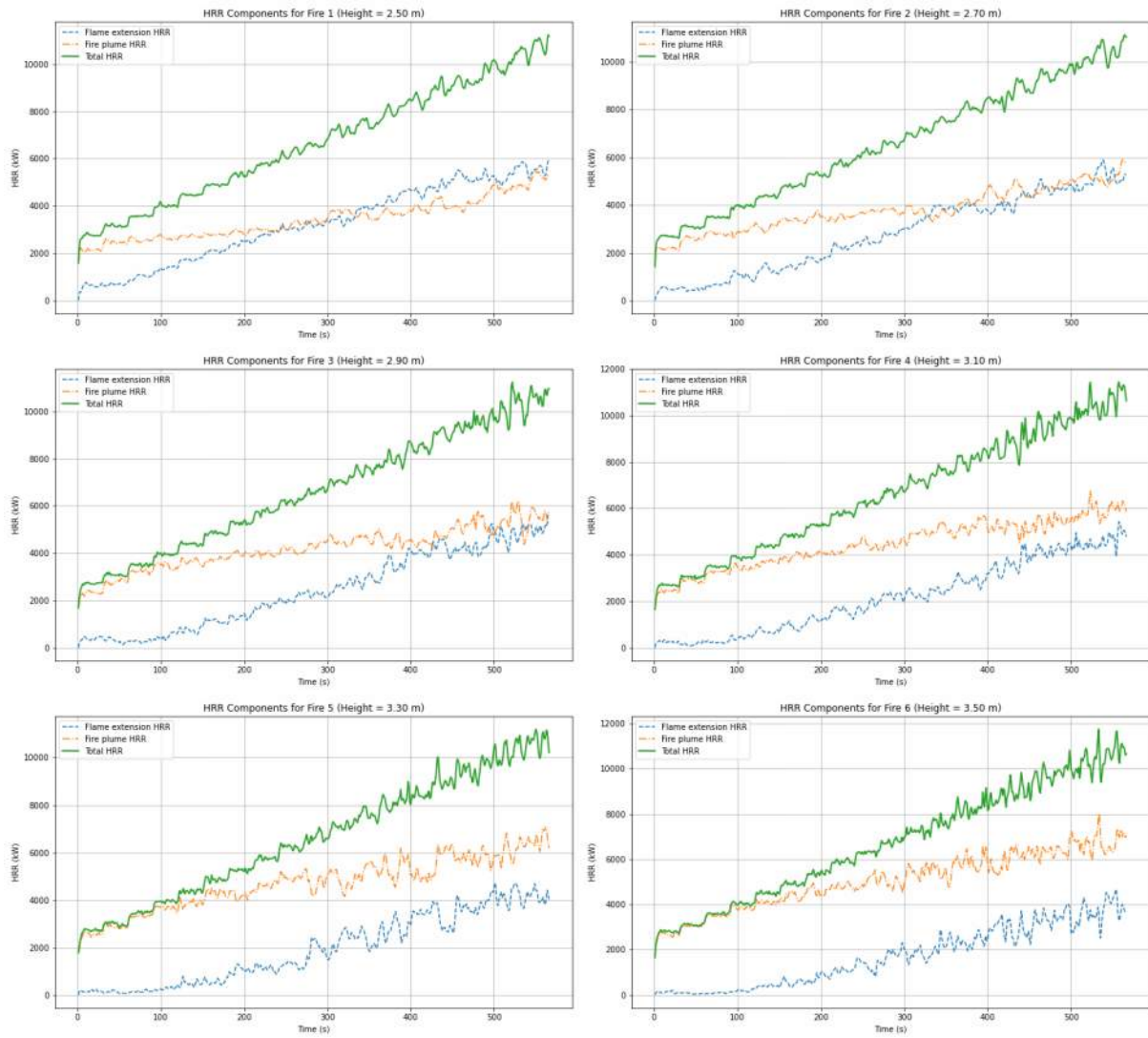


Fig. 36. HRR plots for fires in six different car park heights, for scenario 2.

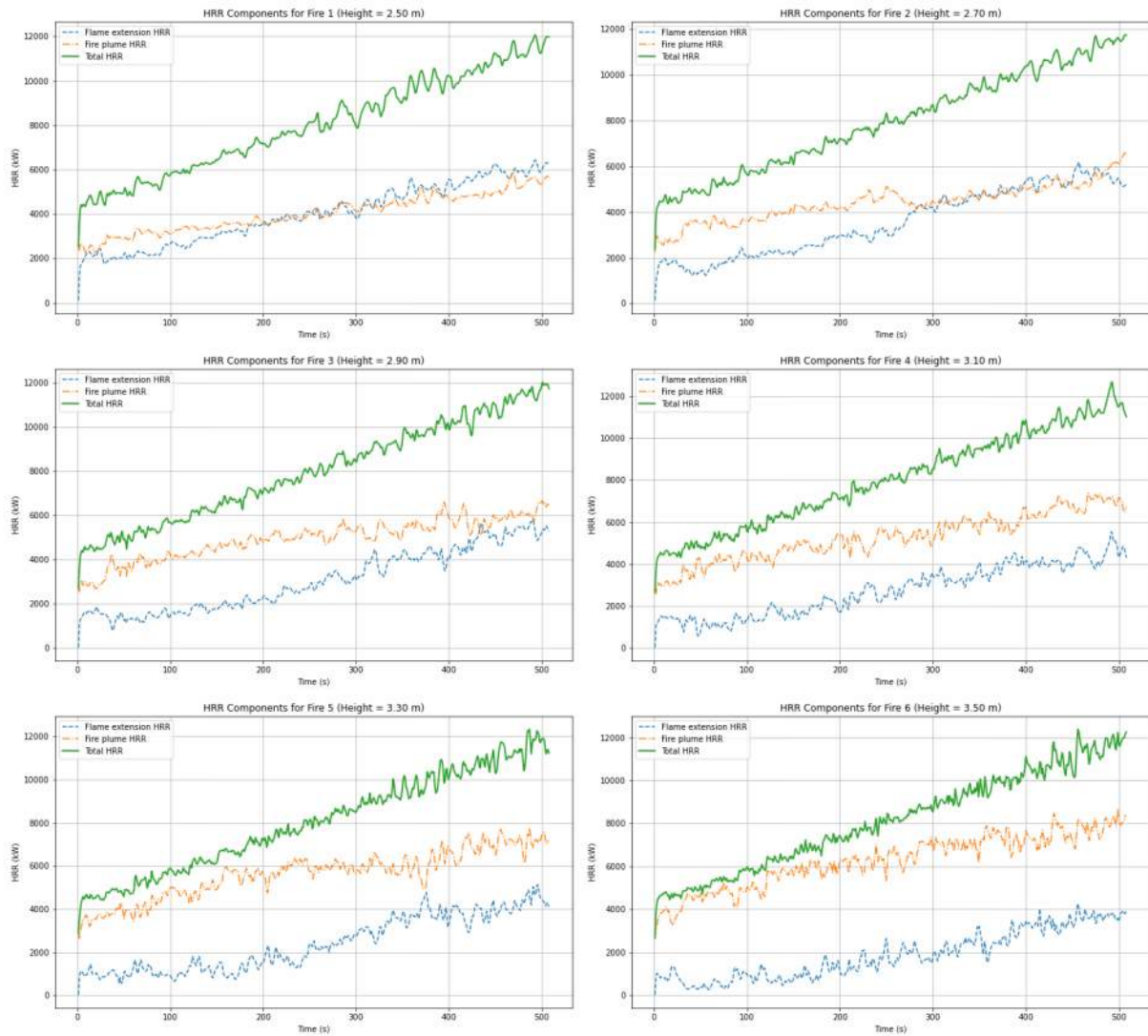


Fig. 37. HRR plots for fires in six different car park heights for scenario 3.

4.2 Results of the calibration study

The results of this calibration study are presented in the form of $q'' = f(Q)$ plots, Fig. 39 – 49. Plots were created for every target vehicle independently, and simple polynomial fits were adapted for easier analysis of the output. Each target is analysed for all three scenarios.

HRR values at which the q'' exceeds values between 10 kW/m^2 and 30 kW/m^2 , for each vehicle and each growth scenario is shown in Fig. 5. These values are referring to the car park height of 2.50 m which in our simulations was the worst case scenarios. The values for other heights of the car park can be estimated from Fig. 39 – 49.

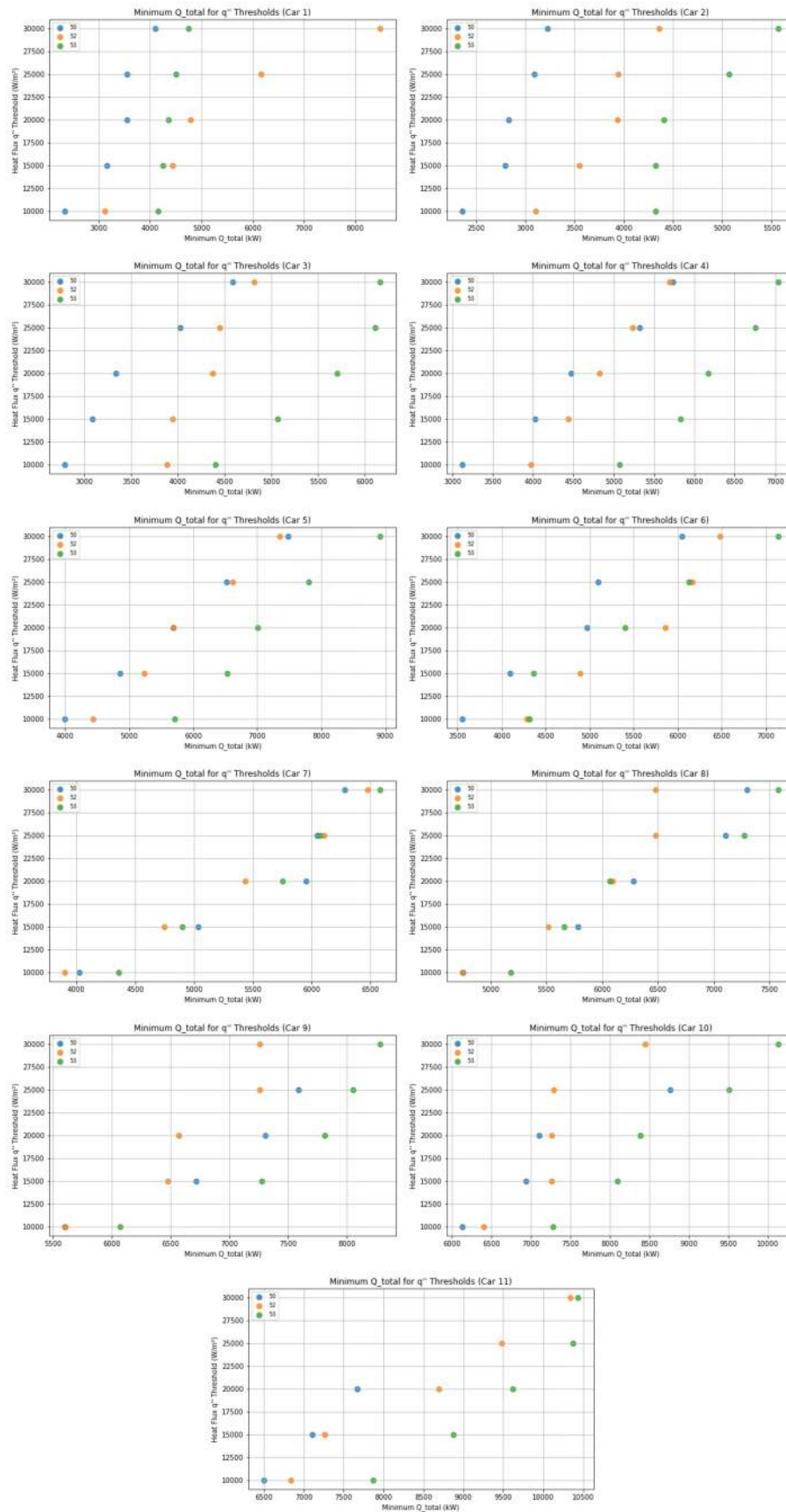
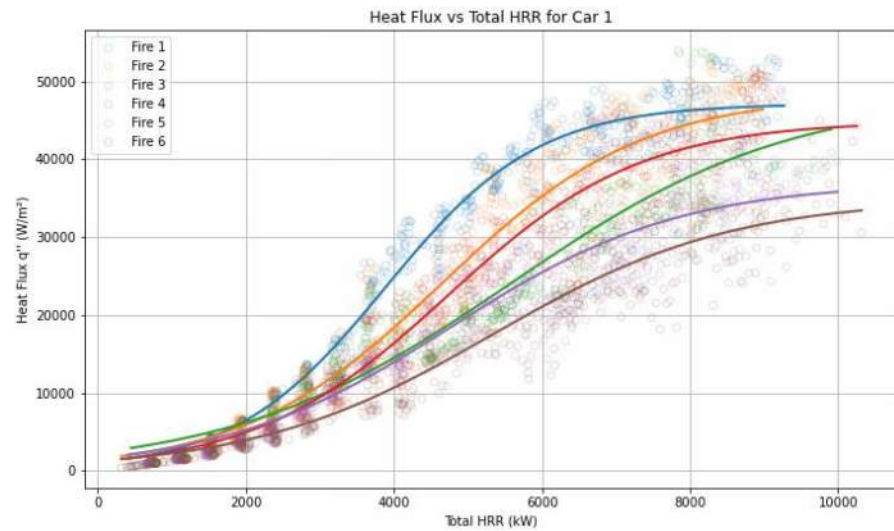
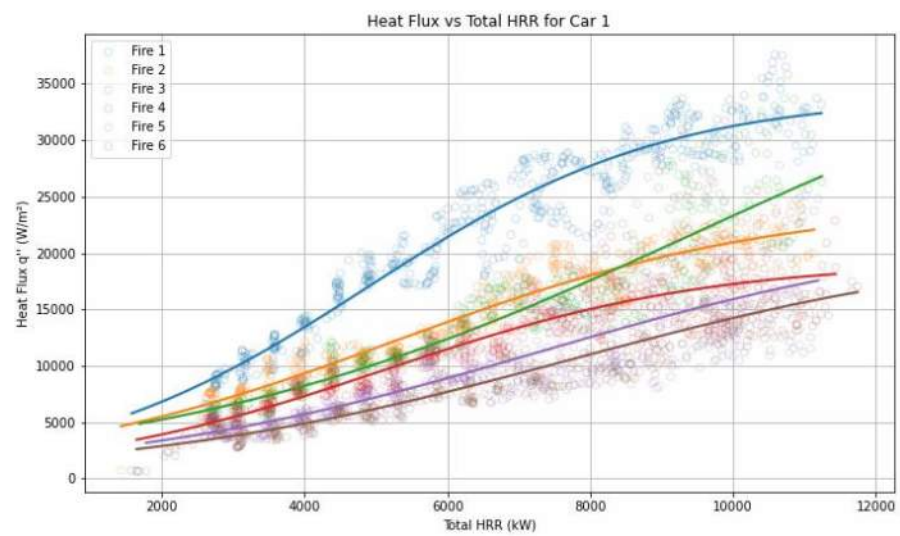


Fig. 38. Minimum values of Q (HRR) at which specified values of q'' were observed, car park of $h = 2.50$

Scenario 1



Scenario 2



Scenario 3

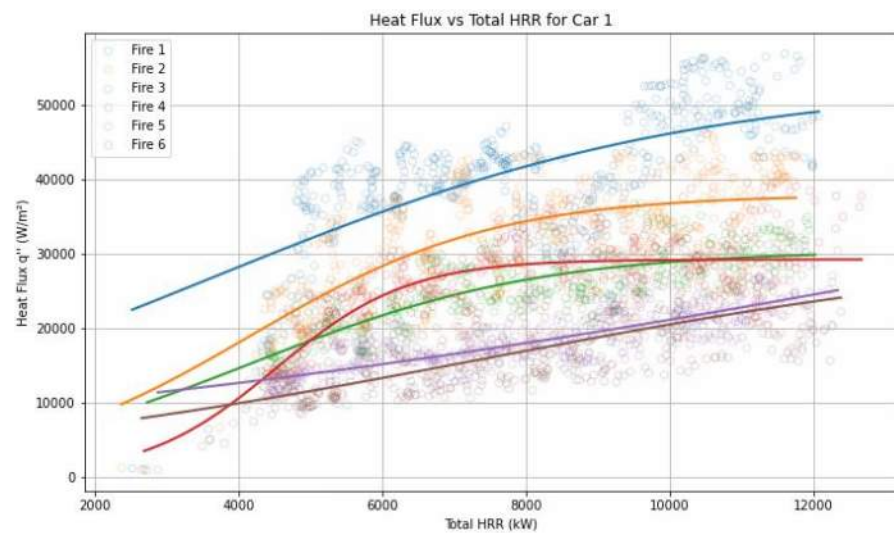
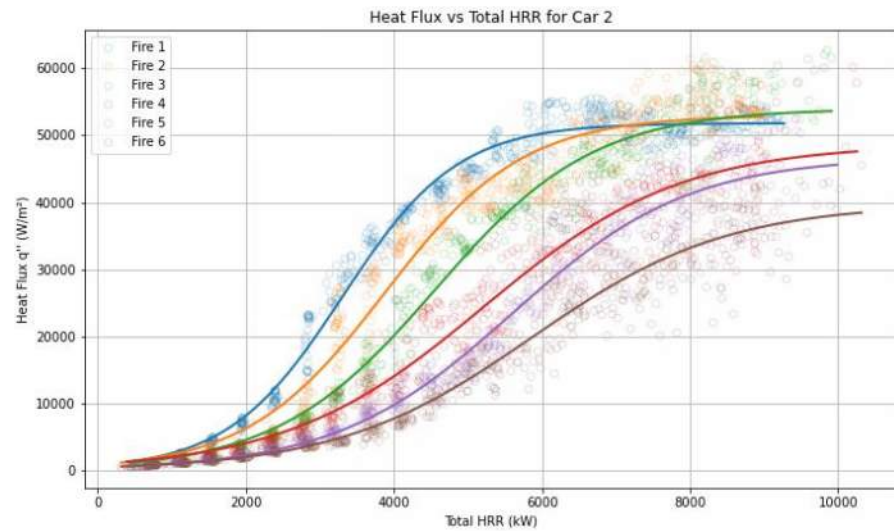
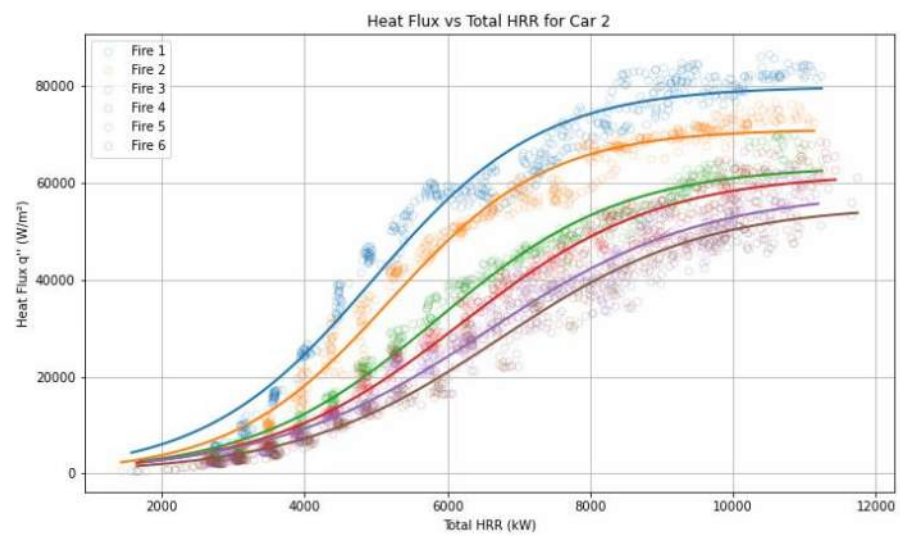


Fig. 40. q'' in function of Q plots for Car 1 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

Scenario 1



Scenario 2



Scenario 3

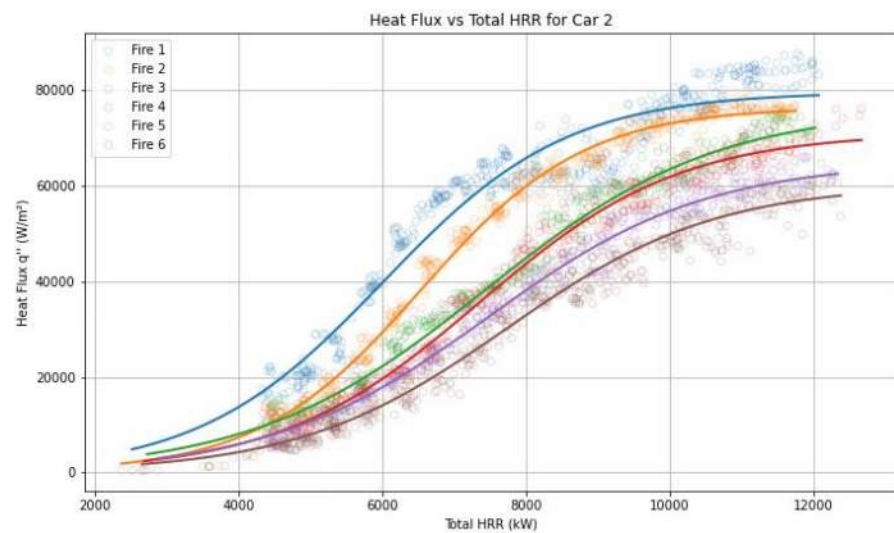
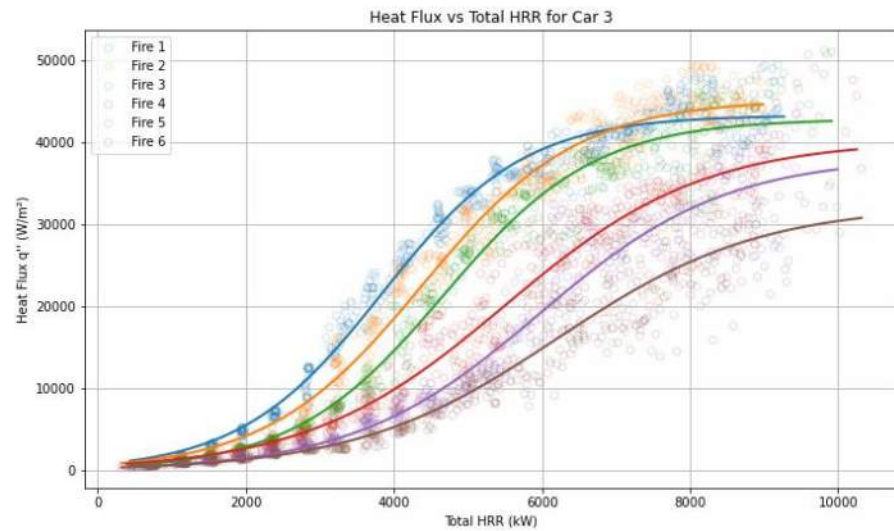
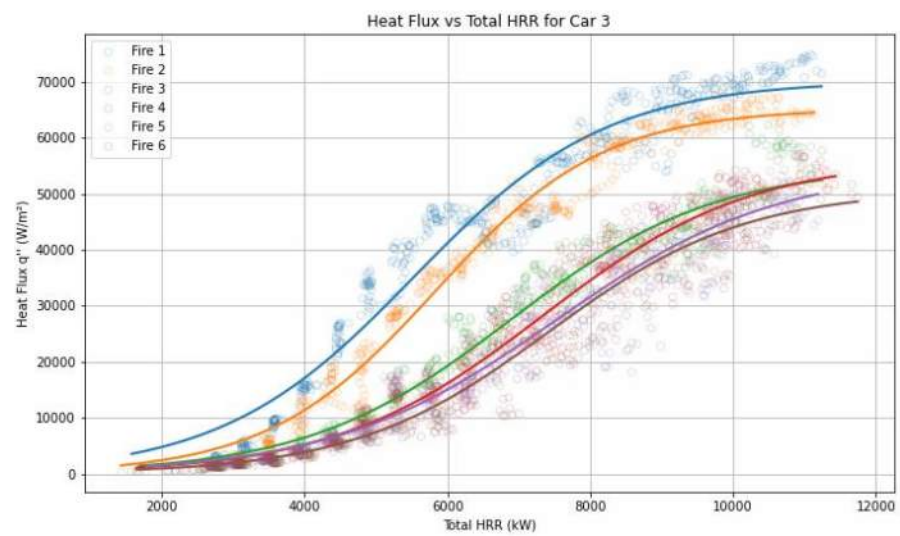


Fig. 41. q'' in function of Q plots for Car 2 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

Scenario 1



Scenario 2



Scenario 3

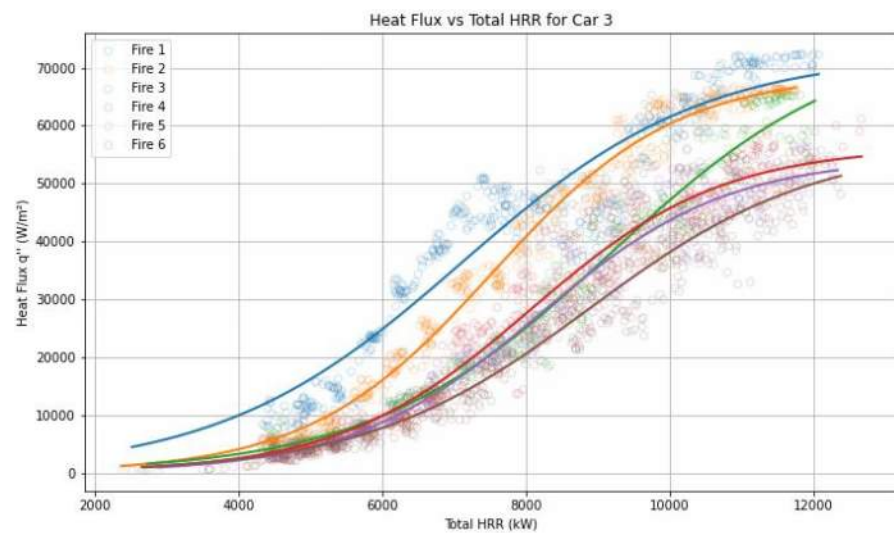
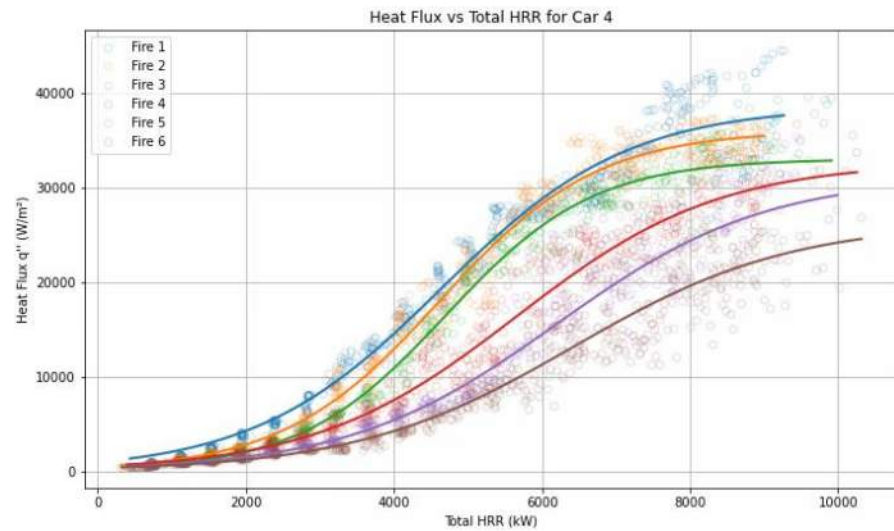
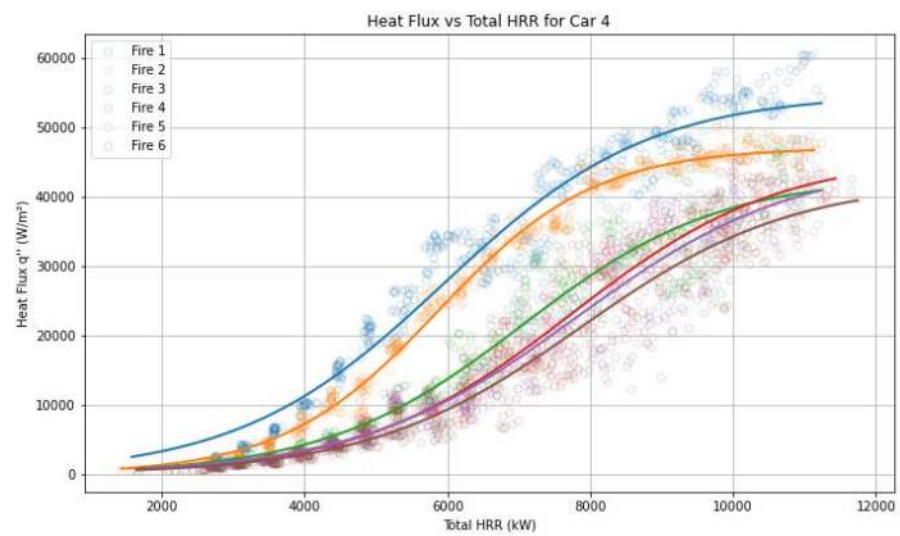


Fig. 42. q'' in function of Q plots for Car 3 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

Scenario 1



Scenario 2



Scenario 3

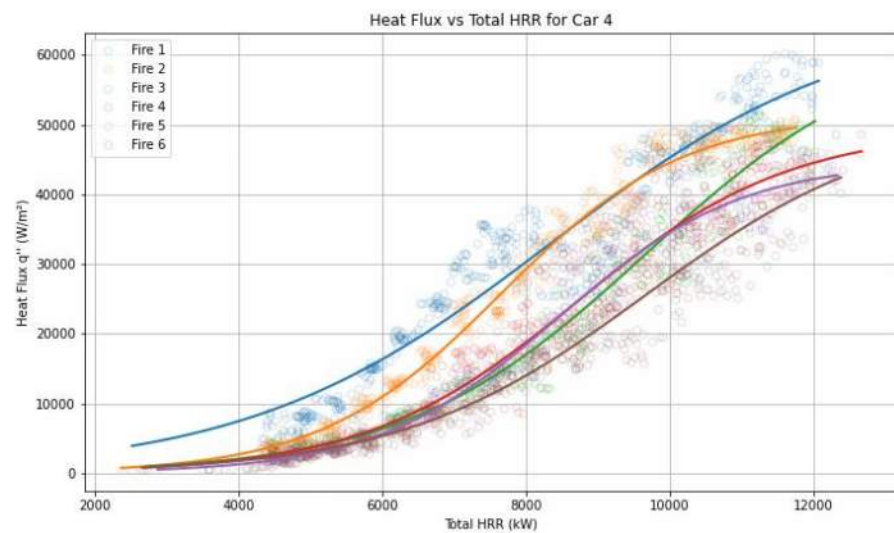
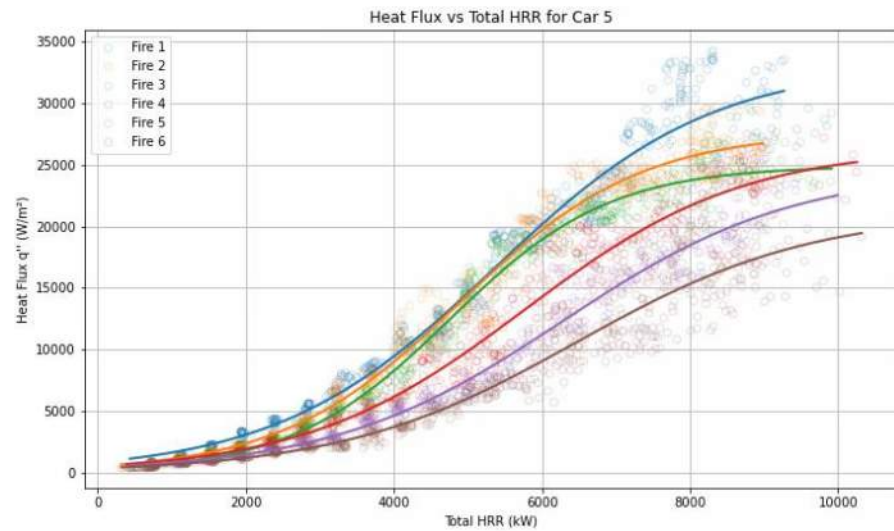
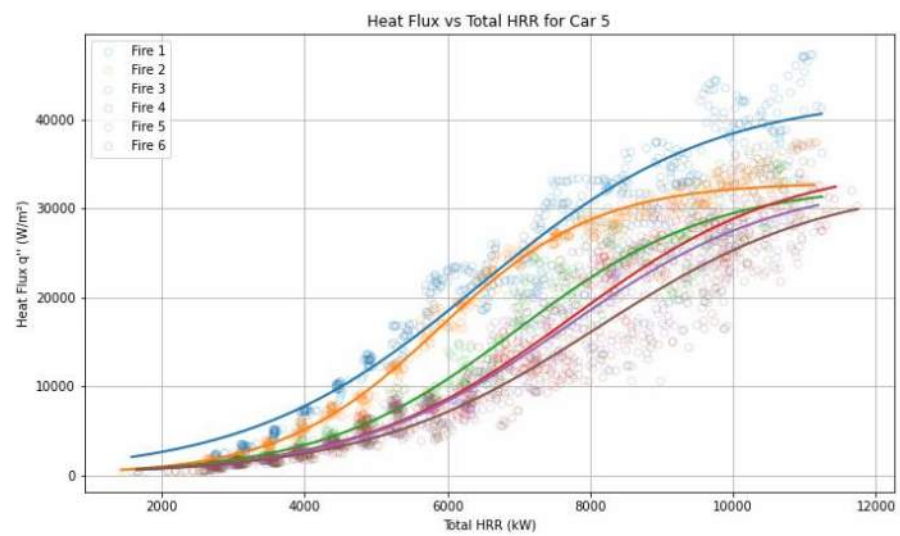


Fig. 43. q'' in function of Q plots for Car 4 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

Scenario 1



Scenario 2



Scenario 3

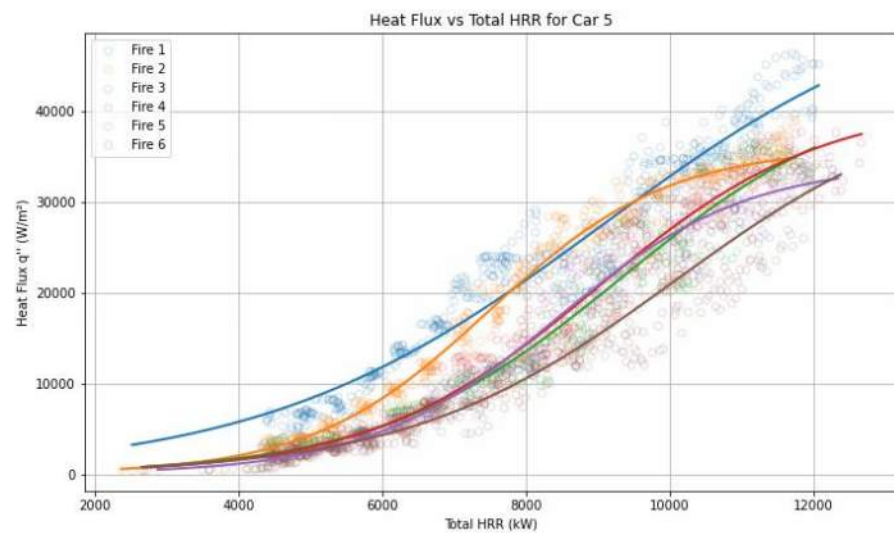
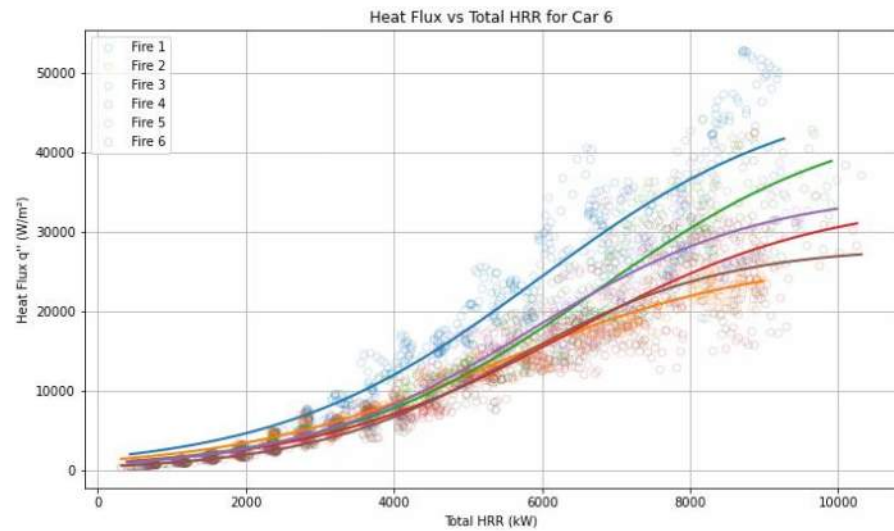
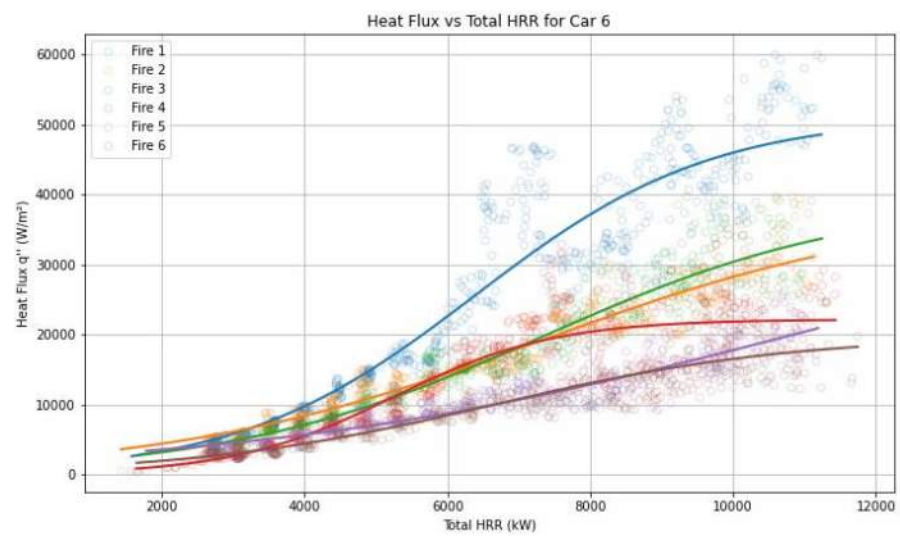


Fig. 44. q'' in function of Q plots for Car 5 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

Scenario 1



Scenario 2



Scenario 3

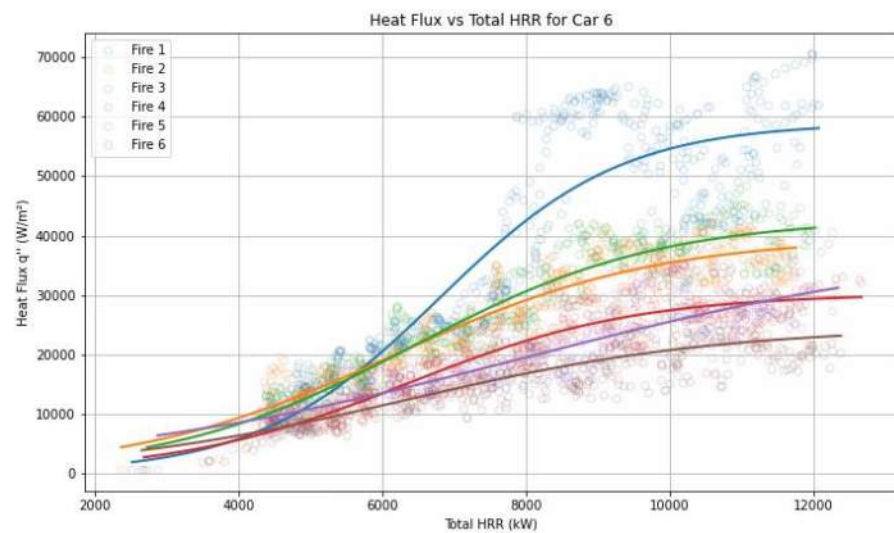
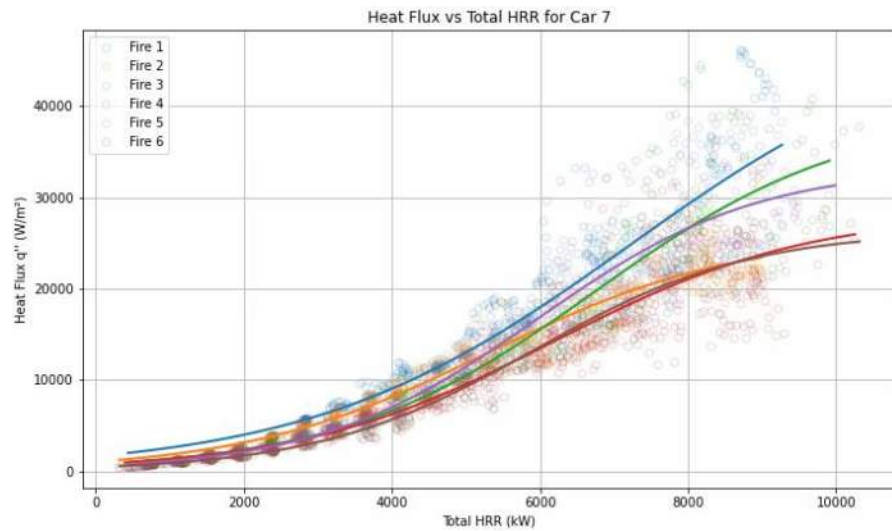
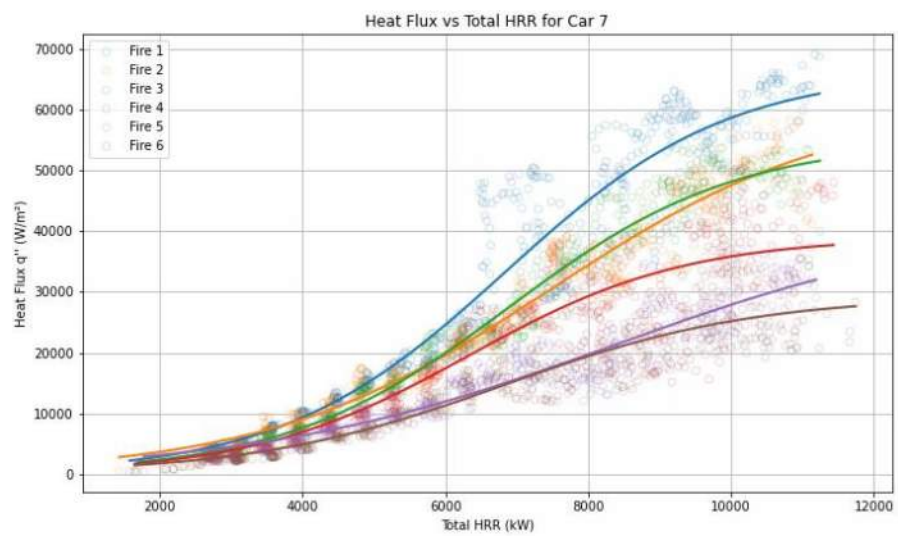


Fig. 45. q'' in function of Q plots for Car 6 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

Scenario 1



Scenario 2



Scenario 3

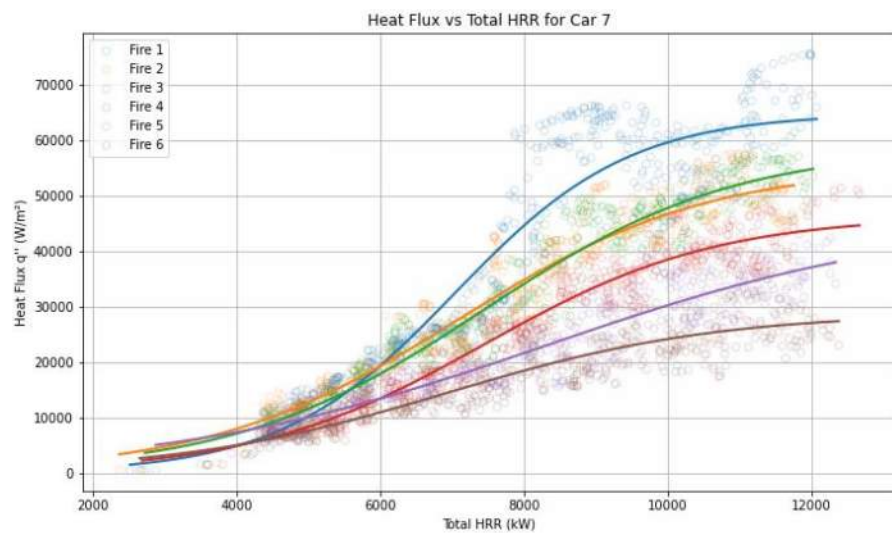
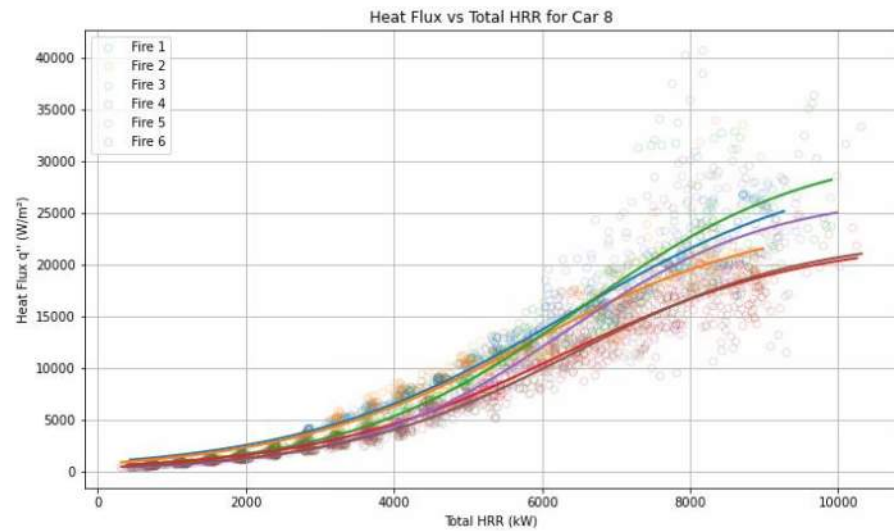
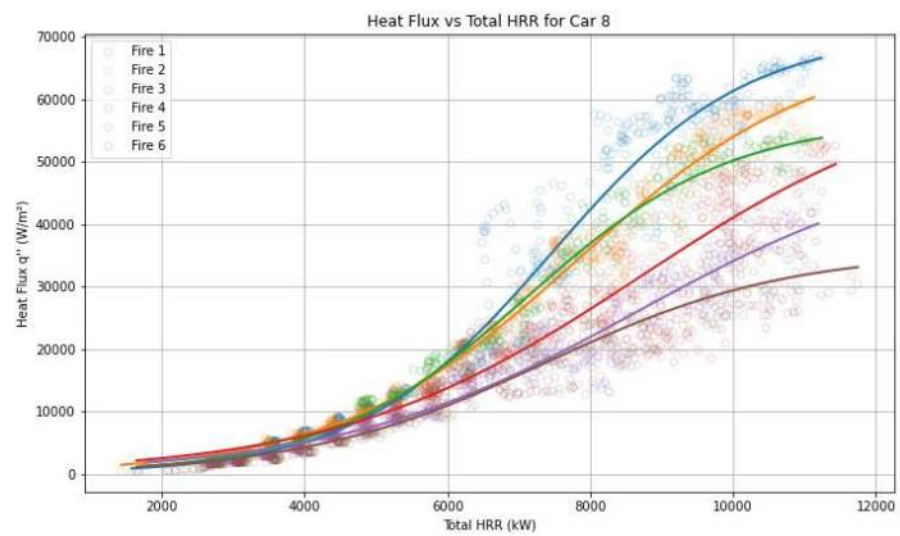


Fig. 46. q'' in function of Q plots for Car 7 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

Scenario 1



Scenario 2



Scenario 3

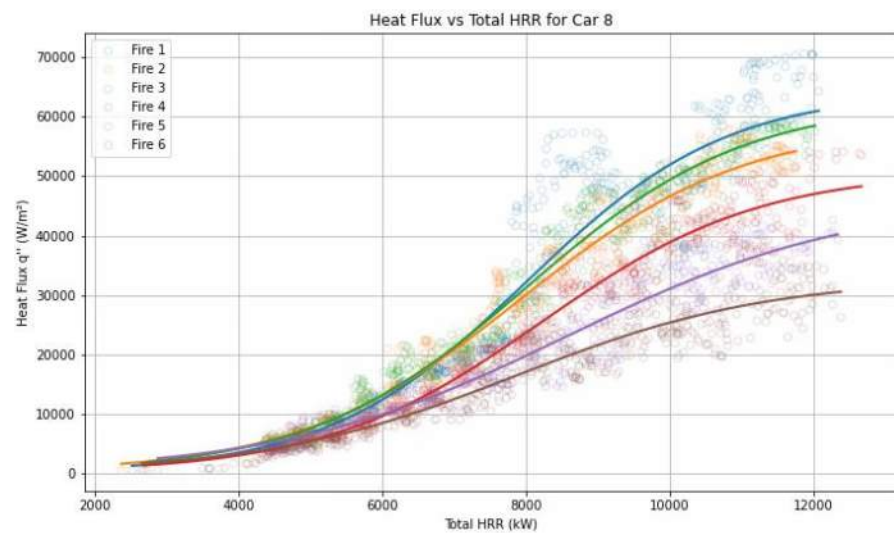
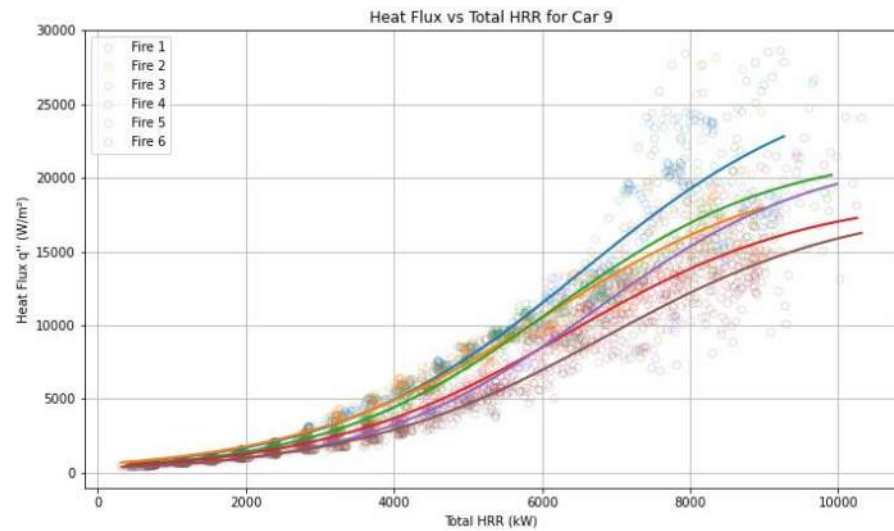
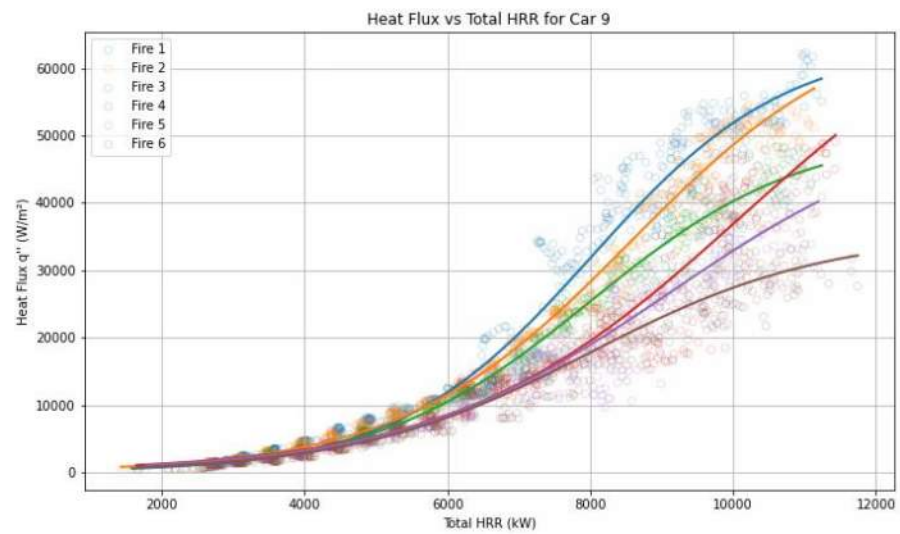


