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Systematic Literature Review on Passenger Car Fire Experiments for Car Park Safety Design

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Abstract
To allow future creation of knowledge-based design fire scenarios for car fires, a systematic literature review was performed. Keywords "fire + passenger vehicle" and "fire + car" were filtered in Scopus, Science Direct and Web of Science databases for 1990–2024 period yielding 11 papers containing relevant data. A further citation mining on references revealed another 33. A total of 148 individual records of fire experiments were identified, with records of the heat release rate (or mass loss rate), total heat release and time to reach peak heat release rate. The database was subdivided by the car size and drivetrain, as well by the age of experiments. Analysing the course of experiments, common phases of fires have been identified, leading to another sub-division of the database by the location of the ignition source. It was found that fires initiated from the underneath the car did lead to higher peak HRR and a shorter time to peak compared to fires starting at other locations. Statistical distributions of peak HRR, time to peak HRR and THR are given for each subset of data. The average Heat of Combustion value of 25 MJ/kg (± 7 MJ/kg) was identified for the entire dataset.

Keywords Car park · Car fire · Passenger car · Fire experiments · HRR

1 Introduction

Investigation into the fire safety of a modern building requires assumptions related to the fire load distribution, which in the case of car parks will consist mostly of passenger cars. Further assumptions necessary for fire modelling exercises often include the fire growth rate characteristics and yields of soot and other combustion products. With the rise in large car park fires that resulted in significant property loss, business disruption, and social consequences, the subject of car park fires is rising in the interest of the fire safety science and engineering communities. A list of recent large car park fires (2017–2024) based on media reports is presented in Table 1.

In all of the abovementioned fires, the loss of property was significant. Due to severe damage, the buildings had to be either demolished or undergo complex and costly repair

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Table 1 Examples of large car park fires mentioned in the media in 2017 – 2024

City, Country	Approx. number of cars involved	Location	Data	Source
Engelen, Netherlands	50	Under residential complex	2024	[1]
Atsugi, Japan	100	Free standing car park	2023	[2]
Munich, Germany	29	Free standing car park	2023	[3]
Luton, England	1500	Airport	2023	[4]
Marsta, Sweden	200	Residential car park	2021	[5]
Warsaw, Poland	50	Under residential complex	2020	[6]
Stavanger, Norway	300	Airport	2020	[7]
Cork, Ireland	60	Above shopping mall	2019	[8]
New York, USA	120	Kings Plaza	2018	[9]
Liverpool, England	1150	Next to a sports arena	2017	[10]

processes [11]. Besides the loss of the building, the property loss also includes the loss in passenger cars, which for the fires in Liverpool or Luton exceeded 1000 cars in each of the fires. In the case of car parks located near airports, sports arenas or shopping malls, the short-term business disruption was related to the fire itself and the ongoing firefighting operations. The disruption continued into the long term, as the reduction in available parking spaces impacted the facilities' everyday operations. In case of the fire in a shopping mall in Cork, the entire mall had to be demolished, influencing the livelihood of over 50 local vendors and significantly impacting the local economy. In the case of the fire in Warsaw, which happened under a large residential complex, over 80 families had to leave the building overnight and could not return to their houses for over two years. This can be considered as an example of an unacceptable social consequence of the fire.

As the fire safety community looks into the fire safety of car parks [12], means of protection [13, 14] or efficient smoke control [15], a growing need for high-quality sources of data on car fires has been observed. This data comes from large-scale fire experiments including cars, and in the past, research summaries published by Janssens in 2008 [16] or Tohir in 2015 [17] have been used. In some cases, particular fire experiments were used as a basis for the proposal of design fire curves (heat release rate, HRR, shown as a function of time), that have been adopted in various design standards and guidance [18, 19]. In the last 10, a significant increase in fire experiments with cars, also with alternative fuels—Battery Electric Vehicles (BEV), Plug-in Hybrid Electric Vehicles (PHEV) and Fuel Cell Electric Vehicles (FCEV), has been observed. The recent doubts expressed by car park designers and fire safety engineers are focused on the relevance of 10+year old curves and data for modern cars, especially those with a different drivetrain, thus justifying revision of the existing state-of-the-art.

While the necessity for high-quality input data is growing, the communities of scientists and practitioners are responding to this need by creating new design fires. As an example, such new approaches for design fire creation are proposed in research papers [20, 21] or guidance documents [22]. The proposed design scenarios in these examples are based on averaging or fitting some of the collected data. In such an approach, multiple biases are often introduced related to, e.g. incomplete dataset, unjustified comparison of experiments carried in varying conditions or the age of the data and in consequence, low representability of the collected data set for a modern car fleet.

Furthermore, some of the approaches use time-averaged values resulting from averaging different experiments. Finally, inevitably, as new research is published, the previously used statistical correlations (i.e., average HRR measured in experiments) will no longer hold. To add to this challenge, not all data available in the literature is published in easily accessible sources accumulated in literature databases (i.e. peer-reviewed journals and books), and it is common to find experimental data in test reports in various institutional repositories.

To enable a new generation of design fires and reduce the bias in the analysis of existing datasets on passenger car fires, a systematic literature review on the subject have been performed. The goal was to create a complete overview of the relevant research so far, extracting the important data for further statistical analysis. In order to ensure the completeness of the database, a systematic review was conducted using three major research repositories—Scopus, ScienceDirect and Web of Science. This was done against the keywords "*fire + passenger vehicle*" and "*fire + car*". Furthermore, the review process has also included the proceedings of the Fires in Vehicles conferences. After identifying the first group of papers, the approach of citation mining was employed, which involves identifying 'new' literature positions from the bibliographies of the previously identified studies. The collected database was focused on the recent 30 year period, and contains data from of 1st January 1994 till 30th March 2024.

After collecting the sources, papers containing fire experiment data on passenger cars have been identified, excluding experiments with early suppression (i.e., the focus of the study was on suppression systems, not the fire's growth). Information related to the measurements in the tests has been extracted, including details on the type of car (mass, age, drivetrain) as well as on the fire testing approach (location and size of the ignition source). After categorising cars into groups by their size and drivetrain, an analysis of the data was conducted, including an evaluation of peak HRR values at different confidence intervals (average, standard deviation, median, 5th, 95th and 99th percentiles), as well as the approximation of the total heat release (THR) and effective heat of combustion for cars of different types.

Inspired by the approach presented by Morrisset et al. [23], an endeavour was made to determine if any distinct phases can be observed in car fires and have associated them with some key events in the car fires. A more detailed analysis for all of the fires in the database regarding these events was impossible due to the scarcity of information on some fire tests. However, based on observations, the data was analysed in sub-sets with regard to the ignition source location, which may trigger the specific course of the car fire. The collected and processed data may find use in the creation of new guidelines and regulations for car parks, research on car park fires and the design of fire protection measures for car parks.

The paper consists of an explanation of the systematic literature method used for the study (Sect. 2), which also introduces the sources and references for data. Section 3 presents a detailed overview of all the investigated tests, highlighting key aspects of the studies, such as vehicle age and ignition methods. Section 4 describes the database structure and introduces the subsets included in the analysis, categorised by mass, drivetrain, and age. Section 5 offers a critical analysis of the database contents, including a discussion on the progression of fires in the experiments and a statistical analysis of the collected data. Section 6 contains the general conclusions of the study, followed by appendices containing the data relevant for the research. While the data analysis in here follows the choices done by the authors, the Reader is welcome to perform their own analyses based on the raw data provided in the appendices.