Fig. 47. q'' in function of Q plots for Car 8 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

Scenario 1



Scenario 2



Scenario 3

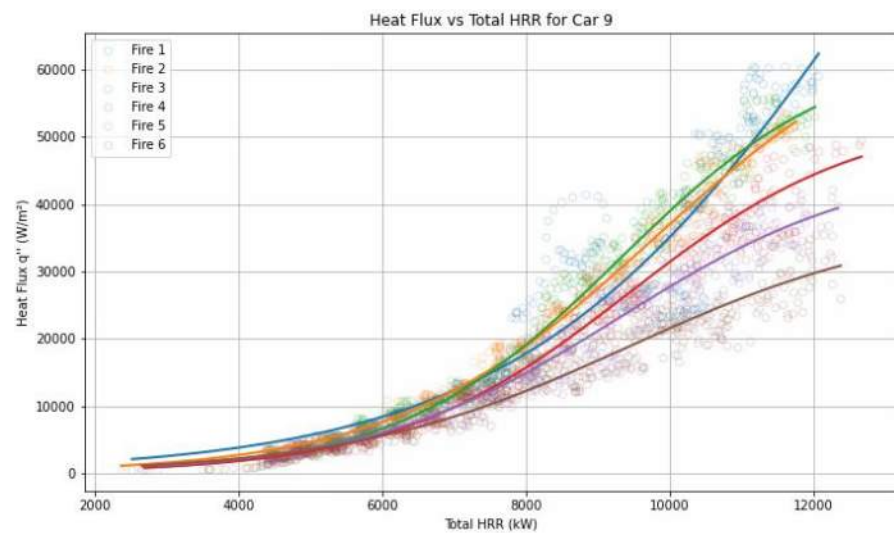
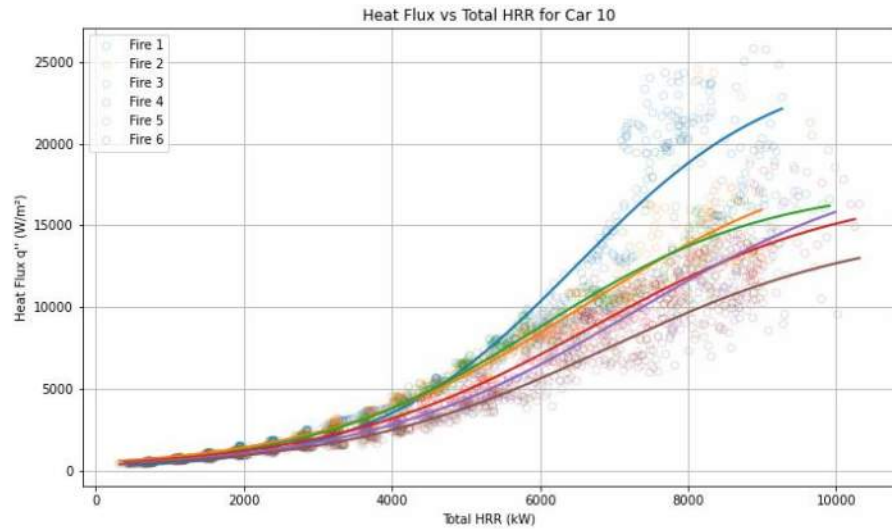
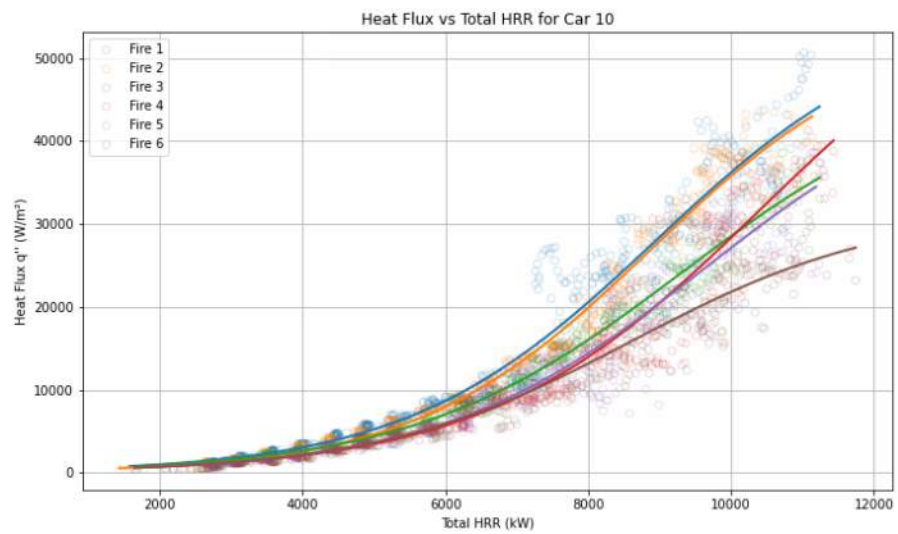


Fig. 48. q'' in function of Q plots for Car 9 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

Scenario 1



Scenario 2



Scenario 3

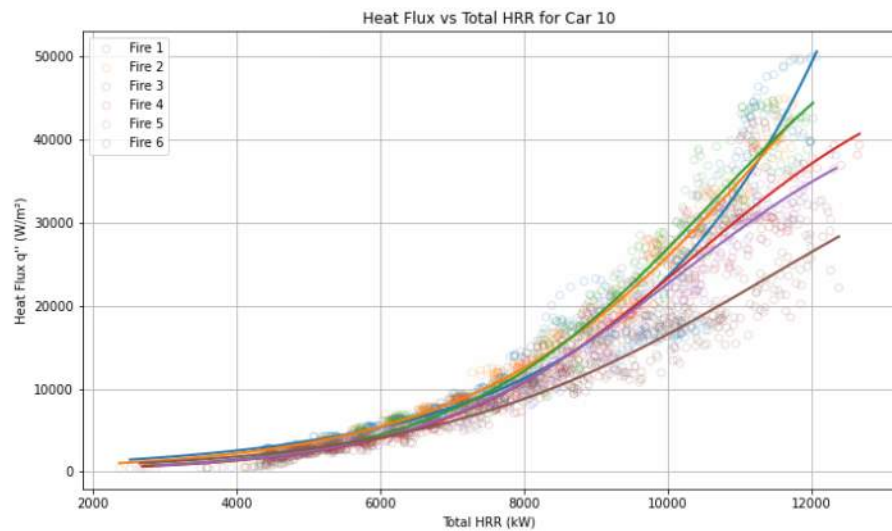
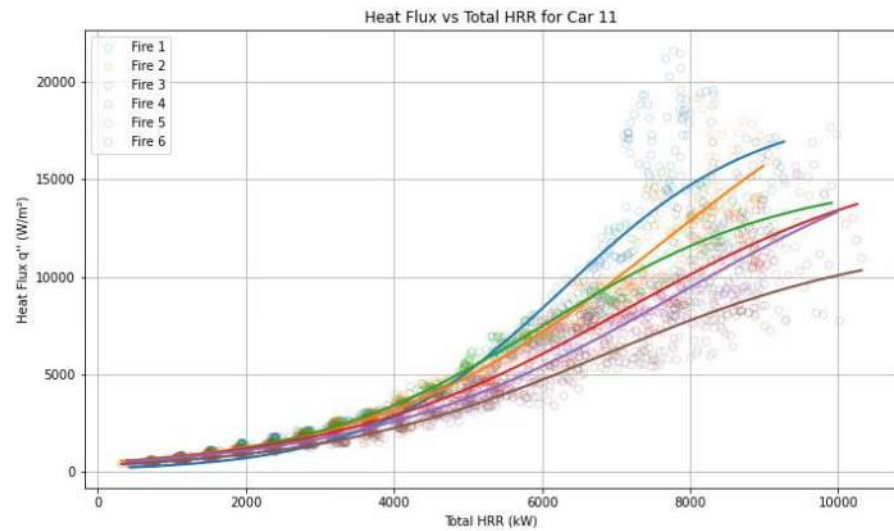
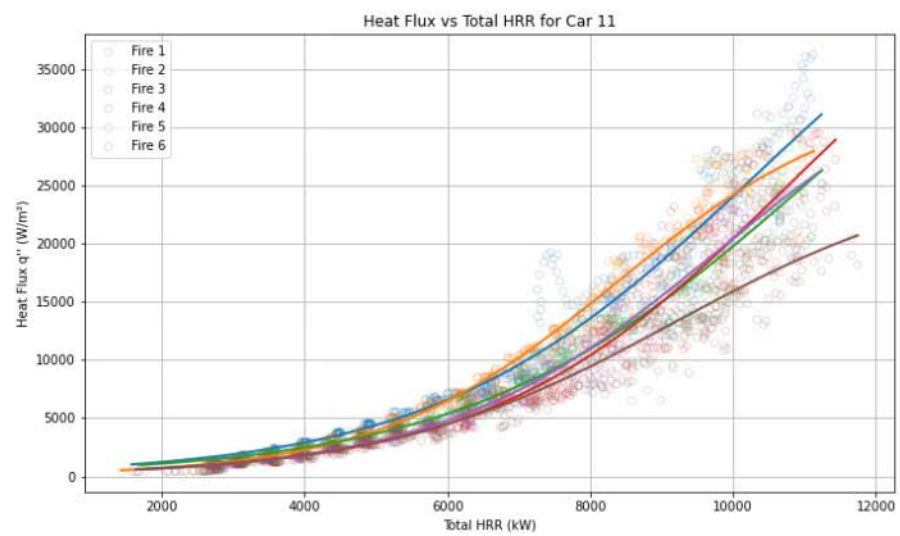


Fig. 49. q'' in function of Q plots for Car 10 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

Scenario 1



Scenario 2



Scenario 3

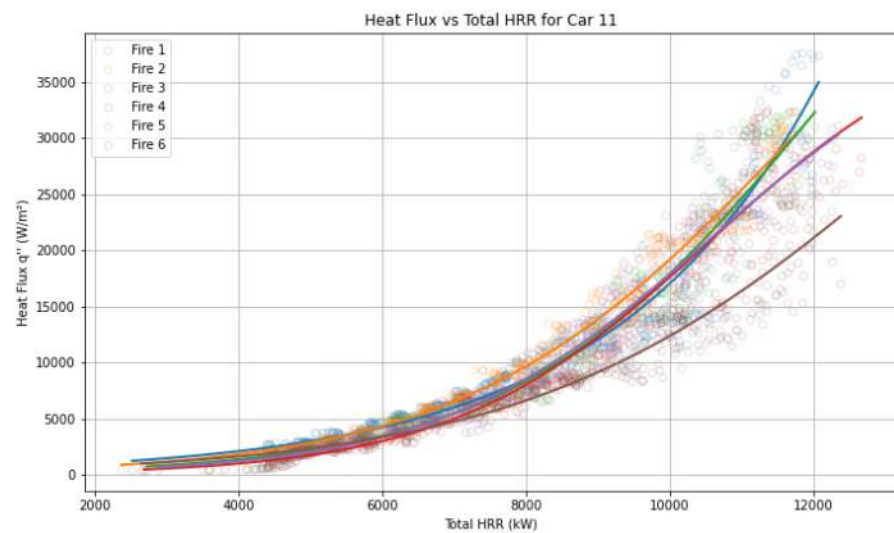


Fig. 50. q'' in function of Q plots for Car 11 for three analysed scenarios of fire development. Fire 1 – 6 refer to car parks of different heights (2.50 m to 3.50 m).

4.3 Investigation of potential implications of wind on the case-study

High loss car park fires are often associated with presence of strong winds. Additional round of simulations was performed, to investigate the potential impact of wind on the conditions inside the car park. For this purpose, the wind was introduced as a forced flow boundary condition at the northern wall of the car park, with the dynamic pressure representing 2 m/s, 4 m/s and 8 m/s flow. The southern wall was left as open boundary condition, which results in a complex flow field in the car park, with one dominant flow direction, Fig. 50. The simulations were only carried for Scenario 3 (as defined in pt. 4.1).

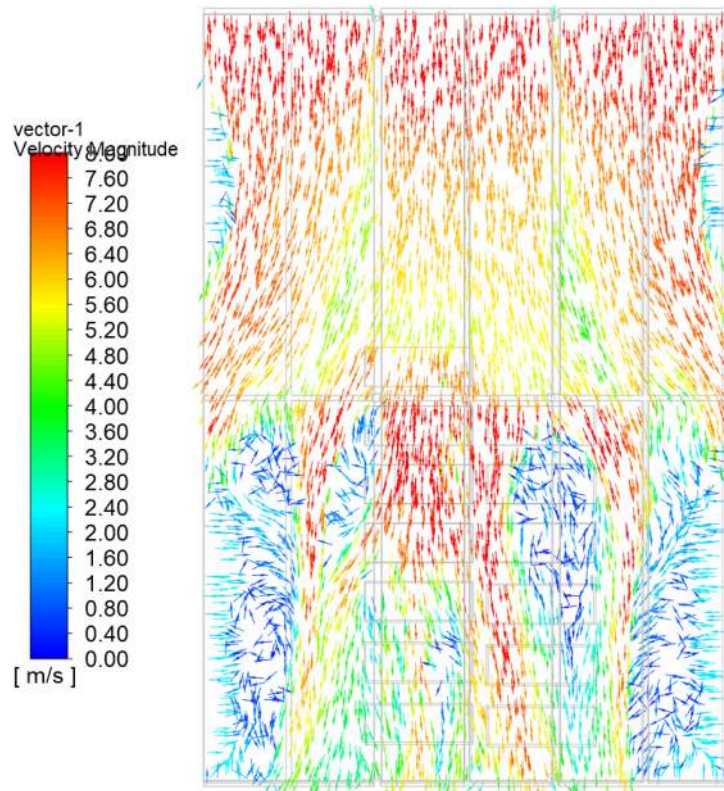


Fig. 51. Vectors of flow velocity in the car park for 2.70 m height and 8 m/s wind case, showcasing complex flow field created in the car park, slice at 1.70 m above the floor

Fig. 51 presents results of heat flux measurement at the ceiling level of the 2.5 m tall car park, for approx. 8MW fire source in the car park in four wind scenarios. The differences in shape of the heat flux contour are clearly visible. Even at low wind velocity of 2 m/s, the upstream spread of smoke to adjacent fire bay is reduced. With increase in wind velocity, the area of very high heat flux imposed on the ceiling is significantly reduced, indicating strong mixing of hot fire gasses with the incoming air. In some cases, the fire is present in adjacent bay (as in 2 m/s case), which may be related to the local flow field inside the car park, but we cannot confirm nor disprove if wind causes smoke to spread in any specific direction.

Fig. 52 presents the same comparison, but including car parks of different heights. Again, different results are observed with and without wind, and in general the outcomes at stronger wind are less severe than at slower wind. Some inconsistencies are observed for car park at different heights, that is the severity does not always decrease with the increase of the height. We attribute these differences to changes in the local flow field caused by the change in geometry.

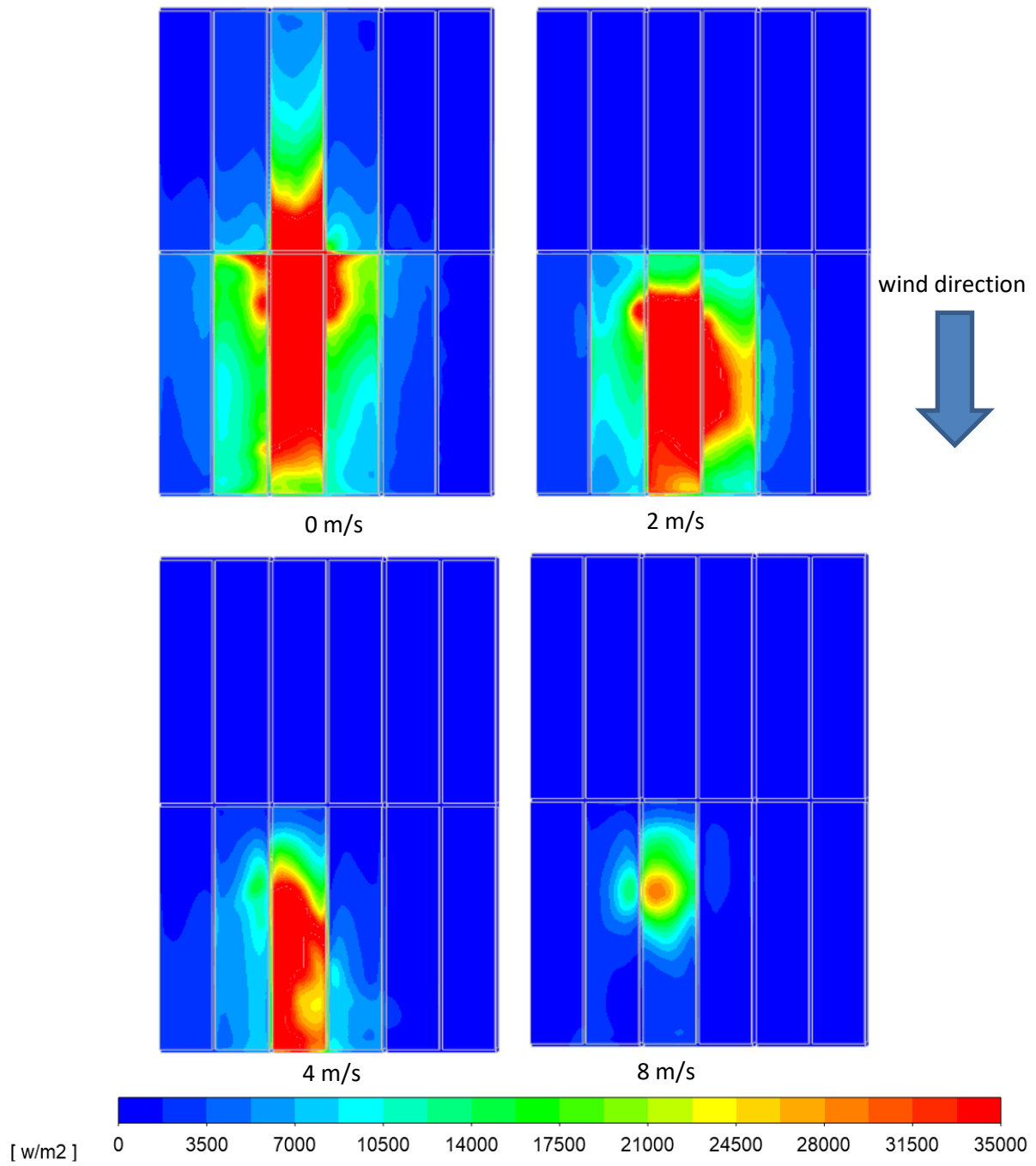


Fig. 52. Radiation contours on the car park ceiling of 2.50 m height, at 8 MW fire and different wind velocities

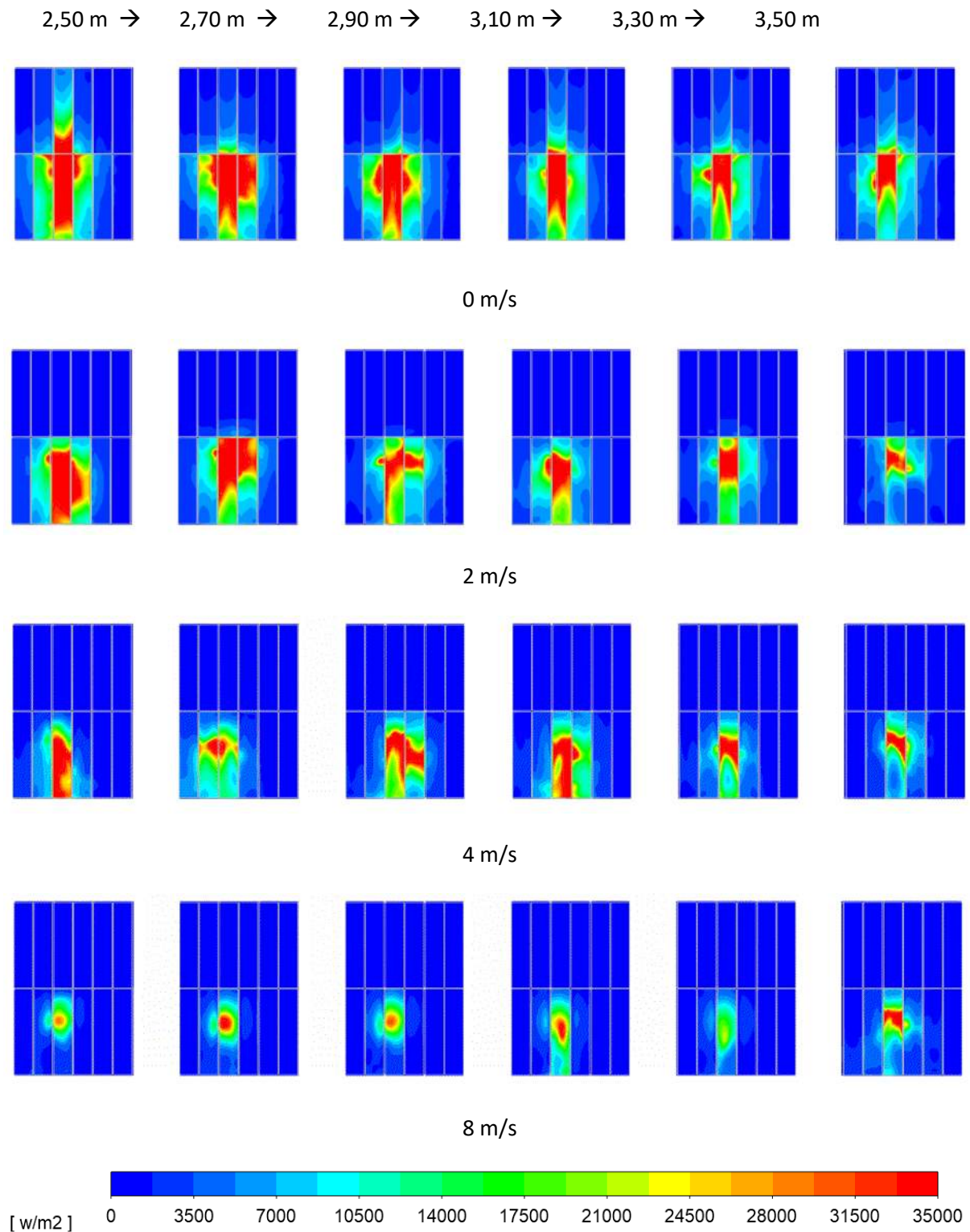


Fig. 53. Radiation contours on the car park ceiling of 2.50 – 3.50 m height, at 8 MW fire and different wind velocities

Fig. 53 presents the iso-contour of flame for wind and fire of approx. 12 MW. This comparison indicates the change of shape of the flame, and potential increase in risk of direct flame contact to neighbouring vehicles in fire. This is a potential fire spread pathway, that is unrelated to heat flux from the smoke in upper smoke layer (which was the main fire spread pathway in no-wind conditions). On the figure, the

colour scale indicates the Z-coordinate of the flame iso-contour. Blue colour indicates presence of the flame at the height of the 1.50 m, representing the flame presence in location where it can be in physical contact with the neighbouring vehicle. In higher wind velocities, the flame is considerably lower, indicating possibility of more rapid flame spread through direct flame contact, which means that in this case the heat flux from the smoke layer is not driving the fire spread.

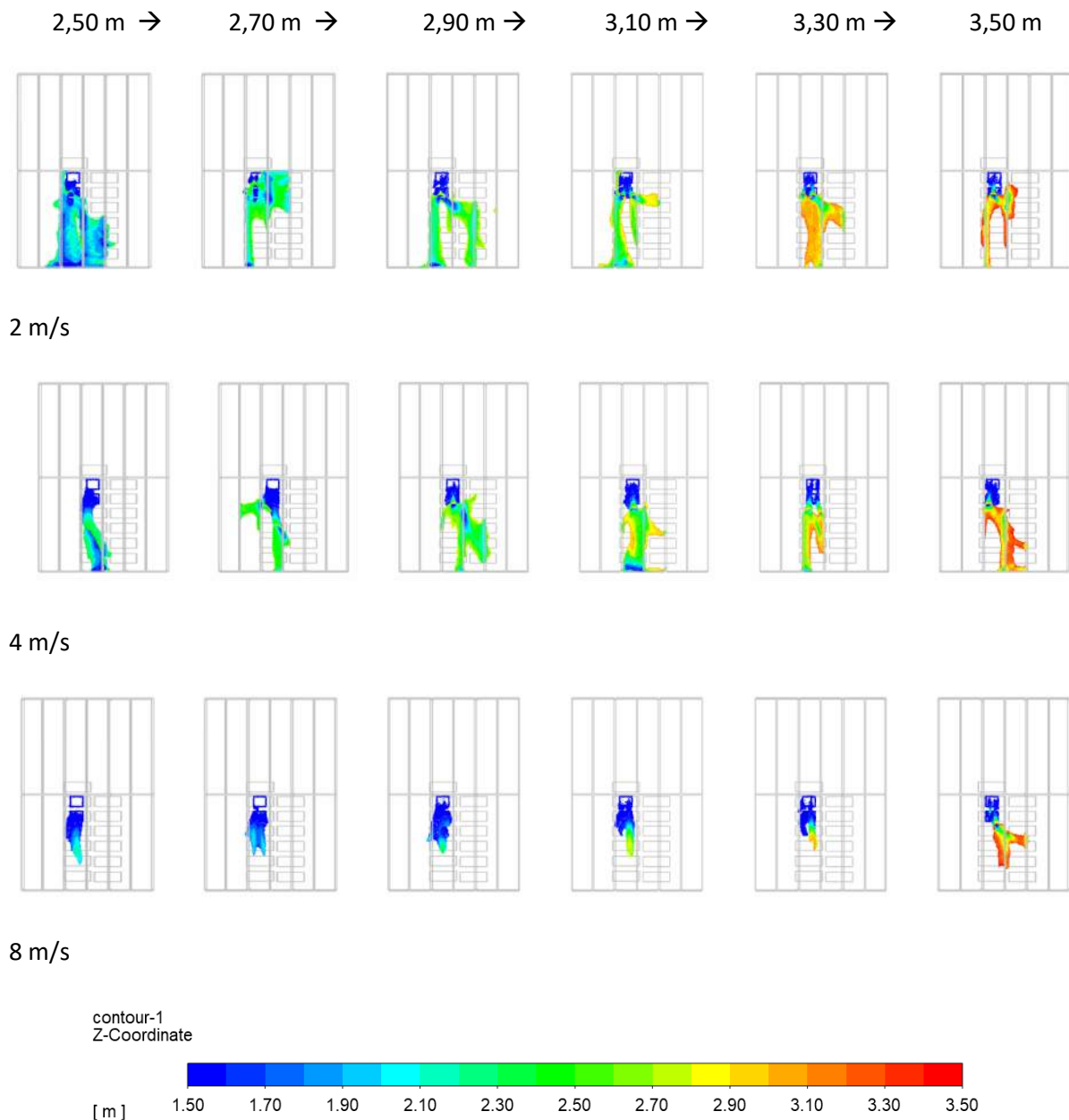


Fig. 54. Iso-contour of flame and the Z-coordinate of the iso contour, for fire of approx. 12 MW in different wind velocities

Fig. 54 – 64 present results of heat flux measurements for total HRR emitted at different target vehicles, for all considered cases and the car park height of 2.50 m. It can be observed, that any wind introduced into the study has caused a significant reduction of q'' at the Car 1 target (upstream), reducing the q'' below 10 kW/m^2 - this potentially means that the fire spread upstream is not possible. Similar was observed for Car 6. For Cars 2 – 5, the differences between 0 m/s, 2 m/s and 4 m/s are insignificant, while for the 8 m/s case and fire size below 10MW, we observe strong reduction in the

heat flux. It is worth noting that 2 m/s wind results in a higher heat flux than the no-wind reference case, indicating possible faster spread rate in wind conditions. For distant vehicles in second row (Cars 7 and 8) it is worth noting that we have not observed $q'' > 10 \text{ kW/m}^2$ at both 4 m/s and 8 m/s cases (up to 10MW of fire), while higher heat flux was observed at more distant cars 9 – 11. This may indicate that while for some vehicles in the fire proximity the consequences of the fire decrease, this is not universally true for all vehicles in the car park.

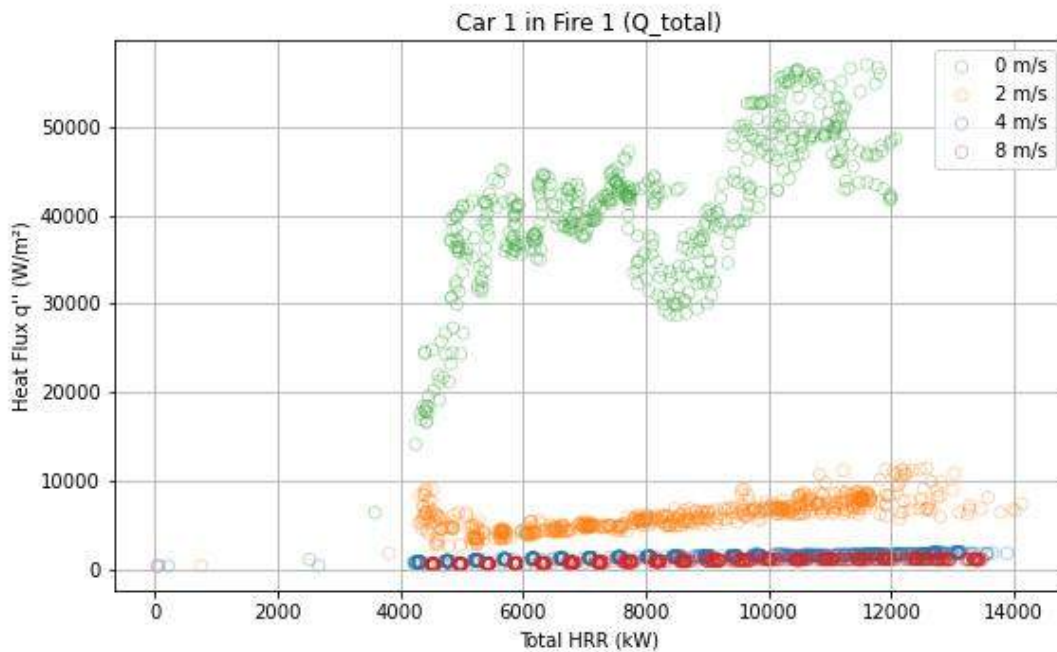


Fig. 55. Maximum incident heat flux measured at Car 1 in function of HRR for four different wind velocities, at car par height $h = 2.50 \text{ m}$

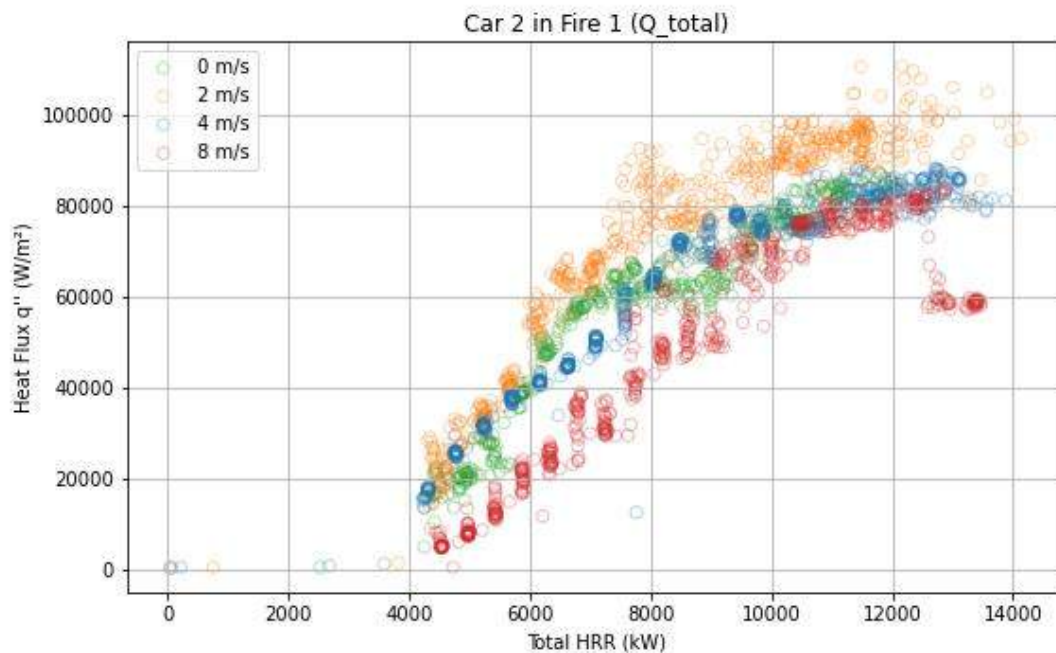


Fig. 56. Maximum incident heat flux measured at Car 2 in function of HRR for four different wind velocities, at car par height $h = 2.50 \text{ m}$

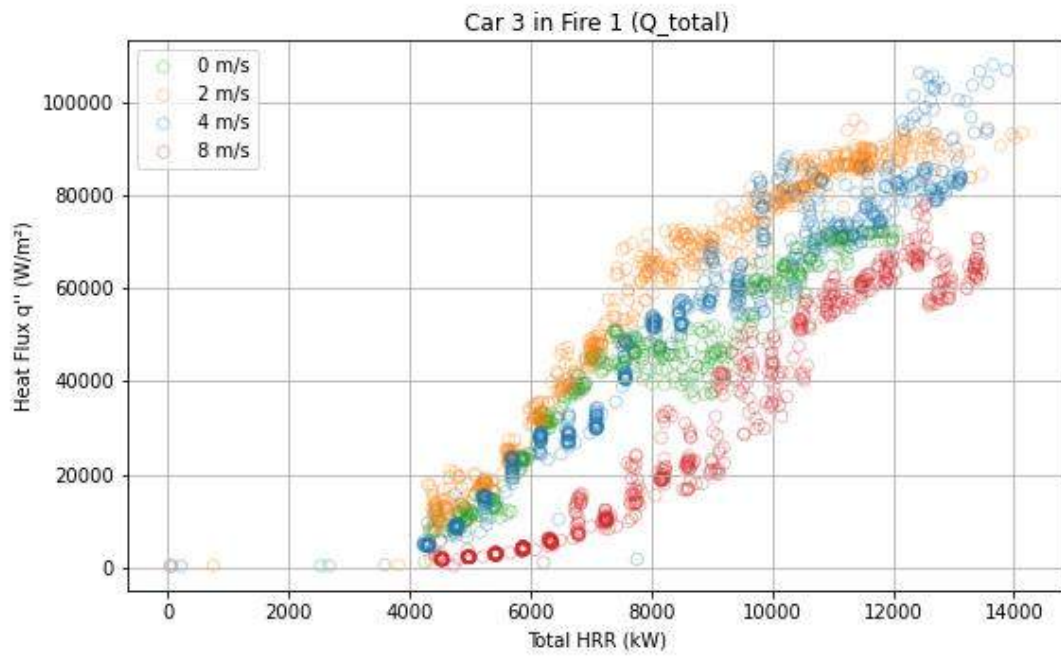


Fig. 57. Maximum incident heat flux measured at Car 3 in function of HRR for four different wind velocities, at car par height $h = 2.50$ m

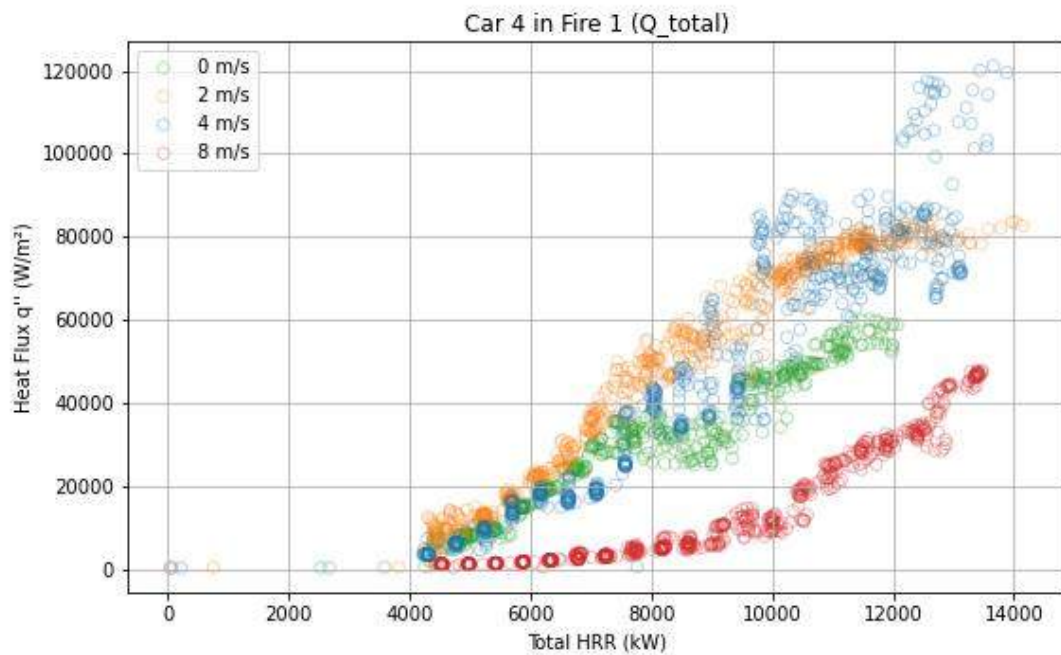


Fig. 58. Maximum incident heat flux measured at Car 4 in function of HRR for four different wind velocities, at car par height $h = 2.50$ m

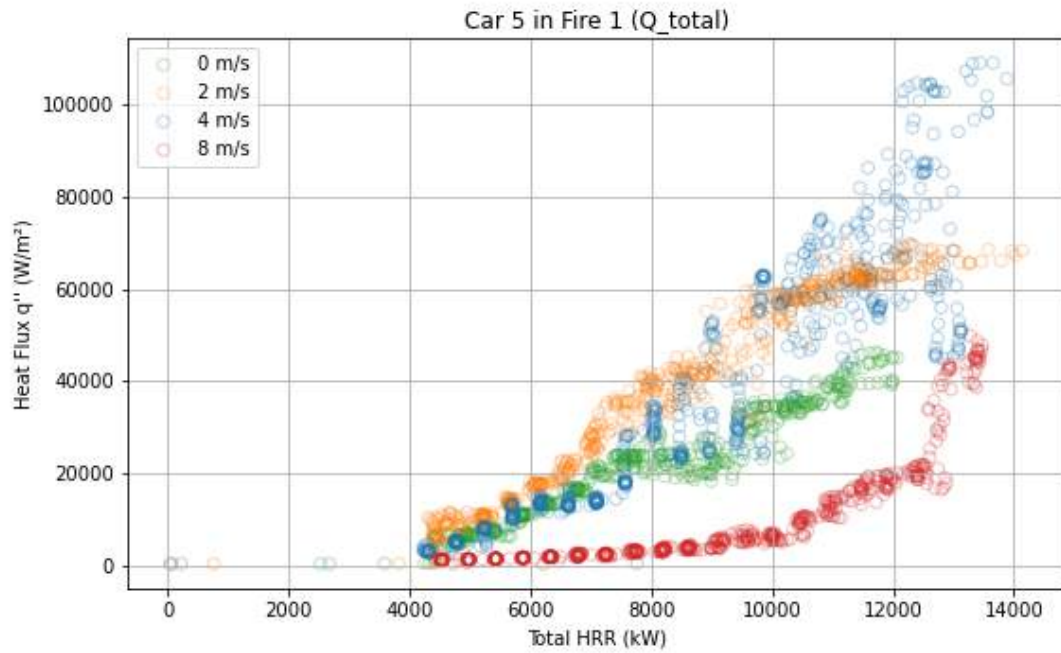


Fig. 59. Maximum incident heat flux measured at Car 5 in function of HRR for four different wind velocities, at car par height $h = 2.50$ m

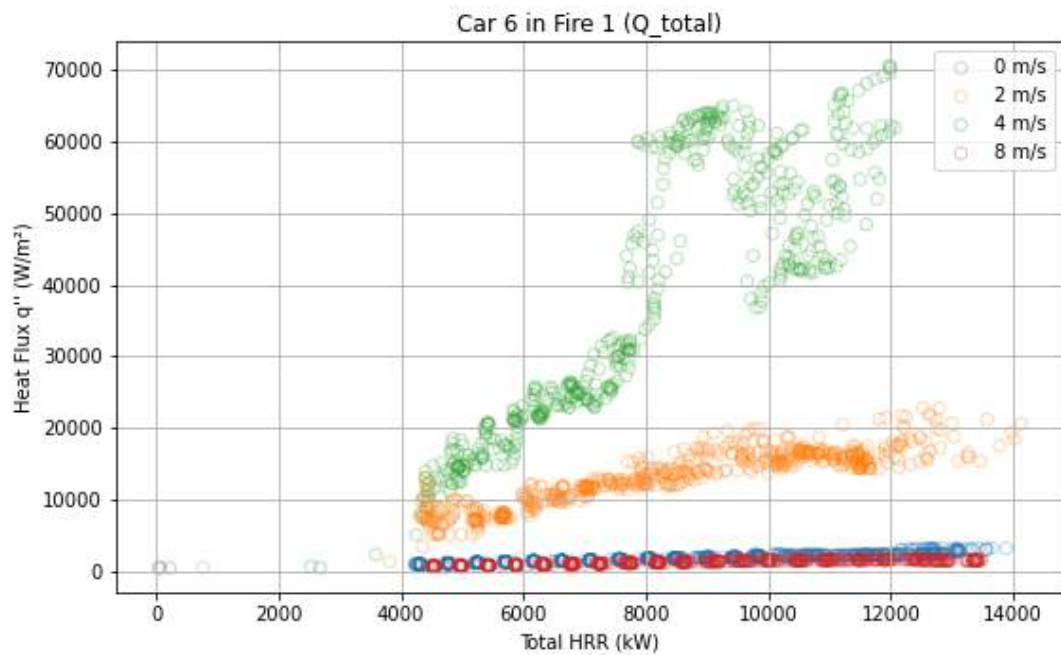


Fig. 60. Maximum incident heat flux measured at Car 6 in function of HRR for four different wind velocities, at car par height $h = 2.50$ m

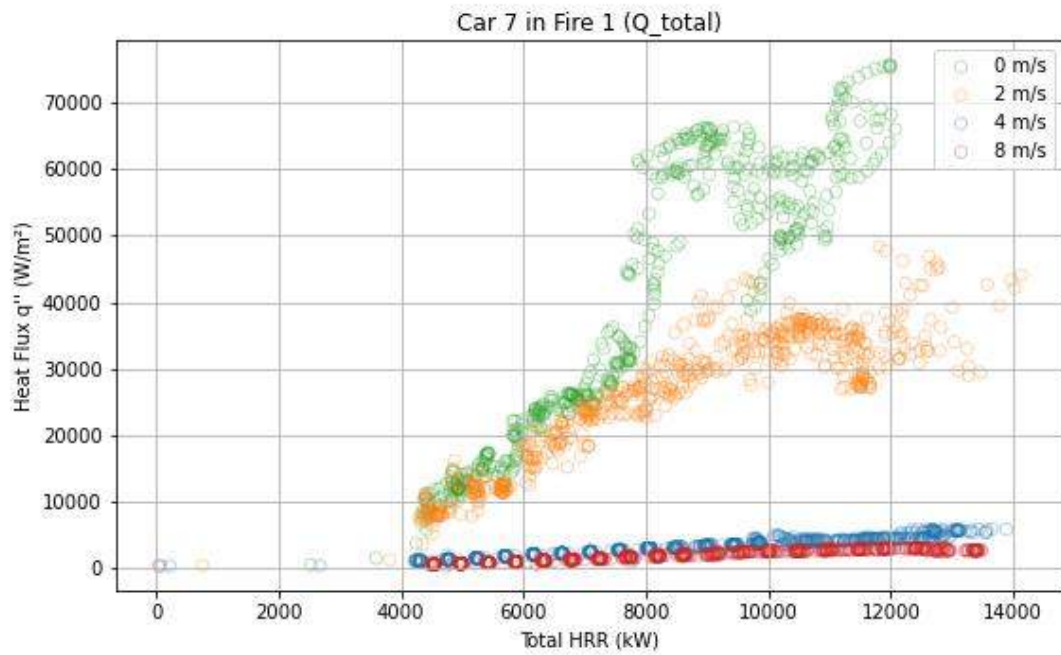


Fig. 61. Maximum incident heat flux measured at Car 7 in function of HRR for four different wind velocities, at car par height $h = 2.50$ m

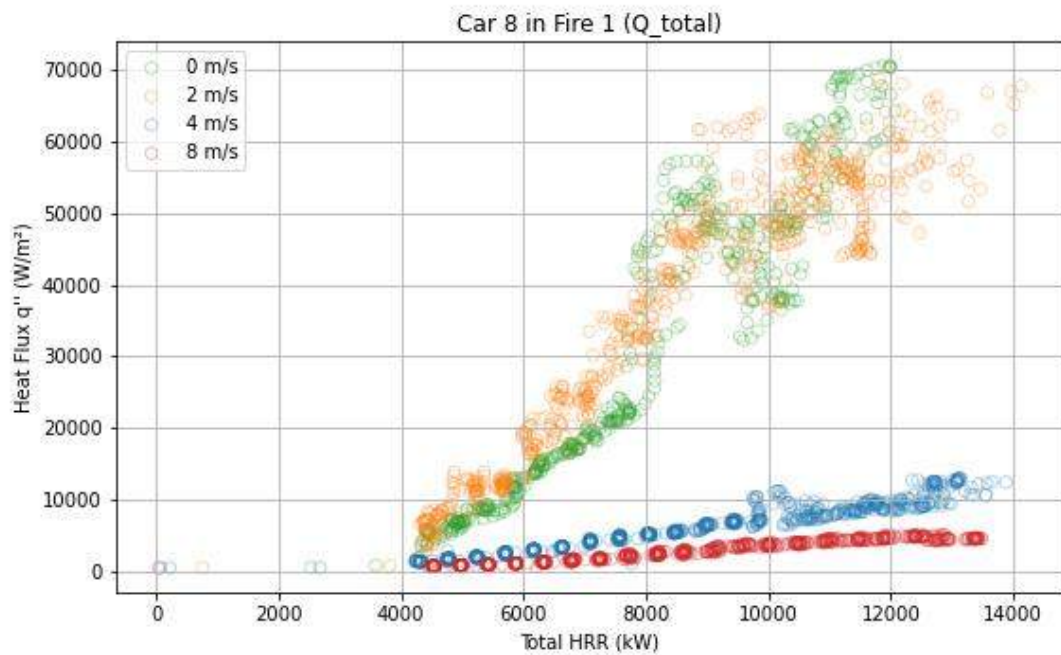


Fig. 62. Maximum incident heat flux measured at Car 8 in function of HRR for four different wind velocities, at car par height $h = 2.50$ m

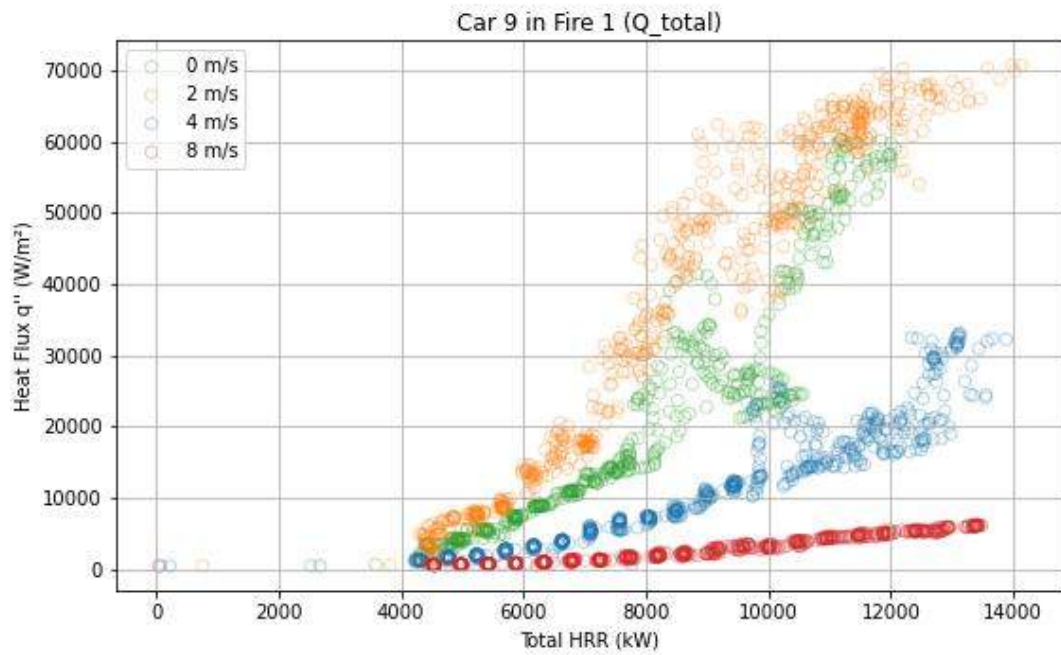


Fig. 63. Maximum incident heat flux measured at Car 9 in function of HRR for four different wind velocities, at car par height $h = 2.50$ m

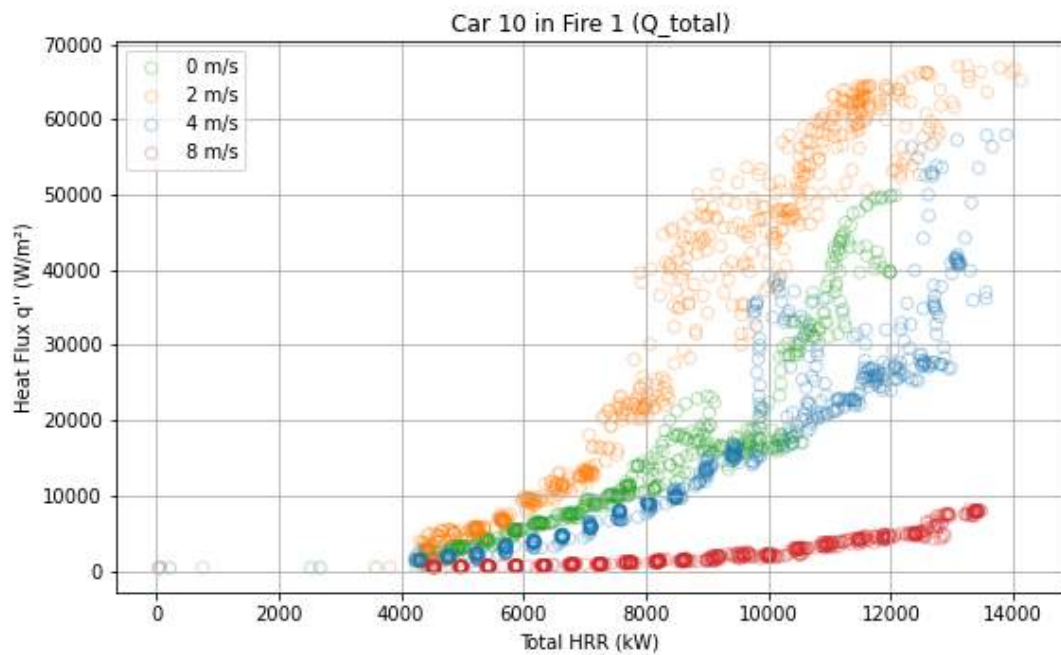


Fig. 64. Maximum incident heat flux measured at Car 10 in function of HRR for four different wind velocities, at car par height $h = 2.50$ m

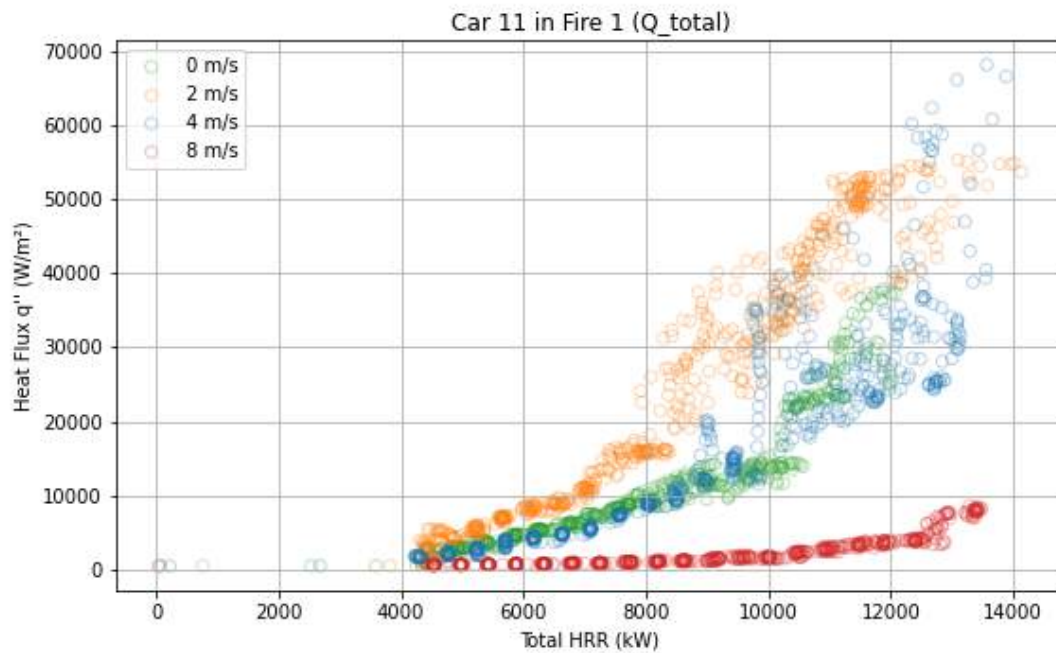


Fig. 65. Maximum incident heat flux measured at Car 11 in function of HRR for four different wind velocities, at car par height $h = 2.50$ m

5 Conclusions

The initial sensitivity study allowed the formulation of four working hypotheses. First three relate to the physics of fires within the car park, and the spatial complexity of the heat release rate within the car park:

Working Hypothesis 1 – as the height between the vehicle and the ceiling is known for a structural design, only a certain amount of heat can be released within the fire plume, and if the fire size exceeds that size, the additional fuel will burn in a flame extension in a ceiling jet below the ceiling.