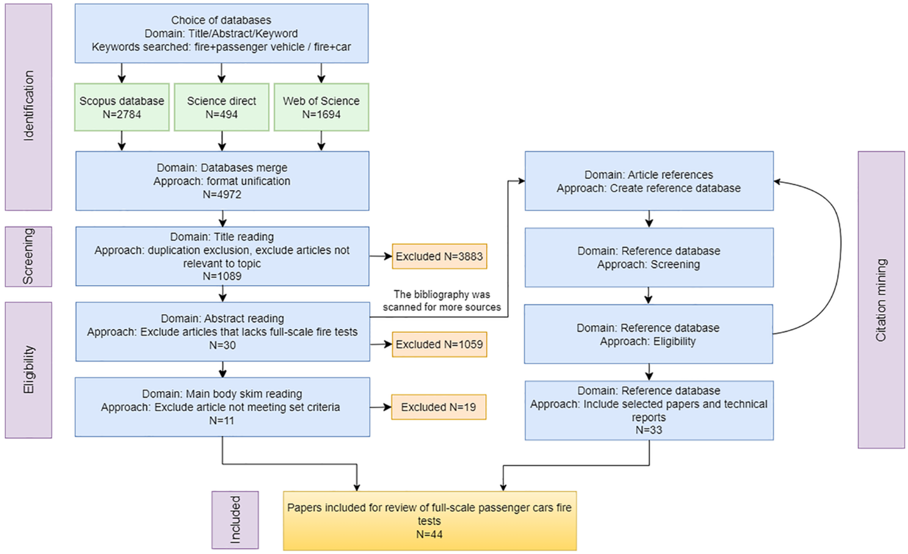


Fig. 1 Flowchart of performed systematic literature review and the citation mining procedure

2 Systematic Literature Review

In order to identify the relevant sources containing information pertinent to the fire experiments with passenger cars, a systematic literature review (SLR) was performed. This method provides methodological rigour to the literature review. The general rules of the SLR were applied after [24], and useful resources were provided at the TU Berlin online repository [25]. The general structure of the literature review included three main steps, that is: (1) identification of all papers of interest that were published after 1990, (2) screening process in which the unrelated papers are excluded, followed by (3) eligibility where all papers are evaluated through first abstract, and then domain skim read. Due to the character of the research, i.e. a significant number of resources in technical reports/conference papers that may not be searchable through online repositories, a parallel search of sources through so-called citation mining was included. The flowchart of the process is shown on Fig. 1.

In the first step, a keyword search was performed on main scientific repositories, that is Scopus, ScienceDirect and Web of Science databases. Two sets of keywords were looked at, that is "*fire + passenger vehicle*" and "*fire + car*". The keywords chosen were intentionally very vague, with the intention of unraveling the largest amount of potentially relevant literature. Unification of the results of the search resulted in 4972 papers. In the next step, duplicates were first excluded, and then papers that were obviously unrelated to fire safety engineering were removed based on their titles. Database after this step included 1089 papers. The next step included analysis of the abstracts of the papers to identify if the paper is in any way related to fire experiments on passenger cars. This step has reduced the size of the database to only 30 papers. Finally, the 30 papers were read to determine if they contained results of full-scale fire experiments of the cars, leaving 11 papers that fulfilled this criterion. Concurrently, an analysis of bibliographic information was performed on the 30 papers identified in the previous step, as well as the proceedings of the *Fires in Vehicles* conferences. From this, a new database was created, which also included technical reports, conference proceedings and other materials. These sources were scouted by applying the same eligibility criteria as the journal papers (inclusion of full-scale experiments on passenger cars), and then also performed citation mining on bibliographies of these sources. This iterative process resulted in additional 33 positions not identified in the previous step. After the merge, the final database consisted of 44 documents describing 148 individual fire experiments. The database is shown in Table 2.

3 Results of the Literature Review

3.1 Context of the Fire Experiments on Cars

This literature review includes a body of experimental work from the early 1990s to March 2024. The earliest research on car fire in the database are the experiments conducted by Mangs and Keski-Rahkonen [26] in 1993, which focused on the combustion characteristics of three different car models using heptane trays as ignition sources. Further research was focused on safety in transportation, including research on fire development in tunnels by Carola Steinert [27] in 1994 and the fire tests conducted on behalf of the European Commission by Joyeux et al. [35]. Some of the research was focused on specific design considerations, such as the Channel Tunnel Safety Unit's [28] assessments. Research undertaken at the TNO in 1999 [31] was oriented towards fire safety of car parks using new at that time jet-fan longitudinal ventilation. In the US, research on fire propagation within cars and the use of fire retarded materials lead to a large research programme by Santrock [34, 36–43]. In 2000's after some tragic fires in Switzerland and UK, as well as a recognised lack of data related to the modern cars at that time triggered an increase in the number of experiments with cars. A notable study was conducted in the BRE [49] which included extinguishing systems and car stacking devices.

The transition from internal combustion engine cars (ICEV) to electric and hybrid cars has introduced new variables into the equation, prompting researchers to review existing research in relation to novel challenges presented by EV's. The interest of the general public also accelerated this, as BEV fires were pictured by the mainstream media as significantly more dangerous than fires in ICE cars. Some of the experiments were focused on studying the fire growth and development in BEVs [62]. In contrast, others, such as Willstrand et al. [59], Kleiman et al. [68], and various other researchers, were focused on the efficacy of extinguishing methods in maritime and other specific environments.

3.2 Description of the Fire Experiments in the Database

In this chapter, all reviewed studies are briefly characterised, highlighting the types of cars, modes of ignition and other relevant specific information. For a better overview of the research timeline on car fires, Fig. 1 presents a visual summary of the experiments conducted and reported via test reports or papers summarised in this paper. Figure 2 also shows the approximate date of production of cars used by particular researchers, compared to the date of the experiments.

In 1994, Mangs and Keski-Rahkonen [26] burned three passenger cars at VTT Technical Research Centre of Finland. The models selected for this study were from the late 70 s (Ford Taunus 1,6, Datsun 160 J, Datsun 180B). Heptane trays were used as the ignition source, placed under the driver's seat (Ford) and in the engine compartment (Datsun). A

Table 2 Documents identified in the Systematic Literature Review and citation mining procedures

No	Authors	Year	Publication type	Number of tests	HRR measure type	Ref
1	J. Mangs, O. Keski-Rahkonen	1994	Journal article	3	Oxygen Consumption	[26]
2	C. Steinert	1994	Conference proceedings	1	Oxygen Consumption	[27]
3	M. Shipp, M. Spearpoint	1995	Journal article	2	Oxygen Consumption	[28]
4	D. Joyeux	1997	Technical report	10	Oxygen Consumption	[29]
5	C. Steiner	1998	Journal article	3	Oxygen Consumption	[30]
6	N. van Oerle et al	1999	Technical report	13	Mass Loss	[31]
7	T. Kitano et al	2000	Conference proceedings	1	No HRR Measure	[32]
8	Stroup D. et al.	2001	Technical report	2	Oxygen Consumption	[33]
9	J. Santrock	2001	Technical report	1	Oxygen Consumption	[34]
10	D. Joyeux et al	2001	Technical report	3	Other*	[35]
11	J. Santrock	2002	Technical report	1	Oxygen Consumption	[36]
12	J. Santrock	2002	Technical report	1	Oxygen Consumption	[37]
13	J. Santrock	2002	Technical report	1	Oxygen Consumption	[38]
14	J. Santrock	2002	Technical report	1	Oxygen Consumption	[39]
15	J. Santrock	2002	Technical report	1	Oxygen Consumption	[40]
16	J. Santrock	2002	Technical report	1	Oxygen Consumption	[41]
17	J. Santrock	2003	Technical report	1	Oxygen Consumption	[42]
18	J. Santrock	2003	Technical report	1	Oxygen Consumption	[43]
19	Y. Shintani et al	2004	Conference proceedings	5	Oxygen Consumption	[44]
20	Anonymous	2004	Technical report	1	Oxygen Consumption	[45]
21	A. Lönnermark, P. Blomqvist	2006	Journal article	1	Oxygen Consumption	[46]
22	K. Okamoto et al	2009	Journal article	4	Mass Loss	[47]
23	D. Crowder, M. Shipp	2009	Technical report	1	No HRR Measure	[48]
24	BRE	2010	Technical report	12	Oxygen Consumption	[49]
25	N. Watanabe et al	2012	Conference proceedings	2	Mass Loss	[50]
26	A. Lecocq et al	2012	Conference proceedings	4	Oxygen Consumption	[51]
27	K. Okamoto et al	2013	Journal article	3	Mass Loss	[52]
28	C. Lam et al	2016	Conference proceedings	7	Oxygen Consumption	[53]
29	P. Santangelo et al	2016	Journal article	7	No HRR Measure	[54]
30	B. Truchot et al	2018	Journal article	4	Oxygen Consumption	[55]
31	X. Jiang et al.	2018	Conference proceedings	2	No HRR Measure	[56]
32	K. Okamoto et al	2018	Journal article	2	No HRR Measure	[57]
33	Y. Park et al	2019	Journal article	2	Oxygen Consumption	[58]
34	O. Willstrand et al	2020	Technical report	3	Oxygen Consumption	[59]
35	J-B Tramoni et al	2021	Journal article	5	No HRR Measure	[60]
36	P. Sturm et al	2022	Journal article	5	Mass Flow Enthalpy	[61]
37	S. Kang et al	2023	Journal article	5	Oxygen Consumption	[62]
38	M. Quant et al	2023	Journal article	3	Oxygen Consumption	[63]
39	J-B. Tramoni et al	2023	Conference proceedings	2	Oxygen Consumption	[64]
40	M. Arvidson, O. Westlund	2023	Journal article	4	Oxygen Consumption	[65]
41	J. Bleye, C. Suarez	2023	Technical report	1	No HRR Measure	[66]
42	J. Hynyneh et al	2023	Journal article	6	Oxygen Consumption	[67]
43	A. Kleiman et al	2023	Technical report	9	No HRR Measure	[68]
44	C. Zhao et al	2024	Journal article	1	No HRR Measure	[69]