Working Hypothesis 2 – in sufficiently high car parks the flame extensions are less likely to happen, therefore the likelihood of fire spread between vehicles is reduced.

Working Hypothesis 3 – if structural elements constrain the flame extension, the fire spread between vehicles parked within the structural bay is more likely than a fire spread to vehicles in adjacent bays.

The parametric study allowed us to observe the “bay effect”, that is, the influence of the structural frame formed by beams on the shape of flame extension under the ceiling. In car parks with beams, the constrained flame extension will lead to higher temperatures underneath the ceiling of the car park, resulting in higher heat flux emitted towards the floor of the car park. In a sufficiently large fire, the fire spread caused by the flame extension is likely the main driver of the fire spread in the car park.

In order to perform multiparametric studies on fire spread within the car parks, and the related fire severity evaluation, the final fourth working hypothesis is formed:

Working Hypothesis 4 – a structural bay can be considered a unit in which the fire severity is somewhat uniform.

Using this hypothesis, a zone-model will be developed to estimate fire growth within a structural bay and its spread to adjacent bays. This approach will allow us to study more scenarios in shorter time, to identify the conditions in which the fire is likely to spread beyond the initial vehicle, and to identify the range of likely fire severities in the car park, as a function of (a) initial fire size; (b) car park height; (c) vehicle distribution in the car park and (d) presence of structural bays. Further CFD analyses are planned to create a substantial body of initial data for the zone-model, and to provide verification to the findings of the zone-model.

We have also determined, that the increased with velocity reduces the heat flux on the car-park structure, but also promotes more direct flame contact to the neighbouring vehicles. Presence of wind significantly reduces the fire spread up-stream, but may increase the fire spread down-stream. This may be considerable when investigating fire spread through free parking spaces, increasing the probability of fire spread across multiple bays.

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- THE END –

30.06.2025

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Appendix C – WP 2



CPD/004/122/039 Real Fires

Open-sided car park fire resistance

WP 2 – Monte Carlo Fire Severity Assessment

Revision: R00
Date: 14 November 2025
Project Number: OX24065



Prepared for: BSR
Project Location: N/A

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Quality Management

Revision	Date	Comment	Author	Reviewer	Approver
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Table of Contents

1	Introduction	5
1.1	Appointment.....	5
1.2	Overview of the deliverable	5
2	A Probabilistic Framework for Structural Fire Performance in Open-Sided Car Parks.....	6
2.1	Framework for Analysis	6
2.2	The Probabilistic Time-Equivalence Method.....	6
2.3	Computational Implementation	7
2.3.1	Time-Equivalence Solver.....	7
2.4	Fire Severity Analysis	7
2.4.1	Defining the Fire Scenario	7
2.4.2	Fire Model.....	8
2.4.3	Geometric, Structural, and Material Parameters	9
2.4.4	Derivation of a car park fire load density and heat release rate per unit area (HRRPUA) ..	9
2.4.5	Stochastic variables summary.....	10
2.5	Interpretation of Analysis Outputs.....	10
3	Analysis Results	11
3.1	Effect of Car Park Utilisation on Fire Severity.....	11
3.2	Effect of Ceiling Height on Fire Severity.....	12
3.3	Effect of Wind Speed on Fire Severity	13
4	Discussion & Conclusion.....	14
4.1	Project Context and Summary of Work	14
4.2	Methodology, Assumptions and Limitations	14
4.3	Summary and Interpretation of Findings	14
4.4	Implications and Next Steps.....	15
5	References.....	16
	Appendix I – Travelling Fire Calculations	17
	Appendix II – Elaboration OF Monte Carlo Analysis Procedure in SFEPRAPY	18

1 INTRODUCTION

1.1 Appointment

OFR Consultants (OFR) was commissioned by the Department for Levelling Up, Housing and Communities (DLUHC) to deliver the “Real Fires” project (Contract No. CPD/004/122/039). The appointment, which commenced on 22 October 2021 and is scheduled to conclude on 28th September 2025, aims to provide fire incident insight and research in support of fire safety technical policy. The contract was subsequently novated to the Building Safety Regulator (BSR), which was part of the Health and Safety Executive (HSE) and now falls under the Ministry for Communities, Housing and Local Government (MHCLG).

A provision within this project allows for ad-hoc research into emerging fire safety matters. Under this provision, the BSR has commissioned OFR to undertake research into the appropriate structural fire resistance periods for purpose-built, open-sided car parks.

The BSR’s primary objectives for this research are to generate data and evidence on fire resistance in car parks, support its understanding of safety levels in new and existing buildings, and provide a robust analysis of options to inform future policy. To meet these objectives, OFR proposed focusing the research on above-ground, open-sided, multi-storey car parks.

The project has been structured into three distinct Work Packages (WPs):

- WP 1: Fire Dynamics Analysis. Investigating fire spread rates and extents in open-sided car parks to establish likely fire sizes and growth rates, based on a review of real incidents and advanced computational modelling.
- WP 2: Structural Reliability Analysis. Conducting a Monte Carlo fire severity analysis to determine the probability of failure for structural elements with different fire resistance and protection solutions.
- WP 3: Cost-Benefit Analysis. Performing a lifetime cost-optimisation analysis for different fire safety strategies to establish the optimal safety level, considering life safety, property protection, and business continuity.

This report constitutes the deliverable for WP 2 and has been revised after BSR comment.

1.2 Overview of the deliverable

This study presents a probabilistic fire severity analysis to determine the required structural fire performance in open-sided car parks. It builds directly upon the findings of Work Package 1 (WP 1), which quantified the fire characteristics (e.g., fire spread rates and ultimate fire sizes / number of parking spaces involved) specific to these structures.

The core of this report is a probabilistic time-equivalence analysis. The methodology is analogous in principle to the approach used for deriving fire resistance periods in contemporary guidance, such as BS 9999:2017, but has been specifically adapted for this research, using a tool developed by OFR [1], [2], [3]. By integrating the statistical distributions of fire characteristics from WP 1B and others from contemporary guidance and literature into a structural analysis framework, this study quantifies the reliability of structural elements under realistic fire exposure.

The analysis outputs the probability of fire induced structural failure for a range of specified fire resistance periods (e.g., 15, 30, and 60 minutes). These results provide a direct measure of the structural reliability achieved by different passive fire protection strategies when subjected to the unique fire dynamics of open-sided car parks.

The findings of this report quantify the structural reliability associated with various fire resistance periods, providing the essential technical foundation for the subsequent cost-benefit and policy analysis in Work Package 3 (WP 3B).

2 A PROBABILISTIC FRAMEWORK FOR STRUCTURAL FIRE PERFORMANCE IN OPEN-SIDED CAR PARKS

2.1 Framework for Analysis

A purely deterministic assessment of structural fire performance in open-sided car parks is inadequate. The potential fire scenarios are subject to significant variability and uncertainty, with factors such as the number and type of vehicles, enclosure geometry, fire spread pathways, rate of fire spread and the influence of external wind conditions all behaving as stochastic variables. A deterministic approach, which typically relies on a single, conservative "design fire," cannot rationally account for the full spectrum of these variables and may lead to designs that are either unconservative or unnecessarily costly.

A probabilistic approach is therefore necessary to rationally account for these variables and quantifies the associated risk. The use of probabilistic risk assessment for complex fire engineering problems is a well-established methodology, endorsed within the framework of the BS 7974 series [4], the UK's code of practice for the application of fire safety engineering principles. This series provides a structured framework for performance-based design, moving beyond prescriptive rules to allow for engineering solutions tailored to the specific risks of a building. Furthermore, this risk-based methodology directly supports the fundamental safety design principle of ensuring risks are As Low As Reasonably Practicable (ALARP). A deterministic approach can struggle to satisfy this principle; its reliance on a single, highly conservative scenario can mandate safety measures that are disproportionately costly for the level of risk reduction they achieve. In contrast, by quantifying the likelihood and consequences of a full spectrum of fire events, a probabilistic assessment enables designers to make informed, justifiable decisions on safety measures, ensuring that resources are allocated effectively to achieve a design that is both safe and economically efficient.

The methodology adopted for this study is rooted in established principles that form the technical basis for fire resistance periods in contemporary national guidance. Seminal research by Kirby et al [5] employed a similar probabilistic methodology to inform the prescriptive fire resistance periods in BS 9999:2017 [6], the code of practice for fire safety in the design, management, and use of buildings. By aligning with these established principles, the framework for this investigation is considered both robust and appropriate for developing evidence to inform national policy. This lineage provides confidence that the methods used are not novel in principle but rather are a specific and advanced application of a well-understood and accepted engineering approach. The tool developed by OFR for this specific application, i.e., SFEPRAPY, has been used to study fire resistance periods in an English context [2], [3] and overseas by other researchers [7].

2.2 The Probabilistic Time-Equivalence Method

The primary metric used to quantify fire severity in this study is time equivalence. This concept is used to relate the severity of a realistic, time-varying fire (also named as "design fire" or "natural fire") to an

equivalent duration of exposure to the standard fire curve, as defined in BS EN 1363-1 [8] and ISO 834 [9]. While codes such as BS EN 1991-1-2 [10], [11] apply this method deterministically to a single, conservative design scenario, this study extends the concept into a fully probabilistic framework.

Several methods exist for calculating time equivalence, including the "equal area" method and concepts based on load capacity or deflection. This study employs the "maximum temperature method," which defines the time equivalence as the duration of standard fire exposure required to produce the same peak temperature in a protected structural steel element as that caused by the design fire. This approach was chosen for its robustness in comparative analysis and its direct relevance to the failure criteria of protected steel elements, which lose a significant proportion of their load-bearing capacity at elevated temperatures. For this analysis, a critical steel temperature of 500°C is adopted as the failure threshold.

The probabilistic analysis is executed via a Monte Carlo Simulation (MCS). This technique allows variables with inherent randomness, such as fuel load, heat release rate, and fire spread speed—to be represented by statistical distributions rather than single fixed values. The simulation proceeds through three key stages for each iteration:

1. **Input Sampling:** Key input variables are randomly sampled from their respective statistical distributions using the efficient Latin Hypercube sampling method.
2. **Fire Severity Calculation:** For each set of sampled inputs, a design fire is generated, and its severity is translated into a time-equivalent value using a custom solver.
3. **Probabilistic Output:** This process is repeated thousands of times to generate a cumulative distribution of time-equivalence results, which describes the probability of experiencing a given fire severity.

To ensure the results are statistically stable, the number of simulations must be sufficient. As defined in PD 7974-7:2019 [4], the coefficient of variation, V , can be used to assess precision:

$$V = \sqrt{\frac{1-P}{P \cdot N}} \leq V_{lim}$$

where P is the probability of reaching a threshold, N is the number of simulations, and V_{lim} is the target precision (typically <0.05). As the target probability is not known a priori, a conservative 100,000 simulations were performed for each case. This ensures a coefficient of variation below 0.05 for probabilities of failure down to approximately 0.8% (i.e., a reliability of 99.2%), providing high confidence in the stability of the results across the full probability spectrum.

2.3 Computational Implementation

The complex and iterative calculations required for this probabilistic analysis were performed using SFEPRAPY (Structural Fire Engineering Probabilistic Reliability Assessment in Python) [1]. SFEPRAPY is an open-source Python library developed by OFR Consultants specifically to automate and streamline the process of probabilistic reliability assessment in structural fire engineering.

The use of an open-source tool for a study intended to inform public policy is a deliberate choice. It provides complete transparency in the methodology, allowing for independent scrutiny and verification of the calculation procedures and results, which is essential for building confidence in the evidence base for policy decisions. The tool's source code is publicly available on GitHub.

The SFEPRAPY tool automates most parts of the workflow described in the preceding section. For each of the 100,000 iterations in a given scenario, the tool performs the following steps:

1. Samples a unique set of input variables from the defined statistical distributions.
2. Generates a time-temperature curve for the design fire based on the sampled inputs.
3. Executes a custom time-equivalence solver, which iteratively adjusts the thickness of a specified insulation material on a steel beam until the peak steel temperature under the design fire is within ± 0.5 °C of the 500 °C critical threshold.
4. Applies this final protection thickness to the same steel element and exposes it to the standard fire curve, recording the time taken to reach 500 °C as the calculated time equivalence.
5. Aggregates the results from all iterations to produce a Cumulative Distribution Function (CDF) of time equivalence for the scenario under investigation.

Appendix II provides further details regarding the process implemented in SFEPRAPY. This automated process allows for a comprehensive and statistically robust exploration of the full range of potential fire severities, forming the core of the analysis presented in this report.

2.3.1 Time-Equivalence Solver

For each sampled fire scenario, a custom solver determines the time equivalence. The solver algorithm proceeds as follows:

- A design fire time-temperature curve is generated from the sampled inputs.
- The solver iteratively adjusts the protection thickness until the peak steel temperature under the design fire is within ± 0.5 °C of the 500°C critical temperature.
- This final protection thickness is applied to the element.
- The element is exposed to the standard fire curve, and the time to reach 500°C is determined. This time is the calculated time equivalence.

2.4 Fire Severity Analysis

For each Monte Carlo (MC) simulation, a fire severity analysis is conducted using the principle of time equivalence. This method quantifies the severity of a design fire by calculating the equivalent exposure duration to the standard fire curve (as defined in BS EN 1363-1). This section outlines the key parameters, stochastic variables, and fixed properties used in the analysis and details the design fire model selected for this study.

2.4.1 Defining the Fire Scenario

The fire dynamics in open-sided car parks differ significantly from those in enclosed compartments, which precludes the use of standard compartment fire models. The thermal exposure for this study is therefore based on the outputs of detailed modelling undertaken in Work Package 1B (WP 1B). This work package used a combination of Computational Fluid Dynamics (CFD) and a bespoke Cellular Automata Monte Carlo Simulation (CA-MCS) to generate a comprehensive dataset characterising car park fires. Generally, in purpose-built open-sided car parks, fires can typically be considered to behave like travelling fires.

From this dataset, two key stochastic parameters, detailed in the WP 1B report, define the fire scenario:

- A probabilistic distribution defining the total number of parking bays involved in the fire (on the assumption of a maximum of 60 linear spaces).
- The fire spread speed, which is the speed at which fire propagates between vehicles.

These parameters are used to define a simplified rectangular fire enclosure for the fire severity analysis. Shown in Figure 2, the fire scenario assumes the involvement of a standard parking bay dimension of 2.4 m x 4.8 m and a single row layout. Based on this, the dimensions of the fire enclosure are set as follows:

- The enclosure width is a fixed value equivalent to the length of a single parking bay (4.8 m).
- The enclosure length is a variable calculated from the number of bays involved in the fire. It is determined by multiplying the total number of ignited bays by the width of a single bay (2.4 m).
- The maximum fire enclosure length is set to 60 bays, i.e., 144 m long. This represents a car park of the scale of that observed at London Luton Airport and is considered broadly representative of a large purpose-built open-sided car park.

2.4.2 Fire Model

Selecting an appropriate fire model is critical, as it directly influences the design fire curve used to determine the time equivalence. The chosen model must be well-established and computationally efficient enough to make the large number of simulations in this study feasible.

While models like the BS EN 1991-1-2 parametric fire curve are common, they are designed for post-flashover fires in enclosed compartments (e.g., offices) and are not suitable for the well-ventilated conditions of an open-sided car park.

Therefore, the Travelling Fire Method (TFM) is adopted for this study. In large or open-plan enclosures, a fire is more likely to travel, meaning the temperature across the space is not uniform at any given time. The TFM, originally proposed by Stern-Gottfried & Rein [12], adopted by Hopkin [13] and Rackauskaite [14] and recognised in PD 7974-1 [15], is designed to capture this behaviour.

A key characteristic of a travelling fire is that the time-dependent temperature profile varies significantly depending on the measurement location, as shown in Figure 1. For this study, the analysis is conducted using the temperature profile measured at a point randomly sampled between 60% and 90% of the enclosure length. This region was determined to produce the most severe thermal exposure and therefore the most conservative time-equivalence results. For completeness, Appendix I documents the correlations informing the travelling fire model.

In practice, car parks would comprise multiple rows of parked vehicles that may be separated by circulation routes. The fire severity does not capture this, as indicated in Figure 2. However, it is expected, owing to the bay effects presented in WP 1B, that the thermal exposure to any given structural element will largely be dominated by the burning vehicles in proximity, represented by a single row of cars in this instance. This is consistent with the fire modelling approach adopted by Tohir [16].

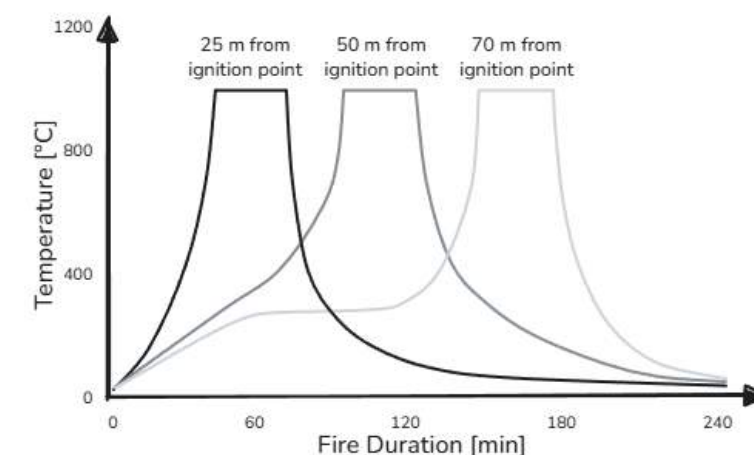


Figure 1. A typical representation of travelling fire behaviour, showing how the temperature-time curve changes at different distances from the ignition point.

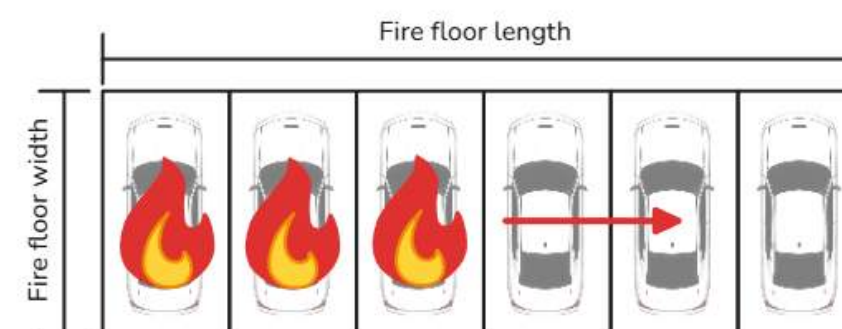


Figure 2. Diagram illustrating the method for calculating the fire enclosure length based on the number of ignited parking bays in a single row configuration.

2.4.3 Geometric, Structural, and Material Parameters

The fixed parameters used in the analysis are summarised below:

- **Fire floor width:** 4.8 m. This is based on the simplified fire scenario in a car park that a single row of car parking bays with a width of 4.8 m. Also see Figure 2.
- **Ceiling height:** Variable. Several compartment heights are assessed as part of this study. See Section 3.
- **Structural element properties:** a typical steel beam is used for the purpose of this analysis with a section area of 0.017 m², exposed perimeter of 2.14 m; and a density of 7850 kg/m³.
- **Structure protection properties:** The structural element temperature is assessed by using the correlations established in BS EN 1993-1-2, the protected steel temperature. For this study, typical thermal properties of plaster board are used. Thermal conductivity of 0.2 W/(m K), density of 800 kg/m³, and specific heat of 1700 J/K/kg. given the nature of the problem is similar to a comparative study. The protection thermal properties are not expected to be something sensitive to the time equivalence results.

2.4.4 Derivation of a car park fire load density and heat release rate per unit area (HRRPUA)

Spearpoint, et al. [17], report on a study that derived fire load densities for car parks using Monte Carlo Simulations (MCS). Therein, they give distributions for the total energy released for five curb weight classifications. These are shown in Table 1.

WP 1A noted the proportions of vehicles on the road by vehicle body size to be: 33% small, 36% medium and 31% large. By grouping the mini, light and compact of Table 1 into the definition of “small” adopted in WP 1A, an aggregated fire load distribution representative of UK vehicle stock can be determined through Monte Carlo sampling. Using 10,000 iterations as a basis, this involves sampling from each vehicle classification in the following proportions: Mini – 1,100, Light – 1,100, Compact – 1,100, Medium – 3,600 and Heavy – 3,100 samples, respectively. The resulting aggregate distribution is as shown in Figure 3. This is expressed as a fire load density by dividing the sampled total energy released by the area of a parking space, i.e. 2.4 x 4.8 m. The outcome is a distribution of fire load density for an occupied UK parking space.

The resulting distribution best fits to that of a Weibull distribution, with applicable parameters shown in Table 2.

The distribution of fire load density can be used to inform a corresponding distribution of heat release rate per unit area (HRRPUA). Deterministic values are given in the literature [3], [17], [18] and national published documents [10], [15]. However, these do not specifically cover car parks or burning vehicles. An estimate is therefore made using the burnout times of cars given in Miechówka and Węgrzyński [19]. Therein, it is shown that the burnout time of cars typically ranges from 30 to 60 min. Again, through the Monte Carlo sampling of Figure 3, alongside a linear distribution of burnout time of between 30 to 60 min, a resulting estimate of HRRPUA is shown in Figure 4. This can be represented as a normal distribution, with applicable parameters shown in Table 2.

Table 1. Mean and standard deviation fire severity characteristics by curb weight classification

Vehicle classification	Curb weight [kg]	Total energy released (MJ)		Weibull distribution parameters	
		Mean	Standard dev,	α	β
Mini	680 – 906	2909	945	4.02	3222
Light	907 – 1134	4471	1677	2.93	5009
Compact	1135 – 1360	5288	692	7.49	5591
Medium	1361 – 1587	6386	695	14.53	6648
Heavy	> 1588	7648	n/a	16.27	7830

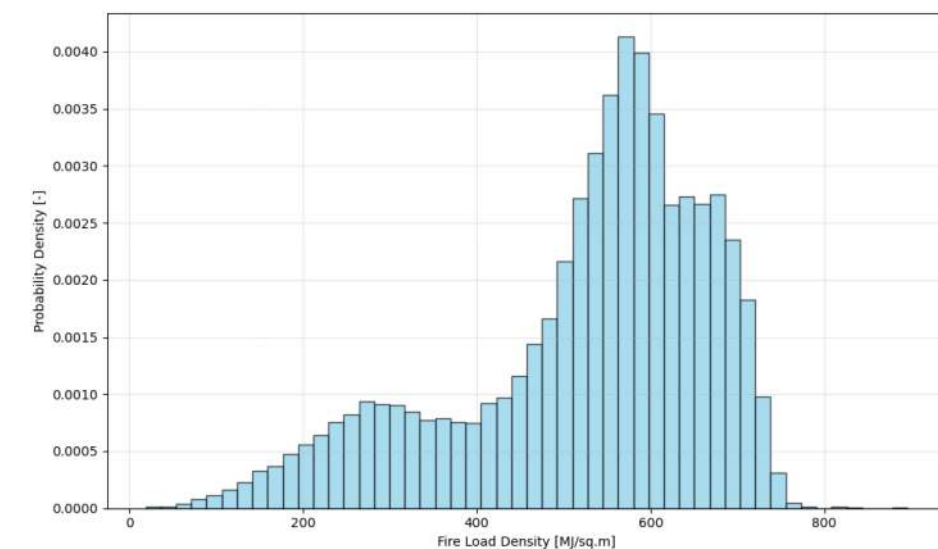


Figure 3. Aggregate fire load density distribution for an occupied UK parking space

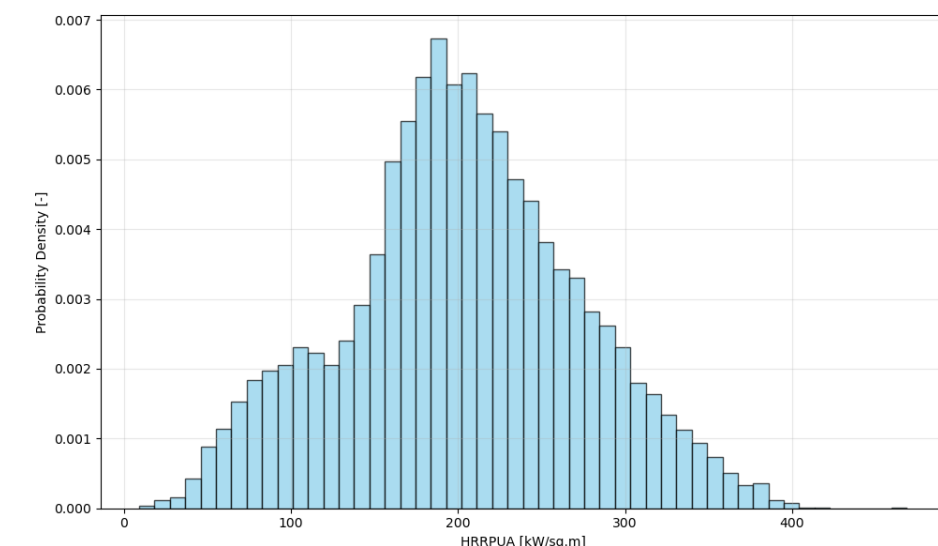
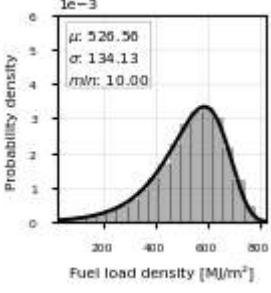
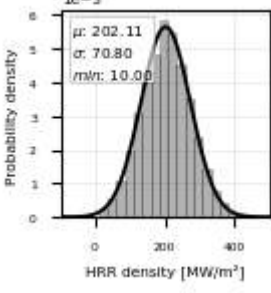
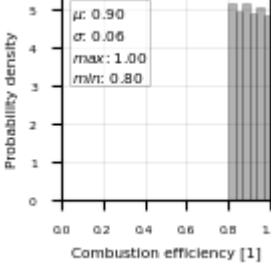
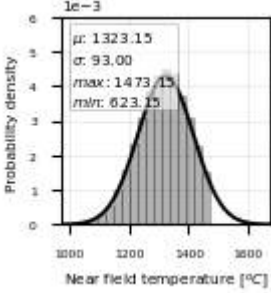


Figure 4. HRRPUA distribution for a UK parking space

2.4.5 Stochastic variables summary

The key variables governing fire severity are treated as stochastic inputs, defined by statistical distributions. The primary stochastic inputs for the carpark fire scenario are detailed in Table 2. These are supported by additional inputs derived from WP 1B. Namely, the spread rate (m/min) and number of bays ignited (-), in consideration of utilisation of the car park, floor to ceiling height and internal air speed. Input distributions for spread rate and bays ignited (involved) are as per Figure 6 to Figure 8.

Table 2. Stochastic variables

	Variable	Value	Note
Fire load density		Weibull distribution loc=-51832274621 scale=51832275211 c=470033397 Mean = 526 MJ/m ² StD = 134 MJ/m ²	See section 2.4.4. A lower limit of 10 MJ/m ² is applied.
Fire HRR density		Normal distribution Mean = 202.1 kW/m ² StD = 70.7 kW/m ²	See section 2.4.4.
Combustion efficiency		Uniform distribution loc = 0.8 scale = 0.2	It is recognised not all available fuel will generally be consumed in event of fire. As a result of the combustion efficiency specified in BS EN 1991-1-2 (80%) and PD 6688-1-2 (100%), a uniform distribution is adopted for combustion efficiency.
Fire near field temperature		Normal distribution loc = 1323.15 K scale = 93 K	Near field temperatures are supported by the literature and are taken directly from full-scale fire experiments. The near field temperature distribution is informed by Stern-Gottfried [12] who analysed experimental data from a range of sources, including the Dalmarnock and Cardington fire experiments. Whilst the reference experiments used are not car parks, the CFD study presented in WP 1B notes comparable near field temperatures, approaching 1173 K. Similar figures were noted by the BRE in their investigations of fire spread in car parks [20].

2.5 Interpretation of Analysis Outputs

The Monte Carlo (MC) simulation produces a large dataset of time equivalence values, with one value generated for each iteration. To make this raw data useful, it is processed to create a cumulative probability curve, as shown in Figure 5. This graph is essential for evaluating the performance of a structural design against a range of potential fire scenarios.

The CDF plots the calculated fire intensity (time equivalence) on the x-axis against the cumulative probability on the y-axis. It illustrates how the probability of structural survival changes with its fire resistance rating. The graph is divided into two key areas:

- **Performance Region (Green Area):** This region represents the cumulative probability that the severity of a fire will be less than the structure's fire resistance rating. It is a direct measure of the design's reliability.
- **Failure Region (Red Area):** This region represents the probability that the severity of a fire will exceed the structure's fire resistance rating, leading to failure.

The cumulative probability curve can be used to determine the reliability of any chosen fire resistance rating. For example, if a structural element with a 120-minute fire resistance rating is considered:

1. Find 120 minutes on the x-axis and trace up to the cumulative probability curve (shown as the solid red line in Figure 5).
2. The corresponding value on the y-axis is approximately 0.80 (or 80%).

This means there is an 80% probability that any given fire will have a severity of less than 120 minutes. This value represents the conditional reliability of the 120-minute design. Consequently, the remaining 20% (1.0 - 0.80) is the conditional probability of failure.

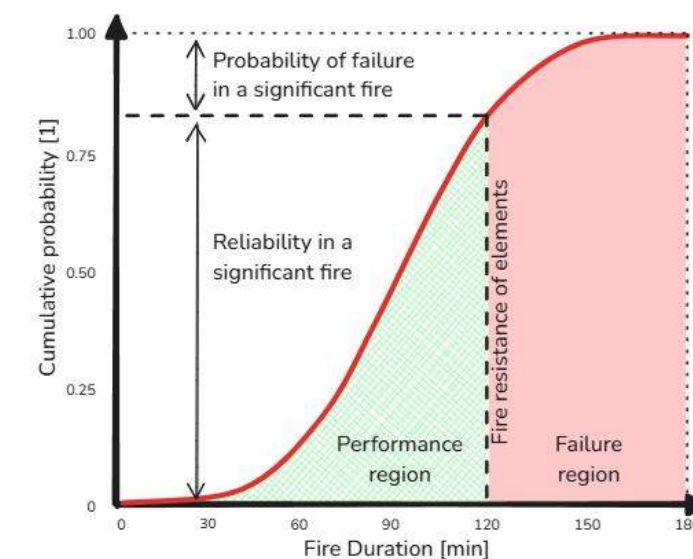


Figure 5. Example of a Cumulative Distribution Function (CDF) for time equivalence results.

3 ANALYSIS RESULTS

3.1 Effect of Car Park Utilisation on Fire Severity

This section presents the results of the probabilistic analysis, focusing on the influence of car park utilisation on the severity of structural fire exposure. Four utilisation scenarios were analysed: 40%, 60%, 80%, and 100%. A higher utilisation rate is translated in the model to an increase in the fire travelling speed and, more significantly, the total number of bays involved in the fire. At 100% utilisation, the cellular automata model from WP 1B showed all scenarios spread to involve the maximum 60 bays simulated.

Figure 6 presents the input distributions and the resulting cumulative probability for the calculated time equivalence for each utilisation level. A brief explanation of how to interpret these plots is provided below:

- The grey bars represent a histogram of the actual sampled values from the Monte Carlo simulation, normalised to show the probability density.
- The continuous black line represents the theoretical distribution. Its close fit to the histogram confirms the validity of the sampling process.
- Each plot includes key statistics: the mean (μ), standard deviation (σ), and where applicable, the minimum (min) and maximum (max) values, which indicate explicit limits applied to the distribution.

As shown in the figure, there is a clear correlation between utilisation and fire severity. The most significant impact is on the number of vehicles drawn into the fire, where the mean number of bays involved (μ) increases significantly from 8 at 40% utilisation to 43 at 80% utilisation.

Consequently, the time-equivalence results show a significant increase in fire severity. The mean time equivalence (μ) increased from 37.31 minutes at 40% utilisation to 48.93 minutes at 100% utilisation. The standard deviation (σ) of the equivalent time also decreases at higher utilisations, suggesting that the fire outcomes become more predictably severe.

This outcome is physically intuitive that higher vehicle density provides a larger and more contiguous fuel bed, resulting in a more severe thermal challenge to the structure. This implies that a higher fire resistance period is needed for a highly utilised car park to achieve the same level of structural reliability or comparable failure probability.

For completeness, Table 3 summarises the time-equivalence results in a numerical format.

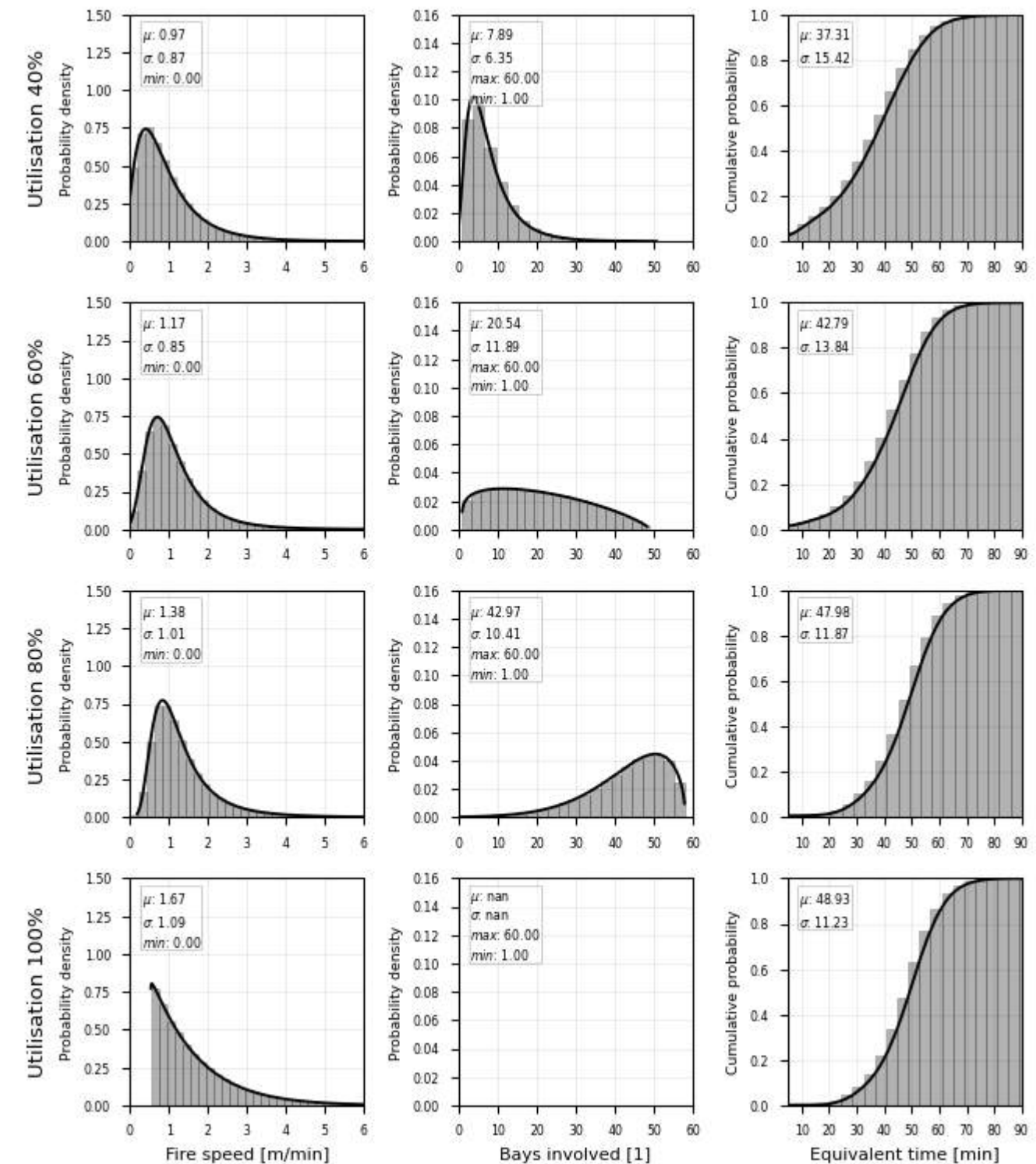


Figure 6. Input distributions for fire speed and bays involved, and resulting time-equivalence CDFs for car park utilisation rates of 40%, 60%, 80%, and 100%.

3.2 Effect of Ceiling Height on Fire Severity

This section evaluates the influence of the car park's ceiling height on the potential fire severity. Four distinct ceiling heights were analysed: 2.5 m, 2.7 m, 3.1 m, and 3.5 m. The ceiling height is a critical geometric parameter that directly influences the fire dynamics and the potential for fire to spread between vehicles. In all cases, the car park utilisation is fixed at a higher value of 80%.

From a fire dynamics perspective, a higher ceiling provides a larger volume for hot gases and smoke to occupy. This increased volume results in lower ceiling-level gas temperatures and reduced radiant heat flux to adjacent vehicles. Consequently, the likelihood of vehicle-to-vehicle fire spread is diminished. This physical mechanism is directly reflected in the fire spread parameters derived from WP 1B, which serve as inputs for this analysis.

Figure 7 presents the input distributions and the resulting cumulative density for the calculated time equivalence for each ceiling height scenario.

The results show that ceiling height is a factor in controlling fire spread and severity.

- Impact on fire floor area: The most significant effect is on the number of vehicles involved. The mean number of bays involved (μ) reduced from 42.97 for a 2.5 m ceiling to just 32.63 for ceilings of 3.5 m and above. No significant change in the distribution shape is observed.
- Impact on fire severity: This reduction in fire size has a large impact on the structural fire exposure. The mean time equivalence (μ) decreases from 48 minutes for the 2.5 m ceiling to 30 minutes for the 3.5 m ceiling. The rate of change in fire severity appear to be consistent as a function of ceiling height.

The key engineering conclusion from this analysis is that even a modest increase in ceiling height can lead to a notable reduction in expected fire severity. This finding is consistent with the detailed CFD modelling in WP 1B, which demonstrated that increased ceiling height reduces the incident heat flux to adjacent vehicles, thereby inhibiting fire spread.

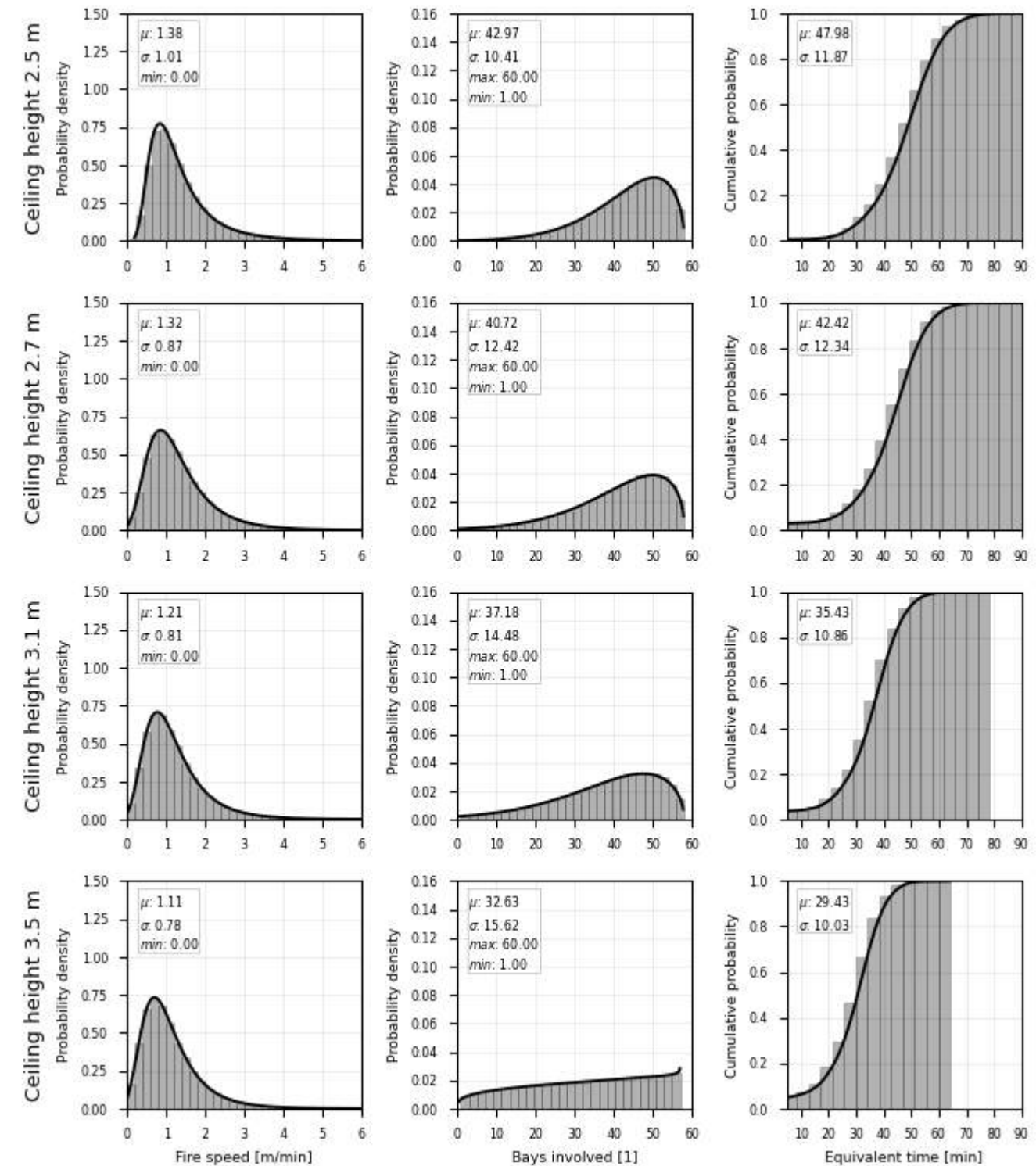


Figure 7. Input distributions and resulting time-equivalence CDFs for ceiling heights of 2.5 m, 2.7 m, 3.1 m, and 3.5 m.

3.3 Effect of Wind Speed on Fire Severity

This section investigates the influence of external wind speed on fire severity in open-sided car parks. The analysis was conducted for four scenarios: 0 m/s (without wind conditions), 2.0 m/s, 4.0 m/s, and 8.0 m/s. In all cases, the car park utilisation is fixed at a higher value of 80%.

In an open-sided car park, wind can have a significant, and perhaps counter-intuitive, effect on fire development. While wind can increase the burning rate of individual vehicles, it also causes significant flame deflection. This deflection can increase down-stream fire spread whilst retarding up-stream fire spread.

Figure 3.3 presents the input distributions and the resulting cumulative density for the calculated time equivalence for each wind speed scenario.

The results clearly indicate that increasing wind speed has a mitigating effect on the overall fire severity.

- **Impact on Fire Spread:** The effect of flame deflection is evident in the input parameters. As wind speed increases from 0 m/s to 8.0 m/s, the mean fire spread speed decreases from 1.38 m/s to 0.56 m/s. More significantly, the mean number of bays involved (μ) falls from 42.97 in calm conditions to 20.23 at 8.0 m/s.
- **Impact on Fire Severity:** The reduced fire spread, and smaller fire size directly lead to a lower thermal exposure on the structure. The mean time equivalence (μ) decreases steadily from 48 minutes in calm conditions to 40 minutes at a wind speed of 8.0 m/s.

The primary conclusion from this analysis is that the most severe fire scenarios in an open-sided car park are likely to occur during calm or low-wind conditions. This is explained by the flame deflection phenomenon identified in the WP 1B CFD modelling, where wind was observed to retard fire spread by pushing the plume away from downstream vehicles. This finding implies that when considering a credible worst-case design fire for an open-sided car park structure, assuming calm conditions is a conservative and appropriate approach.

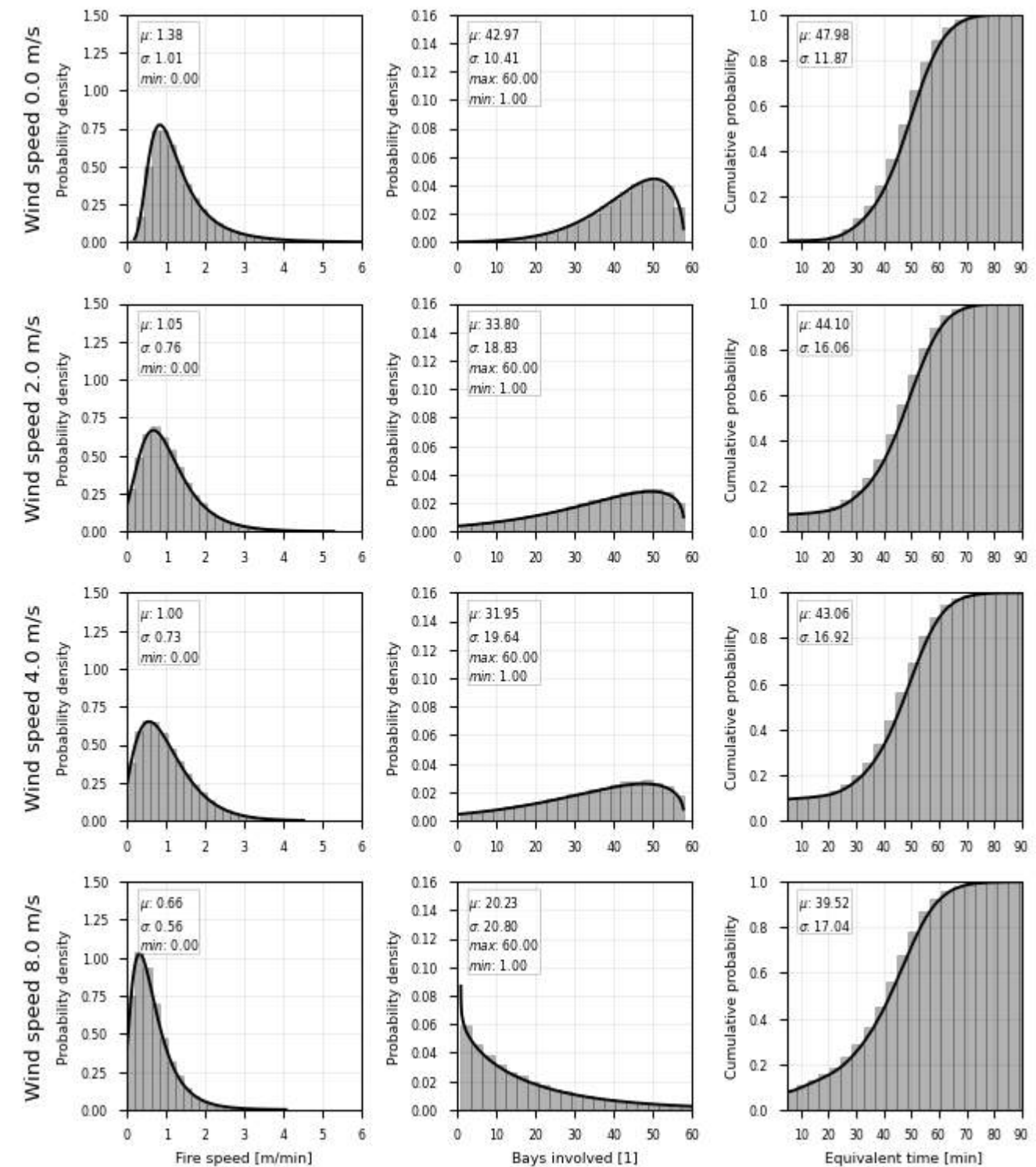


Figure 8. Input distributions and resulting time-equivalence CDFs for external wind speeds of 0 m/s, 2.0 m/s, 4.0 m/s, and 8.0 m/s.

4 DISCUSSION & CONCLUSION

4.1 Project Context and Summary of Work

This research project was commissioned by the Building Safety Regulator (BSR) to generate data and evidence on the appropriate structural fire resistance periods for open-sided car parks in the UK, with the ultimate aim of informing future technical policy. The project is structured into three distinct Work Packages (WPs):

- WP 1: Characterisation of fire dynamics in open-sided car parks.
- WP 2: Probabilistic structural reliability analysis.
- WP 3: Cost-benefit and optimisation analysis.

This report constitutes the deliverable for Work Package 2 (WP 2). It builds directly upon the fire dynamics data generated in WP 1B to quantify the probability of structural failure for elements with varying levels of fire resistance. In the process, it considers the impact of variables such as car park utilisation, floor-to-ceiling height and internal air speed.

4.2 Methodology, Assumptions and Limitations

The core of this study (WP 2) is a probabilistic time-equivalence analysis. This methodology was selected for its ability to rationally account for the significant uncertainties inherent in car park fire scenarios. By using a Monte Carlo simulation framework, the analysis can incorporate the full statistical range of inputs, such as fire spread speed and the number of vehicles involved, rather than relying on single, deterministic values. The methodology is considered robust as it is founded on established principles that also form the basis for contemporary national fire safety guidance, such as in BS 9999.

However, the conclusions of this report should be considered in the context of the following key assumptions and limitations:

- **Validation:** It should be noted that the underlying fire model from WP 1B, which provides the inputs for this study, was validated against empirical data from real-world incidents (WP 1A), including the Stavanger and Luton airport fires. This increases the overall confidence in the results of the present structural analysis.
- **Geometry:** The model assumes a generic, regular car park layout with a linear spread distance not exceeding 144 m. Complex geometric features found in real-world structures, such as sloped ramps or irregular bay arrangements, have not been considered.
- **Active Fire Protection:** The analysis assumes no active fire suppression systems (e.g., sprinklers) or firefighting intervention are present. The results therefore represent the performance of passive structural protection alone. However, the effects of sprinkler if present can be captured in the next step analysis when establishing the performance criteria.

- **Structural Element:** A typical protected steel beam was used for the comparative analysis. While this is suitable for establishing relative performance, the results are not specific to any other structural material or element type.

4.3 Summary and Interpretation of Findings

The key findings from the sensitivity studies detailed in Section 3 are consolidated in Figure 9. This figure presents the cumulative probability of time equivalence, allowing for a direct comparison of the influence of car park utilisation, ceiling height, and wind speed.

Several key observations can be drawn from this consolidated data:

1. **Ceiling height is a significant factor:** Of the parameters studied, ceiling height has the most impact on fire severity. Increasing ceiling height leads to a reduction in the probability of large fire spread rates / extents and, consequently, a much lower time equivalence. This suggests that specifying a minimum ceiling height is an effective passive measure for controlling fire risk.
2. **Utilisation is a key driver of risk:** Car park utilisation is also a critical factor. A clear correlation has been observed that a higher utilisation is expected to result in worse fire conditions.
3. **Wind has a mitigating effect:** The analysis consistently shows that the most severe fires occur in calm (0 m/s) conditions. Increasing wind speed serves to inhibit fire spread between vehicles, thereby reducing the overall fire severity.
4. **90 min fire resistance for car parks would cover all but the most extreme fire intensity cases** when seeking to ensure a reasonable likelihood of the structure surviving the full duration of a fire. However, this should be considered in terms of what costs are optimal when considering the full lifetime of a car park. This is the focus of WP 3B.

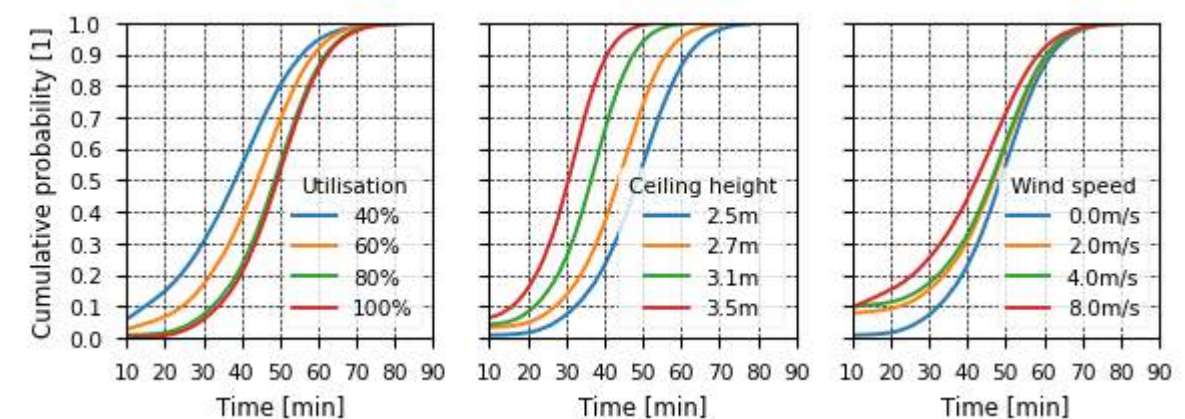


Figure 9. Consolidated time-equivalence cumulative probability showing the sensitivity of fire severity to car park utilisation, ceiling height, and wind speed

Table 3. Time-equivalence results for carpark utilisation of 40, 60, 80 and 100%.

Duration [min]	40 %	60 %	80 %	100 %
10	0.05758	0.02674	0.00786	0.00142
20	0.14781	0.06642	0.01593	0.00668
30	0.30187	0.16753	0.07221	0.05689
40	0.54524	0.38076	0.22782	0.20351
50	0.79935	0.69037	0.55044	0.52606
60	0.94517	0.91611	0.86150	0.85021
70	0.98759	0.98682	0.97795	0.97414
80	0.99654	0.99820	0.99794	0.99714
90	0.99887	0.99958	0.99988	0.99989

Table 4. Time-equivalence results for ceiling heights of 2.5, 2.7, 3.1 and 3.5 m.

Duration [min]	2.5 m	2.7 m	3.1 m	3.5 m
10	0.00786	0.03241	0.04097	0.06260
20	0.01594	0.04759	0.08059	0.15633
30	0.07221	0.13431	0.25327	0.47153
40	0.22782	0.36367	0.65419	0.88209
50	0.55044	0.73933	0.93916	0.99282
60	0.86150	0.95208	0.99650	0.99991
70	0.97795	0.99586	0.99993	0.99999
80	0.99794	0.99983	0.99999	0.99999
90	0.99988	0.99999	0.99999	0.99999

Table 5. Time-equivalence results for external wind speeds of 0, 2.0, 4.0, and 8.0 m/s.

Duration [min]	0 m/s	2 m/s	4 m/s	8 m/s
10	0.00786	0.03241	0.04097	0.06260
20	0.01594	0.04759	0.08059	0.15633
30	0.07221	0.13431	0.25327	0.47153
40	0.22782	0.36367	0.65419	0.88209
50	0.55044	0.73933	0.93916	0.99282
60	0.86150	0.95208	0.99650	0.99991
70	0.97795	0.99586	0.99993	0.99999
80	0.99794	0.99983	0.99999	0.99999
90	0.99988	0.99999	0.99999	0.99999

4.4 Implications and Next Steps

The primary outcome of this work is a set of probabilistic distributions that quantify structural fire exposure under a range of conditions. The findings demonstrate that a single, prescriptive fire resistance requirement (e.g., 15 or 30 minutes) does not provide a uniform level of safety; the actual reliability achieved is highly dependent on the specific design and operational characteristics of the car park.

This detailed, risk-informed output is of direct use and will serve as the primary technical input for Work Package 3B (WP 3B). In the next phase of this project, the CDF curves presented in this report will be used in a cost-benefit analysis to:

- Evaluate the life-cycle costs of providing different levels of fire resistance.
- Quantify the corresponding benefits in terms of risk reduction (considering life safety, property protection, and business continuity).
- Identify an optimal level of fire resistance that balances safety with economic considerations.

Ultimately, the work presented in this report provides the essential evidence base required to develop robust, risk-informed policy and design guidance for open-sided car parks.

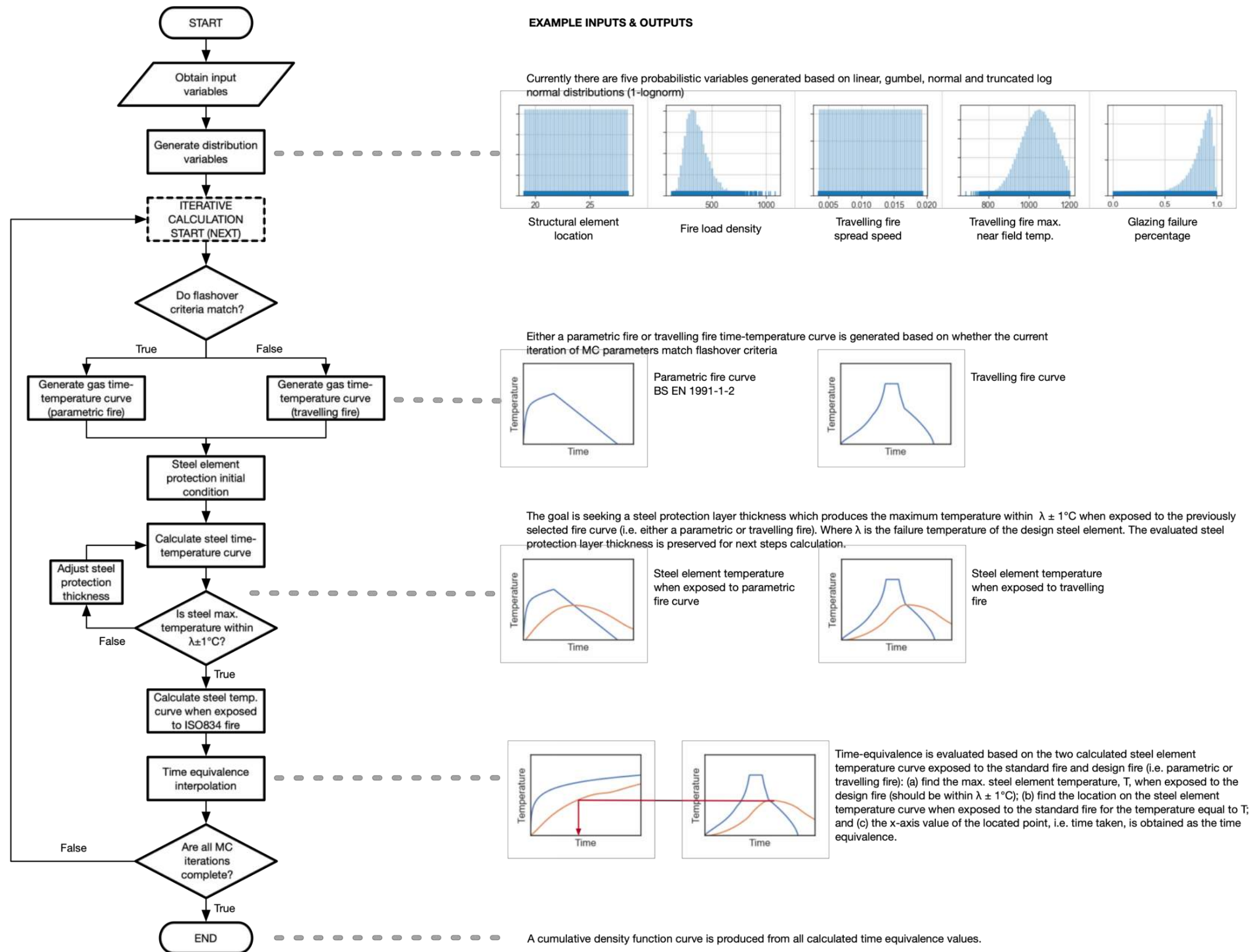
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APPENDIX I – TRAVELLING FIRE CALCULATIONS

Behaviour	Correlation	Input metrics	
Conditions for implementation of parametric fire over travelling fire	$t_{burn} \geq \frac{l}{s}$ or $0.01 < 0 < 0.2$	0	$[m^{1/2}]$ is the opening factor as defined for the parametric fire in BS EN 1991-1-2
Time to consume a unit area of fuel (t_{burn})	$t_{burn} = \frac{q_{fd}}{RHR_f} > 900s$	q_{fd}	$\left[\frac{MJ}{m^2}\right]$ is the fire load density
		RHR_f	$\left[\frac{MW}{m^2}\right]$ is the heat release rate density
Time to onset of decay phase (t_{decay})	$t_{decay} = \max\left[t_{burn}; \frac{l}{s}\right]$	l	$[m]$ is the length of compartment (longest dimension)
		s	$\left[\frac{m}{s}\right]$ is the fire spread rate (m/s)
Time to peak fire size (t_{lim})	$t_{lim} = \min\left[t_{burn}; \frac{l}{s}\right]$	As per other rows in this table	
Heat release rate during growth (Q_{growth}), i.e., $t < t_{burn}$	$Q_{growth} = RHR_f \cdot w \cdot s \cdot t$	t	$[s]$ is the time
		w	$[m]$ is the width of compartment
Maximum (steady) heat release rate (Q_{max}), i.e. $t_{lim} < t < t_{decay}$	$Q_{max} = \min\left[\frac{RHR_f \cdot w \cdot s \cdot t_{burn}}{RHR_f \cdot w \cdot l}\right]$	A_v	$[m^2]$ is the ventilation area
		h_{eq}	$[m]$ is the height of ventilation openings
Heat release rate during decay (Q_{decay}), i.e., $t > t_{burn}$	$Q_{decay} = \text{Max}\left[Q_{max} - \frac{((t - t_{decay}) \cdot w \cdot s \cdot RHR_f)}{0}\right]$	As per other rows in this table.	
Far field temperature of gas (T_g)	$T_g = \begin{cases} \frac{5.38 \left(\frac{Q}{r}\right)^{2/3}}{h} + 20, & \text{if } \frac{r}{h} > 0.18 \\ \frac{16.9 (Q)^{2/3}}{h^{5/3}}, & \text{if } \frac{r}{h} \leq 0.18 \end{cases}$	Q	$[kW]$ time dependant heat release rate, i.e., one of Q_{growth} , Q_{max} or Q_{decay}
		r	$[m]$ is the distance from near field axis location to structural element
		h	$[m]$ height from fuel bed to structural element

APPENDIX II – ELABORATION OF MONTE CARLO ANALYSIS PROCEDURE IN SFEPRAPY



Appendix D – WP 3A

CPD/004/122/039

Real Fires: Open-sided car park fire resistance

WP 3A: Determination of occupant loads of car parks

Revision: R00

Date: 17/11/2025

Project Number: OX24065

Prepared for : The Health & Safety Executive

Project Location : N/A

Prepared by : OFR Consultants Limited

Office address : The Manse, 44 South Bar, Banbury, Oxford OX16 9AB

Project No : OX24065

Revision : R00

Date : 17/11/2025

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Quality Management

Revision	Date	Comment	Author	QA & Technical Review	Approver
D00	21/03/2025	Draft for HSE review	MJS	NA	DJH
D01	04/11/2025	Response to HSE comments	MJS	NA	DJH

Contents

1	Introduction	1
1.1	Background.....	1
1.2	Area of parking bays	1
1.3	Guidance documents.....	2
1.4	Fire hazard	3
2	Vehicle occupancy	4
2.1	Seating capacity.....	4
2.2	Rate per activity trip	4
2.3	Vehicle occupant numbers	5
2.4	Households.....	6
3	Parking bay utilisation	8
3.1	Data sources.....	8
3.2	Representation	9
4	Stationary parking analysis.....	11
4.1	Floor space factor occupancy	11
4.2	Persons per trip activity occupancy	11
4.3	Occupancy using Monte Carlo simulation	11
4.3.1	Procedure	11
4.3.2	Minimum parking bay utilisation.....	14
4.3.3	Number of iterations	15
5	Dynamic parking analysis	16
5.1	Vehicle arrivals and departures	16
5.2	Time-to-park.....	16
5.3	Vehicle access time	17
5.3.1	‘The Green’, Hunstanton, Norfolk	18
5.3.2	Mansfield Road, Shreveport, Louisiana, USA.....	21
5.4	Travel time	24
5.5	Entry and exit flow	25
5.6	Car park occupancy	26
5.6.1	Vehicles with occupants in transit, based on Ma et al.....	27
5.6.2	Vehicles with occupants in transit, based on the IStructE guide	28
5.6.3	Application to the Monte Carlo process	28
5.6.4	Dynamic occupancy findings	28
6	Conclusions	30
7	References.....	32

Figures

Figure 1. Number of passengers in car driver trips by London residents, Transport for London.....	5
Figure 2. Literature data for percentage of occupied parking bays.....	8
Figure 3. Parking space utilisation cumulative density functions	9
Figure 4. Cumulative density and probability density functions for ‘Commuting’ trip activity with 80 th , 95 th and 99 th percentiles indicated	13
Figure 5. Influence of changing the minimum parking bay utilisation on the persons per bay for the ‘All’ trip activity category.....	14
Figure 6. Number of iterations to reach convergence of the 99 th , 95 th and 80 th percentile persons per bay for the ‘All’ trip activity category with the 0.05 minimum parking bay utilisation.....	15
Figure 7. Regression model for the observed time-to-park against parking bay availability	16
Figure 8. Car parking at ‘The Green’, Hunstanton, Norfolk	19
Figure 9. Occupant number frequency for ‘The Green’ compared to the National Travel Survey for ‘Other’ / ‘Day trip’ activities.....	20
Figure 10. ‘The Green’ vehicle access times (a) frequency (b) cumulative probability.....	21
Figure 11. Car parking at Mansfield Road, Shreveport, Louisiana, USA.....	22
Figure 12. Mansfield Road, Shreveport occupant number frequency compared to the National Travel Survey.	23
Figure 13. Mansfield Road, Shreveport vehicle access time (a) frequency (b) cumulative probability.	23
Figure 14. Cumulative probability distribution for 100,000 iterations for walking speed	24
Figure 15. Vehicle entry (top) and exit (bottom) flow	25
Figure 16. Number of vehicles entering and exiting per 15-min period as a fraction of the static capacity from Ma et al.	26
Figure 17. 95 th percentile number of vehicles entering and exiting ‘The Green’.....	26
Figure 18. Fraction of parking bays with 99 th percentile simultaneous occupant transition (a) when all parking bays are occupied, i.e. the utilisation is 1 so that the time-to-park is 275 s (b) when all parking bays are free, i.e. the utilisation is 0 so that the time-to-park is 100 s.....	27
Figure 19. Cumulative density functions for 1, 2, 3, 4 and 5+ persons	56
Figure 20. 95 th and 99 th percentile access times as a function of number of persons.	56

Tables

Table 1. Recommended parking bay dimensions	2
Table 2. Persons per parking bay when applying identified parking efficiencies with occupant densities.	3
Table 3. National Travel Survey statistics for average car or van occupancy and lone driver rate by trip activity, 2023 data.....	5
Table 4. Proposed distributions of people number in vehicles by trip activity type.	6
Table 5. Number of people per household.....	6
Table 6. Modified trip activity rates applying 80 th , 95 th and 99 th percentile parking bay utilisations compared with average vehicle occupancies	11
Table 7. 80 th , 95 th and 99 th percentile persons per bay from Monte Carlo simulations compared with average vehicle occupancies	14
Table 8. Type of population and unimpeded movement speed used in the simulations.	24
Table 9. 99 th percentile persons per bay from Monte Carlo simulations compared with average vehicle occupancies given by Table 3, modified trip activity in Table 6 and the stationary analysis in Table 7.	29
Table 10. 95 th percentile persons per bay from Monte Carlo simulations compared with average vehicle occupancies given by Table 3, modified trip activity in Table 6 and the stationary analysis in Table 7.	29
Table 11. Proposed design values for expected number of persons per bay.	30
Table 12. Implications of 95 th percentile design values for the exemplar 1000 parking bay car park	31
Table 13. Vehicle access times in which wheelchairs or mobility scooters were loaded or unloaded at 'The Green' car park.....	57
Table 14. Vehicle access times in which pushchairs and prams were loaded or unloaded at 'The Green' car park.....	57

Terminology

Vehicle: In this study ‘vehicle’ and ‘car’ are used synonymously. A car is a passenger vehicle typically with a capacity of 5 persons.

Car park: An area designated for the parking of vehicles. The area may or may not have marked bays, it may be in the open or may be covered and/or underground.

Parking bay: The area in a car park designated for the parking of a single vehicle. Also referred to as a parking space.

Static capacity (S_{cap}): The total number of available parking bays in a car park.

Parking bay utilisation (u): The fraction of the static capacity that is occupied by a vehicle. A utilisation of 1 means all parking bays are occupied.

Parking bay availability: The complement of the parking bay utilisation.

Vehicle occupancy: The number of people in a vehicle.

Occupant load: The total number of people in the car park at a given point in time.

Occupant density: The number of people per unit area (i.e. persons per m^2), alternatively expressed as the area occupied by a person (i.e. m^2 per person). The term ‘floor space factor’ is equivalent to ‘occupant density’.

Persons per bay: In a design context the expected occupant load may be determined using a ‘persons per parking bay’ value multiplied by the number of parking bays in the car park. The ‘persons per parking bay’ value can be calculated from the occupant load divided by the number of parking bays.

Access time (t_{access}): The time taken for people to complete their actions when either getting in or getting out of their vehicle including the time to load or unload luggage etc.

Time-to-park (t_{park}): The time taken between a car entering a car park and it coming to a halt in a parking bay. For the purposes of this study ‘time-to-park’ is also used to indicate the time between a vehicle leaving a parking bay and exiting the car park.

Transition time (t_{tran}): The time taken by occupants to park a vehicle in a parking bay after entering a car park (i.e. the time-to-park) combined with their access time and the time it takes to travel (t_{travel}) to the floor exit (e.g. a door to a stairwell etc.). Transition time also includes the access time and the time taken for a vehicle to exit a car park.

Trip activity: The purpose of the people in the cars using the car park. Categories of trip activities include commuting, shopping, etc.

1 INTRODUCTION

1.1 Background

Car parks are integral facilities within urban infrastructures worldwide. As multi-storey, enclosed, or partially open structures, these environments present unique challenges to fire safety design. One critical consideration is the determination of occupant loads—the number of people who could be inside the car park at any given time. This number might be a maximum value, or a stochastic representation of the number of people present throughout the day. Determination of occupant loads helps to ensure that life safety features, such as emergency exits and fire protection systems, are sized and arranged to handle real-world evacuation demands.

Within the field of fire safety engineering, occupant loads serve as a foundation for designing evacuation routes and simulating egress times. Occupant load calculations also indicate the number of people in the building that might be exposed to fire hazards including the effects of smoke or structural failure. Guidelines and reference values help designers and code officials establish occupant loads based on factors including vehicle density, building configuration, and typical human behaviour patterns. However, occupant load calculations in car parks may also necessitate site-specific considerations—such as the ratio of drivers to passengers, the timing of peak usage, and local climate influences—that are not always covered exhaustively by standardised guidelines.

This report explores theoretical and empirical bases for determining occupant loads in car parks, highlighting methods recommended by international standards, as well as common practical approaches adopted in different jurisdictions. Calculations are presented for car park occupant load that consider situations in which all parked cars are occupied simultaneously (referred to as a static parking approach) or situations in which there is a flow of cars and people entering and leaving a car park (referred to as a dynamic parking approach). Design values for persons per bay have been determined for static and dynamic parking using 99th percentiles from distributions using Monte Carlo analysis.

The output provides data in support of the overall project objective, which is to establish appropriate fire resistance ratings for elements of structure forming open-sided car parks as presented in Work Package 3B. As part of this consideration, the potential number of fatalities and injuries in a fire event must be considered, which is dependent on the car park occupancy at the time of a fire event.

1.2 Area of parking bays

The number of people in a car park will be a function of the potential number of vehicles in the building which in turn depends on the size of the available parking bays (also often referred to as ‘spaces’) and the area taken up by aisles for vehicle and people movement.

The IStructE design guidance [1] gives the recommended dimensions of parking bays depending on the likely length of vehicle stay and other factors. The area of medium- and long-stay bays are recommended to be 13 m², as shown in Table 1.

Space is also required for the vehicle movement aisles. Previously Butcher et al. [2] gave parking areas per vehicle in the range of 18.5–26.8 m². According to Hill [3] a ‘good’ parking efficiency ranges from 20 m²/space for 300 parking spaces at 90 deg. up to 35 m²/space for 30 spaces at 45 deg. A survey [4] of open top floors of 41 New Zealand multi-storey car parking buildings using Google Earth found typical static efficiencies are 28.9 ± 5.1 m²/bay.

Table 1. Recommended parking bay dimensions, taken from the IStructE design guidance [1].

Type of parking	Length ^{a,b} (m)	Width ^a (m)	Comment
Short-stay	5.00	2.70	High turnover of bays
Medium-stay ^c	5.00	2.60	Mixed use
Long-stay ^c	5.00	2.60	Low turnover of bays
Accessible	5.00	3.80 ^d	–
Parent/child	5.00	3.40 ^e	–

^a All dimensions are to be clear of any projections.

^b The preferred dimension is 5 m for all bay lengths. However, with restricted space and appropriate signage, this can sometimes be reduced for small/city vehicles.

^c Bays for medium- and long-stay parking are classified as “standard parking bays.”

^d The bay width for use by disabled persons allows for the door to be fully opened to improve movement in and out of the car and to provide greater room for assistance to those with reduced mobility. An additional 1.2 m wide cross-hatched area is required to the driver’s side and to the rear of the vehicle.

^e The bay width for use by parent and child allows for the door to be opened more fully for access to child seats.

1.3 Guidance documents

Several documents across the UK have given guidance on calculating car park occupants loads. The 1983 edition of BS 5588-3 [5] specified 30 m² per person listed under the ‘Storage accommodation, car park’ storey description or alternatively 2 persons per parking bay. Marchant [6] also quoted one person per 30 m² of floor area consistent with BS 5588-3:1983. The 1997 edition of BS 5588-11 [7] specifies 2 persons per parking bay within a separate ‘car park’ storey description and this same value is stated in the 1992 and 2000 editions of Approved Document B (ADB) as well as BS 9999:2008 [8]. In Scotland the Technical Handbook – Non-Domestic [9] gives an occupancy load factor for ‘car park, storage and warehouse accommodation’ as 30.0 m² per person, consistent with BS 5588-3:1983. BS 9999:2017 [10] no longer refers to car parks when using a floor space factor and the largest floor space factor given in its Table 9 is 10 m² per person (for low density offices), i.e. three times more than BS 5588-3:1983 and elsewhere.

Internationally the latest edition of C/AS2 [11] in New Zealand gives the occupant density of car parks as 0.02 persons/m² (i.e. 50 m² per person). C/VM2 [12] retains the same occupant density although now expresses it as 50 m² per person. The 2024 edition of the International Building Code (IBC) [13] uses 200 ft² gross per person (c. 18.6 m² per person) for parking garages. Interestingly, the 2021 edition of the Italian fire prevention code [14] (Table S.4-12) states for public car parks: “2 persone per veicolo parchato” [2 people per parked vehicle] and private car parks: “1 persona per veicolo parchato” [1 person per parked vehicle] rather than per parking bay.

Table 2 shows the calculated persons per bay when the various occupant densities identified in guidance are applied to the upper and lower parking efficiencies.

Table 2. Persons per parking bay when applying identified parking efficiencies with occupant densities.

		Occupant density (m ² per person)		
		18.6	30	50
Efficiency (m ²)	20	1.1	0.7	0.4
	35	1.9	1.2	0.7

1.4 Fire hazard

For a fire starting in car to become a hazard to people in a car park there must be people present, and the fire needs to develop sufficiently. Even a single car on fire may generate sufficient heat and smoke in time to present a hazard to nearby people if they have not moved far enough away from the fire. For a fire to spread to neighbouring cars there needs to be other cars in the car park. These other cars will need to be sufficiently close to already burning cars and / or the thermal conditions with the car park due to the hot gases need to be sufficiently severe to potentially ignite and thus allow the fire to spread. These factors are beyond the scope of this report but are investigated elsewhere as part of this research project, see outputs for WP 1.

2 VEHICLE OCCUPANCY

2.1 Seating capacity

As previously noted, the number of people in a car park will depend on the seating capacity of the vehicles and what proportion of that capacity is utilised. Most cars offer 5 seat positions although people carriers might offer up to 7 seating positions*. Vehicle licensing statistics for the UK [15] show that the top three models in 2022 were the Ford Fiesta, Ford Focus and Volkswagen Golf, all of which have five seats. Thus, a simple and conservative approach to get the occupant load of a car park would be to assume all cars have their maximum seating capacity used, i.e. effectively five people per vehicle. However, this is clearly unrealistic for most real-world situations.

2.2 Rate per activity trip

Data on the number of occupants in a vehicle is available from various sources related to travel demand patterns, etc. In a 2012 study on motor-vehicle growth, fuel use and consequent CO₂ emissions in China, Huo et al. [16] report that the average number of persons per vehicle is 1.4 per in Japan, 1.59 to 1.64 in US from 1994 to 2006, 1.4–1.6 in Europe of which it is 1.43 in Germany, and 1.55 in France. These averages do not examine whether the nature of an activity trip affects the likely number of occupants.

Quoting a 1997 report on the ‘Indicators of Energy Use and Efficiency’ by the International Energy Agency (IEA), a 2000 report by the European Environment Agency (EEA) [17] gives average occupancy rates as 1.1-1.2 when commuting to/from work, 1.4-1.7 on a family trip and 1.6-2.0 for travel and leisure. The EEA report also noted that:

“...occupancy rates of passenger cars in Europe fell from 2.0-2.1 in the early 1970s to 1.5-1.6 in the early 1990s. The decrease is a result of increasing car ownership, extended use of cars for commuting and a continued decline in household size.”

It is plausible that the 2 persons per parking bay given by guidance such as BS 5588-3:1983 comes from data from around the 1970s. Interestingly, in a paper published in 1953 [18] the passenger load average of ‘state-park bound’ cars in the US was found to be 4.1 persons per car although park planners used a figure of 3.8 persons per car.

In England, the Department for Transport has published National Travel Survey [19] statistics for average car or van occupancy and lone driver rate by activity trip categories since 2002 onwards. The latest data from 2023 is shown in Table 3. The data given for England in 2023 are like the 1997 values quoted by the EEA.

* Best cars & SUVs to fit 3 car seats in a row, incarsafetycentre.co.uk/blogs/blog/best-cars-suvs-to-fit-3-car-seats-in-a-row-1

Table 3. National Travel Survey statistics for average car or van occupancy and lone driver rate by trip activity, 2023 data.

Trip activity	Average occupancy per vehicle	Lone driver rate (%)
Commuting	1.15	87
Business	1.16	88
Education	1.94	39
Shopping	1.61	53
Personal business	1.38	70
Leisure*	1.66	57
Holiday or day trip	1.90	42
Other including just walk	1.95	35
All purposes	1.55	61

* Visit friends at home and elsewhere, entertainment and sport

2.3 Vehicle occupant numbers

Average occupancy and lone driver rates have some utility but for a stochastic analysis it would be useful to have distributions of the number of occupants per vehicle. Transport for London (TfL) notes that “Around six in ten car driver trips are made alone, without any passengers, a quarter include one passenger and the remainder have two or more passengers.” Figure 1 shows data for the number of passengers in car driver trips by London residents taken from London Travel Demand Survey 2011/12 [20]. As might be expected, trips with more passengers contribute less trips. More recent data has not been identified but it is considered that the relative percentages are likely to not have significantly altered since 2011/12.

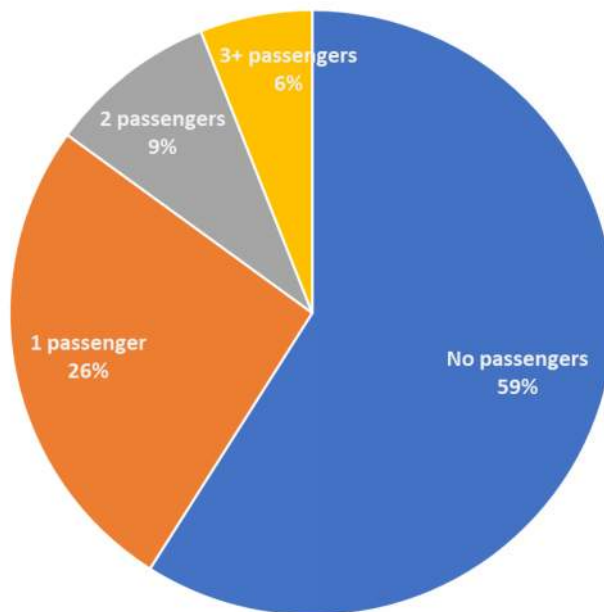


Figure 1. Number of passengers in car driver trips by London residents, Transport for London (London Travel Demand Survey 2011/12).

Distributions for the number of vehicle occupants for different trip activities are proposed for this study by combining the data from the National Travel Survey and TfL. The distributions have been devised to match as closely as practical the percentage of lone drivers, the average occupancies, and to reflect the lesser contribution of trips with high passenger numbers. Since the TfL study only expresses its data up to 3+ passengers it has also been assumed the maximum capacity of a vehicle is four people, recognising the previous comment that typical passenger cars can accommodate five people.

Table 4. Proposed distributions of people number in vehicles by trip activity type.

People	Trip activity					
	Commuting		All		Education*	
	Percentage	Weighted	Percentage	Weighted	Percentage	Weighted
1	87.0%	0.87	61.0%	0.61	35.0%	0.35
2	12.2%	0.24	22.9%	0.46	41.7%	0.83
3	0.8%	0.02	13.5%	0.41	18.1%	0.54
4	0.0%	0.00	2.6%	0.10	5.2%	0.21
Average occupancy		1.14		1.58		1.94

* Education approximates to 'Other' and 'Holiday or day trip'

The weighted values are determined by combining the percentage with the number of people in the vehicle, and hence the average occupancy is found for each trip activity. Note that opposed to the findings from TfL, the 'Other' trip activity (which is like 'Education') has a percentage of vehicles with 2 people that exceeds vehicles with 1 person to achieve the required average occupancy. The distributions in Table 4 are approximations but are considered adequately representative for the purpose of this study.

2.4 Households

An alternative approach to the number of people in passenger vehicles is to examine the UK Office for National Statistics data [21] on the number of people in households (Table 5) and assume the number of vehicle occupants is reflected by this data.

Table 5. Number of people per household (Office for National Statistics, 2023).

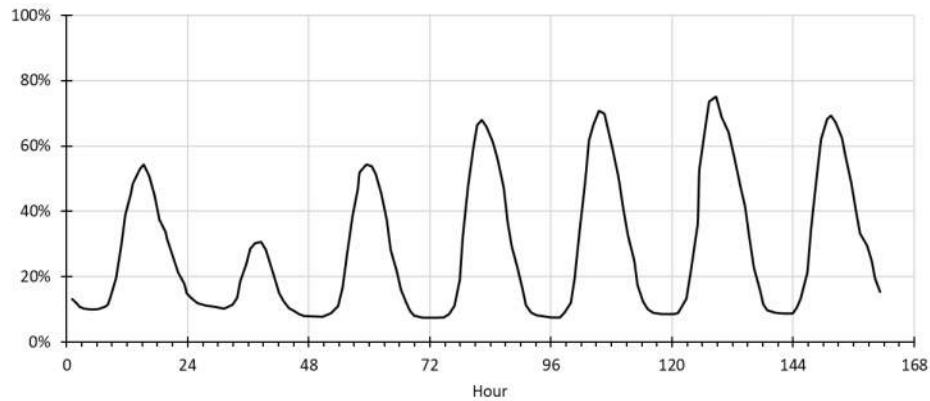
People	Number of households (thousands)	Percentage of households
One person	8,380	30%
Two people	9,698	34%
Three people	4,526	16%
Four people	3,961	14%
Five people	1,249	6%
Six people	374	
Seven or more people	170	
All households	28,358	100%
Average household size	2.36	n/a

For this study, the data for five people or more has been consolidated to 6% of households, meaning the average household size becomes 2.33 rather than 2.36 if it is assumed all these 6% have 5 people. The impact of the 0.03 reduction in the average on the later analysis is considered to be minor. This approach assumes that vehicles are populated by a single household but it is not necessarily the case and a vehicles could be carrying a mixture of friends etc.

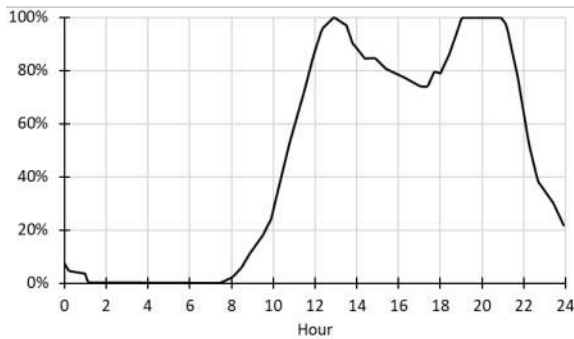
3 PARKING BAY UTILISATION

3.1 Data sources

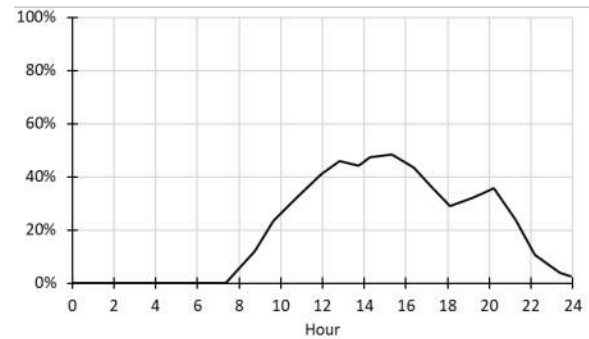
Typical car parks are not fully occupied throughout the day but will exhibit variation that depends on the time of day, day of the week, the season, and the type of occupancies the car park serves. For example, it is likely that the occupancy of car parks serving offices will differ from those serving entertainment venues. There will be a movement of vehicles in and out of the car park which will then have an impact on the number of people present. This dynamic is discussed further in Section 5.1.



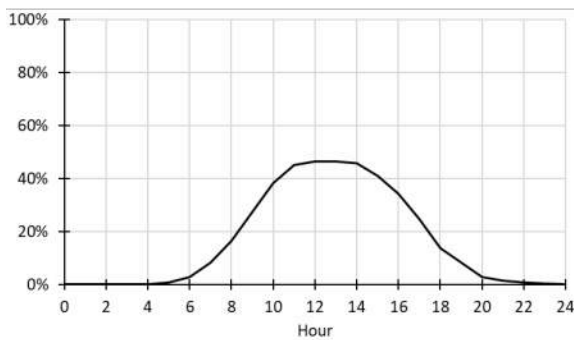
(a)



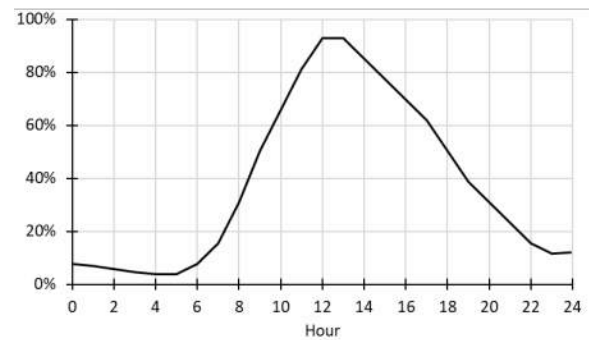
(b)



(c)



(d)



(e)

Figure 2. Literature data for percentage of occupied parking bays (a) Sutter-Sockton (from ref. [22]); (b) and (c) Garage A and Garage B (from ref. [23]); (d) and (e) Moscone and Fifth and Mission (from ref. [24]).

Some data for the number of parking bays occupied by vehicles over a day or days for existing car parks is available in the literature. In a previous study by Tohir and Spearpoint [22] the percentage occupancy is determined for a 24-hour car park providing parking bays for nearby shops and offices in San Francisco.

Figure 2a shows the normalised parking bay occupancy as the number of vehicles parked over the total number of bays available for a typical week from 5th of May 2012 until 5th of May 2013.

Other similar data has been reported by Cherian et al. [23] for two parking buildings referred to as Garage A and Garage B, although the exact location and nearby building types are not reported but street images shown in Cherian et al. suggests they are city centre. The data shows there to be less bays occupied during the day versus the night. This corresponds with the car parks being associated with offices, retail, etc. Car parks that serve residential activities might exhibit an opposite trend in which a larger ratio of bays is occupied at night.

Ma et al. [24] also report the number of parking bays used in two car parks as a function of time for a single day in 2016. The two car parks are referred to as the Moscone Center garage (with 732 bays) and the Fifth and Mission garage (with 2 585 bays) and are both located in downtown San Francisco. The number of bays for each car park is taken from the SFMTA website and differs slightly from that quoted by Ma et al.

3.2 Representation

This study uses the term ‘parking bay utilisation’ to mean the fraction of all available bays that are occupied by a parked car and ‘parking bay availability’ is taken as the complement of utilisation. The parking bay utilisation data from the five car parks is shown in Figure 3 by cumulative distributions from which a combined cumulative distribution has been derived, also shown in Figure 3. Examination of the combined data indicates that there is around a 10% likelihood there are no parked vehicles. For the purpose of later Monte Carlo simulation discussed in Section 4 and thereafter, the combined cumulative distribution is split into 0.05 utilisation bands as indicated by the circles. An alternative to using the bands would be to fit a curve to the combined cumulative distribution.

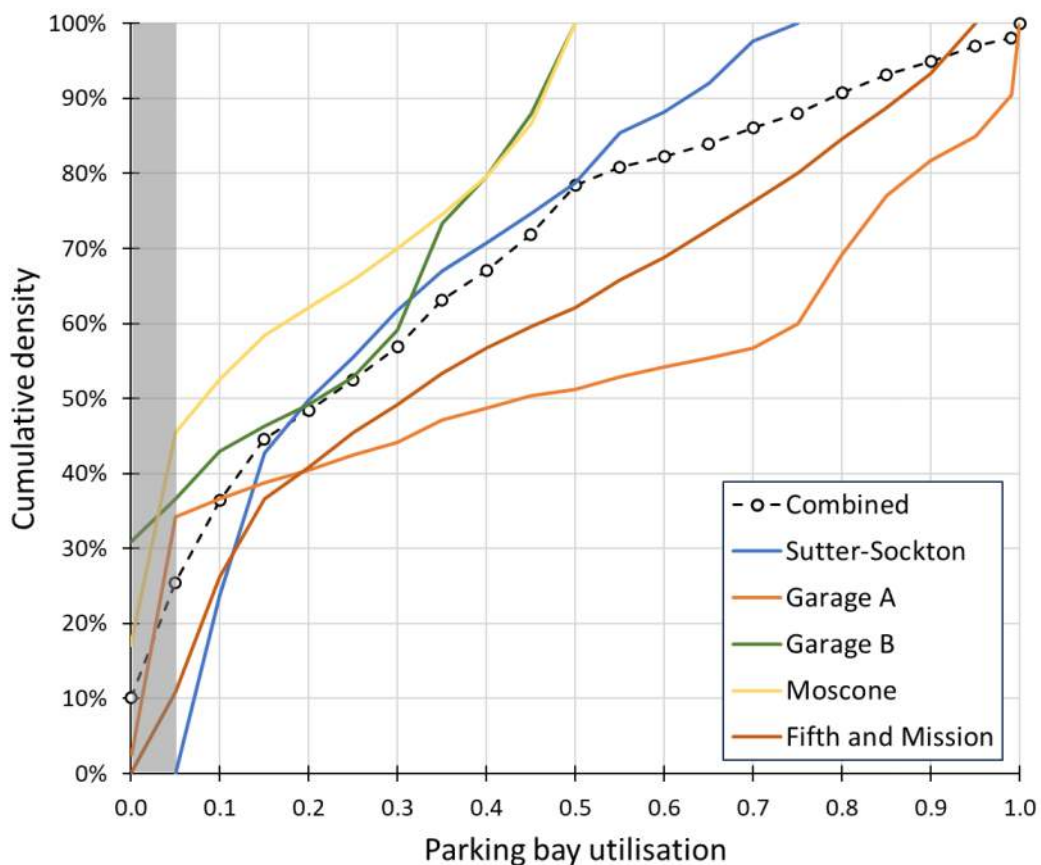


Figure 3. Parking space utilisation cumulative density functions. The grey region indicates the utilisations not considered in the Monte Carlo simulations (see Section 4).

OFFICIAL - SENSITIVE

In the study of occupant loads in retail occupancies, De Sanctis et al. [25] suggest that rounded-up 99% quantiles could be used as design values although they also note that this quantile is high compared to an 80% value that might be used for the assessment of fire loads. The 80th, 95th and 99th percentiles for the parking bay utilisations in Figure 3 are 0.91, 0.97 and 0.98 respectively.

4 STATIONARY PARKING ANALYSIS

4.1 Floor space factor occupancy

To compare the various approaches discussed above an arbitrary 1,000 parking bay car park is examined from which the average number of people per parking bay is computed. In this analysis it is assumed that there is no movement of vehicles in and out of the car park, the alternative scenario is addressed in Section 5.

As noted in Section 1.3, several guidance documents use some form of floor space factor to determine the occupant load of a car park. To maximise the occupant load it is assumed that each parking space has an upper parking efficiency value of 35 m² such that the floor area of 1,000 spaces is 35,000 m². Using a floor space factor of 30 m² per person as per BS 5588-3:1983 [5] results in an occupant load of 1 167 people, or a density of 1.17 persons per bay. Alternatively, for 50 m² per person the occupant load is 700 people and therefore the density is 0.7 persons per bay. Applying the IBC factor of 18.6 m² per person results in a density of 1.88 persons per parking bay. Such methods are less than AD B's recommended 2 persons per space.

4.2 Persons per trip activity occupancy

Section 2.2 has already examined the average number of people in a vehicle in relation to the trip activity. All such values are less than the 2 persons per parking bay recommendation of AD B. The per trip values are not specifically for vehicle parking situations and it is possible that vehicles using car parks have on average more occupants than trips in general.

Applying the per trip activity values also assumes that 100% of parking bays are occupied whereas this is often not the case. As discussed in Section 3, 80th, 95th and 99th percentile parking bay utilisations are 0.91, 0.97 and 0.98. Therefore, the per trip activity values can be modified to reflect this (see Table 6). Note that persons per bay value for 'Commuting / Business' is similar to BS 5588-3:1983 and the 'Other / Education' trip activity is similar to the application of the IBC density (see Section 4.1).

Table 6. Modified trip activity rates applying 80th, 95th and 99th percentile parking bay utilisations compared with average vehicle occupancies given by Table 3.

Trip activity	Average vehicle occupancy	Number of persons per parking bay		
		80 th percentile utilisation	95 th percentile utilisation	99 th percentile utilisation
Commuting / Business	1.16	1.05	1.12	1.13
Education / Other	1.95	1.77	1.88	1.90
Shopping	1.61	1.47	1.56	1.58
All	1.55	1.41	1.50	1.52

4.3 Occupancy using Monte Carlo simulation

4.3.1 Procedure

A simulation approach is used to estimate the number of people in a car park based on vehicle occupancy, incorporating the findings from Section 2.3 and the probability of different levels of parking bay utilisation as outlined in Section 3. As discussed in Section 1.4, a hazard can only exist if at least one vehicle is present in the car park. Since parking bay utilisation is categorised in 0.05 increments (as noted in Section 3), the simulation excludes utilisations of 0.05 or lower, as represented by the grey zone in Figure 3. The sensitivity of selecting this lower bound for parking bay utilisation is explored further in Section 4.3.2.

An iterative method is undertaken using Monte Carlo sampling. For each iteration the following procedure is applied:

1. The number of vehicle occupants per parking bay is determined using the distributions given in Table 4 for a defined trip activity type (i.e. 'Commuting' or 'Other', etc.). At this step it is therefore assumed every parking bay contains an occupied vehicle, i.e. the parking bay utilisation is 1,
2. The fraction of parking bays occupied by a vehicle is determined by randomly selecting a value from the combined parking bay utilisation cumulative density function shown in Figure 3,
3. Each of the 1,000 bays are assessed as to whether there is a vehicle present or not using the parking bay utilisation obtained from Step 2,
4. The total number of people in those parking bays in which a vehicle is present is summed, and
5. The persons per parking bay values are calculated from Step 1 and Step 4.
 6. The iteration is repeated 10,000 times from which cumulative density functions (CDF) are calculated for both when every parking bay is occupied and when the parking bay utilisation probability density function (PDF) is applied. For example, Figure 4 shows the CDFs for the 'Commuting' trip activity.
 7. The general form of the CDFs and PDFs are similar for the other trip activities other than the upper and lower bound persons per parking bay change (see Appendix A). This is because the same parking bay utilisation distribution is used, and it is only the distribution of the number of people in each car that changes for the different trip activities. A more targeted approach would be to apply different parking bay utilisations for the different trip activities. However, only limited data has been identified as discussed in Section 3.1.