*HRR assumed based on different measurements

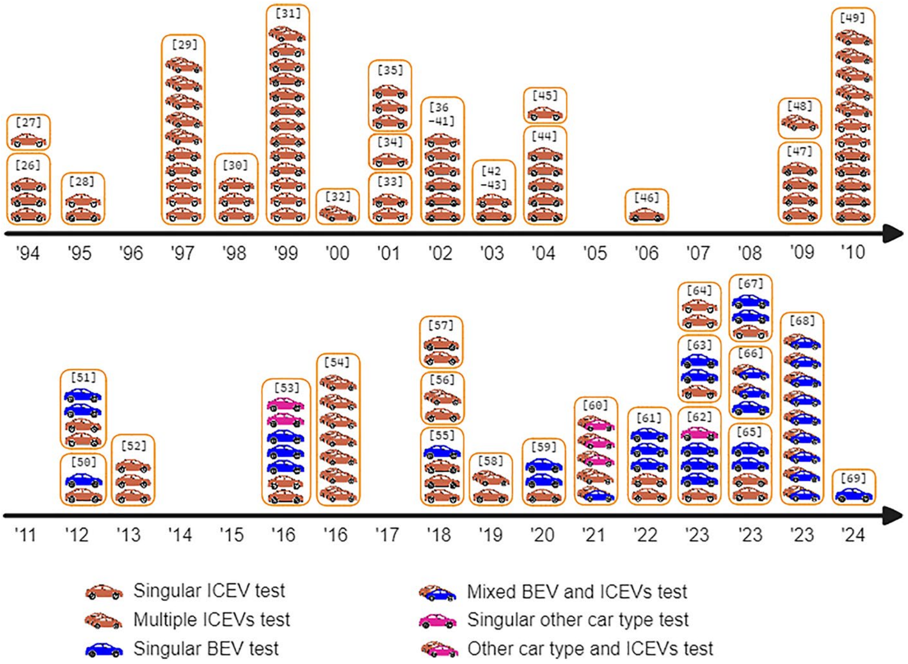


Fig. 2 Timeline presenting performed fire tests on cars, differentiated by drivetrain type