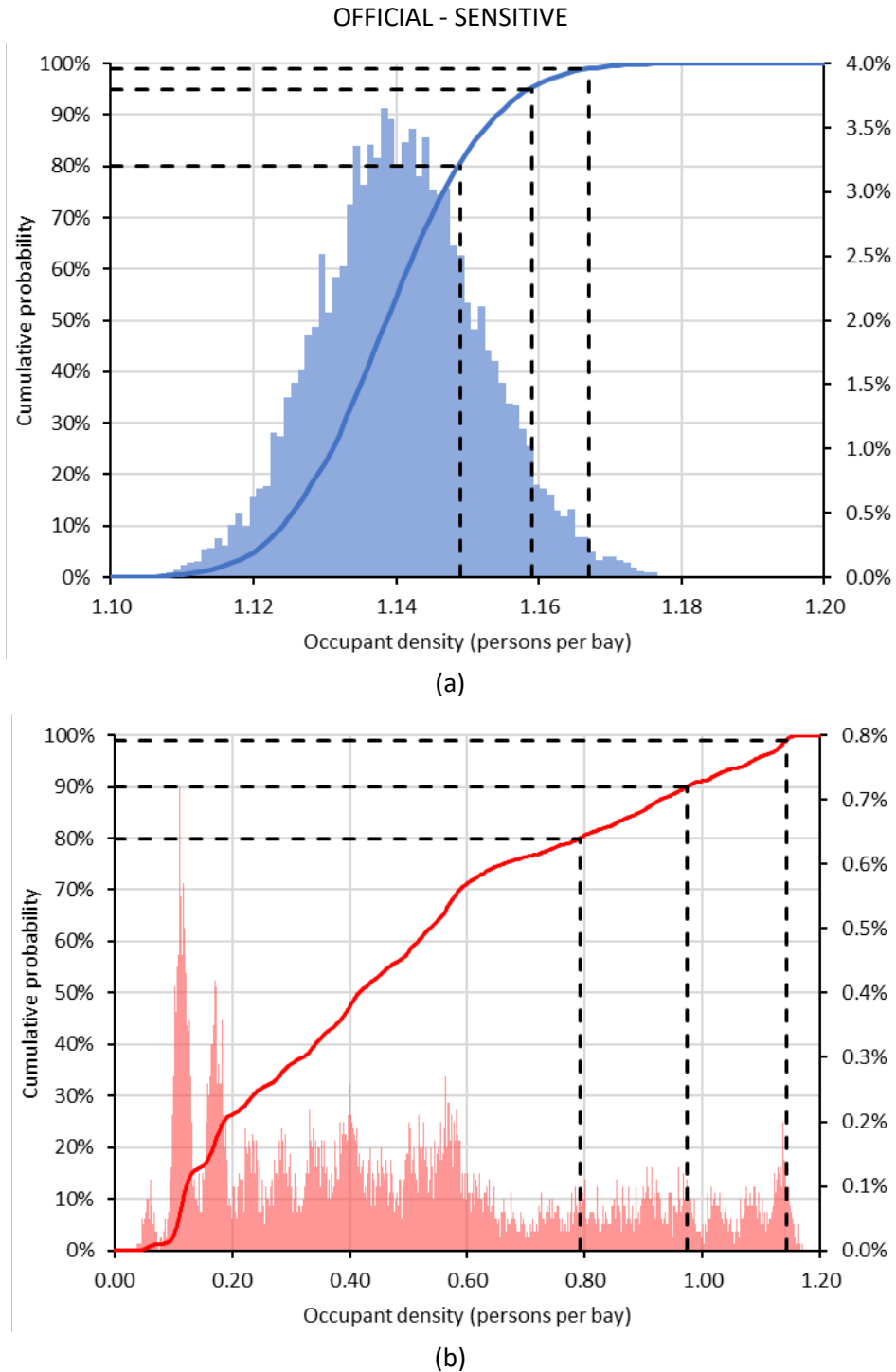


Figure 4. Cumulative density and probability density functions for 'Commuting' trip activity with 80th, 95th and 99th percentiles indicated (a) parking bay utilisation of 1 (b) simulated parking bay utilisation.

The CDFs are then interrogated to obtain the 80th and 99th percentile number of persons per bay (Table 7). As expected, the 99th percentile persons per bay values associated with the parking bay utilisations of 1 are very similar to the average occupancy values presented in Section 2.2. For example, for the 'Commuting' trip activity category the average vehicle occupancy is 1.16 versus 1.17 persons per bay from the Monte Carlo simulations. Furthermore, the 80th, 95th and 99th percentile values for a given trip activity are lower in the case of the simulated parking bay utilisations when compared to a utilisation of 1. Attempts to find algebraic curves to fit the PDF / CDFs have yielded unsatisfactory results.

Table 7. 80th, 95th and 99th percentile persons per bay from Monte Carlo simulations compared with average vehicle occupancies given by Table 3.

Trip activity	Average occupancy	Parking bay utilisation of 1			Simulated parking bay utilisation		
		80 th percentile	95 th percentile	99 th percentile	80 th percentile	95 th percentile	99 th percentile
Commuting	1.16	1.15	1.16	1.17	0.79	0.97	1.14
Education	1.95	1.96	1.98	2.00	1.36	1.66	1.95
All	1.61	1.60	1.62	1.64	1.10	1.36	1.59
Households	2.33	2.29	2.32	2.34	1.58	1.95	2.27

Other than assuming vehicles are occupied in a way that corresponds to the size of UK households, the persons per bay results for the Monte Carlo simulations in Table 7 never exceed the AD B 2 persons per space recommendation. The 'Education' trip activity category results in 2 persons per bay for the 99th percentile (actually 99.04% to two decimal places) when the parking bay utilisation is 1. A 99.97th percentile matches the AD B recommendation for the simulated parking bay utilisation for the 'Education' trip activity category.

The 99th percentile value for 'Commuting' trip activity of 1.17 persons per bay matches the Scottish Technical Handbook – Non-Domestic [9] recommendation discussed in Section 4.1 whereas all the values in Table 7 exceed 0.7 persons per bay when applying 50 m² per person.

4.3.2 Minimum parking bay utilisation

In this section the impact of selecting the 0.05 as the minimum parking bay utilisation is investigated using the 'All' trip activity category with 10,000 iterations of parking bay utilisations starting at 0.05 and going up to 0.95. Figure 5 plots the 80th, 95th and 99th percentile persons per bay. As the minimum utilisation increases (i.e. the likelihood of more parking bays being occupied by a vehicle) the number of persons per bay asymptote to maximum. The 99th percentile is not very sensitive to the minimum utilisation, whereas the 95th and 80th percentiles exhibit noticeable differences at the lower utilisation values when compared with the higher values.

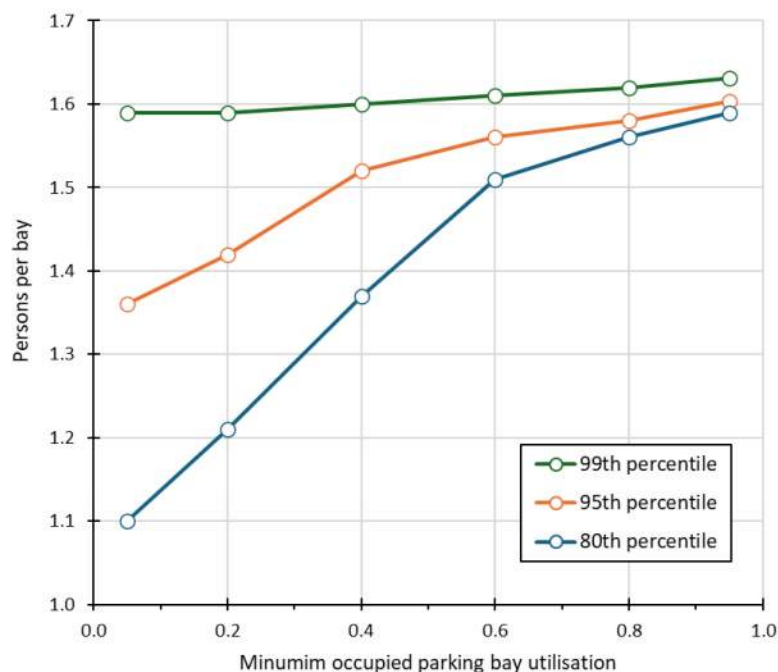


Figure 5. Influence of changing the minimum parking bay utilisation on the persons per bay for the 'All' trip activity category.

4.3.3 Number of iterations

The Monte Carlo simulations used 10,000 sampling iterations. It is prudent to investigate whether 10,000 is sufficient to achieve convergence. Figure 6 shows the percentile persons per bay results for 10, 100, 1,000, 10,000 and 50,000 iterations of the 'All' trip activity category with the 0.05 minimum parking bay utilisation compared to the average of all results. For the 99th percentile only around 1,000 iterations are required to obtain a reasonable level of convergence, whereas around 10,000 iterations are necessary for the 80th and 95th percentiles.

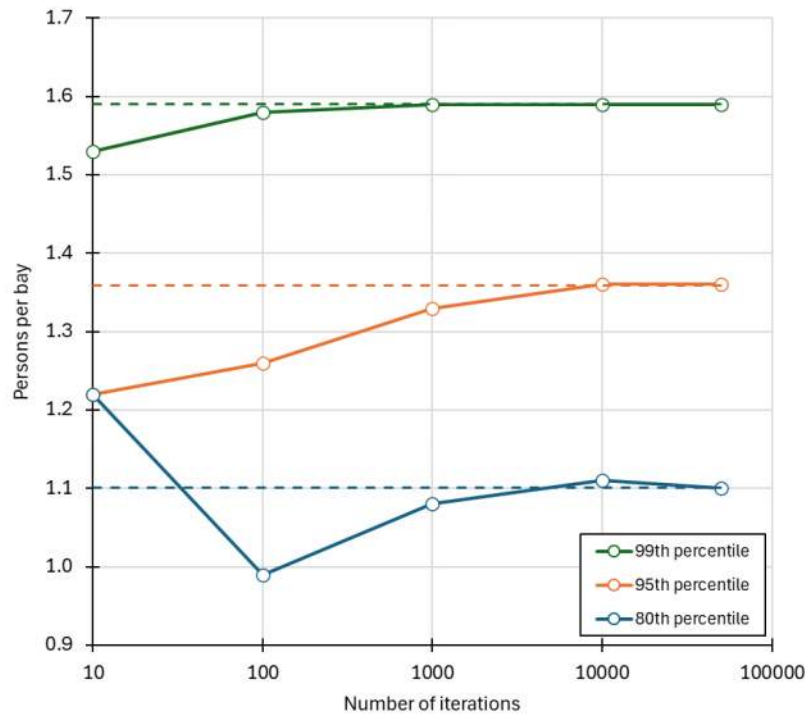


Figure 6. Number of iterations to reach convergence of the 99th, 95th and 80th percentile persons per bay for the 'All' trip activity category with the 0.05 minimum parking bay utilisation.

5 DYNAMIC PARKING ANALYSIS

5.1 Vehicle arrivals and departures

The analysis to this point is likely to be applicable to occupant evacuation assessment in the event of a fire in which an assumption is made that a very high proportion of the vehicle occupied bays have people present. This scenario might be more applicable to a car park that serves an entertainment-like occupancy in which many vehicle users enter a car park simultaneously at the end of some event. However, in car parks that serve other types of occupancy such as office, retail or residential it is likely that there will be a movement of vehicles in and out of the car park throughout the day.

An example in which vehicle movement is considered is given by Section 4.1.2 of the IStructE guidance [1] which states “As a general rule, the dynamic capacity should be sufficient to permit up to 25% of the static capacity to enter or leave the car park within 15 minutes (i.e., up to 100% turnover in an hour).” This guidance is similar to that given in Section 6.5 of Hill [3] which states “In the absence of more accurate information it is normal practise to assume that the peak flow rate in either direction will be 25% of the static capacity in any 15 minute period.”

To get the number of people in a car park at a given point in time one approach might be to carry out an analysis similar to that by Spearpoint and Hopkin [26]. The analysis would consider a simulation of the temporal entry and exit of vehicles along with an estimate of the time the drivers spend finding an empty space or the time it takes to exit the car park (t_{park}), the time spent accessing (i.e. loading or unloading from their vehicle) their vehicle (t_{access}), and the time spent moving to and from exits, e.g. a door on the parking floor to a stair core (t_{travel}).

The time spent can be expressed as a transition time (t_{tran}) such that:

$$t_{tran} = t_{park} + t_{access} + t_{travel}$$

The vehicle access time might be thought of as being analogous to the pre-evacuation time in conventional egress analysis. Data on vehicle entry and exits flows, etc. can be found in the literature such as from Ma et al. [24]. However, precisely simulating the flows of vehicles and people would be a complex task. Therefore, a simplified approach is taken herein as described below.

5.2 Time-to-park

Cherian et al. [23] developed a regression model for the time-to-park in relation to the number of available parking bays (Figure 7). The model assumes that the time-to-park increases with how full the car park is, as there will be fewer free bays which take longer to find.

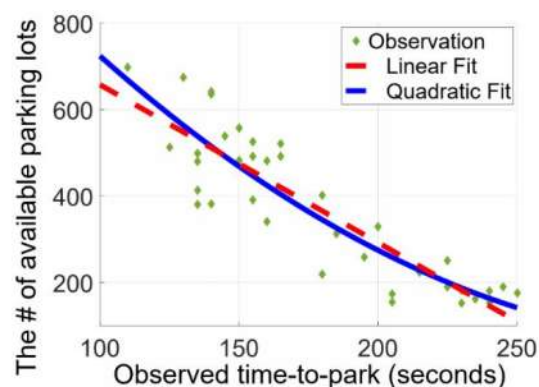


Figure 7. Regression model for the observed time-to-park against parking bay availability, extracted from Cherian et al. [23].

To use the regression model from Cherian et al. a linear fit is applied. The data comes from the previously mentioned Moscone Center garage which has 732 bays and therefore it takes 100 s to park when the parking bay availability is 1 (i.e., 732 / 732). Interpreting Figure 7 suggests that when 100 bays are free (i.e. the parking bay availability is 100 / 732 = 0.13) then it takes 250 s to park. Thus, for a linear model in the form $y = mx + c$ where m is the gradient and c is the intercept.

$$m = (0.13 - 1)/(250 - 100) = -0.0058$$

$$c = 1 - (100m) = 1.58$$

For a given parking bay availability $0 - 1$ (p), the time to park (t_{park}) in seconds is

$$t_{park} = \frac{(p - c)}{m}$$

$$t_{park} = \frac{(p - 1.58)}{-0.0058} \quad (1)$$

where the maximum time to park is around 275 s (notwithstanding that if there are no bays free then in practice the time to park is effectively infinity).

It is assumed for simplicity that the time for vehicles to leave the car park is also represented by Cherian et al.'s regression model. On the one hand assuming the time to exit the car park is the same as the time to find a bay may be an over-estimate as exiting does not require any time searching for an empty bay. However, as vehicles exit, they may need to pass through a barrier where there may be a queue particularly where there is a lower parking bay availability (i.e. the parking bay utilisation is high, meaning more of the bays are occupied by vehicles) and thus more vehicle movements occurring simultaneously.

One approach to determine the fraction of vehicles where the occupant are in transition (F_{tran}) is to apply Cherian et al.'s [23] regression to the IStructE guidance by assuming the time-to-park is the controlling factor. Thus, for a 25% turnover in 15 min:

$$F_{tran} = \frac{0.25 \times t_{park}/60}{15} \quad (2)$$

For $t_{park} = 100$ s then $F_{tran} = 2.8\%$ and for $t_{park} = 275$ s then $F_{tran} = 7.6\%$.

5.3 Vehicle access time

As noted in Section 5.1, it takes time for people to access (i.e. enter or exit) their vehicle as part of parking their car. There are a range of potential actions that might be required, such as:

- Unbuckling seatbelts,
- Gathering personal belongings,
- Ensuring the vehicle is locked and/or
- Exiting the vehicle and possibly waiting for passengers.

These actions will be compounded by factors, such as:

- Purpose of the visit (e.g., quick errands vs. longer stays),
- Number of occupants (a single driver vs. driver plus passengers),
- Accessibility needs (mobility impairments can increase access time),
- Weather conditions (rain or cold may prompt searching for umbrellas, coats, etc.),
- Vehicle type (a higher wheelbase vehicle like an SUV can facilitate easier access for some individuals, while a low-slung sports car may be more cumbersome).

A review of the literature found nothing on access times. Therefore, data has been collected as part of this study. Live webcam feeds from two car parks have been accessed to get observations. Neither car park had

entry or exit barriers and did not charge for parking. Both areas were uncovered and therefore allowed for the surveillance of a relatively large number of bays. Being outside also meant that vehicle occupants were exposed to the weather. This may have encouraged people to access their vehicle more quickly in poor weather, conversely, they would put on coats etc. which may not have happened if they were under cover.

Each vehicle movement involved that manual observation and recording of the time people took to make their access. When cars were entering a bay, the recorded time was between when the vehicle stopped and when the occupants walked away. When exiting a bay, the recorded time was between when the people began the process of entering their vehicle and once it had pulled out of the bay. Any time spent to reposition the parking of a vehicle (i.e. backing in and out to adjust the vehicle alignment) has not been included. The times are necessarily approximate as judgements were needed to decide when a vehicle had finally stopped etc. but are generally considered to be within ± 2 s of 'actuality'.

Observations were mainly made during daylight hours as the quality on the images degraded during the night. The number of people, and whether the people were adults, children (i.e. aged approximately 5 to 12 years), toddlers (i.e. aged approximately between 2 and 4 years), babies, and elderly was noted. The actions of people using the seats and/or the boot to place or collect items was noted. Factors such as the type of vehicle (e.g. number of doors, whether it was an SUV, etc.), the duration of its stay were not noted.

The analysis herein focuses on observations from 'The Green' (see Section 5.3.1) since it had a greater diversity of parking activities, in which a larger dataset has been collected. Much of the data has focused on the weekends as this seemed to be where more family groups etc., were using the car park. However, it is recognised that this means the data is limited to one specific car park, over a relatively few partial days and so not every vehicle access time has been observed on the days monitored.

The data also includes records in which people stayed in their cars to eat, etc. Since this analysis is assessing the types of car parks in which occupants do not stay in their car as an integral activity it is realistic to exclude those records from the dataset. To determine an appropriate cut off limit for these excessive time periods, typical durations allowed for free parking in short-stay car parks have been examined. These times likely correspond to what parking operators consider to be reasonable upper times that people need when entering or exiting their vehicle to continue on to other activities without undue waiting around. Discussions regarding grace periods and consideration periods can be found on various websites, for example UK Parking Patrol Office Ltd[†] notes:

"The 10 minute grace period will begin immediately after your permitted period of parking ends. So if you have parked for an hour you should be given an extra 10 minutes to exit the car park before you are issued with a parking charge notice [...] the grace period is the amount of time you are allowed to get back to your car if you slightly overstay your permitted period of parking [...] Under the new code of practice from the British Parking Association and International Parking community the consideration period, which should be a minimum 5 minutes, is the time given to motorists to allow them to read the signage, check out the charges and find a parking space."

A search across various websites has found that airport drop off times are typically in the range between 10–20 min. Considering these findings regarding grace periods, consideration periods and drop off times a cut off of 15 min (900 s) is applied herein. Access times longer than 15 min have been omitted from the analysis.

5.3.1 'The Green', Hunstanton, Norfolk

The car park is an outside parking area located next to a green space opposite a hotel. The area monitored had space for around 20 vehicles. Parking bays are not marked on the ground therefore the space between vehicles varied as they arrived and left. During weekends visitors to the parking area were a mixture of family

[†] What is the 10 minute grace period for parking law in UK? parkingpatrol.co.uk/what-is-the-10-minute-grace-period-for-parking-law-in-uk

groups, couples, etc. which appeared to be primarily on leisure activities throughout much of the day. During weekdays there were several vehicles that regularly parked in the morning with a single adult occupant suggesting the users were workers. The longest time recorded was for three adults and child to exit their vehicle 27 min 45 s (1,665 s) after parking in which it appeared they stayed in the vehicle to eat.



Figure 8. Car parking at 'The Green', Hunstanton, Norfolk, (top) Image taken from live feed, hunstanton.webcam/the-green, (bottom) image from Google Streetview towards camera location.

Early in the morning the parking area had few vehicles parked, of the order of 3 or 4. Vehicles arriving in the morning predominately had only a single occupant who likely was arriving for work or similar. During the main part of the day, the parking area generally had a utilisation of between 0.8 and 1. The maximum number of observed concurrent vehicle accesses was no more than three, where three was very rare (once or twice over the whole sampling period).

A total of 433 vehicle movements were observed involving 848 people, averaging to 1.96 persons per vehicle. This average is similar to the 'Other' trip activity in the National Travel Survey statistics reported in Table 3. Figure 9 shows the share of vehicles with different occupant numbers in which a comparison of the National

Travel Survey for 'Other / Day trip' shows a lesser share of vehicles containing three persons whereas vehicles containing two persons exceeds the National Travel Survey.

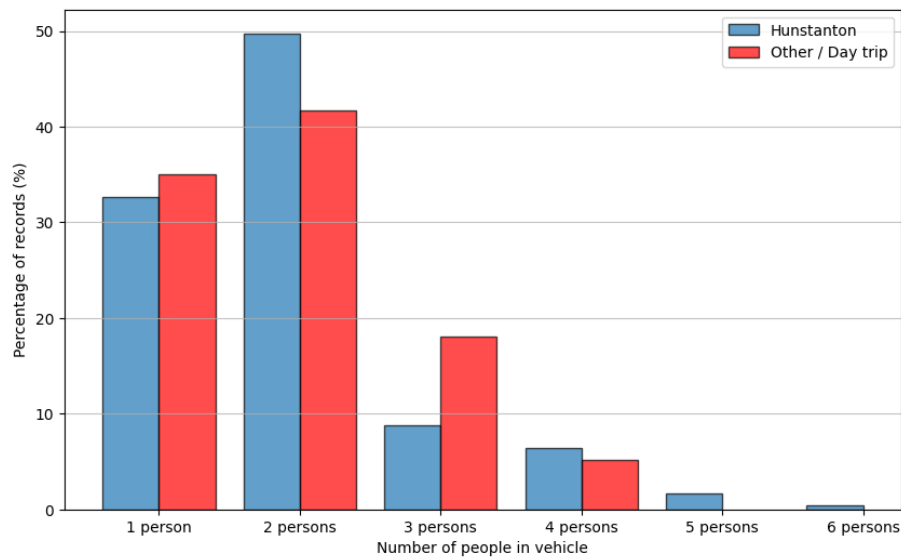
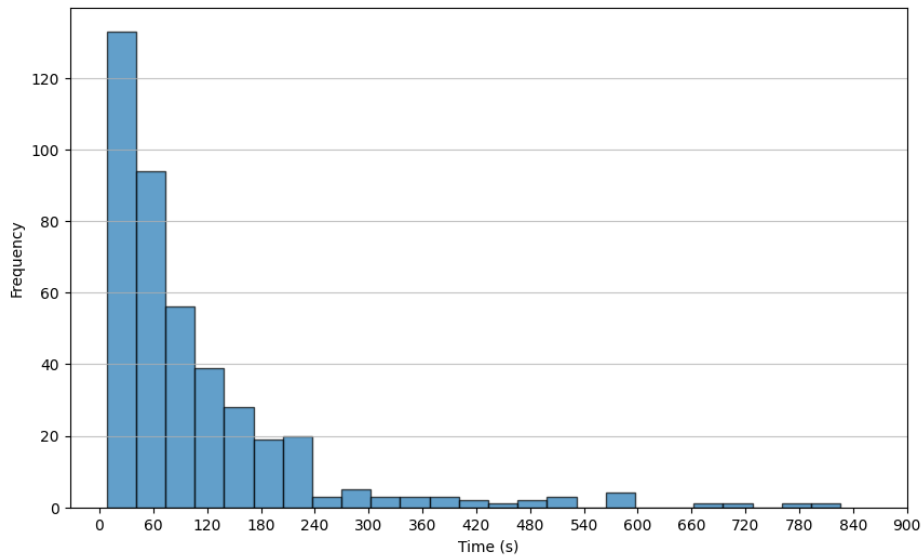
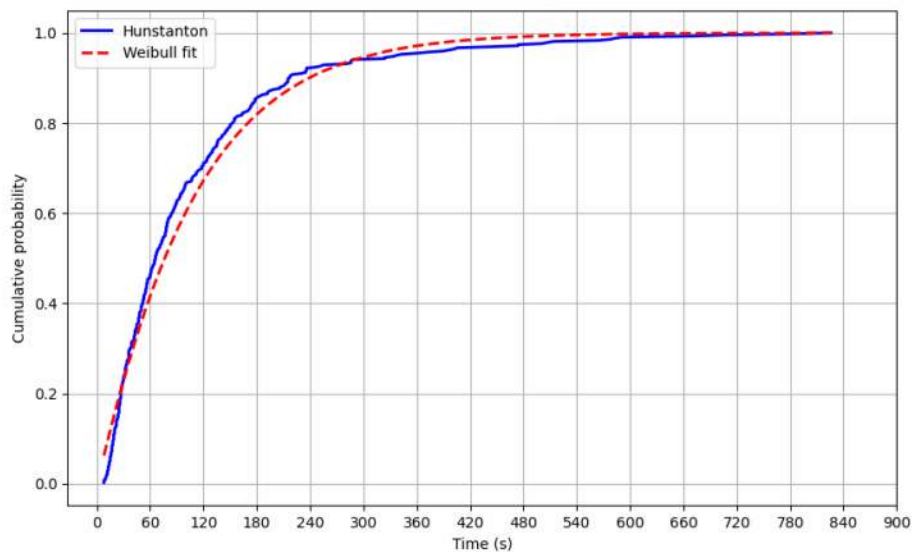


Figure 9. Occupant number frequency for 'The Green' compared to the National Travel Survey for 'Other' / 'Day trip' activities.

Figure 10a shows a histogram of the access time of all 422 records excluding times that exceed 15 min. Figure 10b shows the same data as a cumulative probability function with a Weibull best-fit curve with its offset at the origin. The vehicle access times have an 80th percentile of 153 s, 95th percentile of 337 s, and a 99th percentile of 589 s.



(a)



(b)

Figure 10. 'The Green' vehicle access times (a) frequency (b) cumulative probability.

5.3.2 Mansfield Road, Shreveport, Louisiana, USA

A second car park was monitored, but not to the same level as the one in Hunstanton. This was located outside a barbeque restaurant on Mansfield Road in Shreveport, Louisiana, USA (Figure 11) which includes a takeaway menu. 19 marked bays were monitored of which four were disabled bays in front of the building. The disabled spaces were used infrequently during the observations, mainly by people who appeared not to have an visible disability.

Shipp Outdoor Live Traffic Camera
9838 Mansfield Road, Shreveport, LA
North Face

2025-02-03 CST 07:23:12



Figure 11. Car parking at Mansfield Road, Shreveport, Louisiana, USA, (top) Image taken from live feed, www.insecam.org/en/view/757737/, (bottom) image from Google Streetview towards camera location.

In general vehicles were able to rapidly park up and often only a single adult was seen accessing the vehicles (Figure 12) in which the distribution corresponds to a 'Commuting' activity trip. The access times were quicker than observed for 'The Green' (Figure 13). The vehicle access times have an 80th percentile of 60 s, 95th percentile of 130 s, and a 99th percentile of 248 s. These results illustrate the potential diversity of parking times that depend on the travel activity of the vehicle occupants. The data from the Mansfield Road car park has not been used in the analysis because of the noticeably more rapid access times when compared to 'The Green'.

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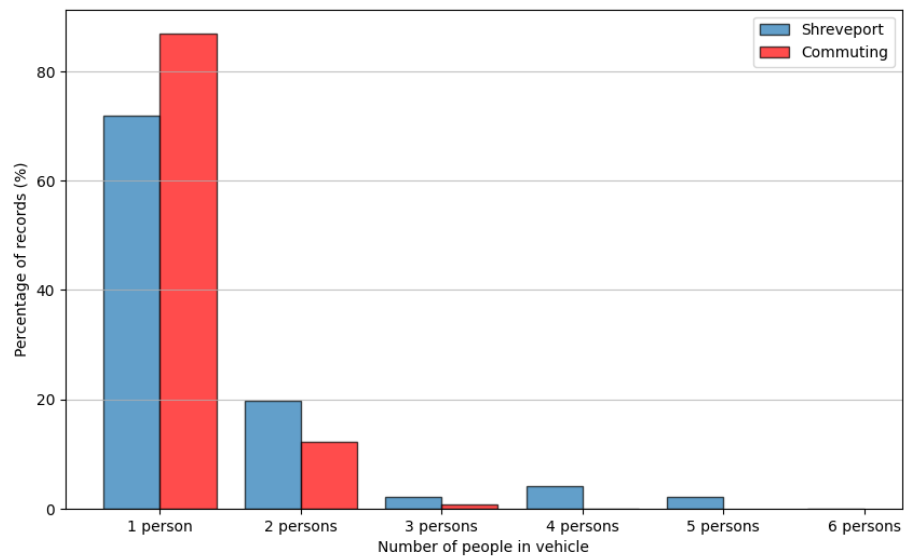
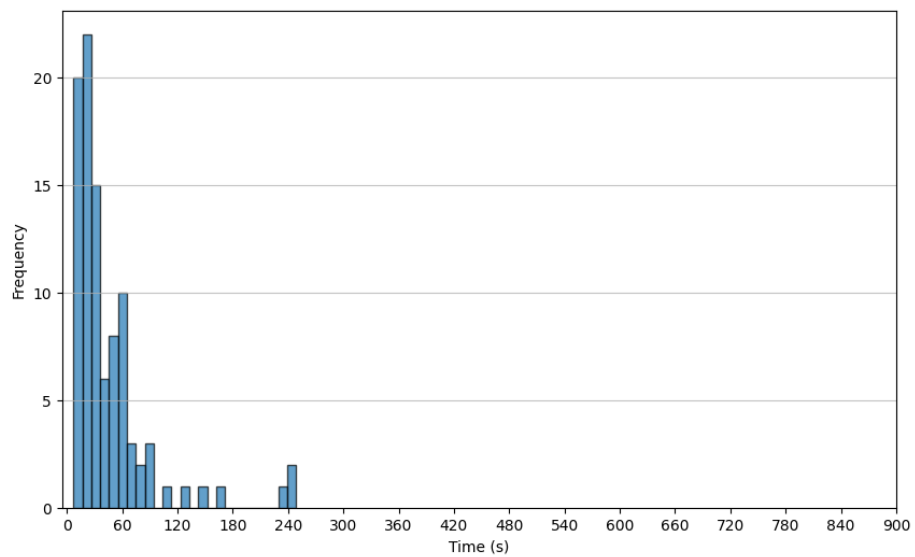
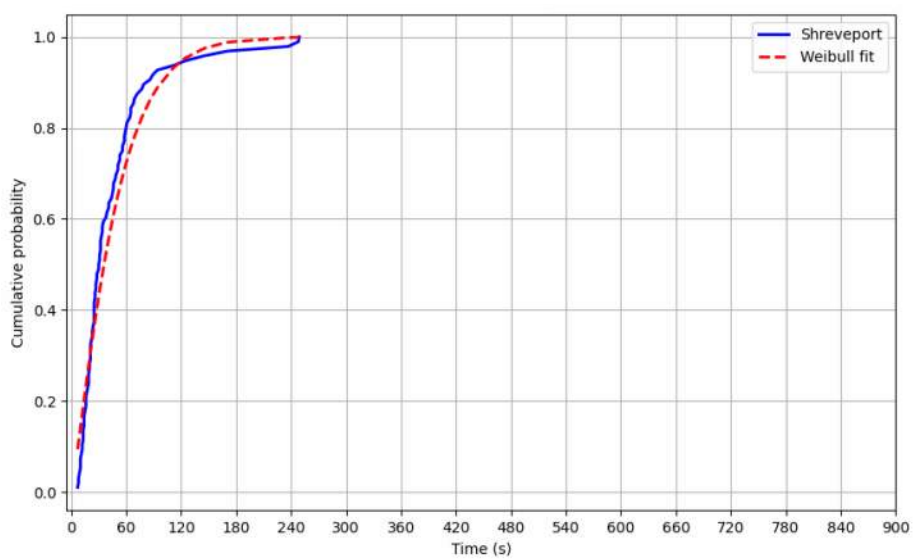


Figure 12. Mansfield Road, Shreveport occupant number frequency compared to the National Travel Survey.



(a)



(b)

Figure 13. Mansfield Road, Shreveport vehicle access time (a) frequency (b) cumulative probability.

5.4 Travel time

The travel time is the time required for people to walk to and from their vehicles to get to the floor exit (or equivalent) of the car park. For the exemplar 1000 bay car park investigated herein a simple approximation is made where it is assumed the parking area has a square footprint, the travel distance is the sum of the parking bay widths, and the people have parked in the centre of the parking bay arrangement. Assuming the bays are 2.7 m wide equivalent to short-stay parking (Table 1), then the travel distance is:

$$d_{travel} = \sqrt{2.7 \times 1000} = 52 \text{ m}$$

In reality some of the people in the car park will only need to travel a lesser distance depending on how close they park to an exit. It should also be noted that ADB does not recommend a maximum travel distance for multi-storey car parks, and the longest distance ADB gives for enclosed spaces is 45 m.

Adapted from the work of Spearpoint et al. [27], Table 8 shows that the unimpeded walking speed is assumed to depend on the likelihood that people have movement impairments, and whether they are dependent on others to help them. For a travel distance of 52 m, using the walking speeds given by Table 8 in the range 0.1 m/s to 1.4 m/s, then travel times could be from 37 s up to 520 s.

Table 8. Type of population and unimpeded movement speed used in the simulations.

Population type	Percentage of population	Walking speed	Lower and upper travel times t_{travel} (s)
Non-movement impaired person	80%	Uniform distribution of 1.0 m/s to 1.4 m/s	37 – 52
Movement reduced person	15%	Uniform distribution of 0.4 m/s to 0.8 m/s	65 – 130
Movement dependent person	5%	Uniform distribution of 0.1 m/s to 0.5 m/s	104 – 520

The likelihood of having a movement dependent person with the slowest walking speed of 0.1 m/s is low, therefore a separate Monte Carlo simulation has been carried out using the percentages and walking speed ranges in Table 8. Figure 14 shows the cumulative probability distribution from 100,000 iterations in which the 1st percentile walking speed is 0.18 m/s, which gives an assumed travel time for the exemplar car park of $52 / 0.18 = 290$ s, and a 5th percentile walking speed of 0.42 m/s which results in a travel time of around 125 s.

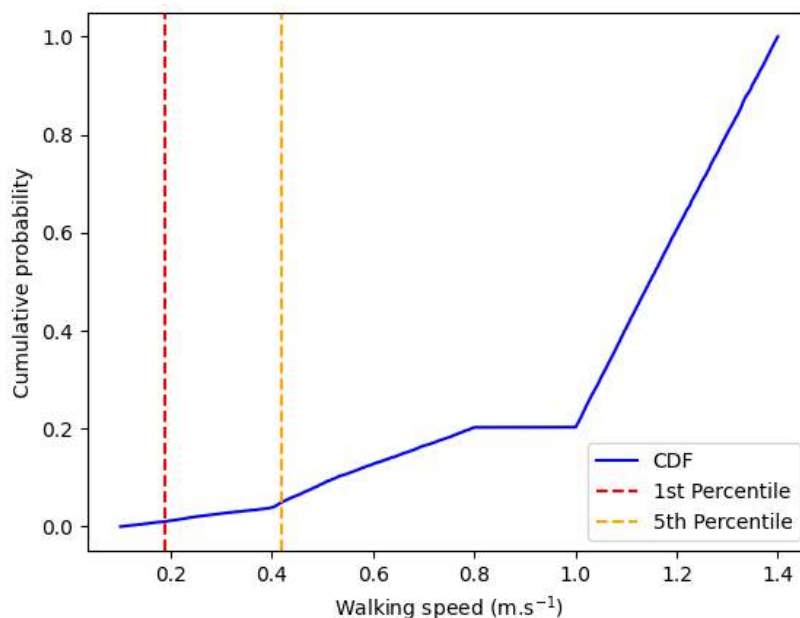


Figure 14. Cumulative probability distribution for 100,000 iterations for walking speed using Table 8.

5.5 Entry and exit flow

The movement of vehicles within a car park is needed to determine whether a vehicle is occupied at the time a fire starts in a car park. Vehicle entry and exit flow has been reported by Ma et al. [24] in which their data is divided into 15-min intervals across a whole day as shown in Figure 15.

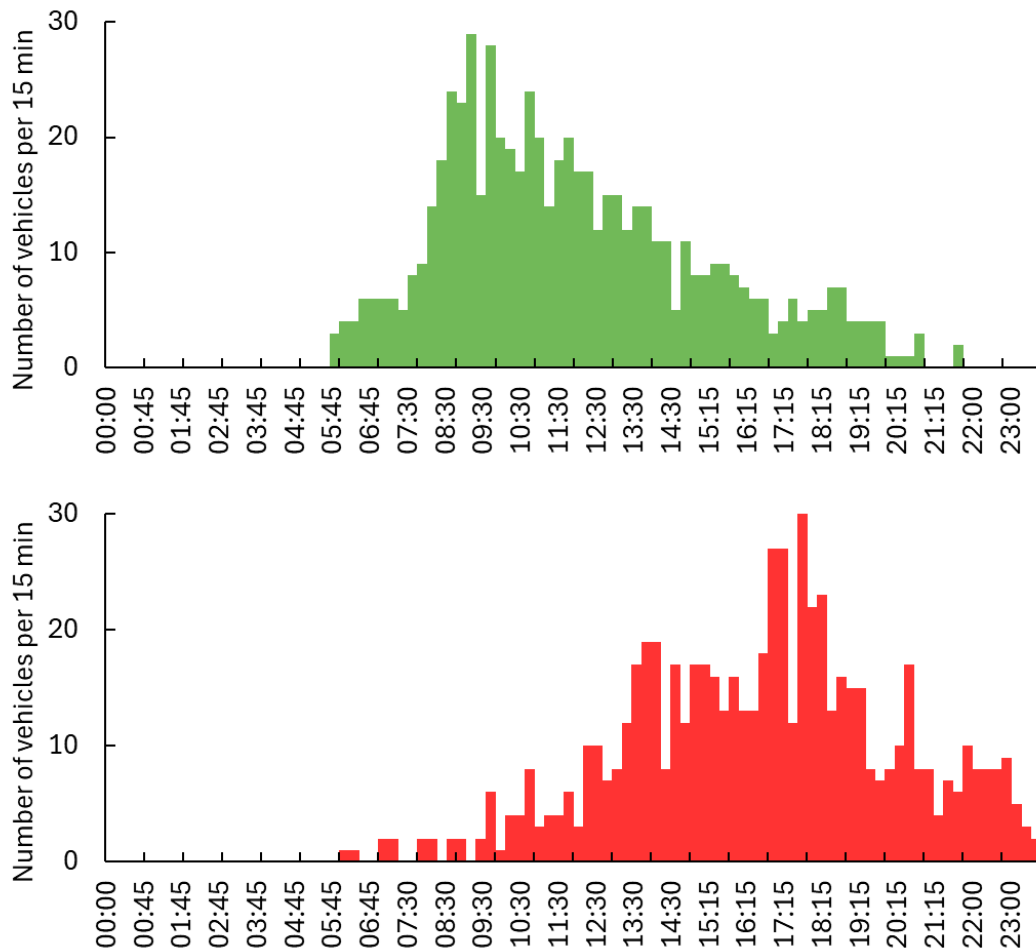


Figure 15. Vehicle entry (top) and exit (bottom) flow, extracted from Ma et al. [24]

As part of this analysis Ma et al.'s interval data have been expressed in 1-min intervals by slicing each 15 min interval into 15 sub-records so that the entry or exit flow is 1/15 the original interval value. These 1-min vehicle entry and exit values are used to determine the flow as a fraction of the available parking bays (where Moscone Center car park has 732 bays). This allows the flows to be used for a car park with any number of available bays. However, examination of Ma et al.'s data reveals that maximum entry and exit flows do not exceed much more than 35 vehicles per 15-min period. Given the static capacity is 732 bays, this means that there is a turnover of not more than $35 / 732 = 0.05$ (), i.e. 5 % compared with 25 % as given in the IStructE guidance.

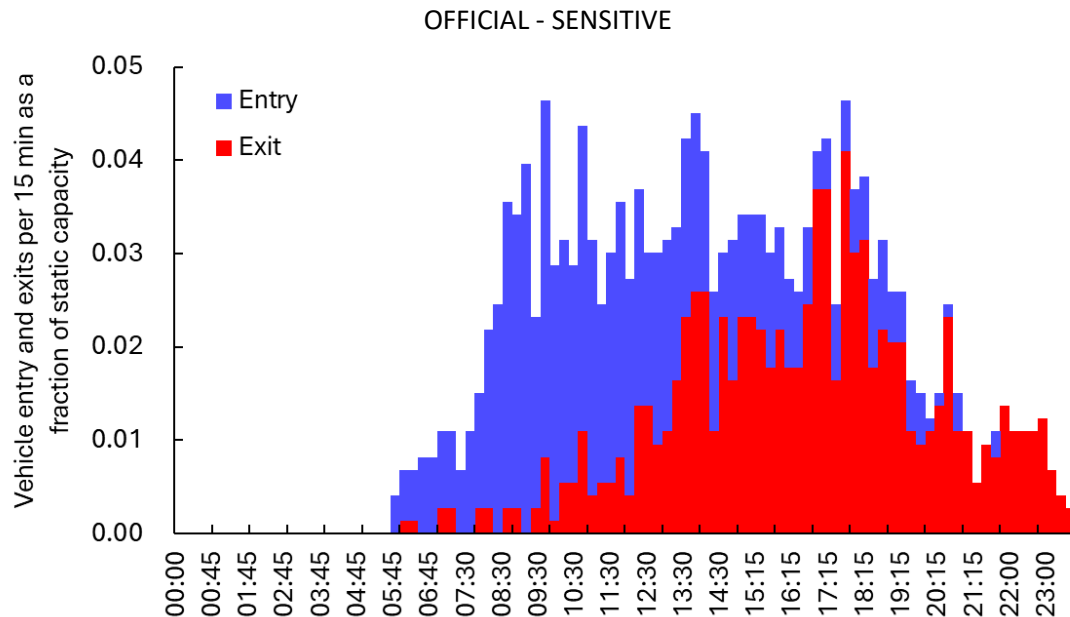


Figure 16. Number of vehicles entering and exiting per 15-min period as a fraction of the static capacity from Ma et al.

Entry and exit flows have also been recorded for 'The Green' in which 15-min intervals have been taken over several days (see Appendix B). Although the data has not been collected for full days but only partial days, it has been consolidated into the 95th percentile integer number of vehicles that entered and exited for each interval, as shown in Figure 17. Results show that up to seven vehicles entered and exited over more than one 15-min period, i.e. 35 % of the static capacity, where a more typical number is five vehicles (i.e. 25 % of the static capacity) which aligns with the IStructE guidance.

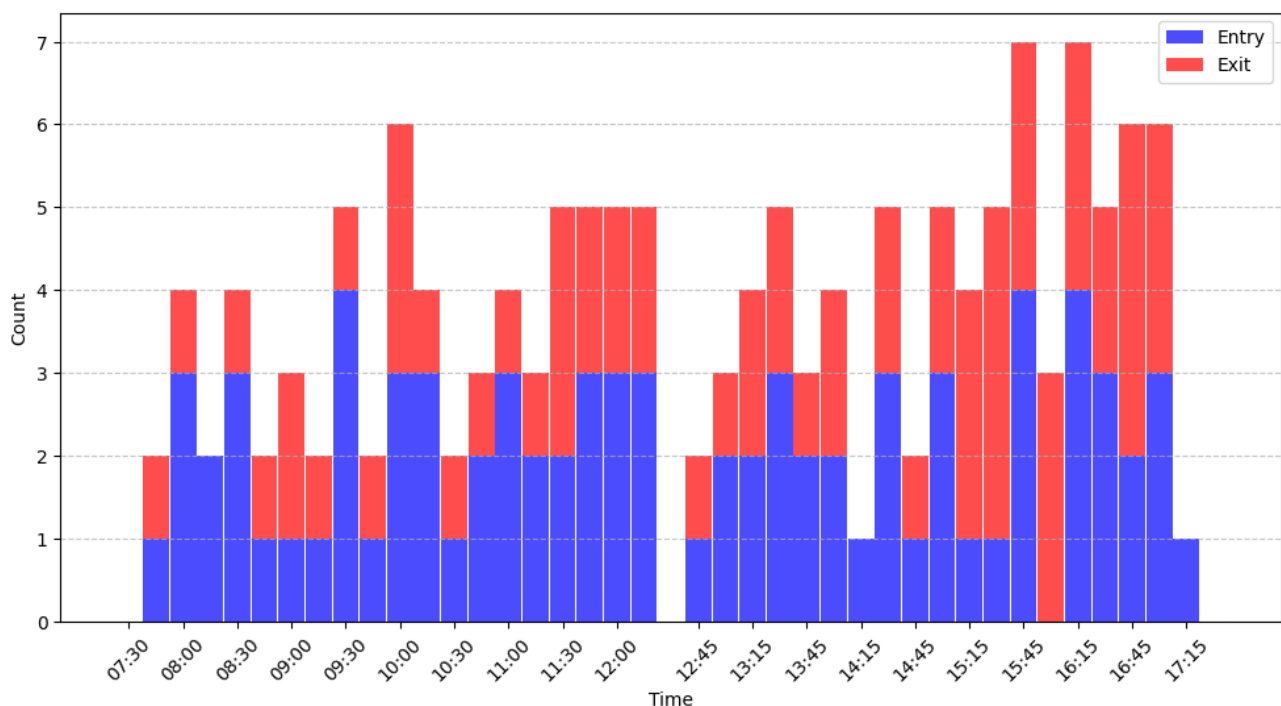


Figure 17. 95th percentile number of vehicles entering and exiting 'The Green'.

5.6 Car park occupancy

The dynamic car park occupancy, i.e., those occupants of vehicles within the car park at any given time either because they have arrived or are in the process of exiting, can be determined by considering how many

occupants of vehicles are simultaneously undertaking activities that form the transition time. In practice, the transition time associated with the occupants of any given vehicle is probabilistic. However, a conservative representation can be established via a semi-probabilistic transition time, comprising appropriately high / low percentile inputs for the time-to-park, access time and travel time. The flow rate of vehicles in/out of the car park during this transition time is then used to estimate the dynamic occupancy.

The time-to-park (t_{park}) is taken from the Cherian et al. regression, as discussed in Section 5.2. Access times (t_{access}) for either the 99th or 95th percentiles from the analysis of 'The Green' car park (i.e. 589 s and 337 s), as discussed in Section 5.3, are considered here. Travel times (t_{travel}) of either 290 s or 125 s are included using the analysis discussed in Section 5.4.

5.6.1 Vehicles with occupants in transit, based on Ma et al.

The summed rolling transition window fractions are determined as a function of the time of day. From this, the maximum fraction of bays with simultaneous occupant transition (F_{tran}) is determined when the car park is initially empty and when it is full.

Figure 18 shows the fractions when the 99th percentile $t_{access} = 589$ s and $t_{travel} = 290$ s are used. F_{tran} ranges from 0.051 (5.1 %) when the bays are free to 0.059 (5.9 %) when the bays are full, i.e. at most around 5% of vehicles have occupants in transition at the same time. This result is as expected when considering the comments made in Section 5.5 in which the maximum vehicle turnover was estimated to be around 5%.

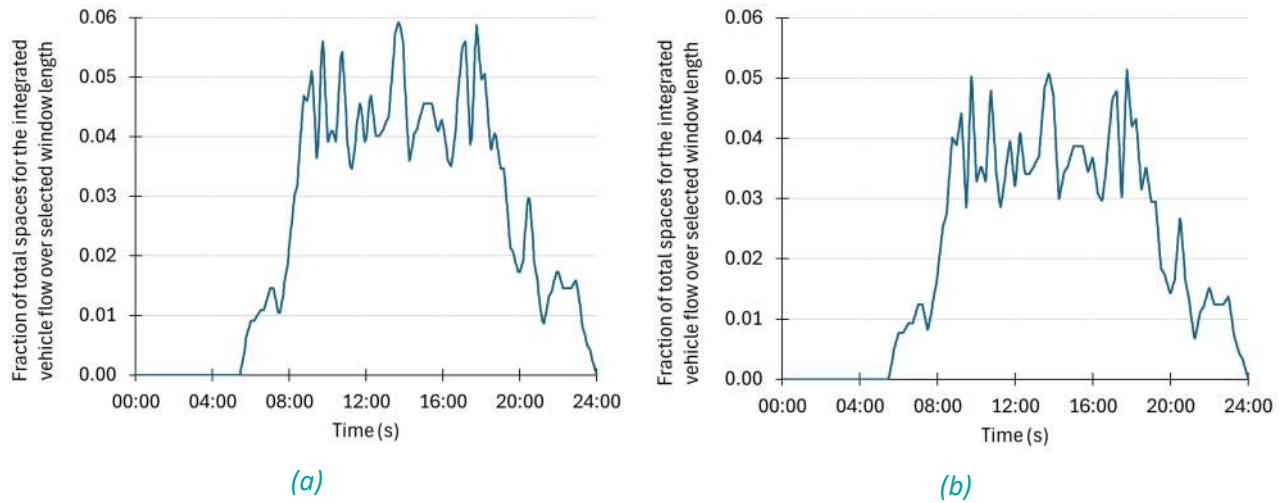


Figure 18. Fraction of parking bays with 99th percentile simultaneous occupant transition (a) when all parking bays are occupied, i.e. the utilisation is 1 so that the time-to-park is 275 s (b) when all parking bays are free, i.e. the utilisation is 0 so that the time-to-park is 100 s.

Similarly, the fractions when the 95th percentile $t_{access} = 337$ s and $t_{travel} = 125$ s are used. F_{tran} ranges from 0.031 (3.1 %) when the bays are free to 0.040 (4 %) when the bays are full.

A simple linear model in the form $y = mx + c$, where m is the gradient and c is the intercept, can be developed to express the fraction of parking bays with simultaneous occupant transition as a function of the utilisation (u between 0 and 1). For the 99th percentile results, this gives:

$$m = (0.051 - 0.059)/(1 - 0) = -8 \times 10^{-3}$$

$$c = 0.046 - m = 5.9 \times 10^{-2}$$

thus

$$F_{tran,99} = -8 \times 10^{-3}u + 6 \times 10^{-2} \quad (3)$$

and for the 95th percentile:

$$F_{tran,95} = -9 \times 10^{-3}u + 4 \times 10^{-2} \quad (4)$$

5.6.2 Vehicles with occupants in transit, based on the IStructE guide

This analysis using the data of Ma et al. under-estimates the flow of vehicles compared with the IStructE guidance resulting in low persons per parking bay values. Therefore, alternatively the number of vehicles with occupants simultaneously in transit (V_{tran}) can be computed on the presumption that one quarter of the car park occupancy turns over every 15 min, i.e.

$$V_{tran} = \frac{0.25S_{cap}}{900} (t_{park} + t_{access} + t_{travel}) = \frac{0.25S_{cap}}{900} t_{tran}$$

which if normalised by the car park static capacity S_{cap} becomes:

$$F_{tran} = \frac{V_{tran}}{S_{cap}} = \frac{0.25}{900} (t_{park} + t_{access} + t_{travel}) = \frac{0.25}{900} t_{tran} \text{ or } 2.78 \times 10^{-4} t_{tran}$$

For the 99th percentiles, t_{tran} ranges between $100 + 589 + 290 = 979$ s and $275 + 589 + 290 = 1154$ s, depending on the initial car parking bay utilisation. This results in $F_{tran} = 27\text{--}32\%$ per vehicle. For the 95th percentiles, t_{tran} ranges between $100 + 337 + 125 = 562$ s and $275 + 337 + 125 = 737$ s, then $F_{tran} = 16\text{--}20\%$ per vehicle. The calculated values are similar to the IStructE guidance and also the findings from 'The Green' in Section 5.5.

As above, a simple linear model in the form $y = mx + c$, where m is the gradient and c is the intercept, can be developed to express the fraction of parking bays with simultaneous occupant transition as a function of the parking bay utilisation (u between 0 and 1). At the 99th percentile, the constants m and c are derived below, with the resulting correlations expressing the fraction of parking bays with simultaneous occupant transition as a function of the parking bay utilisation for the 99th and 95th percentiles:

$$m = (0.32 - 0.27)/(1 - 0) = 0.05$$

$$c = 0.32 - m = 0.27$$

thus

$$F_{tran,99} = 5 \times 10^{-2}u + 2.7 \times 10^{-1} \quad \text{for 99th percentile } t_{access} + t_{travel} \quad (5)$$

and

$$F_{tran,95} = 4 \times 10^{-2}u + 1.6 \times 10^{-1} \quad \text{for 95th percentile } t_{access} + t_{travel} \quad (6)$$

5.6.3 Application to the Monte Carlo process

The simulations described in Section 4.3 are modified to account for the occupant transitions such that Step 4 now becomes:

4. The total number of people in those parking bays in which a vehicle is present AND that the parking bay is one in which there is occupant transition.

5.6.4 Dynamic occupancy findings

Table 9 shows the 99th percentile results with the 99th percentile transition time and similarly, Table 10 shows the 95th percentile results with the 95th percentile transition time. Both tables also show the previous results from Table 7 and the average vehicle occupancies given by Table 3. As expected, accounting for the transition time results in noticeably smaller persons per bay values.

Table 9. 99th percentile persons per bay from Monte Carlo simulations compared with average vehicle occupancies given by Table 3, modified trip activity in Table 6 and the stationary analysis in Table 7.

Trip activity	Average occupancy	Modified trip activity	Parking bay utilisation of 1	Simulated parking bay utilisation	Simulated parking bay utilisation and IStructE transition time	Simulated parking bay utilisation and Ma et al. transition time
Commuting	1.16	1.13	1.17	1.14	0.38	0.07
Education	1.95	1.90	2.00	1.95	0.64	0.12
All	1.61	1.58	1.64	1.59	0.52	0.10
Households	2.33	1.52	2.34	2.27	0.75	0.14

Table 10. 95th percentile persons per bay from Monte Carlo simulations compared with average vehicle occupancies given by Table 3, modified trip activity in Table 6 and the stationary analysis in Table 7.

Trip activity	Average occupancy	Modified trip activity	Parking bay utilisation of 1	Simulated parking bay utilisation	Simulated parking bay utilisation and IStructE transition time	Simulated parking bay utilisation and Ma et al. transition time
Commuting	1.16	1.12	1.16	0.97	0.19	0.03
Education	1.95	1.88	1.98	1.66	0.33	0.06
All	1.61	1.56	1.62	1.36	0.27	0.05
Households	2.33	1.50	2.32	1.95	0.38	0.07

6 CONCLUSIONS

The findings from this study suggest that the design values given in Table 11 can be considered for determining the occupant load of a car park for three groups of trip activity categories. The persons per parking bay values when including occupant transition are based on the application of the IStructE guidance for the turnover of vehicles (see Section 5.6.4). These trip activity categories are associated with the building types related with parking as indicated. It is unclear which design value might be most appropriate for residential occupancies. In such buildings the residents will be coming / going to other activities, whether that be going to work, going on holiday etc. at different times of the day. At this point it would seem the 'All' trip activity category would incorporate the range of times and activities.

Table 11. Proposed design values for expected number of persons per bay.

Trip activity	99 th percentile persons per parking bay		95 th percentile persons per parking bay		Likely building types associated with parking
	When all vehicles are occupied concurrently	When occupant transition is considered	When all vehicles are occupied concurrently	When occupant transition is considered	
Commuting / Business	1.2	0.4	1.0	0.2	Offices
Education / Holiday	2.0	0.6	1.7	0.3	Airports, schools, tertiary institutions
All / Shopping / Leisure	1.6	0.5	1.4	0.3	Retail, entertainment, residential, mixed use

The proposed design value for 'Education' / 'Holiday' when all vehicles are assumed to be occupied concurrently is the only case which matches the 2 persons per parking spaces (bay) guidance given in AD B. All the other proposed values are less than that given by AD B. The persons per bay values that includes occupant transition are around 20 to 30 % of the values when it is assumed that all vehicles are occupied concurrently.

The analysis presented in this study has several limitations. The literature sources consulted for parking bay utilisation provides data that is at least a decade or so old and is not from the UK (and are likely all from San Francisco). Furthermore, the utilisation data only comes from car parks that were likely associated with office and retail occupancies. The time-to-park regression model is derived from a single car park, as is the vehicle access time distribution. Certainly more data would increase the robustness of the analysis. However, inevitably it is not always possible to identify such data from the open literature.

In part to counter the limitations with the data, the design values in Table 11 are derived from 95th or 99th percentile outcomes which, as noted in Section 3.2, are conservative when compared with other safety fields. However, by using the 99th percentile results from the Monte Carlo simulations this study suggests that the average vehicle occupancies for different trip activities published in the National Travel Survey [19] in Table 3 give sufficient design values for persons per bay when it is assumed all vehicles are occupied concurrently. The 95th percentile results give reduced persons per bay values when compared with the 99th percentile results and likely provide pragmatic design values.

For arriving at proportionate fire safety measures for a car park, it is the authors' view that the dynamic occupancy, i.e., those bays in which a vehicle is present AND that the bay is one in which there is occupant transition, could form the basis of assessment. This is because the dynamic capacity better reflects the number of occupants likely to be exposed to a fire hazard if one should occur. The implications of this are shown in Table 12 for the exemplar 1,000 bay car park.

Table 12. Implications of 95th percentile design values for the exemplar 1000 parking bay car park

Trip activity	Likely building types associated with parking	95 th percentile persons per parking bay		95 th percentile occupancy for a 1,000 bay car park		AD B occupancy
		When all vehicles are occupied concurrently	When occupant transition is considered	When all vehicles are occupied concurrently	When occupant transition is considered	
Commuting / Business	Offices	1.0	0.2	1,000	200	2,000
Education / Holiday	Airports, schools, tertiary institutions	1.7	0.3	1,700	300	
All / Shopping / Leisure	Retail, entertainment, residential, mixed use	1.4	0.3	1,400	300	

The work could be further extended to apply different car park utilisations that depend on the trip activity type should more data be identified (see Section 4.3.1). The opportunity to collect more car parking activity observations is ever present. This could include more data on the number of vehicles arriving and leaving car parks (see Section 5.1) as a comparison with the guidance from the IStructE. It could be useful to continue to observe vehicle access times for the already identified car parks (see Section 5.3), along with other car parks. It is likely that including additional data will incur diminishing returns when determining the cumulative probability distribution but may identify further specific access times for cases of people using mobility devices or those with young children (see Appendix C).

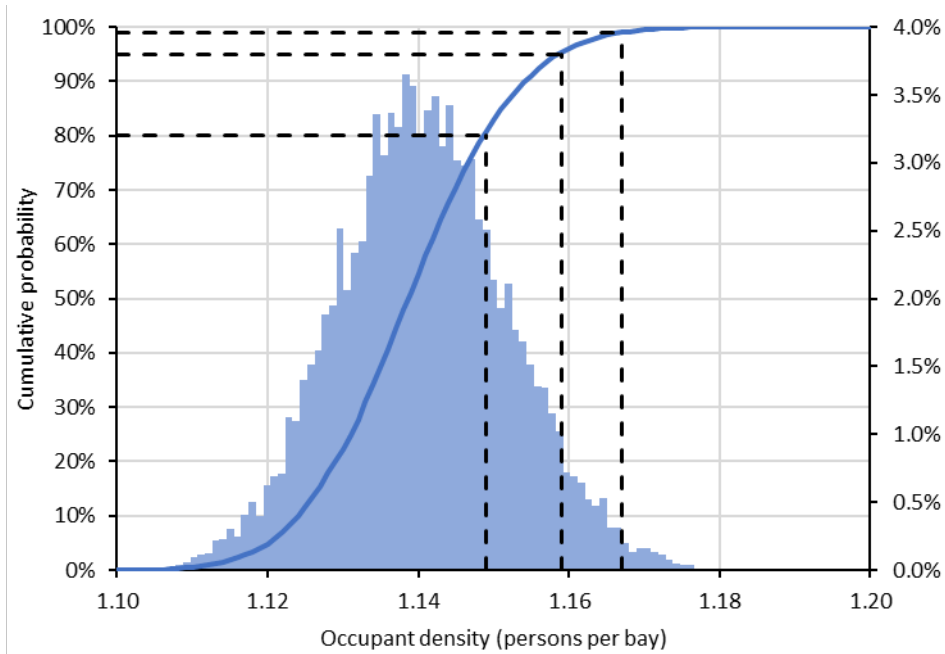
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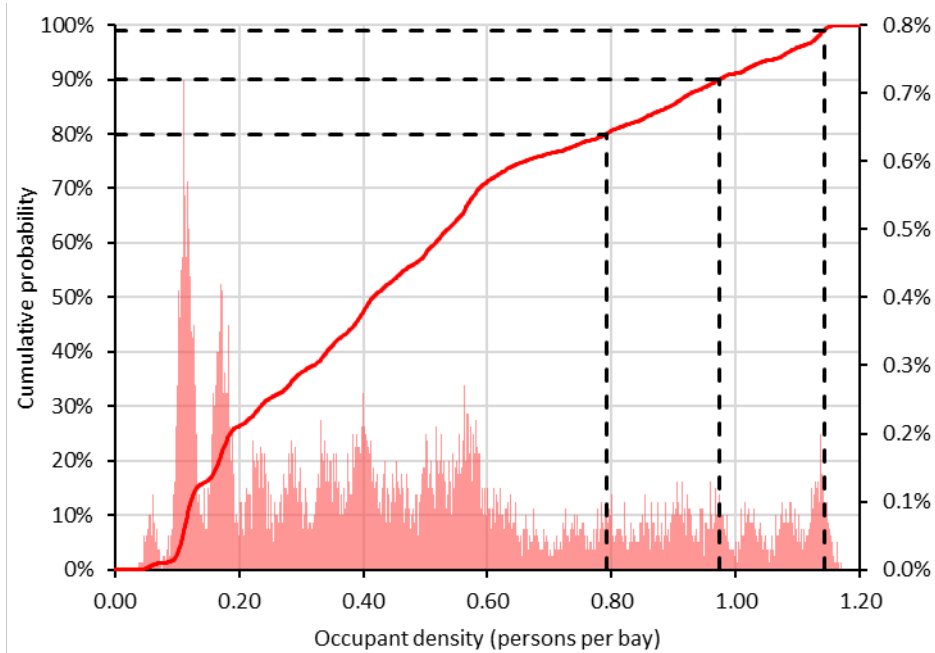
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Appendix A

Cumulative density and probability density (Commuting)

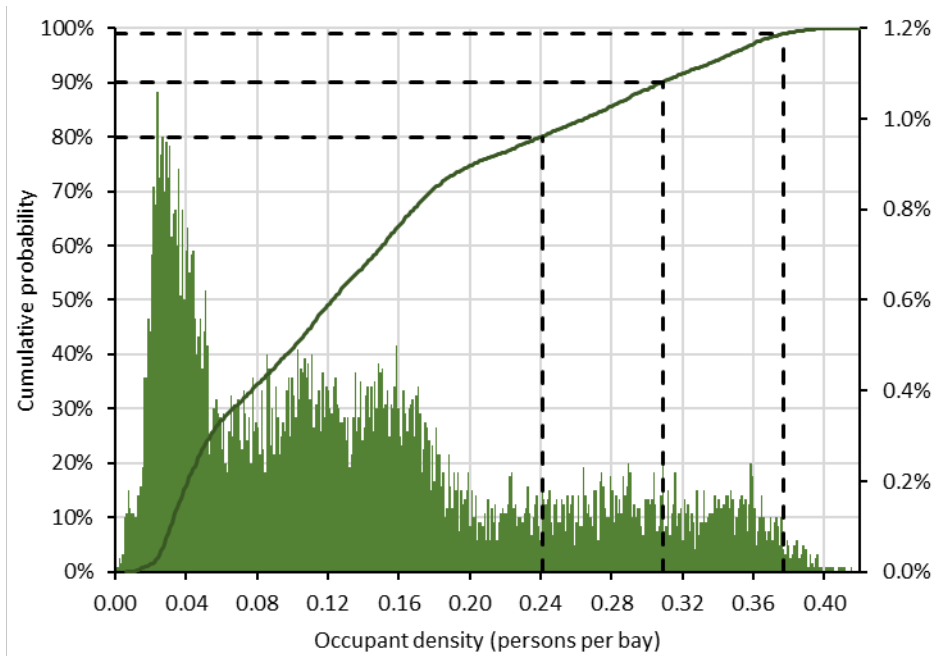


(a) 100% parking space use



(b) Simulated parking space use

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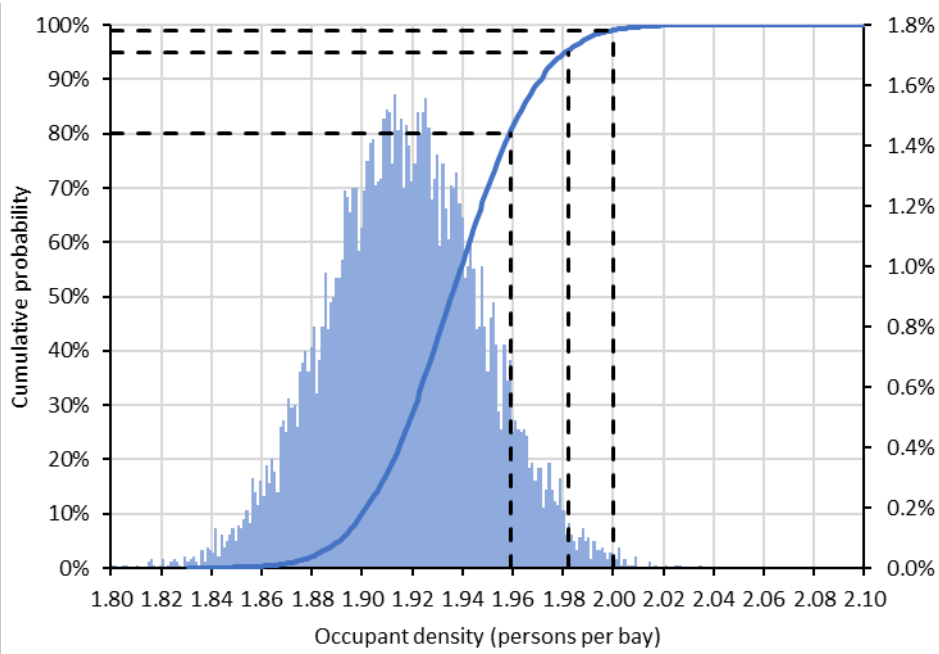


(c) Simulated parking bay utilisation with 99th percentile transition time

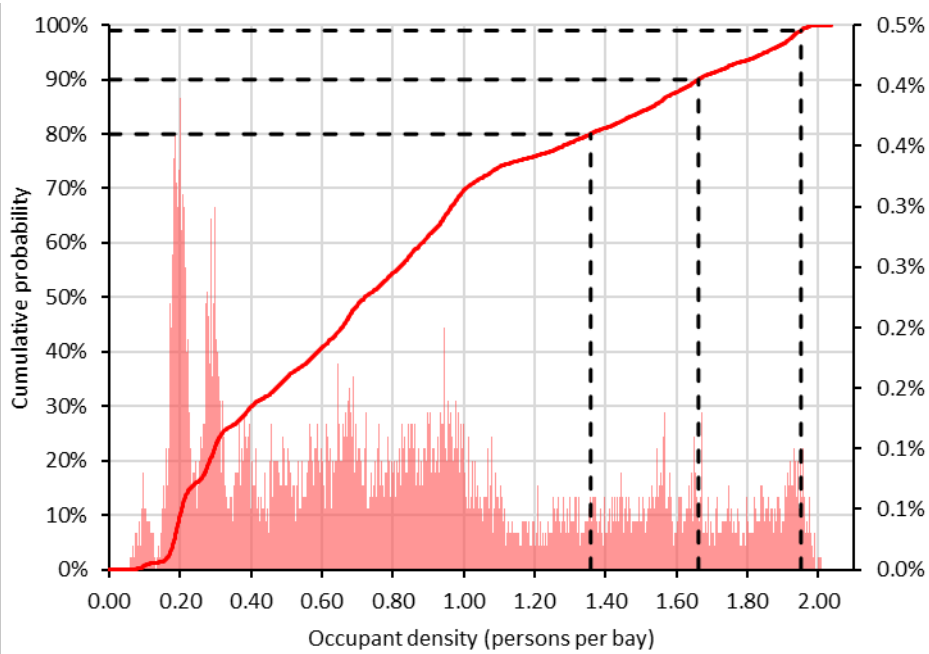
Persons per bay

Statistic	Parking bay utilisation of 1	Simulated parking bay utilisation	Simulated parking bay utilisation with 99 th percentile transition time	Simulated parking bay utilisation with 95 th percentile transition time
80 th percentile	1.15	0.79	0.24	0.15
95 th percentile	1.16	0.97	0.31	0.19
99 th percentile	1.17	1.14	0.38	0.24

Cumulative density and probability density (Education / Other)

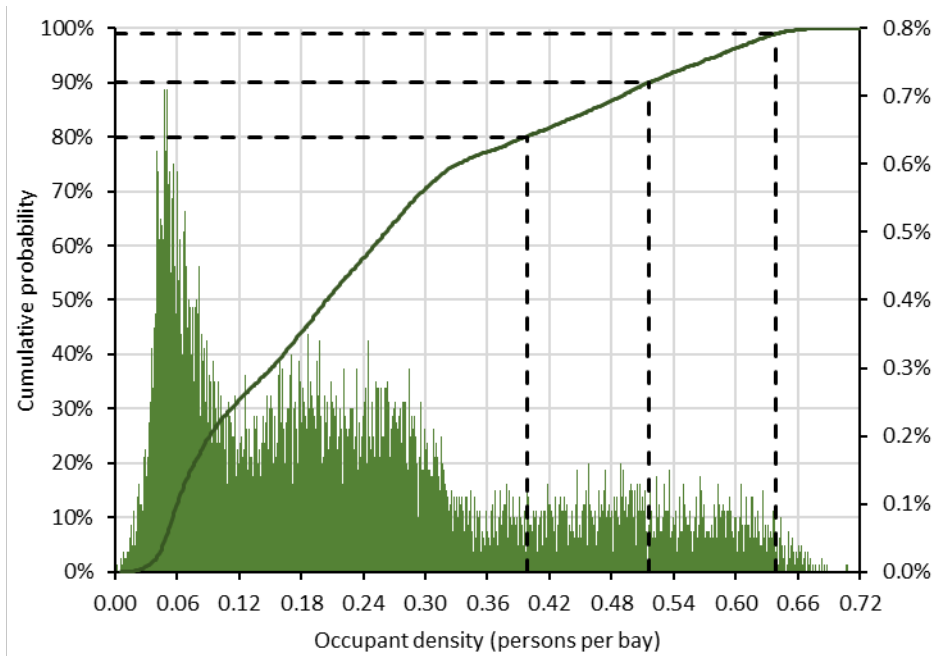


(a) 100% parking space use



(b) Simulated parking space use

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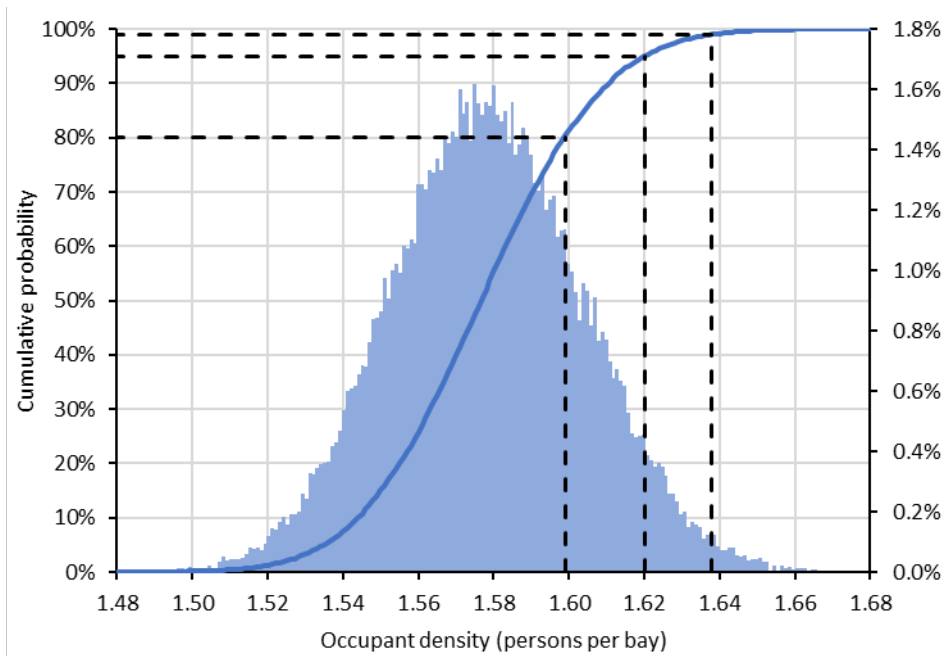


(c) Simulated transition parking bay utilisation

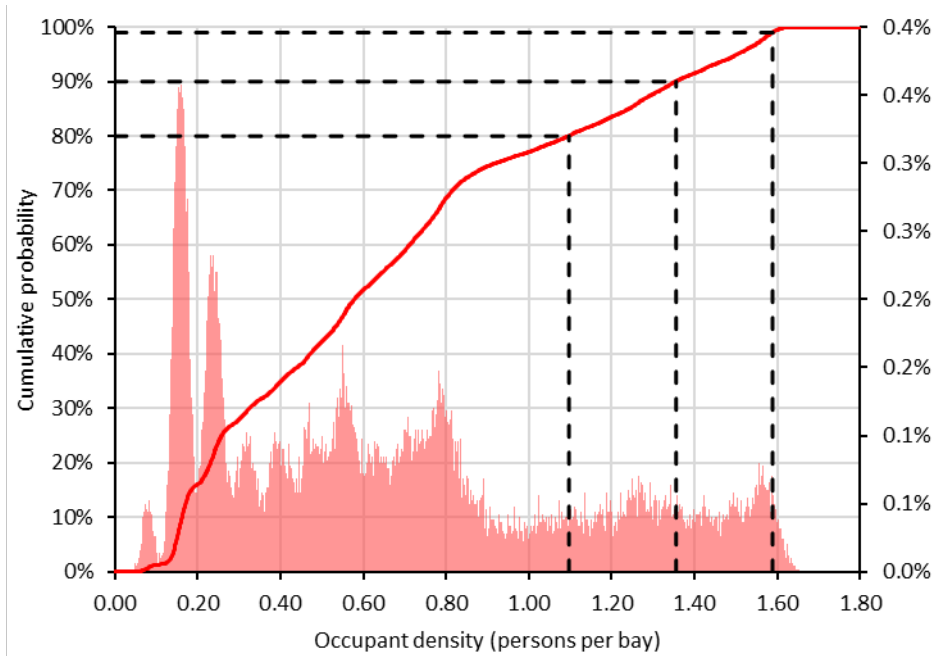
Persons per bay

Statistic	Parking bay utilisation of 1	Simulated parking bay utilisation	Simulated parking bay utilisation with 99 th percentile transition time	Simulated parking bay utilisation with 95 th percentile transition time
80 th percentile	1.96	1.36	0.40	0.25
95 th percentile	1.98	1.66	0.52	0.33
99 th percentile	2.00	1.95	0.64	0.41

Cumulative density and probability density (All)

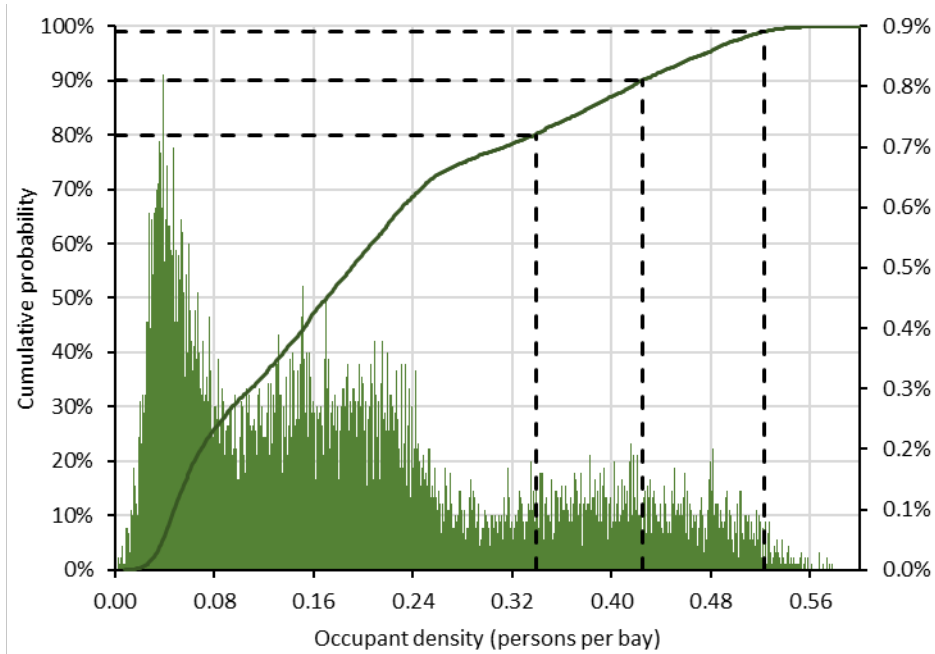


(a) Parking bay utilisation of 1



(b) Simulated parking bay utilisation

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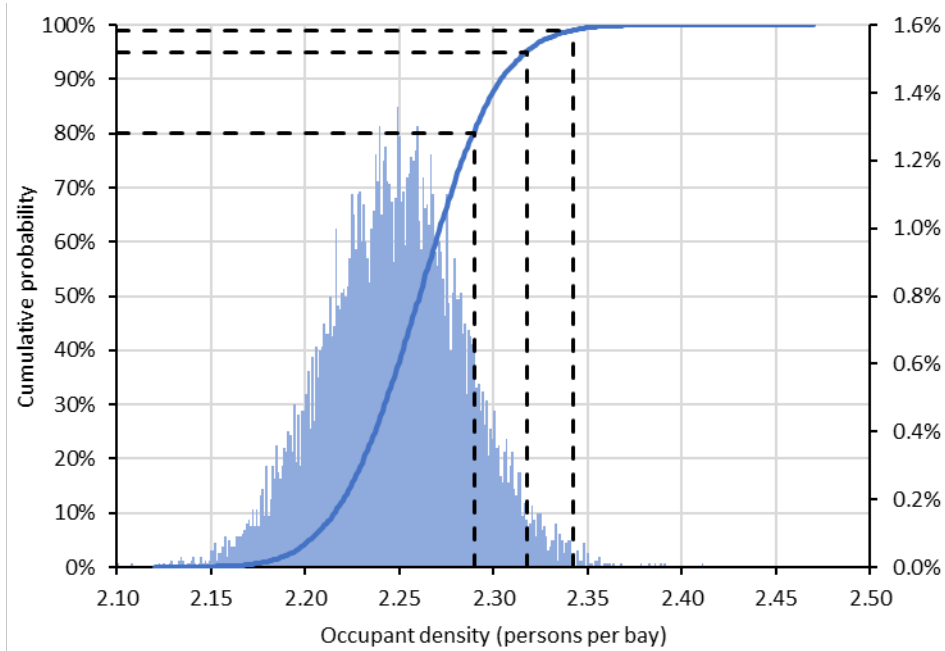


(c) Simulated transition parking bay utilisation

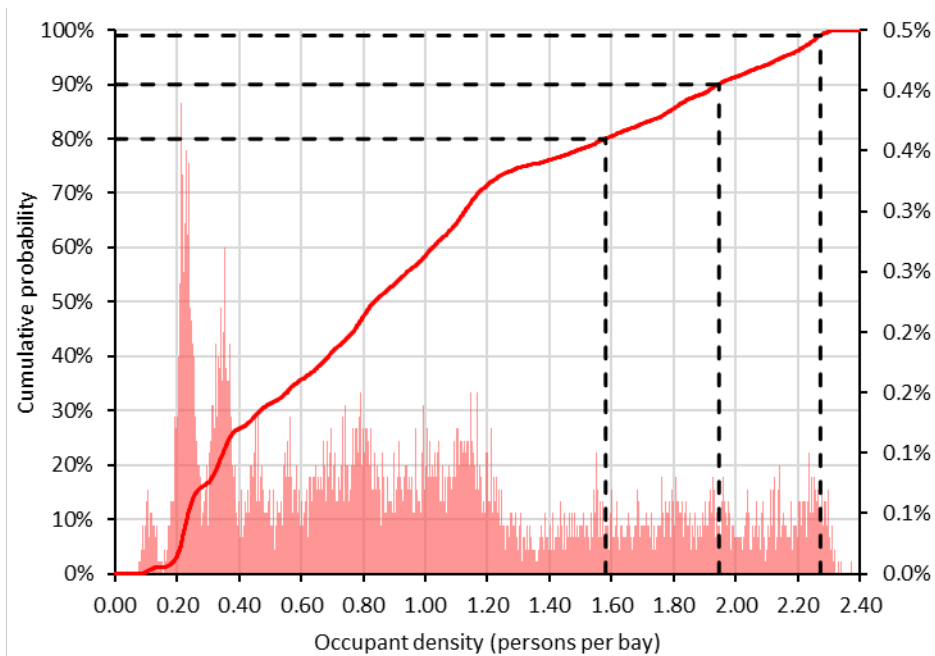
Persons per bay

Statistic	Parking bay utilisation of 1	Simulated parking bay utilisation	Simulated parking bay utilisation with 99 th percentile transition time	Simulated parking bay utilisation with 95 th percentile transition time
80 th percentile	1.60	1.10	0.34	0.21
95 th percentile	1.62	1.36	0.43	0.27
99 th percentile	1.64	1.59	0.52	0.33

Cumulative density and probability density (Households)

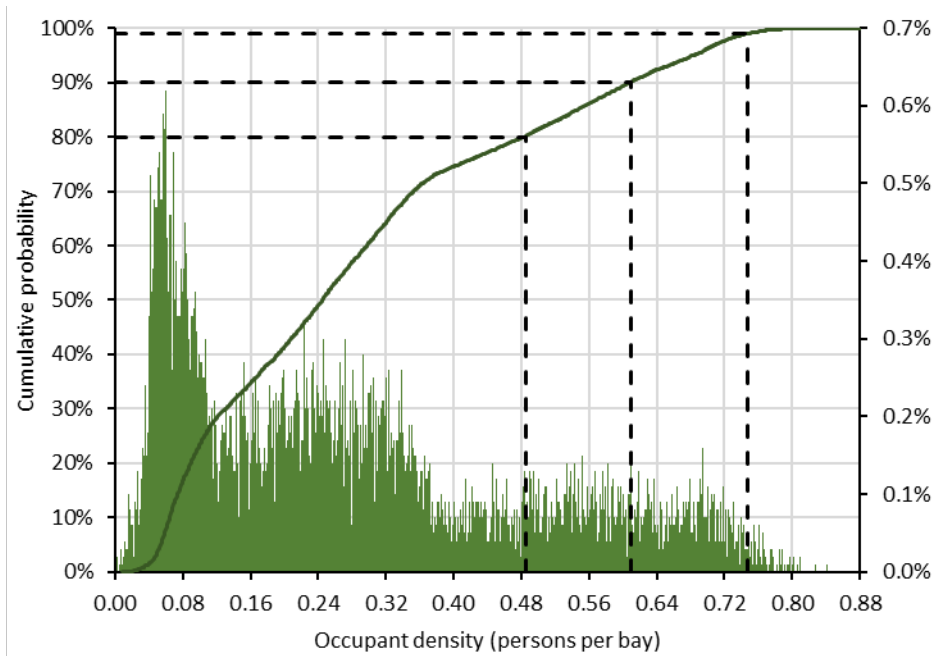


(a) 100% parking space use



(b) Simulated parking space use

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(c) Simulated transition parking bay utilisation

Persons per bay

Statistic	Parking bay utilisation of 1	Simulated parking bay utilisation	Simulated parking bay utilisation with 99 th percentile transition time	Simulated parking bay utilisation with 95 th percentile transition time
80 th percentile	2.29	1.58	0.49	0.30
95 th percentile	2.32	1.95	0.61	0.38
99 th percentile	2.34	2.27	0.75	0.48

Appendix B

Access time, The Green, Hunstanton

Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
1	1 adult	Out	86	86					
2	1 adult	Out	24	24					
3	1 adult	Out	31	31					
4	1 adult	Out	32	32					
5	1 adult	Out	100	100					
6	2 adults. Unloading small bag from boot	Out	55	55					
7	3 adults and 1 dog. Rearranged items in boot	In	94			94			
8	2 adults, one of them elderly	Out	60		60				
9	4 adults	In	27				27		
10	2 adults	Out	66		66				
11	3 adults. Rearranged items in boot and seats	In	145			145			
12	2 adults and 2 children. Took coats etc. from boot	Out	130				130		
13	4 adults	Out	46				46		
14	2 adults. One collected coat etc from back seat	Out	54		54				
15	2 adults. Placed coats etc in boot	In	71		71				
16	2 adults and 1 toddler. Remove items from boot and back seat, get toddler from back seat	Out	193			193			
17	2 adults. Collected coats from the back seat	Out	109		109				
18	2 adults	Out	42		42				
19	2 adults	Out	39		39				
20	1 adult	Out	36	36					
21	2 adults and 2 children. Put on coats etc	Out	100				100		
22	1 adult	Out	34	34					
23	2 adults and 1 child. Put on coats	Out	75			75			
24	2 adults. Put on coats etc, went to boot to get dog	Out	170		170				
25	2 adults	Out	71		71				
26	1 adult	Out	155	155					
27	2 adults	Out	36		36				
28	2 adults and 2 children. Put on coats etc from boot	Out	163				163		
29	1 adult	Out	12	12					
30	1 adult	Out	53	53					
31	2 adults	Out	28		28				
32	1 adult	In	83	83					
33	2 adults and 2 children. Put coats etc into boot (probably same group as record 28)	In	98				98		
34	1 adult	Out	19	19					
35	2 adults	Out	89		89				
36	1 adult	Out	13	13					

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Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
37	2 adults	In	34		34				
38	2 adults. Placed coat on back seat	In	236		236				
39	2 adults. Placed items on the back seat	In	75		75				
40	2 adults	In	78		78				
41	3 adults. Placed items in the boot	In	405			405			
42	2 adults of which 1 was elderly. Took wheelchair from boot for elderly man to sit in	Out	136		136				
43	2 adults	Out	12		12				
44	3 adults. Put on coats	Out	136			136			
45	2 adults. Collected dog from the boot	Out	55		55				
46	2 adults. Collected items from the back seat	Out	86		86				
47	2 adults and 1 child.	Out	35			35			
48	2 adults, one of which was elderly. Loaded mobility scooter into the boot, and items on the back seat	In	286		286				
49	2 adults	Out	24		24				
50	2 adults	In	49		49				
51	4 adults and 2 children. Put on coats	Out	147						147
52	2 adults	Out	53		53				
53	2 adults	Out	157		157				
54	2 adults. Items placed in the boot	In	175		175				
55	1 adult	Out	10	10					
56	2 adults. Placed items on back seat	In	192		192				
57	2 adults. Removed dog from the boot, and items from the back seat	Out	120		120				
58	2 adults	Out	25		25				
59	2 adults	In	136		136				
60	2 adults with a dog	In	90		90				
61	2 adults and 3 children. Saying goodbye to friends / family	In	218					218	
62	2 adults. Got dog from back seat	Out	96		96				
63	2 adults	In	50		50				
64	4 adults and 2 children. Put on coats (same group as record 51)	In	67						67
65	2 adults. Used the boot	Out	53		53				
66	2 adults	Out	18		18				
67	2 adults and 1 child. Two dogs	Out	125			125			
68	2 adults	In	45		45				
69	2 adults. Items into boot and back seat	In	139		139				
70	2 adults. Took items from back seat, put on coats	Out	99		99				
71	2 adults. Put a dog on the back seat	In	93		93				
72	2 adults. 1 dog	In	22		22				
73	2 adults. Put on coats.	Out	62		62				
74	2 adults and 2 toddlers. Items collected from back seat and boot	Out	56				56		
75	2 adults.	Out	36		36				

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Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
	2 adults and 2 toddlers. Items placed in the boot (same group as record 74)	In	123				123		
76									
77	1 adult and 4 children	In	230					230	
	2 adults and 2 babies. Loaded pushchair into boot	In	514				514		
78									
	1 adult. Waited in car until person arrived as noted in record 80	Out	288	288					
79									
80	1 adult. See record 79	Out	12	12					
81	1 adult	Out	27	27					
82	1 adult	Out	32	32					
83	1 adult	Out	16	16					
	1 adult. Delivery driver who arrived as record 83	In	113	113					
84									
	1 adult. Stood outside car using e-cigarette	Out	127	127					
85									
	1 adult	Out	1035	1035					
86									
	1 adult. Loaded 2 dogs into the boot	In	63	63					
87									
	1 adult	Out	15	15					
88									
	1 adult	Out	30	30					
89									
	1 adult	Out	1340	1340					
90									
	2 adults. Put dog on back seat	In	215		215				
91									
	1 adult	Out	17	17					
92									
	2 adults. Placed item on the back seat	In	92		92				
93									
	1 adult	Out	16	16					
94									
	2 adult	Out	15	15					
95									
	1 adult	Out	32	32					
96									
	1 adult	Out	19	19					
97									
	1 adult	Out	16	16					
98									
	1 adult. Waited for a colleague to arrive before leaving	Out	1000	1000					
99									
	1 adult	Out	55	55					
100									
	1 adult	Out	337	337					
101									
	2 adults. Placed items on the back seat	In	361		361				
102									
	1 adult	Out	24	24					
103									
	2 adults. Put on coats etc.	Out	199		199				
104									
	1 adult	Out	36	36					
105									
	2 adults. Items taken from the boot	Out	177		177				
106									
	1 adult	Out	141	141					
107									
	1 adult	Out	12	12					
108									
	1 adult	In	19	19					
109									
	1 adult	Out	16	16					
110									
	1 adult	Out	26	26					
111									
	1 adult	Out	27	27					
112									
	1 adult. Waited in car for most of the time	Out	974	974					
113									
	1 adult	Out	22	22					
114									
	2 adults	Out	33		33				
115									
	1 adult	Out	26	26					
116									

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Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
117	2 adults. 2 dogs	Out	48		48				
118	1 adult	Out	33	33					
119	1 adult. Took items from back seat	Out	58	58					
120	2 adults. Took items from boot, put on coats	Out	145		145				
121	1 adult	Out	43	43					
122	1 adult	Out	32	32					
123	1 adult	Out	18	18					
124	1 adult (same car as record 113)	In	47	47					
125	2 adults. Took items off back seat	Out	45		45				
126	1 adult. Items put in the boot	In	107	107					
127	3 adults	Out	127			127			
128	3 adults	Out	28			28			
129	2 adults	Out	15		15				
130	2 adults. 1 dog	Out	158		158				
131	2 adults. Placed items in the boot	In	130		130				
132	1 adult	Out	36	36					
133	2 adults. Sat waiting	In	1111		1111				
134	2 adults. Took items from boot	Out	94		94				
135	2 adults. Both had walking sticks	Out	181		181				
136	2 adults. Unloaded mobility scooter from boot	Out	206		206				
137	2 adults	In	19		19				
138	4 adults. 1 adult was elderly, items placed in boot	In	215				215		
139	1 adult	Out	777	777					
140	4 adults. Took coats from boot	Out	135				135		
141	2 adults. Took coats from boot	Out	47		47				
142	1 adult	In	25	25					
143	2 adults	Out	63		63				
144	2 adults. Person waited in car for second passenger	In	373		373				
145	2 adults	Out	57		57				
146	1 adult	In	21		21				
147	1 adult	Out	403	403					
148	2 adults. Dog from back seat	Out	72		72				
149	4 adults	Out	52				52		
150	2 adults. Items from back seat	Out	86		86				
151	3 adults	In	68			68			
152	2 adults	In	66		66				
153	1 adult	Out	51	51					
154	3 adults	Out	25			25			
155	1 adult	Out	74	74					
156	2 adults	Out	10		10				
157	2 adults. Coats from boot	Out	25		25				
158	2 adults	Out	77		77				
159	2 adults	Out	39		39				
160	2 adults	Out	22		22				
161	2 adults. Dog from back seat	Out	112		112				

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Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
162	3 adults. Dog from back seat and coats from boot	Out	247			247			
163	2 adults	Out	565		565				
164	2 adults	Out	106		106				
165	2 adults. Ate food	In	1068		1068				
166	2 adults	Out	148		148				
167	2 adults. Disposed of rubbish in nearby waste bin	In	155		155				
168	2 adults. Dog from back seat	Out	52		52				
169	2 adults	Out	23		23				
170	2 adults. Coats in boot	In	155		155				
171	4 adults. 1 dog	Out	56				56		
172	2 adults, 2 teenagers	Out	55				55		
173	1 adult	Out	24	24					
174	1 adult	Out	215	215					
175	2 adults	Out	27		27				
176	1 adult	Out	42	42					
177	1 adult	Out	34	34					
178	2 adults. Items placed on back seat	In	211		211				
179	1 adult	Out	22	22					
180	2 adults	Out	20		20				
181	2 adults. Items taken from boot	Out	206		206				
182	1 adult	Out	17	17					
183	2 adults. Items placed in boot and on back seat	In	209		209				
184	2 adults, 1 teenager	Out	50			50			
185	2 adults	Out	39		39				
186	2 adults. Items taken from boot and back seat	Out	96		96				
187	2 adults	Out	39		39				
188	1 adult	Out	43	43					
189	1 adult	Out	34	34					
190	1 adult	Out	13	13					
191	1 adult	Out	33	33					
192	2 adults	In	48		48				
193	2 adults	In	171		171				
194	2 adults. 1 dog, items from back seat	Out	71		71				
195	2 adults	Out	111		111				
196	3 adults. Items taken from back seat	Out	173			173			
197	1 adult	Out	61	61					
198	2 adults	Out	132		132				
199	2 adults	Out	57		57				
200	2 adults. Items from back seat	Out	178		178				
201	2 adults. 1 teenager	Out	27			27			
202	3 adults	In	65			65			
203	2 adults	Out	43		43				
204	2 adults. 1 teenager	In	28			28			
205	1 adults. 2 children	In	125			125			

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Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
206	1 adult	Out	60	60					
207	1 adult	Out	8	8					
208	3 adults. 1 child. Likely ate in car	Out	1665				1665		
209	2 adults. 1 dog	Out	48		48				
210	2 adults. 1 child	Out	120			120			
	2 adults. Wheelchair from boot. Put on coats. Male wandered off for several minutes while female in wheelchair waited by car	Out	396		396				
211									
212	1 adult	Out	14	14					
213	2 adults	Out	79		79				
214	4 adults. 1 dog from boot	Out	57				57		
215	2 adults	Out	173		173				
216	2 adults. Put on coats etc.	Out	217		217				
217	4 adults	In	53				53		
218	2 adults. Items from boot	Out	94		94				
219	5 adults. Items into boot	In	73					73	
220	2 adults	In	192			192			
221	1 adult	Out	474	474					
222	2 adults. Put on coats etc	Out	118		118				
223	2 adults	Out	14		14				
	1 adult. Item in boot and on back seat	In	77	77					
224									
225	1 adult	Out	24	24					
226	2 adults. Items from boot	Out	120		120				
227	2 adults. Items in boot	In	130		130				
228	2 adults. Items from back seat	Out	74		74				
229	2 adults, 1 teenager. Put on coats	Out	213			213			
230	2 adults. 1 dog	Out	235		235				
231	2 adults. Items on back seat	In	80		80				
232	2 adults. Changed footwear	Out	150		150				
233	2 adults	Out	61		61				
234	1 adult	Out	30	30					
235	2 adults. Items from back seat	Out	141		141				
	2 adults. Item from boot and back seat	Out	97		97				
236									
237	4 adults. Luggage from boot	Out	252				252		
238	2 adults, 1 teenager (as record 229)	In	220			220			
	2 adults. 1 dog, items unloaded from boot	Out	128		128				
239									
240	2 adults. Items in boot	In	184		184				
241	1 adult	Out	17	17					
242	1 adult	In	15	15					
243	1 adult	Out	69	69					
	2 adults. Item placed in boot and back seat	In	180		180				
244									
245	3 adults	Out	118			118			
246	2 adults. 1 dog	Out	48		48				
247	2 adults	Out	60		60				
248	2 adults. Items placed in boot	In	67		67				

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Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
	2 adults. Items placed in boot. Passenger walked off to look signs etc	In	324		324				
249									
250	2 adults	Out	178		178				
251	2 adults	Out	43		43				
252	3 adults (group as record 245)	In	152			152			
253	2 adults	Out	32		32				
254	1 adult	Out	20	20					
255	2 adults. Coats from boot	Out	107		107				
256	2 adults	Out	78		78				
257	2 adults. Coats from boot	Out	99		99				
258	2 adults. Coats and dog from boot	Out	390		390				
259	2 adults	Out	140		140				
260	2 adults, 1 child	Out	51			51			
261	2 adults. 1 dog	Out	88		88				
262	4 adults. 1 dog	Out	442				442		
	3 adults. 1 dog in boot, elderly person with 2 walking sticks got into back seat	In	90			90			
263									
	2 adults. Sat in their car before leaving	Out	591		591				
264									
	2 adults, 2 teenagers. Items from boot	Out	78				78		
265									
	2 adults	Out	29		29				
266									
	2 adults. 1 elderly person with two walking sticks	In	118		118				
267									
	2 adults	In	52		52				
268									
	4 adults	In	98				98		
269									
	1 adult. Took items from front seat	Out	83	83					
270									
	1 adult. 2 dogs	Out	87	87					
271									
	1 adult	Out	18	18					
272									
	1 adult	Out	22	22					
273									
	2 adults. Item from boot	Out	67		67				
274									
	1 adult. 1 dog	Out	343	343					
275									
	1 adult	Out	908	908					
276									
	1 adult	Out	13	13					
277									
	2 adults	In	27		27				
278									
	1 adult	Out	11	11					
279									
	2 adults. Loaded golf clubs and bag etc. onto back seat and boot	In	286		286				
280									
	2 adults	In	123		123				
281									
	2 adults	Out	15		15				
282									
	2 adults	Out	36		36				
283									
	2 adults	Out	50		50				
284									
	2 adults	Out	135		135				
285									
	2 adults. 1 dog	Out	81		81				
286									
	1 adult	Out	17	17					
287									
	2 adults	In	236		236				
288									
	1 adult	In	11	11					
289									
	1 adult	Out	26	26					
290									

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Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
291	2 adults, 1 baby. Baby placed in pushchair from boot	Out	90			90			
292	2 adults. Coats taken from back seat	Out	78		78				
293	1 adult, 1 child	Out	88		88				
294	2 adults, 2 children	Out	107				107		
295	2 adults. Coats from back seats	Out	172		172				
296	2 adults	Out	36		36				
297	2 adults	In	68		68				
298	4 adults	Out	44				44		
299	2 adults. 2 dogs	In	164		164				
300	2 adults, 1 baby. Pushchair placed in boot. Occupants waited in car for most of time (same group as record 291)	In	1350			1350			
301	2 adults, 1 baby. Baby placed in pushchair from boot. This group also linked with group in record 302	Out	236			236			
302	2 adults, 3 children. Elderly adult using walking frame	Out	137					137	
303	2 adults	Out	37		37				
304	1 adult	Out	19	19					
305	2 adults	Out	31		31				
306	2 adults	Out	23		23				
307	1 adult	Out	60	60					
308	2 adults. Items taken from boot	Out	77		77				
309	2 adults. 1 dog	Out	195		195				
310	2 adults	Out	62		62				
311	2 adults, 2 children. Took items from the boot including a child's scooter	Out	164				164		
312	2 adults	Out	56		56				
313	1 adult. Briefcase from boot	Out	61	61					
314	2 adults. Coats etc. from back seat	Out	87		87				
315	3 adults, 1 child	Out	73				73		
316	2 adults	Out	26		26				
317	2 adults. One adult disassembled a mobility scooter and loaded it into the boot of an SUV	In	167		167				
318	2 adults	Out	116		116				
319	1 adult	Out	826	826					
320	2 adults	In	56		56				
321	2 adults	In	20		20				
322	2 adults	In	124		124				
323	3 adults	Out	56			56			
324	1 adult. 1 dog	Out	25	25					
325	1 adult	Out	13	13					
326	1 adult	Out	85	85					
327	1 adult	Out	27	27					
328	1 adult. Item taken from back seat	Out	40	40					
329	1 adult	Out	65	65					

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Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
330	1 adult	Out	334	334					
331	1 adult	Out	30	30					
332	2 adults	Out	501		501				
333	2 adults. 1 dog from back seat plus items taken from boot	Out	474		474				
334	2 adults	In	45		45				
335	2 adults, 2 children. Put on coats etc from boot	Out	235				235		
336	2 adults, 3 children	Out	66					66	
337	1 adult, 1 child	Out	28		28				
338	2 adults, 3 children	Out	114					114	
339	1 adult	Out	14	14					
340	1 adult. Items from boot and back set	Out	93	93					
341	1 adult	Out	80	80					
342	2 adults. Coats etc from back seat and boot	Out	175		175				
343	1 adult	Out	47	47					
344	2 adults. 1 dog	In	280		280				
345	1 adult	Out	66	66					
346	1 adult. Items from front seat, coat	Out	79	79					
347	1 adult	Out	17	17					
348	2 adults, 1 baby. Pushchair from boot	Out	507			507			
349	1 adult	Out	29	29					
350	2 adults	Out	286		286				
351	1 adult	Out	44	44					
352	1 adult	Out	19	19					
353	2 adults	Out	84		84				
354	1 adult	Out	30	30					
355	2 adults	Out	64		64				
356	1 adult	In	8	8					
357	1 adult, 1 child	Out	32		32				
358	1 adult	Out	84	84					
359	1 adult	Out	25	25					
360	1 adult	Out	26	26					
361	1 adult	Out	47	47					
362	1 adult	In	22	22					
363	2 adults. Put on coats	Out	101		101				
364	2 adults, 1 child. Put on coats	Out	150			150			
365	2 adults. Appeared to wait to speak to a third pedestrian who arrived later but did not get in car	In	706		706				
366	1 adult	Out	18	18					
367	1 adult	Out	28	28					
368	1 adult	Out	47	47					
369	2 adults. 2 dogs, items taken from boot	Out	135		135				
370	2 adults	Out	215		215				
371	2 adults	Out	124		124				

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Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
372	1 adult	In	29	29					
373	2 adults. 1 dog, items taken from boot and back seat	Out	131		131				
374	2 adults, 1 baby. Pram taken from boot and baby put into pram with blankets etc.	Out	583			583			
375	2 adults	In	324		324				
376	2 adults. 1 dog	Out	212		212				
377	1 adult	Out	17	17					
378	2 adults	In	147		147				
379	2 adults. 1 dog	Out	133		133				
380	2 adults, 1 child, 1 toddler	Out	174				174		
381	2 adults	Out	52		52				
382	1 adult	Out	20	20					
383	2 adults	Out	45		45				
384	5 adults	In	81					81	
385	1 adult	Out	25	25					
386	1 adult (same person as record 385)	In	150	150					
387	1 adult	Out	48	48					
388	1 adult	Out	25	25					
389	2 adults. 1 dog	Out	57		57				
390	1 adult	Out	8	8					
391	1 adult	Out	10	10					
392	1 adult	Out	54	54					
393	2 adults	Out	26		26				
394	2 adults	In	78		78				
395	1 adult	Out	18	18					
396	2 adults	In	80		80				
397	1 adult	Out	143	143					
398	1 adult	Out	79	79					
399	2 adults. 1 dog	Out	77		77				
400	1 adult	Out	578	578					
401	1 adult	Out	42	42					
402	3 adults. 1 wheelchair user, items from boot of SUV	Out	255			255			
403	2 adults	In	50		50				
404	2 adults	Out	69		69				
405	2 adults	In	178		178				
406	2 adults	Out	79		79				
407	2 adults. 1 disabled person	In	670		670				
408	2 adults	Out	27		27				
409	2 adults	Out	38		38				
410	1 adult. 1 dog	Out	50	50					
411	2 adults	Out	144		144				
412	2 adults	In	37		37				
413	2 adults	Out	36		36				
414	2 adults. 1 dog	In	217		217				
415	2 adults	In	43		43				