year later, in 1994 Carola Steinert [27], as part of the EUREKA project, published the results of research on the development of fires in tunnels. One of the cases studied was a passenger car fire ignited from underneath. In the publication, the author refers to the vehicle as a "plastic car". In 1995, Shipp and Spearpoint [28] conducted two full-scale fire tests on passenger cars for the Channel Tunnel Safety Unit (CTSU). The measurements were performed using a test rig constructed from two hood calorimeters connected by a duct. Cars were placed in the middle of the ducts. Based on popularity analysis, the models chosen for the study were the 1982 Austin Maestro and the 1986 Citroen BX. The ignition method selected was a gasoline tray in the engine compartment (Citroen) and a No. 7 Crib on the driver's seat (Austin). In years 1997, CTICM [29] conducted ten fire tests on passenger cars. Half were singular cars, and the other half was a test of two cars. In 7 of those tests, the car was ignited using a petrol-filled tray under the left front seat. The tray has been moved under the car's gearbox in the remaining tests. The tests were performed in a mockup simulating garage conditions. The mockup was covered with some extraction hood to conduct calorimetric measurements.

In 1999, van Oerle et al. [31] conducted studies on the efficiency of jet fan longitudinal ventilation in enclosed car parks, during which they carried out 13 fire tests of various passenger cars. The studies were conducted in a specially prepared car park with a filling level of 25%. For the purposes of the research, three variants of ignition location in the garage were selected, depending on the assumed scenario. The cars were ignited using gasoline trays placed under the car. In 2000, Kitano et al. [32] conducted a full-scale fire test of a 4-story car park. The purpose of this study was to determine the impact of fire on the steel structural frame of the car park. In order to simulate sufficient fire, 12 cars placed on the first floor were used (two rows, six cars each). According to the authors, this setup provided the most violent scenario possible in terms of structural integrity. The fire was set to the second car in the first row, quickly spreading to seven nearby cars. The method of igniting the first car is not specified. In 2001, Stroup et al. [33] conducted a fire test of a passenger car at the NIST Research Facility. The study was divided into two parts. In the first part, the authors initiated a fire using a stack of paper on the passenger seat, which did not lead to the fire spreading beyond the seat. In the second part, 2 L of gasoline were spilt inside the cabin, and the fire was extinguished after 4 min for safety reasons. In 2001, Joyeux et al. [35] performed fire tests on passenger cars in open and closed car parks for the European Commission. Various configurations of parked cars were tested to check the possibility of fire spreading between them. Heptane-filled trays placed under the cars were used to ignite the cars.

In the years 2001–2003, Santrock [34, 36–43], conducted a series of ten fire tests on passenger cars for General Motors and the US Department of Transportation. For the purpose of study, cars from the ‘90 s were chosen, and ignited in various locations: four times in the engine compartment, five times under the car, and one on the body. In 2004, Shintani et al. [44] performed full-scale fire tests of cars to determine design source strengths for performance-based safety design. For this purpose, five cars were burned, including one in the open air and four under the calorimeter, using methanol-soaked fibres placed on the driver’s seat for ignition. In 2006, Lönnermark and Blomqvist [46] conducted a fire test of a passenger car to analyse the toxic gases emitted from the fire. Wood wool soaked in alcohol was placed in the engine compartment to initiate combustion. In 2009, Okamoto et al. [47] performed a fire test on four copies of the same passenger car model for fire investigation purposes. Three tests were conducted by igniting the rear splash guard and observing the different fire development progressions. An additional test involved igniting the car from a gasoline-soaked driver’s seat. The cars were burned on a weighting platform to measure HRR. In 2009, D. Crowder, M. Shipp [48] performed a fire test of a vertical car stacker protected by a sprinkler system. For the test 1992 Land Rover Discovery (at bottom) and 2001 Ford Mondeo (on top) was chosen. Each car was fueled with 20 L of fuel. For ignition, a crib No. 7 soaked in methylated spirit, placed on the driver’s seat of the Land Rover. In order to develop the fire inside, the driver’s door window was open. The sprinkler system chosen for this test had a K-factor of 80 and a quick response frangible bulb rated at 68 °C. The year after, BRE [49] conducted a total of 12 fire tests on passenger cars in various experimental configurations, ranging from tests of single cars to testing four cars simultaneously. Additionally, tests were conducted for a method of stacking cars on top of each other. The ignition method chosen was a No. 7 crib on the driver’s seat. The authors also conducted two studies in which the car windows were closed, resulting in no fire development in both cases.