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Record	Description	Getting in or out of car	Time (s)	1 person	2 person	3 person	4 person	5 person	6 person
416	2 adults. 1 dog	Out	108		108				
417	2 adults	Out	73		73				
418	2 adults	Out	21		21				
419	2 adults. 1 dog	Out	61		61				
420	2 adults	Out	186		186				
421	3 adults. Unloaded mobility scooter from boot	Out	154			154			
422	2 adults, 4 children. Exit from a van. Coats etc	Out	153						
423	2 adults	Out	65		65				
424	3 adults	In	99			99			
425	2 adults	Out	30		30				
426	1 adult	Out	41	41					
427	3 adults	Out	20			20			
428	2 adults	Out	65		65				
429	1 adult. 1 dog	Out	112	112					
430	2 adults	Out	39		39				
431	1 adult	Out	42	42					
432	2 adults, 1 teenage, 1 child	Out	89				89		
433	1 adult. On motorcycle	Out	14	14					

Vehicle entry and exit, The Green, Hunstanton

Date	Time	Bays occupied at start	Fraction of bays	Entry	Exit	Sum	Fraction	Fraction per min
15-Feb	11:30	n/a		4	0	4	0.20	0.013
	12:00	n/a		3	2	5	0.25	0.017
	13:30	n/a		3	2	5	0.25	0.017
	14:30	n/a		3	2	5	0.25	0.017
	14:45	n/a		1	0	1	0.05	0.003
	15:00	n/a		0	0	0	0.00	0.000
16-Feb	10:00	13	0.65	3	0	3	0.15	0.010
	10:15	16	0.80	0	0	0	0.00	0.000
	10:30	16	0.80	1	0	1	0.05	0.003
	10:45	17	0.85	2	0	2	0.10	0.007
	11:00	19	0.95	1	1	2	0.10	0.007
	15:00	19	0.95	3	2	5	0.25	0.017
	15:15	20	1.00	0	0	0	0.00	0.000
	15:30	20	1.00	1	4	5	0.25	0.017
	15:45	17	0.85	4	3	7	0.35	0.023
17-Feb	07:30	11	0.55	0	0	0	0.00	0.000
	07:45	11	0.55	1	0	1	0.05	0.003
	08:00	12	0.60	3	0	3	0.15	0.010
	08:15	15	0.75	2	0	2	0.10	0.007
	08:30	17	0.85	1	0	1	0.05	0.003
	09:30	19	0.95	1	1	2	0.10	0.007
	09:45	20	1.00	1	1	2	0.10	0.007
	10:00	21	1.05	1	1	2	0.10	0.007
	15:45	16	0.80	2	1	3	0.15	0.010
	16:15	17	0.85	1	2	3	0.15	0.010
22-Feb	16:30	16	0.80	2	2	4	0.20	0.013
	07:30	13	0.65	0	0	0	0.00	0.000
	07:45	13	0.65	0	0	0	0.00	0.000
	08:00	13	0.65	1	0	1	0.05	0.003
	08:15	14	0.70	2	0	2	0.10	0.007
	08:30	16	0.80	3	0	3	0.15	0.010
	08:45	19	0.95	1	1	2	0.10	0.007

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	09:00	19	0.95	1	2	3	0.15	0.010
	09:45	18	0.90	1	0	1	0.05	0.003
	10:00	19	0.95	1	0	1	0.05	0.003
	10:15	20	1.00	1	1	2	0.10	0.007
	10:30	20	1.00	0	0	0	0.00	0.000
	11:30	19	0.95	1	3	4	0.20	0.013
	11:45	17	0.85	3	0	3	0.15	0.010
	12:45	19	0.95	1	1	2	0.10	0.007
	17:00	20	1.00	0	0	0	0.00	0.000
	17:15	20	1.00	1	0	1	0.05	0.003
	17:30	20	1.00	0	0	0	0.00	0.000
23-Feb	07:30	16	0.80	0	0	0	0.00	0.000
	07:45	16	0.80	1	0	1	0.05	0.003
	08:00	17	0.85	0	0	0	0.00	0.000
	08:15	17	0.85	1	0	1	0.05	0.003
	08:30	18	0.90	0	0	0	0.00	0.000
	08:45	18	0.90	1	0	1	0.05	0.003
	09:00	19	0.95	0	0	0	0.00	0.000
	10:45	17	0.85	0	1	1	0.05	0.003
	11:00	16	0.80	3	1	4	0.20	0.013
	11:15	18	0.90	2	1	3	0.15	0.010
	11:30	19	0.95	2	1	3	0.15	0.010
	11:45	20	1.00	1	1	2	0.10	0.007
	12:00	20	1.00	1	2	3	0.15	0.010
	12:15	19	0.95	3	2	5	0.25	0.017
	14:30	18	0.90	1	0	1	0.05	0.003
	14:45	19	0.95	1	1	2	0.10	0.007
	15:00	20	1.00	1	0	1	0.05	0.003
	15:15	20	1.00	1	3	4	0.20	0.013
24-Feb	07:30	15	0.75	0	0	0	0.00	0.000
	07:45	15	0.75	0	0	0	0.00	0.000
	08:00	15	0.75	2	0	2	0.10	0.007
	08:15	17	0.85	0	0	0	0.00	0.000
	09:15	15	0.75	1	1	2	0.10	0.007
	09:30	15	0.75	4	1	5	0.25	0.017
	14:00	18	0.90	2	2	4	0.20	0.013
	14:15	18	0.90	1	0	1	0.05	0.003
	16:15	16	0.80	1	0	1	0.05	0.003
	16:30	17	0.85	1	2	3	0.15	0.010
	16:45	16	0.80	1	1	2	0.10	0.007
	17:00	16	0.80	3	3	6	0.30	0.020
25-Feb	08:00	12	0.60	0	0	0	0.00	0.000
	08:15	12	0.60	0	0	0	0.00	0.000
	08:30	12	0.60	3	0	3	0.15	0.010
01-Mar	08:00	17	0.85	1	0	1	0.05	0.003
	08:15	18	0.90	0	0	0	0.00	0.000
	08:30	18	0.90	2	1	3	0.15	0.010
	08:45	19	0.95	1	1	2	0.10	0.007
	09:00	19	0.95	0	0	0	0.00	0.000

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02-Mar	09:15	19	0.95	1	1	2	0.10	0.007
	10:00	20	1.00	0	3	3	0.15	0.010
	10:15	17	0.85	3	1	4	0.20	0.013
	10:30	19	0.95	0	1	1	0.05	0.003
	13:00	19	0.95	0	1	1	0.05	0.003
	13:15	18	0.90	2	0	2	0.10	0.007
	13:30	20	1.00	0	0	0	0.00	0.000
	07:45	15	0.75	1	1	2	0.10	0.007
	08:00	15	0.75	0	1	1	0.05	0.003
	08:30	14	0.70	0	0	0	0.00	0.000
	11:45	17	0.85	1	2	3	0.15	0.010
	12:00	16	0.80	3	2	5	0.25	0.017
	13:00	17	0.85	2	1	3	0.15	0.010
	13:15	18	0.90	1	2	3	0.15	0.010
	13:30	17	0.85	2	1	3	0.15	0.010
	13:45	18	0.90	2	1	3	0.15	0.010
	15:45	16	0.80	4	3	7	0.35	0.023
	16:00	17	0.85	0	3	3	0.15	0.010
	16:15	14	0.70	4	3	7	0.35	0.023
	16:30	15	0.75	3	1	4	0.20	0.013
	16:45	17	0.85	2	4	6	0.30	0.020
	17:00	15	0.75	2	2	4	0.20	0.013

Appendix C

Section 5.3 presents a relatively simple approach to get the access time in which no consideration is made on the number of people associated with the vehicles, the actions they are taking, whether they have disabilities, etc. In this Appendix a slightly more complex access time model is investigated in which the 99th percentile access times are split by the number of people in the vehicle using the data from 'The Green', excluding times greater than 900 s (Figure 19). Due to the low number of records with 5 or 6 people, these have been amalgamated for the analysis.

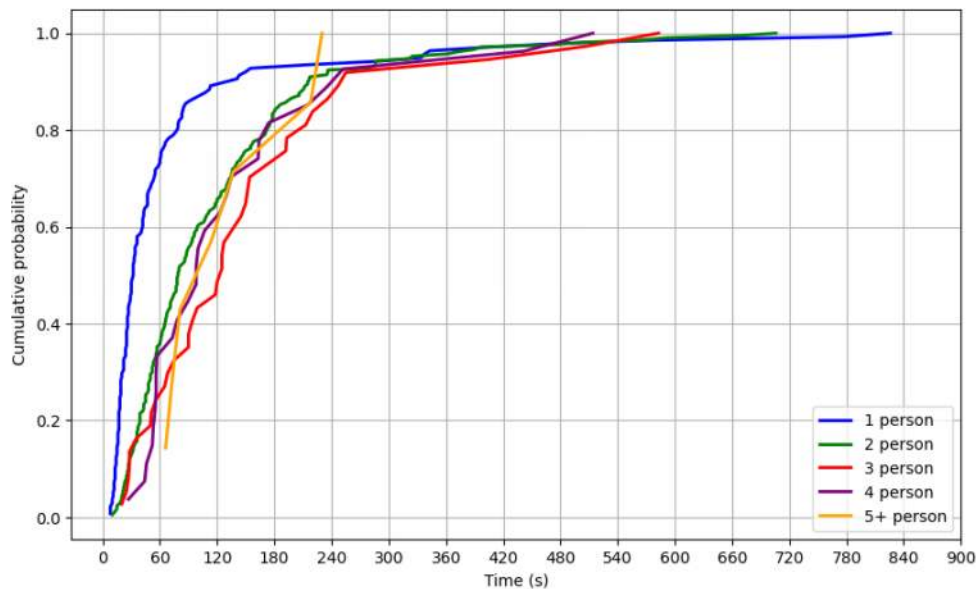


Figure 19. Cumulative density functions for 1, 2, 3, 4 and 5+ persons

Figure 20 shows a graph of the 95th and 99th percentile access times versus the number of people in the vehicles showing that in general the access time decreases with the number of people. Part of the reason may simply be because there were relatively few records in which 3 or 4 people were present, and there was even less data for 5 and 6 people.

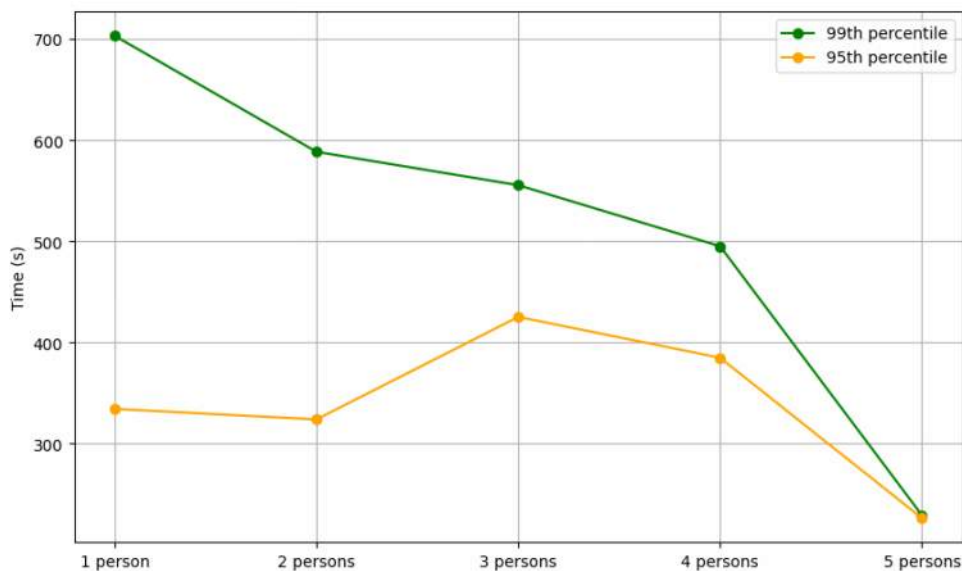


Figure 20. 95th and 99th percentile access times as a function of number of persons.

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One specific factor to investigate is the impact on access time where there were cases of the loading or unloading of wheelchairs, mobility scooters or walking frames. Within records from 'The Green' there were seven such instances (Table 13) with a 95th percentile time of 363 s and a 99th percentile of 389 s.

Table 13. Vehicle access times in which wheelchairs or mobility scooters were loaded or unloaded at 'The Green' car park.

Description	Number of people	Access time (s)
Took wheelchair from boot for elderly man to sit in	2	136
Loaded mobility scooter into the boot, and items on the back seat	2	286
Unloaded mobility scooter from boot	2	206
Wheelchair from boot. Put on coats. Male wandered off for several minutes while female in wheelchair waited by car	2	396
One adult disassembled a mobility scooter and loaded it into the boot of an SUV	2	167
1 wheelchair user, items from boot of SUV	3	255
Unloaded mobility scooter from boot	3	154

Another similar factor is where babies' prams and pushchairs are loaded or unloaded. Six records from 'The Green' are shown in Table 14. Ignoring the case in which the occupants waited longer than 900 s, the 95th percentile time is 569 s and a 99th percentile is 580 s.

Table 14. Vehicle access times in which pushchairs and prams were loaded or unloaded at 'The Green' car park.

Description	Number of people	Access time (s)
2 babies. Loaded pushchair into boot	4	514
1 baby. Baby placed in pushchair taken from boot	3	90
1 baby. Pushchair placed in boot. Occupants waited in car for most of time	3	1350
1 baby. Baby placed in pushchair from boot	3	236
1 baby. Pushchair from boot	3	507
1 baby. Pram taken from boot and baby put into pram with blankets etc.	3	583

The limited data suggests that the loading or unloading of prams and pushchairs has some bearing on the access time given that when all the records have been analysed the 95th percentile time is 337 s, and a 99th percentile is 589 s (see Section 5.3.1). Loading or unloading of wheelchairs and mobility scooters has a lesser impact on access time.

The findings presented herein suggest that exploring more complex relationships to determine vehicle access time may yield interesting results but for the purpose of this study the simple approach applied in Section 5.3 is sufficient. If nothing else, more data is required to further investigate the specific impacts of mobility devices, pushchairs etc. on the access time.

Appendix E – WP 3B



CPD/004/122/039

Real Fires: Open-sided car park fire resistance

WP 3B: Life-time cost optimisation (LCO) study

Revision: R00
Date: 19th November 2025
Project Number: OX24065

Prepared for : Health & Safety Executive

Prepared by : OFR Consultants Limited

Insert office address : The Manse, 44 South Bar, Banbury, Oxford OX16 9AB

Project No : OX24065

Revision : R00

Date : 19/11/2025

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Quality Management

Revision	Date	Comment	Author	QA & Technical Review	Approver
D00	16/10/25	Draft for HSE Comment	DJH / MA	NA	MJS
D01	14/11/2025	Update after HSE Comment	DJH	NA	MJS
R00	19/11/2025	Final issue	DJH	NA	MJS

Contents

1.	Introduction	7
1.1	Appointment	7
1.2	Overview of deliverable.....	7
2.	Selection of a reference case car park.....	9
2.1	Overview	9
2.2	Construction materials	9
2.3	Geometrical Scenarios.....	10
2.4	Fire safety interventions.....	10
2.5	Other presumptions	10
3.	Lifetime cost optimisation principles	11
3.1	Total lifetime cost.....	11
3.2	Discounting	11
3.3	Ongoing maintenance costs	11
4.	Fire resistance fragility curves.....	12
4.1	Fragility curves	12
4.2	Application to the LCO.....	12
5.	Probability of a structurally significant car park fire	14
5.1	Annual fire occurrence rate	14
5.1.1	Fire statistics in car parks in England	14
5.1.2	Number & size of car parks	15
5.1.3	Summary	16
5.2	Probability of an uncontrolled car park fire	16
6.	Costs associated with the construction and fire safety interventions in purpose-built car parks	18
6.1	Cost of constructing a multi-storey car park	18
6.2	Costs associated with fire safety interventions	18
6.2.1	Passive fire protection	19
6.2.2	Active fire safety systems (sprinklers)	19
7.	Costs associated with damage and loss of business	20
7.1	Fatalities.....	20
7.2	Property and contents loss	21
7.3	Other indirect costs	22
8.	Lifetime cost-optimisation (LCO) analysis	23
8.1	Prerequisites	23
8.2	Optimal structural fire resistance in the absence of sprinklers.....	23
8.2.1	Sensitivity to car park utilisation	24
8.2.2	Sensitivity to the SCCR	25
8.3	Introduction of sprinkler protection	25
8.3.1	Sensitivity to car park utilisation	26

8.3.2	Sensitivity to the SCCR	26
8.4	Sensitivity study using Green Book inputs	26
9.	Comparison of options using the cost-benefit ratio	27
9.1	The fire safety J-Value	27
9.2	Interpretation of the J-Value	27
9.3	Cost-benefit ratios.....	27
9.3.1	Without sprinklers	27
9.3.2	With sprinklers	28
9.3.3	Sensitivity to SCCR	28
9.4	Comparison of safety measure interventions	29
10.	Discussion & recommendation	30
10.1	Discussion	30
10.2	Considerations	32
10.3	Recommendation	32
11.	References.....	33
	Appendix I – Green Book Sensitivity Study.....	35

List of Figures

Figure 1.	Plan view of reference car park from Google Earth	9
Figure 2.	Consolidated time-equivalence cumulative probability showing the sensitivity of fire severity to car park utilisation, ceiling height, and internal air speed	12
Figure 3.	Number of fires in MSCPs attended by fire and rescue services, England 2010/11-2023/24.....	15
Figure 4.	Lifetime cost optimisation for four, eight and twelve storey reference car parks, impact of fire resistance on lifetime cost.....	24
Figure 5.	Lifetime cost optimisation for four, eight and twelve storey reference car parks, impact of fire resistance on lifetime cost including sprinklers.....	25
Figure 6.	J-Value in function of structural fire resistance, 100% utilised car park case.....	27
Figure 7.	J-Value in function of structural fire resistance, 100% utilised car park case with OH2 sprinklers	28
Figure 8.	J-Value in function of structural fire resistance, 100% utilised car park case but reduced SCCR: (left) without sprinklers, (right) with OH2 sprinklers	29
Figure 9.	Lifetime cost evaluation for 4 to 12-storey cases, modified for Green Book inputs, without sprinklers	36
Figure 10.	Lifetime cost evaluation for 4 to 12-storey cases, modified for Green Book inputs, with sprinklers	36
Figure 11.	J-Value assessment using Green Book inputs (left) without sprinklers, (right) with sprinklers.	37

List of Tables

Table 1.	Model car park scenarios	10
Table 2.	Failure probability in function of parking space utilisation.....	13
Table 3.	Number of fires in car parks attended by fire and rescue services in England 2010-2024 [16]	14
Table 4.	Summary of the car park statistics used in the cost benefit analysis	16
Table 5.	Annual probability of a structurally significant fire in the model car park case, without sprinklers and 100% utilisation.....	17
Table 6.	Annual probability of a structurally significant fire in the model car park case, with sprinklers and 100% utilisation	17
Table 7.	Cost of constructing a multi-storey car park in 2019 and 2025 estimate.....	18
Table 8.	Estimated costs to construct a large footprint car park in 2025	18
Table 9.	Passive fire protection costs as of September 2025	19
Table 10.	Intumescent costs for three scales of car park as of September 2025	19

Table 11. Sprinkler costs as of September 2025	19
Table 12. Car park utilisation scenarios.....	20
Table 13. Car park occupancy scenarios based on 99 th percentile transition case	20
Table 14. Upper bound SCCR associated with each scenario.....	21
Table 15. Credible SCCR associated with each scenario	21
Table 16. Used car costs and number of vehicles available in 2020 vs 2025	22
Table 17. Estimated vehicle losses in function of utilisation	22
Table 18. Estimation of indirect costs associated with loss of function	22
Table 19. LCO application considering 30 min fire resistance to the four-storey reference car park.....	24
Table 20. Credible VPF associated with each scenario	35
Table 21. Comparison of LCO optimal fire resistance periods – base study vs. Green Book inputs	37

1. INTRODUCTION

1.1 Appointment

OFR Consultants were engaged by the Department for Levelling Up, Housing and Communities (DLUHC) to deliver the “Real Fires” project (CPD/004/122/039) in support of fire safety technical policy, which commenced on 22nd of October 2021, and will run until the 28th of September 2025. The contract has since been novated to the Building Safety Regulator (BSR), originally formed within the Health & Safety Executive (HSE) and now residing as part of the Ministry for Housing, Communities and Local Government (MHCLG). As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations from real fires. Through this mechanism, OFR have been engaged to undertake research on the structural fire resistance for purpose-built open-sided car parks.

The BSR stated that the research project is to be organised to generate data and evidence on the fire resistance ratings in car parks to support the BSR’s understanding of the level of safety in existing and new buildings, along with an analysis of options coupled with their respective supporting information to shape policy decisions. OFR proposed that this focus on above ground, purpose-built, open-sided multi-storey car parks.

To deliver on the requirements, OFR considered three sub work packages (WPs) to be necessary, which are summarised below:

- WP 1: Investigation of fire spread rates and extents in open sided car parks.
- WP 2: Monte Carlo fire severity analysis to investigate the probability of failure of structural elements subject to different fire resistance / protection solutions.
- WP 3: Lifetime cost-optimisation analysis for different fire resistance / protection solutions to establish the optimal safety level considering sensitivity to life safety, property protection and business continuity goals. This has evolved to include a study of occupant loads as a prerequisite.

This report forms part of the deliverable for WP 3 (WP 3B), providing a lifetime cost optimisation study on the costs and benefits associated with different car park policy decisions, like increased structural fire resistance and the inclusion of sprinklers. The report makes use of inputs from previous work packages. Namely, WP 2, which has provided the failure probabilities of structural elements considering different car park fire scenarios, and WP 3A, which studied occupant loads in car parks.

1.2 Overview of deliverable

The deliverable applies cost-benefit tools, specifically, lifetime cost optimisation [1], [2] and the J-Value [3], [4], [5], [6], to review the efficacy of possible car park policy interventions, i.e., changes in structural fire resistance and / or the inclusion of sprinklers.

The study adopts a model car park like that which suffered a fire at Luton Airport. The floor plan of the car park, which could be considered representative of a large purpose-built open-sided car park, is applied to three cases: four, eight and twelve above ground storeys, which would span three current Approved Document B [7], [8] trigger heights of < 18 m, 18 to 30 m and +30 m, from the topmost occupied level to the lowest ground level. In all cases the top storey is used for parking, i.e., there is no dedicated roof covering.

Using failure probabilities of structural elements derived in WP 2, alongside occupant loads from WP 3A, future uncertain damage costs are considered alongside upfront safety investments (i.e., passive fire protection and sprinklers). Two approaches are considered. The first looks at what investments in safety measures upfront balance against future damage costs. This identifies which safety interventions, e.g. increases in fire resistance with or without sprinklers, are at least cost neutral over the 25-year design life of the safety intervention. The second looks at what changes in safety measures provide the best return on investment by considering the reduction in damage costs relative to current ADB provisions versus the cost of implementing the safety measures. This allows the comparison of fire safety interventions by way of a cost-benefit ratio, which in this application is the J-Value.

2. SELECTION OF A REFERENCE CASE CAR PARK

2.1 Overview

Purpose-built multi-storey car parks can take many forms depending upon their intended use, age and location. This research project has been motivated by observations of real fire incidents, including most recently, the fire at London Luton Airport. The fire occurred in terminal car park 2 (TCP2) and has been the subject of a significant incident report by Bedfordshire FRS [9]. TCP 2 is the larger of two adjacent purpose-built multi-storey car parks, built after TCP1.

For selecting a reference case benchmark car park, TCP1 has been chosen as its slightly smaller size is considered more representative of the scale at which most are built. Estimates of the capacity and overall scale of TCP1 have been derived from several sources that include: the London Luton Airport 19 MPPA Expansion – Travel Plan [10], and Google Earth, see Figure 1.

The reference case is estimated to have a floor area of ca. 42,500 m², ground floor and roof inclusive, both of which are available for parking. The noted travel plan states it provides ca. 1,700 spaces. These are spread over five storeys, i.e., ground plus four, giving a mean storey area of 8,500 m².

Based on a mean parking bay size of 2.4 x 4.8 m, this would suggest a parking area of ca. 19,600 m², yielding an efficiency (parking area to overall area) of ca. 46%. The remaining area of the car park comprises pedestrian and vehicle access routes, etc.



Figure 1. Plan view of reference car park from Google Earth

2.2 Construction materials

Car parks commonly feature structures formed from either reinforced concrete frames and slabs or steel frames with pre-cast concrete / composite slabs. Concrete inherently achieves its fire resistance through a combination of element sizing and cover to reinforcement. Therefore, considering potential fire safety interventions that involve increasing structural fire resistance are likely to be more impactful on steel structures, which require supplementary passive fire protection. For this reason, the reference building is assumed to be formed from a steel frame with concrete slabs. Subsequently, it is assumed that any increase in fire resistance only impacts the quantum of fire protection applied to steel elements, i.e., any impact on slabs is nominal.

2.3 Geometrical Scenarios

Starting with the plan area of Luton TCP1 as a reference, three scenarios have been conceived which span Approved Document B trigger thresholds. These are four, eight and twelve above ground storeys, respectively. These scenarios are summarised in Table 1.

Table 1. Model car park scenarios

Above ground storeys	Parking storeys	Approx. internal area [m ²]	Parking spaces per storey [-]	Number of parking spaces [-]
Four	Five	34,000	340	1,700
Eight	Nine	68,000		3,060
Twelve	Thirteen	100,000		4,420

2.4 Fire safety interventions

The study considers one or a combination of two fire safety interventions. The first is an increase in structural fire resistance. For multi-storey open-sided car parks, ADB would currently recommend a minimum of 15 min structural fire resistance subject to a topmost occupied storey not exceeding 30 m above lowest ground level. For steel elements, this can be achieved inherently through sizing. Fire resistance increases beyond this would be through applied fire protection, such as intumescent paint.

The second option is to introduce active measures, i.e., sprinklers. Sprinklers can be instead of or alongside increases in structural fire resistance. Three grades of sprinkler installation have been considered in terms of their installation cost according to the hazard classifications in BS EN 12845 [11]. These are Ordinary Hazard 2 (OH2), OH3 and High Hazard Process 3 (HHP3). However, in terms of the lifetime cost optimisation and J-Value studies, only the OH2 grade has been considered as it is considered that the reliability of all three grades are comparable but the cost differences are shown to be significant. Given this, OH2 would likely provide the best return on investment.

2.5 Other presumptions

It is assumed that the car park is constructed in a developed urban area with a local fire and rescue service provision. Costs relating to the construction of the car park reflect English averages. Sprinkler costs assume the availability of an urban water supply, i.e., additional costs relating to water infrastructure for installation in rural areas has not been considered.

3. LIFETIME COST OPTIMISATION PRINCIPLES

3.1 Total lifetime cost

Lifetime cost optimisation considers that when a building is constructed, upfront investments are made in safety measures to offset future uncertain incidents that may result in damage related losses. The optimal design is one that optimises the lifetime costs. This optimisation point is typically located at the point where the fire safety intervention is neutral, i.e., the upfront safety investment cost is balanced with the future uncertain damage related losses. This can be expressed per the below equation where the lifetime cost is Y , the cost of the building excluding the safety intervention is C_0 , the cost of the safety intervention is C_1 and the damage related losses are D . This is adapted from Rackwitz [12].

$$Y = C_0 + C_1 - D$$

The damage related losses only occur in the event of a fire that brings about a structural collapse, i.e.

$$Y = C_0 + C_1 - p_{fi}(1 - R_{FR})D$$

Where p_{fi} is the annual probability of a structurally significant fire, discussed in section 5 and R_{FR} is the conditional reliability of the structural fire protection solution, which can alternatively be thought of as the conditional failure probability of the structure in the event of a significant fire, see section 4.

3.2 Discounting

As the safety investment relates to the reduction of future risk, the cost-benefit analysis requires that future costs and benefits incurred at different times are discounted to a common reference point, or annualised, using a (continuous) discount rate (γ), i.e.

$$Y = C_0 + C_1 - p_{fi}(1 - R_{FR}) \frac{D(1 - e^{-\gamma L})}{\gamma}$$

Where L is the life of the building [years].

3.3 Ongoing maintenance costs

When a safety investment requires ongoing periodic maintenance, this is expressed through the net present value, i.e.

$$Y = C_0 + C_1 + m_\gamma - p_{fi}(1 - R_{FR}) \frac{D(1 - e^{-\gamma L})}{\gamma}$$

Where m_γ is the maintenance cost net present value, which over the life of the building is determined via:

$$m_\gamma = \sum_{t=1}^L m / (1 + \gamma)^t$$

Where m is the annual maintenance cost [£].

4. FIRE RESISTANCE FRAGILITY CURVES

4.1 Fragility curves

Fragility curves in this context describe the relationship between the safety measure and the failure probability. The safety measure is the structural fire resistance, with its reliability established in WP 2. Reliability in this context is the probability that the intensity of the fire is no more onerous than a period of exposure under furnace conditions.

The derivation of the fragility curves is not repeated here as it is subject to a specific evaluation and elaboration in WP 2. However, the main outputs from WP 2 are reproduced in Figure 2.

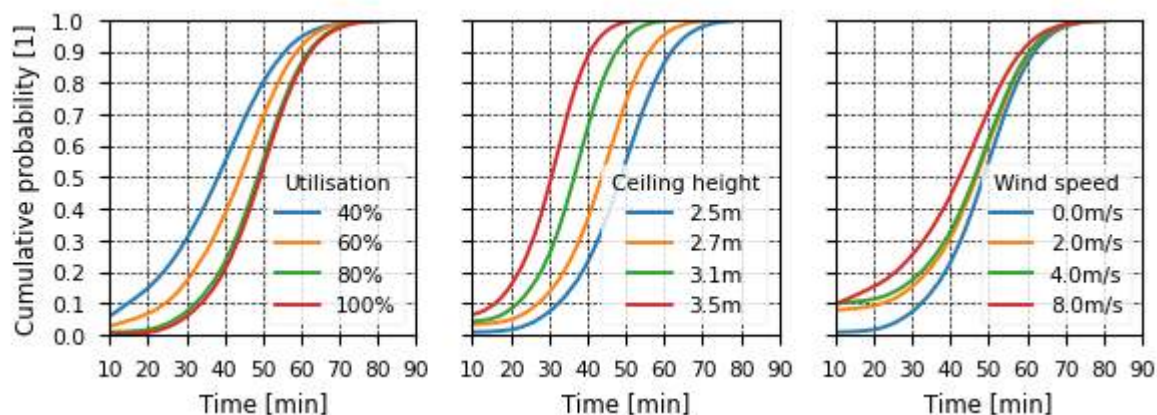


Figure 2. Consolidated time-equivalence cumulative probability showing the sensitivity of fire severity to car park utilisation, ceiling height, and internal air speed

As directed by the BSR, it is unlikely that Approved Document B would seek to provide specific guidance in relation to ceiling height. Further, the WP 2 study showed that the windspeed had nominal effect on the fire resistance cumulative probability curves, often reducing their severity. Given this, the study focusses on the impact of utilisation, expressed in the leftmost plot of Figure 2.

4.2 Application to the LCO

Figure 2 does not explicitly express fragility. It is simply the probability of a car park fire scenario having intensities that do not exceed different durations of exposure in fire resistance testing conditions. Fragility for this application must express the probability of fire induced structural failure in function of different fire resistance solutions. This requires that a limit state be introduced, i.e., a condition under which structural failure is deemed to occur. Various considerations of limit states for such an application have been considered in the literature, including in the NFSC [13] expressed in terms of a probability of exceeding a design fire load and in Hopkin, et al. [1], where the limit state corresponds with the probability that an isolated element's utilisation exceeds unity. The latter case introduced uncertainty in respect of the thermal action, the mechanical action and the mechanical resistance. For this study, a simple limit state is adopted whereby if the fire intensity exceeds the intensity of the design duration of furnace exposure (fire resistance), the structural system will fail. The concept of equivalent intensity is discussed in more detail in WP 2 but is commonly known as time equivalence. This approach posits that the most significant factor influencing stability is the thermal action and that the impact of uncertainty in the mechanical action and resistance is proportionally small. This philosophy is more aligned to that of the NFSC and Eurocode 1 part 1.2 [14], than the work of Hopkin, et al. Importantly, the limit state disregards any potential positive or negative system effects that might affect the failure probability. These could include the positive impact of load-redistribution or the negative influence of restrained thermal expansion. Instead it assumes that if an isolated element is exposed to a fire of greater equivalent intensity to its design fire resistance rating, the structural system will fail.

Under such a simplification, the fragility curves simply become the complement of Figure 2, resulting in the relationship between failure probability and fire resistance given in Table 2.

Table 2. Failure probability in function of parking space utilisation

Duration [min]	Failure probability for different space utilisations			
	40 %	60 %	80 %	100 %
0	1.000	1.000	1.000	1.000
10	0.942	0.973	0.992	0.999
20	0.852	0.934	0.984	0.993
30	0.698	0.832	0.928	0.943
40	0.455	0.619	0.772	0.796
50	0.201	0.310	0.450	0.474
60	0.055	0.084	0.139	0.150
70	0.012	0.013	0.022	0.026
80	0.003	0.002	0.002	0.003
90	0.001	0.000	0.000	0.000
120	0.000	0.000	0.000	0.000

For the lifetime optimisation process, the conditional failure probability of the structure ($P_{f,FR}$) is included as per the below:

$$Y = C_0 + C_1 - p_{fi}(1 - R_{FR}) \frac{D(1 - e^{-\gamma L})}{\gamma} = C_0 + C_1 - p_{fi}P_{f,FR} \frac{D(1 - e^{-\gamma L})}{\gamma}$$

This signifies that the discounted damage costs only arise under the condition of the occurrence of a significant fire (p_{fi}) and subsequently that fire being intense enough to cause failure ($P_{f,FR}$).

5. PROBABILITY OF A STRUCTURALLY SIGNIFICANT CAR PARK FIRE

5.1 Annual fire occurrence rate

To understand the benefit of a given fire safety measure, it is often necessary to determine the fire occurrence rate. For this work, the fire occurrence rate has been calculated as the likelihood of a fire per car parking space in a multi-storey car park (MSCP) in England, per year. The analysis does not account for the occupancy rate of car parking spaces but provides an average likelihood of fire per parking space. Nor does the analysis consider factors such as the age of vehicles or the drivetrain (i.e., internal combustion engine vehicles or electric vehicles). In their indicative study, Breunese and Both [15] highlighted the age and drivetrain to be factors relating to the ignition likelihood.

Ascertaining the annual fire occurrence rate requires both a review of fire incidents in car parks and an estimation of the number of car parking spaces in England.

5.1.1 Fire statistics in car parks in England

In the UK, fire incident attendance is recorded by fire and rescue services through the incident recording system (IRS), which provides fire statistics in terms of the number of fires, casualties and fatalities for all building typologies, including car parks. The Home Office first published an ad-hoc statistical release of an analysis of fires in car parks in England in February 2021 which has subsequently been updated in January 2025 [16]. The latest update compiled data that was consistent with the records that reached the IRS by August 2024. Critically for this work, this dataset provides the number of fires attended by fire and rescue services in MSCPs in England for a period of 14 years from 2010/11 to 2023/24. The dataset also includes statistics for underground and “other” (understood to represent single-level surface car parks), both of which are out with the scope of this project. Table 3 replicates the dataset published by the Home Office with regards to the number of car park fires in England.

Table 3. Number of fires in car parks attended by fire and rescue services in England 2010–2024 [16]

Financial year	MSCP	Underground	Other
2010/11	43	26	15
2011/12	29	16	19
2012/13	29	16	10
2013/14	34	18	19
2014/15	26	23	19
2015/16	41	20	16
2016/17	52	24	22
2017/18	59	19	13
2018/19	51	23	17
2019/20	43	27	20
2020/21	38	17	30
2021/22	75	22	32
2022/23	70	25	22
2023/24	83	38	28
Total	673	314	282
Average	48.1	22.4	20.1

Figure 3 shows the trend in the number of MSCP fires attended by fire and rescue services in England over the time period, indicating an upward trend in recent years [16].

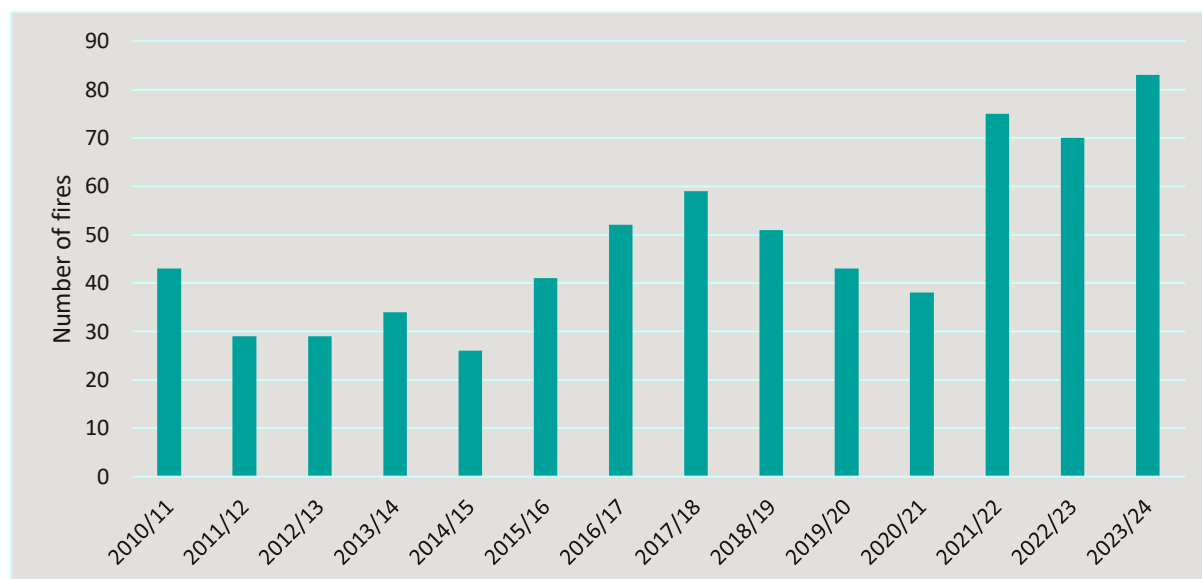


Figure 3. Number of fires in MSCPs attended by fire and rescue services, England 2010/11–2023/24

For input into the cost benefit analysis, the number of MSCP fires attended by fire and rescue services in England is taken as an average of 48.1 fires per year. This reflects the average number of fires attended over the 14-year period for which specific car park statistics have been gathered. It could be said that data for 2021 to 2024 suggests an increase in fires attended in recent times. This is considered later in the context of conclusions drawn and in consideration of any justifications for deviating from current policy provisions.

5.1.2 Number & size of car parks

As mentioned, it is also necessary to estimate the number of MSCPs in England and subsequently, the number of car parking spaces therein. There is limited information publicly available as to the number of MSCPs in England; however, the British parking Association (BPA) has previously published data [17], whereby they estimated the number of public car parks in the UK to be 17,000 – 20,000 in 2015. In their work, Alimzhanova et al. [4] contacted the BPA to ascertain an updated figure in 2021, with the BPA then estimating there to be between 23,000 and 26,000 public car parks in the UK. In the cost benefit analysis carried out by Alimzhanova et al., an average of 24,500 car parks in the UK is used.

Alimzhanova et al. processed the dataset from the BPA, allowing this to be categorised per UK region, as well as per car park type (to align with the IRS categories). It is noted that the dataset only included car parks that have obtained the “Park Mark” award¹, with data provided for a total of 4,723 car parks. The number of MSCPs in England (the relevant value to this work) in the BPA dataset was identified as 614 of the 4,723 car parks that made up the dataset. Alimzhanova et al. then extrapolated this ratio, and that of the other car park types and other UK regions to devise the composition of UK car parks using the BPA estimated total of 24,500 car parks. This resulted in an estimated 3,185 MSCPs in England, which is used in this study.

As with the number of car parks in the UK, the size or number of car parking spaces in these is not well-documented. A report by the RAC Foundation in 2012 [18] obtained data on non-residential parking from two sources – Parking Data & Research International (PDRI) and Parkopedia. Both estimate the number of public, non-residential car parks in Great Britain from their database, with an average of 18,500 car parks, which is

¹ Schemes that are police-supported accreditations that certify car parks on a variety of factors aimed at approving safety, security, accessibility, customer service and wellbeing amongst motorists.

comparable to the BPA estimate, albeit at the lower end. These sources include the size of each car park, in terms of the number of parking spaces, allowing the authors to estimate that the total number of non-residential car parking spaces as between 3 and 4 million. Plainly, this equates to an average car park size c. 190 spaces for all car park types. However, it is posited that the average MSCP would be larger than this as this average includes smaller, surface-level car parks.

Previous researched undertaken by Tellus 42 on behalf of Friends of the Earth in 1998 and published on the UK Parliament website as Memorandum H185 [19] investigated the scale of off-street car parking for public use. This research was based on a questionnaire sent to 356 local authorities in England to which 140 responded (c. 40%). The data obtained was categorised into surface-level and multi-storey car parks, including the number of spaces. From the sample data, there were a reported 301 MSCPs providing a total of 162,174 spaces. This results in an average MSCP size of 539 spaces. To compare to the average value of 190 spaces obtained for all car park types in the RAC Foundation research, the total number of all car parks (i.e., surface-level and MSCPs) in the Tellus 42 research sample is 2,965, with a total of 452,192 spaces and an average size of 153 spaces.

5.1.3 Summary

Table 4 provides a summary of the parameters that have been obtained from the literature regarding the number of fires, the number of MSCPs and their average size in terms of car parking spaces. This allows the total number of car parking spaces in MSCPs in England to be estimated at 1,716,715 spaces, resulting in an estimated annual fire occurrence rate of 2.8×10^{-5} fires/year/space. If emphasis were placed on the most recent three years of statistics, i.e., 2021 to 2024, this would increase to 4.4×10^{-5} fires/year/space.

In their similar work analysing vehicle fire statistics in car parks in New Zealand, Li and Spearpoint [20] estimated there to be 200,000 spaces in New Zealand. Together with an average annual number of fire incidents of 12, results in an annual fire occurrence rate of 6×10^{-5} fires/year/space which is comparable to the value obtained for England as part of this research (noting that this data is from 2007 and is specific to New Zealand).

Table 4. Summary of the car park statistics used in the cost benefit analysis

Parameter	Value	Source
No. of fires in MSCPs	48.1 fires/year	IRS
No. of MSCPs	3,185 car parks	Alimzhanova et al.
Avg. MSCP size	539 spaces	Tellus 42
No. MSCP spaces	1,716,715 spaces	Calculated
Annual fire occurrence rate	2.8×10^{-5} fires/year/space	Calculated

The annual fire occurrence rate given in Table 4 is expressed relative to the total number of parking spaces estimated in England. This is aggregated across all spaces regardless of whether they are occupied by a vehicle. It is therefore more useful to present this in terms of annual fires per occupied space when later considering the impact of car park utilisation. Literature by the British Parking Association [21] notes that:

“Occupancy rates for car parking spaces appear to be lower among local authorities than other parking providers. Most local authorities operate between 50% and 80% occupancy whereas most other providers operate above 80%.”

Taking 80% as the common figure between local authority and private car parks, the annual fire occurrence rate per occupied space becomes 3.5×10^{-5} fires/year/space over the preceding 14-year period.

5.2 Probability of an uncontrolled car park fire

An estimate of the probability of a structurally significant fire p_{fi} , i.e., one that can challenge a structures stability, is adapted from the Natural Fire Safety Concept (NFSC) Valorisation project, with:

$$p_{fi} = p_1 p_2 p_3 p_4 N_{space}$$

- p_1 probability of severe fire including the effect of occupants and standard public fire brigade² (per occupied parking space),
- p_2 additional reduction factor depending on the fire brigade types and on the time between alarm and firefighter intervention (p_2 is also the probability of failure of fire brigade in stopping the fire),
- p_3 reduction factor if automatic fire detection (by smoke or heat) and / or automatic transmission of the alarm are present,
- p_4 reduction factor if sprinkler system is present (p_4 is also the probability of failure of sprinkler in stopping the fire), and
- N_{space} is the number of occupied parking spaces.

The probability of a severe fire, p_1 , has been derived in section 5.1. According the NFSC, the parameter p_2 depends on the speed and professionalism of the fire service. Where the intervention time is < 10 min, $p_2 = 0.05$, this increases to 0.1 for an intervention time of 10 to 20 min and 0.2 for an intervention time of 20 to 30 min. For the purposes of this study, it is assumed that the intervention time correlates with height, with the four-storey reference case having faster fire service intervention time than the eight and twelve storey cases. Automatic fire detection is not typically included in car parks, therefore, the parameter p_3 is unity. A case could be made for sprinklers offering the dual functionality of a suppression system and heat detection system. However, the latter has not been considered for the sprinkler protected cases as the benefits of early warning in terms of earlier fire service intervention are considered much lower in a car park where permanent personnel are not often present. Parameter p_4 is only present in cases where sprinklers are provided. Estimates of the annual probability of significant fire occurrence without and with sprinklers are given in Table 5 and Table 6.

Table 5. Annual probability of a structurally significant fire in the model car park case, without sprinklers and 100% utilisation

Number of above ground storeys	Max occupied spaces	p_1	p_2	p_3	p_4	p_{fi}
Four	1,700	3.5×10^{-5}	0.05	1.0	1.0	2.98×10^{-3}
Eight	3,060		0.10	1.0	1.0	1.07×10^{-2}
Twelve	4,420		0.20	1.0	1.0	3.09×10^{-2}

Table 6. Annual probability of a structurally significant fire in the model car park case, with sprinklers and 100% utilisation

Number of above ground storeys	Max occupied spaces	p_1	p_2	p_3	p_4	p_{fi}
Four	1,700	3.5×10^{-5}	0.05	1.0	0.1	7.44×10^{-5}
Eight	3,060		0.10	1.0	0.1	2.68×10^{-4}
Twelve	4,420		0.20	1.0	0.1	7.74×10^{-4}

Given the initial ignition rate, p_1 , is expressed in terms of per occupied parking space per annum, the p_{fi} figures scale to the car park utilisation, e.g., an 80% utilisation would correspond to a 20% reduction in p_{fi} .

² The standard public fire brigade reflects the lower provisions available within the Eurocode member states at the point of publishing the NFSC. These were often volunteer fire services with additional enhancements for professional fire services reflected through the parameter p_2 .

6. COSTS ASSOCIATED WITH THE CONSTRUCTION AND FIRE SAFETY INTERVENTIONS IN PURPOSE-BUILT CAR PARKS

The upfront costs associated with a car park can be considered to fall into two categories for this study. These are the construction costs necessary to deliver a functional car park capable of generating revenue. For this purpose, it is assumed that structural fire precautions are minimal, as per current guidance in Approved Document B. Therefore, these construction costs concern structural materials, labour, etc., but exclude passive fire protection or any active fire safety systems. The other categories comprise potential policy interventions. These include additional passive fire protection, e.g., such that the structure achieves 30-120 min fire resistance and / or the inclusion of sprinklers.

6.1 Cost of constructing a multi-storey car park

Cost estimates for the construction of purpose-built multi-storey car parks can be made based on construction market surveys. The Turner and Townsend survey [22] gives figures per m² of internal area (for England) as noted in Table 7. To estimate the costs in 2025, the Office for National Statistics (ONS) data on construction output price indices [23] are used. The mid-2019 index was 114, increasing to 148 in June 2025. This suggests a 29.8% increase in construction output cost.

Table 7. Cost of constructing a multi-storey car park in 2019 and 2025 estimate

Region	Cost per m ² of internal area [£] in 2019	Adjusted cost per m ² of internal area [£] in 2025
London	747	970
North	595	773
Central	663	861
South	677	879
Mean	671	871

If it is assumed that purpose-built multi-storey car parks are uniformly distributed around England, this yields a mean cost of £871 per m² of internal area in 2025. If most of such car parks are designed to Approved Document B and meet the criteria for an open-sided car park, it would be reasonable to assume that the costs exclude specific fire safety interventions of interest to this project, such as enhanced passive fire protection and sprinklers.

Taking the reference cases presented in Section 2, the approximate base construction cost would be as per Table 8, using the mean unit area rate. The four-storey case could be considered comparable to that damaged and rebuilt at Luton Airport, with the Construction Enquirer [24] estimating the contract value to be up to £37.5 million. Adopting the “South” unit area rate of £879 in lieu of the mean would yield a cost of £29.9 million, i.e., there is confidence that the cost estimates are broadly correct.

Table 8. Estimated costs to construct a large footprint car park in 2025

Above ground storeys	Approx. internal area [m ²]	Cost in 2025 [£]
Four	34,000	£29,614,000
Eight	68,000	£59,228,000
Twelve	100,000	£87,100,000

6.2 Costs associated with fire safety interventions

The report considers two types of possible fire safety interventions, increased passive fire protection and the inclusion of active systems, i.e., sprinklers. Figures for both have been provided by the BSR’s cost advisors and are adopted herein.

6.2.1 Passive fire protection

Costs for passive fire protection have been provided for three solutions, intumescent paint, cementitious spray and boarding. The cost per m² of floor area are given in Table 9.

Table 9. Passive fire protection costs as of September 2025

Fire resistance period [min]	Cost per m ² of floor area [£]		
	Intumescent	Cementitious Spray	Boarding
30	28	108	90
60	44	NA	90
90	91	214	134
120	111	214	134

Given the costs noted, it is probable that intumescent paint would be the preferred protection solution for car parks. Therefore, estimated fire protection costs for three scales of building are given below in Table 10.

Table 10. Intumescent costs for three scales of car park as of September 2025

Above ground storeys	Approx. internal area [m ²]	Cost [£] of intumescent			
		30 min	60 min	90 min	120 min
Four	34,000	952,000	1,496,000	3,094,000	3,774,000
Eight	68,000	1,904,000	2,992,000	6,188,000	7,548,000
Twelve	100,000	2,800,000	4,400,000	9,100,000	11,000,000

6.2.2 Active fire safety systems (sprinklers)

Costs for sprinkler systems have been provided for three hazard classifications (OH2, OH3 and HHP3). Costs are provided considering four, eight and twelve above ground storeys in Table 11. As noted in section 2.5, it is assumed that the car park is constructed in an urban area, with available water infrastructure.

Table 11. Sprinkler costs as of September 2025

Above Ground Storeys	Approx. internal area [m ²]	OH2		OH3		HHP3	
		£	£ / m ²	£	£ / m ²	£	£ / m ²
Four	34,000	1,892,000	56	2,317,000	68	2,447,000	73
Eight	68,000	3,387,000	50	4,015,000	59	4,166,000	61
Twelve	100,000	4,889,000	48	5,682,000	56	6,002,000	59

For estimating ongoing maintenance costs of a sprinkler system, a flat rate of £500 per annum at a discount rate of 3.5% is adopted, which equates to £8,240 net present value over a 25-year design life, applying Section 3.3.

7. COSTS ASSOCIATED WITH DAMAGE AND LOSS OF BUSINESS

7.1 Fatalities

WP 3A studied occupant loads in car parks, concluding in proposed design values that are expressed in terms of occupants per parking bay.

The study considers two situations, one where all vehicles are occupied concurrently, i.e., every vehicle within the car park has associated occupant(s), and one where occupant transition time is considered, i.e., noting that car parks generally have a dynamic occupancy where people arrive and leave at different points through the day. The former case logically gives the highest occupant loads, i.e., 1.7 to 2.0 persons per parking bay at the 95th and 99th percentile, respectively. However, this would typically over-estimate those who might come to harm in the event of a fire induced structural failure as most people present in a car park at any given time are either in the process of entering or leaving ahead of onward activities. In this case, the occupant load based on those in transition reduces to 0.3 to 0.6 persons per parking bay at the 95th and 99th percentile, respectively. It is proposed that those in transition provides a better representation of those who might come to harm for the purpose of this LCO study. Table 12 gives the number of spaces occupied in function of the space utilisation for the four reference cases.

Table 12. Car park utilisation scenarios

Above ground storeys	Parking storeys	Number of occupied parking spaces for different utilisations [-]			
		100%	80%	60%	40%
Four	Five	1,700	1,360	1,020	680
Eight	Nine	3,060	2,448	1,836	1,224
Twelve	Thirteen	4,420	3,536	2,652	1,768

Applying 0.6 persons per occupied bay to the cases in Table 12 results in the occupancies for the reference cases shown in Table 13.

Table 13. Car park occupancy scenarios based on 99th percentile transition case

Above ground storeys	Parking storeys	Number of occupants for different utilisations [-]			
		100%	80%	60%	40%
Four	Five	1,020	816	612	408
Eight	Nine	1,836	1,469	1,102	734
Twelve	Thirteen	2,652	2,122	1,591	1,061

Estimating the costs associated with fatalities in the event of an accident is challenging. Valuing a preventable fatality (VPF) presents numerous methodological challenges. Whilst Thomas and Waddington [25] propose using revealed preferences (e.g. risk premiums in wages), Sunstein [26] highlights substantial variations in observed VPF across sex, race, and social status—discrepancies unsuitable for societal decision-making. Furthermore, revealed preferences may reflect bounded rationality and information constraints rather than rational economic behaviour.

Where revealed preferences are unavailable, stated preference methods have been employed, but these are scenario-dependent and cannot be reliably transferred across different decision contexts. Most critically, design decisions require aggregate societal VPF values: determining how much society is willing—or able—to invest to prevent the fatality of an unidentified member of the population.

Nathwani et al. [27] argue that explicitly valuing preventable fatalities is superfluous. Whilst lives cannot be assigned monetary values, risk reduction measures can be—and society routinely purchases them. Therefore, the appropriate comparison is between society-wide risk reduction and the corresponding reduction in available resources. This is where the life quality index (LQI) referenced in PD 7974-7 [28] offers value through the metric the Societal Capacity to Commit Resources (SCCR).

$$SCCR_{1-life} = \frac{g}{q} C_x$$

Where $SCCR_{1-life}$ is the SCCR for a risk reduction regime saving one statistical life [£], g is the gross domestic product per capita (GDP) in [£], q is a work-leisure trade-off factor which PD 7974-7 suggests is taken as 0.18 in the UK, and C_x is a demographic constant for the specific mortality regime over the population. PD 7974-7 suggests an SCCR of £2.6 million per person based on 2016 GDP values. The 2024 GDP per capita is ca. £39,330. This results in an SCCR value of £3.6 million for risk reduction saving one statistical life that would be broadly aligned with current GDP. This is above the ca. £2.8 million quoted in the Green Book, which is derived for road-traffic accidents.

Applying this SCCR to the occupancy scenarios in Table 13 results in the total SCCR per car park case shown in Table 14. This could be considered an upper bound as there is currently no consideration of the occupancies likely leaving the car park once they become aware of a fire.

Table 14. Upper bound SCCR associated with each scenario

Above ground storeys	Parking storeys	SCCR for different utilisations [£]			
		100%	80%	60%	40%
Four	Five	3.7 x10 ⁹	2.9E x10 ⁹	2.2 x10 ⁹	1.5 x10 ⁹
Eight	Nine	6.6 x10 ⁹	5.3 x10 ⁹	4.0 x10 ⁹	2.6 x10 ⁹
Twelve	Thirteen	9.5 x10 ⁹	7.6 x10 ⁹	5.7 x10 ⁹	3.8 x10 ⁹

In studies of offices, Hopkin, et al. [29] note that the number of fatalities arising from fire induced structural failure are generally much lower than the design occupancy owing to the prospect that most will choose to leave a building significantly far in advance of a fire causing instability. The potential occupants affected by fire induced structural failure was estimated through a risk rating. The rating was determined through integrating the product of the probability of failure of a structure in function of time and the residual occupants present. For lower-rise buildings (6 storeys), this figure was 1.5% of the occupancy at ignition, increasing to ca. 8% of the occupancy at ignition for taller buildings (20 storeys). Whilst these figures are specific to the case studied in Hopkin, et al., they suggest that a conservative order of magnitude estimate can be made. Therefore, a more credible case of 10% of the occupants at ignition remaining present at the point of fire induced structural failure is applied across all cases when considering the likely SCCR. This presumes the common provision of manual call points connected to an alarm system which would serve to alert those in the car park of the presence of a fire. The more credible SCCR associated with each scenario is shown in Table 15.

Table 15. Credible SCCR associated with each scenario

Above ground storeys	Parking storeys	SCCR for different utilisations [£]			
		100%	80%	60%	40%
Four	Five	3.7 x10 ⁸	2.9 x10 ⁸	2.2 x10 ⁸	1.5 x10 ⁸
Eight	Nine	6.6 x10 ⁸	5.3 x10 ⁸	4.0 x10 ⁸	2.6 x10 ⁸
Twelve	Thirteen	9.5 x10 ⁸	7.6 x10 ⁸	5.7 x10 ⁸	3.8 x10 ⁸

7.2 Property and contents loss

The direct property loss can be attributed to the construction cost, as discussed in Section 6. The building contents cost relates to the vehicles lost. According to a recent study, the median value of a used car in the UK is just over £16,000.

Table 16. Used car costs and number of vehicles available in 2020 vs 2025

Used Vehicle Cost Range	Number of Vehicles Available (2020)	Number of Vehicles Available (2025)
£0 - £2,500	25,052	22,492
£2,500 - £5,000	43,746	41,223
£5,000 - £10,000	114,329	74,381
£10,000 - £20,000	163,216	149,180
£20,000 - £30,000	59,982	79,103
£30,000 - £40,000	23,478	31,957
£40,000 - £50,000	9,917	14,199
£50,000 - £100,000	13,400	18,106
£100,000+	2,855	5,287

The estimated vehicle loss in function of utilisation is given in Table 17. To derive this, the mean value of a used car, i.e. £16,000 is applied to the occupied number of spaces given in Table 12.

Table 17. Estimated vehicle losses in function of utilisation

Above ground storeys	Parking storeys	Vehicle value [£]			
		100%	80%	60%	40%
Four	Five	2.72 x10 ⁷	2.18 x10 ⁷	1.63 x10 ⁷	1.09 x10 ⁷
Eight	Nine	4.90 x10 ⁷	3.92 x10 ⁷	2.94 x10 ⁷	1.96 x10 ⁷
Twelve	Thirteen	7.07 x10 ⁷	5.66 x10 ⁷	4.24 x10 ⁷	2.83 x10 ⁷

7.3 Other indirect costs

In the case of other average material losses, data from Kanda and Shah [30] is adopted, where material damage is attributed to: (a) damage to contents, (b) function loss, (c) injuries, and (d) psychological damage. Given the contents is explicitly considered through the value of vehicles, only the function loss term from Kanda and Shah is adopted as an indirect cost in this study. In the event of structural failure, it is difficult to distinguish injuries from fatalities, with the latter presumed for any occupants remaining. The psychological damage is a relatively small contribution to damage costs and, thus, is provisionally disregarded.

Kanda and Shah relate losses to the base construction cost, expressing these as a fraction of the cost of constructing the building. Kanda and Shah do not specifically reference car parks in their assessment of indirect losses in the event of structural failure. However, there are commercial premises examples, e.g., offices, where function loss is expressed as 20% of the construction cost.

For the four reference cases considered, this yields indirect failure costs as indicated in Table 18. This is simply 20% of the construction cost attributed to damage from loss of function.

Table 18. Estimation of indirect costs associated with loss of function

Above ground storeys	Approx. internal area [m ²]	Construction cost in 2025 [£]	Costs due to loss of function [£]
Four	34,000	£29,614,000	£5,922,800
Eight	68,000	£59,228,000	£11,845,600
Twelve	100,000	£87,100,000	£17,420,000

8. LIFETIME COST–OPTIMISATION (LCO) ANALYSIS

8.1 Prerequisites

As discussed in Section 3.2, future costs and benefits incurred at different times are annualised using a discount rate. This is taken as 3.5% from the Green Book [31] for all costs and benefits, noting that health related benefits are often discounted at a lower rate. The design life of a car park would typically be expected to be 50 years to align with a category 4 structure as defined in BS EN 1990 [32], which includes building structures and other common structures. However, for the discounted period in the LCO, 25 years is adopted to reflect the service life of the considered fire safety interventions, after which it is assumed that they will be replaced and costs reincurred. This allows the computation of a discount factor (β), i.e.

$$\beta = \frac{(1 - e^{-\gamma L})}{\gamma} = 16.66$$

This discount factor multiplies the damage costs to annualise them over the design life of the building. For example:

$$D_{\gamma} = \frac{(1 - e^{-\gamma L})}{\gamma} (D_f + D_v + D_i + C_0 + C_1) = \beta (D_f + D_v + D_i + C_0 + C_1)$$

That is, the discounted damage costs arise from multiplying the discount factor by the future uncertain losses, defined as the cost of fatalities (D_f), the cost of vehicles (D_v), other indirect costs (D_i) and the cost of replacement of the building ($C_0 + C_1$).

The discounted costs only arise in the event of an adverse event, which requires both a significant fire and a subsequent structural failure, i.e.

$$D_{\gamma,fi} = p_{fi} P_{f,FR} \beta (D_f + D_v + D_i + C_0 + C_1)$$

The lifetime cost becomes:

$$Y = C_0 + C_1 - D_{\gamma,fi} = C_0 + C_1 - p_{fi} P_{f,FR} \beta (D_f + D_v + D_i + C_0 + C_1)$$

Only the parameters C_1 and $D_{\gamma,fi}$ have a dependency on the safety intervention as it is presumed that the intent to construct a car park would remain regardless. Given this, the modified lifetime cost (Y^*) can be expressed only in terms of those cost terms dependant on the fire safety intervention, i.e.

$$Y^* = C_1 - D_{\gamma,fi} = C_1 - p_{fi} P_{f,FR} \beta (D_f + D_v + D_i + C_0 + C_1)$$

It follows that Y^* is positive when the cost of the safety measure exceeds the cost of damage, is negative when the cost of the damage exceeds the cost of the safety measure and is neutral where the costs cancel each other out.

8.2 Optimal structural fire resistance in the absence of sprinklers

Considering an intervention whereby structural failures are mitigated through passive fire protection; the modified lifetime cost equation can be solved for different scales of car park considering different fire resistance solutions. It should be noted that higher fire resistance demands will serve to increase C_1 whilst reducing $P_{f,FR}$. The optimal fire resistance in this context will therefore be the one where the upfront investments in safety balance against the future uncertain damage related losses when forecast over the safety intervention design life of 25 years.

Taking 30 min fire resistance as a potential intervention, Table 18 sets out a derivation for the modified lifetime cost Y^* when applied to the four-storey reference case.

Table 19. LCO application considering 30 min fire resistance to the four-storey reference car park

No of above ground storeys	4	Construction cost (C_0)	£29,614,000
No of spaces occupied	1700	Protection cost (C_1)	£952,000
Probability of a significant fire (p_f)	2.98×10^{-3} per annum	D_f - SCCR (£)	£370,000,000
Trialled FR solution	30 min	D_v - Cost of lost vehicles (£)	£27,200,000
Discount factor	16.66	D_i - Indirect damage (£)	£5,922,800
Potential fatalities	102	Total damage cost, $D_f + D_v + D_i + C_0 + C_1$ (£)	£433,688,800
$D_{y,fi}$	£20,273,597	Y^*	-£19,321,597

As Y^* ends up negative in Table 19 it implies that the future uncertain damage over a 25-year period exceeds the upfront cost of the safety measure. Applying this process across the domain of different fire resistance options and for the additional cases of eight and twelve storey car parks results in Figure 4. The figure starts at a fire resistance of zero on the presumption that steel elements can exist that do not inherently achieve 15 min of fire resistance and may require additional sizing to do so.

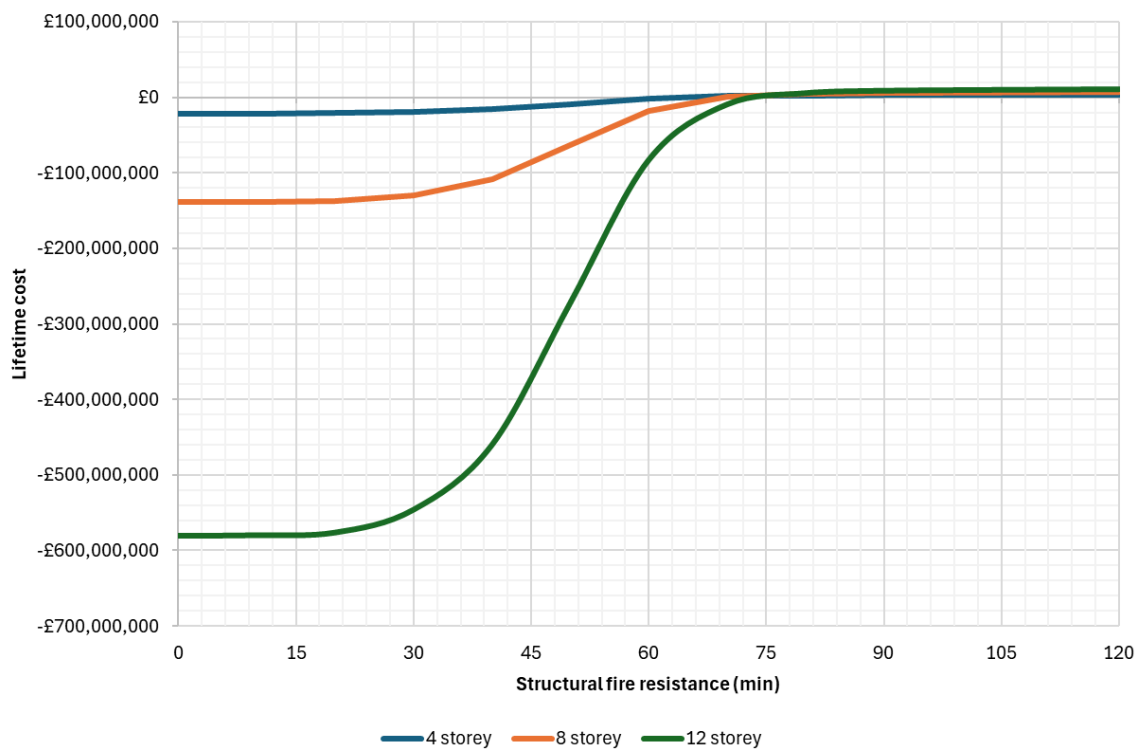


Figure 4. Lifetime cost optimisation for four, eight and twelve storey reference car parks, impact of fire resistance on lifetime cost

Figure 4 would indicate that the optimal life-time fire resistance periods for the four, eight and twelve storey reference cases are 65 min, 69 min and 76 min, respectively.

8.2.1 Sensitivity to car park utilisation

The car park utilisation affects several factors in the cost-benefit analysis, from the ignition rate and subsequent fire severity, through to the number of cars damaged and potential people harmed. Reducing the utilisation from 100% to 80% results in the optimal fire resistance periods for the four, eight and twelve storey reference

cases of 62 min, 68 min and 73 min, respectively. That is, utilisation serves to marginally reduce the optimal fire resistance but not substantially.

8.2.2 Sensitivity to the SCCR

The total SCCR underpinning the cost-optimisation is expressed as 10% of the occupants in transition (99th percentile), adopting a cost of £3.6 million for risk reduction saving one statistical life. For the large car park cases considered herein, this results in fatalities of the order of 10^2 in the event of a structural failure. This places the number of fatalities in the same order of magnitude as a Consequence Class 4 structure in ISO 2394 [33], which includes high-rise buildings, grandstands, etc.

Consideration of fatalities in the order of 10^1 would place a car park in Consequence Class 3, which considers most residential buildings, typical bridges and tunnels, typical offshore facilities, etc. Such a change results in the optimal fire resistance periods for the four, eight and twelve storey reference cases of 56 min, 64 min and 69 min, respectively, for a fully utilised car park.

8.3 Introduction of sprinkler protection

Sprinklers do not impact the failure probability of a structure in the event of an uncontrolled fire. However, they do reduce the likelihood of a fire becoming uncontrolled in the first place. In the absence of specific reliability figures for a car park, a failure probability of 10% is taken based on the data in PD 7974-7. Costs for a sprinkler system are premised on an OH2 specification. This is because it is assumed that OH2, OH3 and HHP3 sprinklers would all have comparable reliabilities yet become increasingly expensive. OH2 is therefore considered because it is likely the most cost-effective.

At 100% car park utilisation and a corresponding total SCCR relating to 10% of the occupants in transition (99th percentile), the modified lifetime cost is as shown in Figure 5.

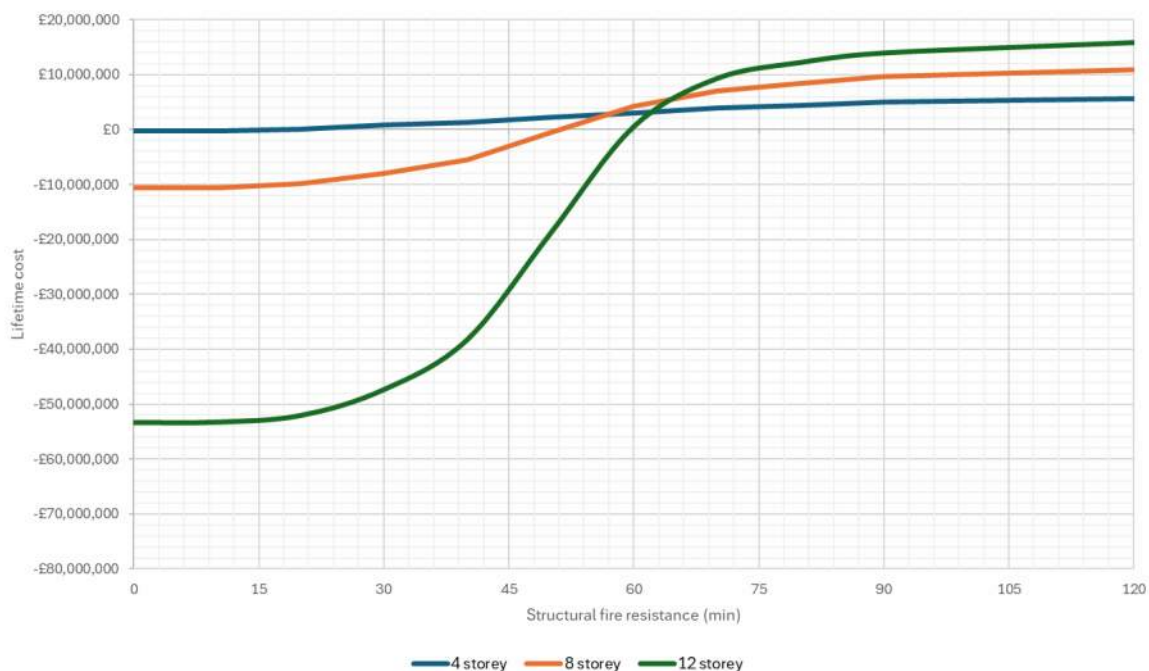


Figure 5. Lifetime cost optimisation for four, eight and twelve storey reference car parks, impact of fire resistance on lifetime cost including sprinklers

Figure 5 would indicate that the optimal fire resistance periods for the four, eight and twelve storey sprinkler protected reference cases are 18 min, 51 min and 59 min, respectively.

8.3.1 Sensitivity to car park utilisation

For four storey case, reducing the car park utilisation from 100% to 80% with the inclusion of sprinklers results in safety investment costs that are greater than the cost of damage regardless of the structural fire resistance. That is, there would be an acceptance of disproportionately between the costs and benefits, with sprinklers unlikely to provide a return on their investment over the 25-year design life.

Reducing the car park utilisation from 100% to 80% with the inclusion of sprinklers for the eight and twelve storey cases, results in optimal fire resistance periods of 44 min and 56 min, respectively.

8.3.2 Sensitivity to the SCCR

At 100% utilisation, reducing the SCCR by an order of magnitude for the four and eight storey cases results in safety investment costs that are greater than the cost of damage regardless of the structural fire resistance. That is, there would be an acceptance of disproportionately between the costs and benefits, with sprinklers unlikely to provide a return on their investment over the 25-year design life. For the twelve storey case, the optimal fire resistance is 46 min.

8.4 Sensitivity study using Green Book inputs

Appendix I studies the impact of adopting the discount rate provisions and value of a preventable fatality as per the Green Book on the LCO analysis. The implications are discussed in section 10.

9. COMPARISON OF OPTIONS USING THE COST-BENEFIT RATIO

The lifetime cost optimisation study presented in Section 8 considers how best, over a 25-year period, to balance the upfront cost of safety measures with future uncertain damage related losses. It does not directly consider what fire safety interventions provide the largest ratio of damage reduction to cost relative to the current policy baseline. To do this, a form of the fire safety J-Value proposed in Hopkin, et al. [3], is applied to compare possible fire safety interventions.

9.1 The fire safety J-Value

In simple terms, the fire safety J-Value can be thought of as the ratio between the cost of a fire safety intervention and the reduction in damage it achieves, i.e.

$$J_{fi} = \frac{C_1}{\Delta(p_{fi}P_{f,FR}\beta(D_f + D_v + D_i + C_0 + C_1))}$$

To determine the denominator, the change in discounted damage relative to currently policy is determined, i.e. the losses associated with a 15 min fire resistance rating for the four and eight storey cases, and a 60 min rating for the twelve-storey case, referencing Approved Document B, Volume 2.

9.2 Interpretation of the J-Value

The J-Value will always be positive subject to the intervention improving safety. The costs and benefits are in balance when $J_{fi} = 1.0$. If $J_{fi} > 1.0$ this suggests the costs exceed the marginal improvement in safety. $J_{fi} < 1.0$ confirms the safety investment is viable as there is a return on investment. The smaller J_{fi} is the larger the return on investment as the benefits far exceed the costs.

9.3 Cost-benefit ratios

9.3.1 Without sprinklers

Revisiting the analysis in Section 8.2, i.e., starting with a fully utilised car park and SCCR with fatalities of the order of 10^2 , the J-Value in function of fire resistance is plotted in Figure 6. The curves start at 30 min structural fire resistance as this is the first logical increment of fire resistance intervention relative to the currently policy position of 15 min. For the twelve-storey case, this increases to 75 min.

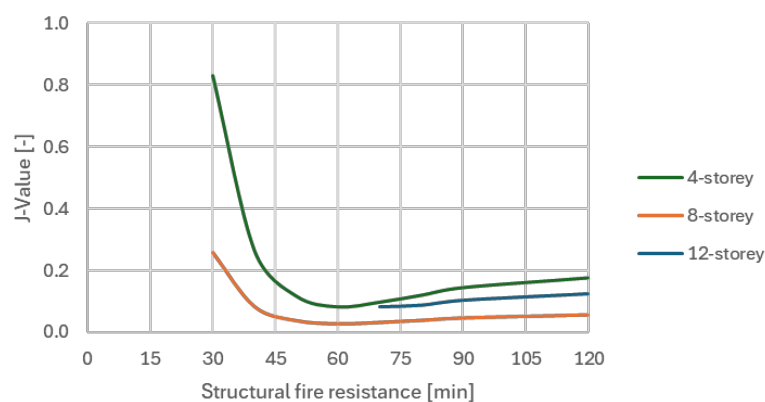


Figure 6. J-Value in function of structural fire resistance, 100% utilised car park case

The intervention that provides the greatest return on investment corresponds to the lowest J-Value. The minima for the four and eight storey cases are at ca. 60 min, with J-Values of ca. 0.08 and 0.03, respectively. Both are viable interventions and have a positive return on investment, but fire resistance of 60 min in the eight-storey case offers a better return. No minimum is present for the 12-storey case, suggesting that deviating from the current ADB position of 60 min is unlikely to add significant value. Based on the costs provided to OFR, the safety intervention at the four and eight storey cases will likely be ca. £1.5 million and £3 million, respectively.

It is worth noting that even an intervention of 30 min provides a return on investment as the J-Value is less than one for all increases in structural fire resistance beyond 15 min for the four and eight-storey cases.

9.3.2 With sprinklers

Applying the same procedure to the sprinkler cases as per Section 8.3 allows conclusions to be drawn regarding the cost-benefit ratio of active systems. In this instance, the sprinklers have an upfront safety cost but reduce the frequency of uncontrolled fires.

Figure 7 shows the J-Value for cases where OH2 sprinklers are included, in function of structural fire resistance. This also adopts a fully utilised car park and SCCR with fatalities of the order of 10^2 .

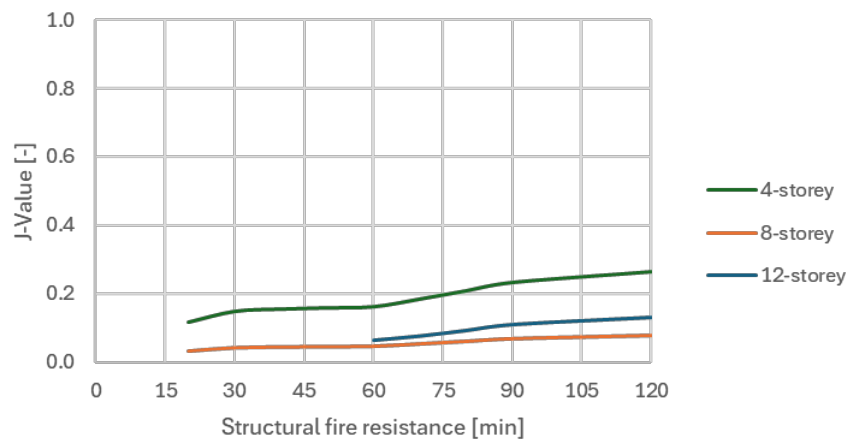


Figure 7. J-Value in function of structural fire resistance, 100% utilised car park case with OH2 sprinklers

It can be seen there is no minima in Figure 7 which confers that if sprinklers were provided, the current policy positions of 15 min and 60 min structural fire resistance would not warrant an increase. Specifically in the 12-storey case, the absence of a minimal inflexion point would suggest that sprinklers could be introduced alongside a reduction in structural fire resistance, i.e. below 60 min. To what extent has not been investigated.

Assuming the current fire resistance policy positions are retained, the J-Values are ca. 0.09, 0.03 and 0.06 for the four, eight and twelve storey cases, respectively.

9.3.3 Sensitivity to SCCR

It has been previously noted in Section 8 that provisional estimates of fatalities based on 10% of the in-transit occupancy is conservative based on current statistics. Reducing the fatalities by an order of magnitude, i.e. to 10^1 , provides an opportunity to reappraise the cost-benefit ratios. Cases with and without sprinklers are shown in Figure 8.

Such a change does not materially change the position of the minimum inflexion points for the cases considered as the reduction in damage is relative to the current policy positions which would also benefit from the same reduction in SCCR.

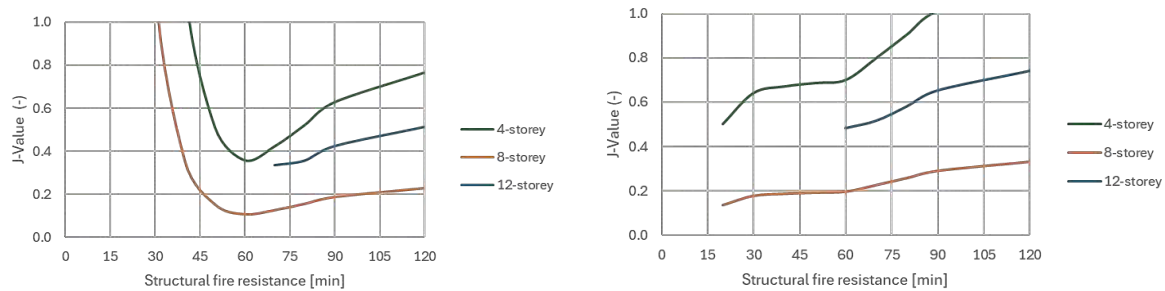


Figure 8. J-Value in function of structural fire resistance, 100% utilised car park case but reduced SCCR: (left) without sprinklers, (right) with OH2 sprinklers

The change in SCCR does, however, alter the J-Values at the minimum inflection points as the costs remain static but the benefits reduce. For example, with a reduced SCCR, 60 min fire resistance delivers a J-Value of 0.36 compared to 0.09 in the base case presented in section 9.3.1. Sensitivity study using Green Book inputs

Appendix I studies the impact of adopting the discount rate provisions and value of a preventable fatality as per the Green Book on the J-Value analysis. The implications are discussed in section 10.

9.4 Comparison of safety measure interventions

In the event of a structural failure resulting in a high number of casualties in a fully occupied car park, the optimal ratio of safety investment to damage reduction arises at ca. 60 min structural fire resistance for the four, eight and twelve storey cases investigated. These yield a benefit to cost ratio (i.e., $1/J_{fi}$) of 12 to 40. When the number of casualties is reduced by an order of magnitude the optimal ratio continues to occur at 60 min, albeit the benefit to cost ratio reduces to a range of 3 to 9. Below the 60 min threshold, fires are typically too severe to substantially impact the failure probability. Above this threshold, the cost of protection increasingly becomes disproportionate to the reduction in failure probability.

For sprinklers introduced at an OH2 grade, when considering relative reduction in damage compared to cost of safety measures, the optimal fire resistance appears to coincide with the current policy positions, i.e., 15 min for the four and eight-storey cases and 60 min for the twelve-storey case. Despite this, sprinklers offer a benefit which is at least balanced against the costs of safety measure. For the higher SCCR, this benefit to cost ratio range is 10 to 37. When the SCCR is reduced, the ratio is in the range 2 to 9.

Considering the four and eight storey cases, sprinklers plus a currently policy position of 15 min structural fire resistance results in a comparable benefit-to-cost ratio as a sole increase in structural fire resistance to 60 min. This is the case regardless of the SCCR. For the twelve-storey case, the benefit-to-cost ratio for the inclusion of sprinklers is positive, implying there is a return on investment over the current policy position. This is more apparent for the high SCCR case than the reduced case. Given the currently policy position of 60 min structural fire resistance for a twelve-storey car park, it is probable that if sprinklers were to be introduced a reduction in structural fire resistance would be justifiable, albeit this has not been specifically investigated.

10. DISCUSSION & RECOMMENDATION

10.1 Discussion

The report considers three reference car park cases that broadly align to terminal car park 1 at Luton Airport, using images and documentation in the public domain. This is a large purpose-built open-sided multi-storey car park that could be considered, at least in plan area, at the extremes of what might be expected for such a case. Therefore, it has the high potential to exhibit large losses in the event of fire induced structural failure and can form a conservative reference point against which different fire safety measures can be tested.

The three reference cases are four, eight and twelve storeys, respectively. The currently policy position, i.e., the guidance in ADB, would suggest that such cases be afforded 15 min structural fire resistance for the two lower cases, increasing to 60 min for the twelve-storey case. In no cases would sprinklers be recommended at present.

Whilst car parks can be constructed from a variety of structural materials, the most common and likely onerous case for a policy intervention perspective would be a steel frame supporting concrete slabs. This is because steel frames can be designed to achieve 15 min fire resistance inherently but would typically require passive fire protection for fire resistance demands above this. That is, any variation from the currently policy for the lower-rise cases would be an additional cost for the sole purpose of improving fire safety and reducing fire related losses. Concrete structures may achieve higher levels of fire resistance inherently and, therefore, the impact of policy change would be less onerous.

This lifetime cost-optimisation report makes use of data from other contract deliverables that should be referenced for a complete picture of the work undertaken. This includes data derived on occupancy loads (WP 3A), fire spread rates / extents (WP 1B) and failure probabilities in function of structural fire resistance ratings (WP 2). Importantly, WP 2 has identified that in highly occupied car parks, fires have the potential to be severe and spread to involve large areas. Because of this, failure probabilities at lower fire resistance specifications can be relatively high before reducing. Applying fire protection to steel structures therefore requires a minimum effective dose beyond which reasonable levels of damage reduction for the relative cost can be expected.

OFR have been provided costs by BSR's cost advisors for potential policy interventions that include passive protection and sprinkler protection. The study has focussed on the most cost-effective of each of these solutions which were found to be intumescent paint and Ordinary Hazard 2 sprinkler protection to BS EN 12845. Other costs were provided for alternative protection systems and higher hazard classification sprinkler systems. These were not studied further under the constraints of the contract as they were deemed to offer comparable efficacy but for generally higher costs.

WP 2 found that varying ceiling height could be an effective measure for reducing fire spread rates, extents and therefore fire intensities in car parks. However, such an intervention has not been considered at the request of BSR as such constraints would represent a change in the type of guidance that Approved Document B typically provides.

The study has used structural failure probabilities in function of structural fire resistance to introduce simple failure probabilities through an idealised limit state. The limit state is such that the entire structure is considered to fail if an element is subject to heating of severity greater than its equivalent fire resistance rating. That is, any uncertainty that might arise is simplified to the thermal load and any structural interactions that may occur, e.g., load-redistribution, membrane action, restrained thermal expansion, etc., are disregarded.

The failure probabilities allow future uncertain failure costs to be estimated over a safety interventions design life through the process of annualization, using an appropriate discount rate. The study has used a 25-year design life. The optimal fire safety interventions considered over their service life therefore ensure, at a minimum, that the upfront costs in safety measures yield at least the same costs in terms of future damage reduction.

One of the challenges of estimating future damage reduction is in estimating the number of potential casualties / fatalities that may occur. At present, the authors are not aware of a fatality in a UK car park because of fire. Nevertheless, given the limited historical occurrence of fire induced structural failures, it would be inappropriate

to presume such an instance could not cause a multi-fatality event in the future. Other car park cost-benefit studies [4] have neglected such a prospect by only referencing historical statistics without forecasting future low probability high consequence events that could occur. For this study, car park occupant loads have been revisited in WP 3A. Therein, it is shown that the ADB presumption of 2 persons / space is conservative in the event all cars are simultaneously occupied. Further, it introduces the concept of persons-in-transit, which are those people simultaneously present in a car park because they are either leaving or returning to their vehicle enroute to another destination. Despite this significantly reducing the occupancy of a car park, there can still be many people present when a fire occurs and with limited provision for warning due to a typical lack of automatic fire detection. In turn, this means there could be a high occupancy present at the point of structural failure. This is reflected through the work of Hopkin, et al. [29], where a relatively conservative estimate of 10% of the people-in-transit being present at the point of structural failure is made.

The impact of potential fatalities on the efficacy of a fire safety intervention has been made through the life quality index. This introduces the figure, Societal Capacity to Commit Resources (SCCR), which is an expression of the cost in risk reduction that can be made to save one statistical life that simultaneously maintains or improves societal welfare. At 2025 rates, this figure was estimated to be £3.6 million per statistical life saved as per PD 7974-7 but adjusted to 2025 rates. This is higher than the value of a preventable fatality (VPF) figure adopted in the Green Book of ca. £2.8 million at 2025 rates. For completeness, a sensitivity study on this parameter has been incorporated in Appendix I which is more aligned to the Green Book both in terms of the VPF and the discount rates recommended for health benefits.

When considering the lifetime costs on a 25-year horizon in Section 8, the base case of a car park with 100% space utilisation is demonstrated to have optimal fire resistances of 65 min, 69 min and 76 min for four, eight and twelve storey cases, respectively. Sensitivity studies were undertaken to establish if the optimal values significantly altered when considering key inputs, namely the space utilisation and the SCCR. Reducing the utilisation to 80% nominally impacted the fire resistance, i.e., 62, 68 and 73 min. Reducing the SCCR such that the fatalities represented 1% of the people-in-transit result in fire resistances of 56 min, 64 min and 69 min, respectively. The lack of significant sensitivity to the SCCR and utilisation is because the safety intervention costs are relatively small, compared to the losses which are significantly impacted by the rebuild cost of the car park, the loss of contents and function. A lesser investment in safety measures would likely be justified if the sole focus was a reduction in injuries and fatalities, with property, content and function loss disregarded.

Considering the inclusion of OH2 sprinklers alongside structural fire resistance resulted in optimal lifetime fire resistances of ca. 18, 51 and 59 min for four, eight and twelve storeys, respectively, when 100% space utilisation is considered alongside an SCCR derived from 10% of the in-transit occupancy. Reducing the utilisation to 80% resulted in the four-storey case having safety costs that always exceeded future uncertain damage, i.e., no optimum was identified. For the eight and twelve storey cases, the optimal fire resistance was 44 min and 56 min, respectively. Reducing the SCCR to 1% of people in transit resulted in the four and eight-storey cases having safety costs that always exceeded future uncertain damage, i.e., no optimum was identified. For the taller twelve-storey case, the fire resistance derived was 46 min.

The base case study, i.e. 100% utilisation and 10% of the in-transit occupancy, was revisited in Appendix I adopting Green Book inputs for the VPF and adopting a lower discount rate of 1.5% for health benefits. This did not materially affect the fire resistance recommendations from the LCO study as the reduced VPF was offset by the lower discount rate over the 25-year discounting period.

It is important to stress that the term optimal in the lifetime optimisation study simply implies that upfront costs align with future uncertain losses. However, the improvement in safety for each pound spent relative to current policy positions provides a means of comparing the efficacy of potential interventions. This was the subject of a J-Value study in section 9. Therein, the damage expected for the current policy positions for the three car park cases is compared to the damage expected post-safety-intervention. This provides an estimate of damage reduction arising from a fire safety intervention that can be compared to the cost of improving safety.

For the 100% utilised case, adopting the 10% persons in transit for the derivation of the SCCR, the optimal ratio of safety investment to damage reduction arises at ca. 60 min structural fire resistance for the four, eight and twelve storey cases investigated. These yield a benefit to cost ratio (i.e., $1/J_{fi}$) of 12 to 40. When the number of casualties is reduced by an order of magnitude the optimal ratio continues to occur at 60 min, albeit the

benefit to cost ratio reduces to a range of 3 to 9. That is, relative to the provision of 15 min fire resistance, 60 min fire resistance will offer a significant benefit relative to the cost.

Considering the four and eight storey cases, sprinklers plus a currently policy position of 15 min structural fire resistance results in a comparable benefit-to-cost ratio as a sole increase in structural fire resistance to 60 min. This is the case regardless of the SCCR. For the twelve-storey case, the benefit-to-cost ratio for the inclusion of sprinklers is also positive, implying there is a return on investment over the life of a building.

10.2 Considerations

The study has chosen a large reference car park for the purpose of evaluation. Such scale may offer economies in the installation of measures such as sprinklers that reduce the overall cost per unit area. Installing sprinklers in smaller car parks for example could be substantially less cost effective when considering the per unit area rate. Similarly, if sprinklers were introduced in rural areas, there may be additional costs beyond those considered herein, thus affecting the potential return on investment.

The study has used a steel car park as a reference where the cost of increasing fire resistance will result in a direct increase in construction costs. Increasing the fire resistance of concrete-frame car parks might be less impactful from a cost perspective, meaning the potential for an improved cost-benefit ratio.

Section 5 has noted a potential increase in frequency of car park fires when considering the most recent three years of statistical data. The significant fire occurrence rates adopted in the analyses are based on a 14-year time horizon. Increasing significant fire occurrence rates to align with short-term data would further justify changes to current technical policy.

Finally, no direct consideration has been given to the loss of spaces and, thus, revenue, that might arise from the installation of sprinklers. This is not insignificant and would affect the utility of a carpark.

10.3 Recommendation

The results present an interesting conundrum that is beyond OFR's scope to conclude. That is deciding between what is optimal over the life of the building or implementing the measures that provide the best improvement in safety relative to their cost. As Sections 8 and 9 show, what is optimal over the design life of a safety investment and what provides the biggest improvement for the cost are not always aligned, especially when considering sprinklers. Sprinklers can provide a similar improvement in safety relative to their cost as 60 min fire resistance when benchmarked against current policy positions for the four and eight storey cases. However, for the residual damage costs to be balanced against upfront safety investments, additional fire protection could be justified.

Tentative consensus between the lifetime cost study and J-Value study could be taken to suggest that passive fire protection is a justified intervention and that this could be between 60 and 75 min depending upon the size / height of the car park. Such an intervention balances upfront costs and damages over the life of a building and also provides an attractive cost-benefit ratio when measured relative to the current policy position. It is also aligned to recent industry guidance produced by the Institution of Structural Engineers [34].

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Appendix I – Green Book Sensitivity Study

This Appendix revisits the analysis presented in section 8 and section 9, using inputs that are aligned to the Green Book, so far as is practicable. The most significant changes to that presented previously relate to (a) the value of a preventable fatality, and (b) the discount rate applied to health benefits.

Value of a preventable fatality (VPF)

The analyses in section 8 and section 9 utilise the life quality index to determine the benefits of risk reduction when saving one statistical life. This is through the metric, societal capacity to commit resources (SCCR), which is set at ca. £3.6m per statistical life saved at 2025 rates. The Green Book references the Department for Transport, transport analysis guidance, which places the VPF at ca. £2.8m in 2025.

Revisiting Table 15, but adopting £2.8m in lieu of £3.6m per life saved results in the following:

Table 20. Credible VPF associated with each scenario

Above ground storeys	Parking storeys	SCCR for different utilisations [£]			
		100%	80%	60%	40%
Four	Five	2.9 x10 ⁸	2.3 x10 ⁸	1.7 x10 ⁸	1.2 x10 ⁸
Eight	Nine	5.1 x10 ⁸	4.1 x10 ⁸	3.1 x10 ⁸	2.0 x10 ⁸
Twelve	Thirteen	7.4 x10 ⁸	5.9 x10 ⁸	4.4 x10 ⁸	3.0 x10 ⁸

Discount rates

The analyses in section 8 and section 9 discount future uncertain cost and benefits to today's values using a constant discount rate of 3.5% over the 25-year service life of the safety intervention. The Green Book proposes that benefits relating to health should be subject to a lower discount rate of 1.5% for a discount period of up to 30 years.

In the analysis presented in section 8 and section 9, this means applying a different discount factor to benefits relating to reductions in property damage, car losses and loss of service (3.5%) to those that relate to fatalities (1.5%). This can be considered through the modified lifetime cost as follows:

$$Y^* = C_1 - D_{\gamma,fi} = C_1 - p_{fi}P_{f,FR}\beta_p(D_v + D_i + C_0 + C_1) - p_{fi}P_{f,FR}\beta_h D_f$$

With β_p the discount factor relating to property and business loss being:

$$\beta_p = \frac{(1 - e^{-\gamma_p L})}{\gamma_p} = 16.66$$

And β_h the discount factor relating to health as:

$$\beta_h = \frac{(1 - e^{-\gamma_h L})}{\gamma_h} = 20.85$$

Where γ_p is the property and business loss discount rate of 3.5%, γ_h is the health discount rate of 1.5% and L is the duration of the discounting period, taken as 25 years.

Impact on LCO study

The LCO analysis considering 100% car park utilisation and 10^2 magnitude fatalities was revisited noting the presented changes to the VPF and discount factors. The lifetime cost in function of structural fire resistance is shown in Figure 9. Lifetime costs are neutral at 65 min, 70 min and 76 min, for the four, eight and twelve-storey cases, respectively.

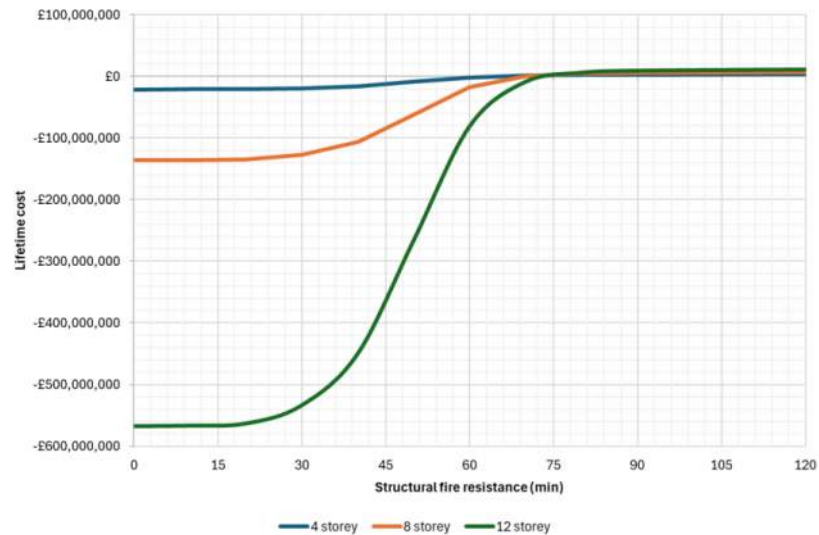


Figure 9. Lifetime cost evaluation for 4 to 12-storey cases, modified for Green Book inputs, without sprinklers

For the same case but with the inclusion of OH2 sprinkler protection, the lifetime cost in function of structural fire resistance is shown in Figure 10. Lifetime costs are neutral at 16 min, 51 min and 60 min, for the four, eight and twelve-storey cases, respectively.

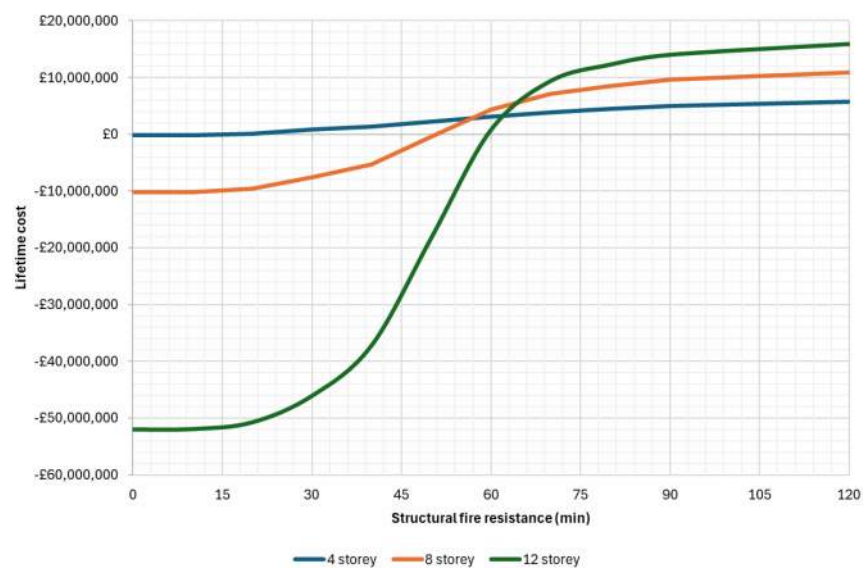


Figure 10. Lifetime cost evaluation for 4 to 12-storey cases, modified for Green Book inputs, with sprinklers

Impact on J-Value study

The J-Value expresses the cost-benefit ratio of a safety intervention relative to the current policy position, providing insight into what options provide the best return on investment. Using Green Book inputs the analysis in sections 9.3.1 and 9.3.2, i.e., 100% car park utilisation and 10^2 magnitude fatalities. The plots of structural fire resistance vs. J-Value are shown in Figure 11.

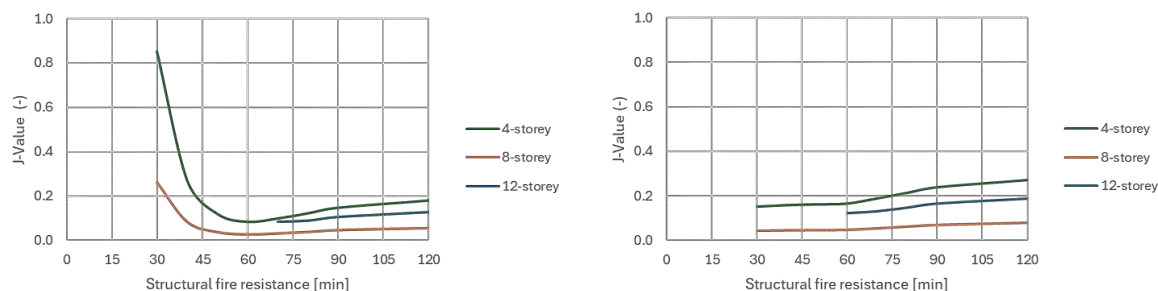


Figure 11. J-Value assessment using Green Book inputs (left) without sprinklers, (right) with sprinklers.

In the absence of sprinkler protection, the inflection point of the J-Value curves for the four and eight storey cases occur at 60 min, giving benefit-to-cost ratios of 12 and 39, respectively. There is no inflection point present for the twelve-storey case, again suggesting that the current provision is close to optimal.

When sprinklers are installed, all J-Values are below unity, implying the benefits outweigh the costs. At the current policy positions of 15 min and 60 min structural fire resistances, the benefit-to-cost ratios are 10, 36 and 8 for the four, eight and twelve-storey cases, respectively.

Much like the study presented in the main body of the report, this seems to suggest that for the four and eight storey cases, sprinkler protection offers a similar return on investment to increases in structural fire protection to 60 min. For the twelve-storey case, the lack of an inflection point suggests sprinklers could go hand-in-hand with a reduction in structural fire resistance from the current policy position, albeit to what extent has not been investigated.

Comparison against base study

Table 21 compares the fire resistance recommendations from the LCO study using the base study inputs, i.e., as per section 8 vs adopting the Green Book input variations discussed in this appendix. The outcomes are largely the same. This is because the adoption of the VPF over the SCCR is offset by the change in discount rate for health benefits, moving to 1.5% from 3.5%.

It is therefore expected that the conclusions in the main body of the report would hold if reproduced using Green Book inputs throughout.

Table 21. Comparison of LCO optimal fire resistance periods – base study vs. Green Book inputs

Above ground storeys	Parking storeys	Optimal structural fire resistance (min)			
		Without sprinklers		With sprinklers	
		Base study	Green Book	Base study	Green Book
Four	Five	65	65	18	16
Eight	Nine	69	70	51	51
Twelve	Thirteen	76	76	59	60