In 2012, Watanabe et al. [50] performed comparative studies on the fire behaviour of an electric car and a combustion engine car, choosing cars with similar characteristics (Nissan Leaf and Honda Fit). The cars were ignited using a gel-fuel tray placed under the rear splash guard. The experiments were performed on top of the weighing platform. That same year, Lecocq et al. [51] conducted comparative studies on the consequences of fires in electric and combustion engine cars at the INERIS fire gallery. A gas burner with an approximate power of 6 kW directed at the driver’s seat was used for ignition. Cars of corresponding models from two different manufacturers were tested. In 2013, Okamoto et al. [52] conducted fire tests on passenger minivans, performing four tests on three cars (one car was used in two tests). To acquire data from test, the cars were placed on a weighing platform. For ignition, 80 g of alcohol gel fuel was used. In the first test, the car was ignited from the right rear splash guard and the car burned out. The second test involved ignition from the front bumper, and the car also burned out. In the third test, the ignition point was the middle row of seats in the passenger compartment. The test was conducted with windows closed, and the fire self-extinguished within 20 min. In the fourth experiment, the ignition point was changed to the last row of seats and the front left window was left open about 20 cm. The car burned out. In 2016, Lam et al. [53] conducted fire tests on combustion, electric, and hybrid passenger cars, performing a total of seven tests. A 2 MW gas burner placed under the car, simulating a gasoline pool fire of the same area, was used as the ignition source. Also, during that year, Santangelo et al. [54] conducted seven car fire studies aiming to compare the effectiveness of the sprinkler and water-mist systems. Every test contained of three internal combustion engine cars arranged parallel to each other lengthwise. As an ignition source, two trays filled with 14 l of heptane and 14 l of water each placed under the central car. As a result of this study, two tests with sprinklers and five tests with water-mist were carried out.

In 2018, Truchot et al. [55] conducted fire tests on passenger cars regarding the emission of toxic gases and heat in tunnels and underground car parks. The tests were conducted at the INERIS fire gallery, similar to the tests conducted by Lecocq in 2012. The tests used three combustion engine cars and one electric car. In 2018 Xiao-Hui Jiang et al. [56] performed two free-burn tests on ICE passenger cars. One test contained a single burning car with windows and doors open, while the second one contained two cars parked parallel to each other with all windows and doors closed. For ignition purposes, a sponge soaked in gasoline was placed inside the engine compartment. In 2018, Okamoto et al. [57] conducted studies aimed at determining the heat flux of burning cars. For this purpose, two full-scale free-burn fire tests of minivans were performed. 80 g of alcohol gel fuel was used to initiate the fire. The right rear splash guard and the rear bumper were chosen as the points of ignition. During the experiment, the windows were closed, and the tank contained 10 L of fuel. The cars were left until the fire extinguished itself. In 2019, Park et al. [58] conducted studies to examine the spread of fire within and between cars. In this case, two tests were conducted: one on a single internal combustion engine car and the second test on two internal combustion engine cars set parallel to each other at a close distance. The cars were ignited from the front left seat. In 2020, Willstrand et al. [59] conducted fire tests on a combustion engine car and two electric cars at RISE. For igniting the ICEV, 44 L of diesel oil were spilt under it, creating a pool fire. For electric cars, a 30 kW gas burner was placed under the car and directed at the battery pack. In 2021 Tramoni et al. [60] performed five fire tests, with four of them involving different configurations of ICEV and alternative fuel cars. Alternative fuels included in this study were fuel cell(hydrogen) car, NG(Natural Gas) car, electric with LMP(Lithium Metal Polymer) battery car and LPG (Liquified Petroleum Gas) car. The fifth test was a reference experiment with two ICE cars. The main goal of this study was to assess how alternative fuel cars fires impact unprotected steel structures representative from cat parks. As the ignition point, the inside of the passenger compartment of the alternative fuel car was chosen. In 2022, Sturm et al. [61] conducted fire tests on passenger cars, focusing on the firefighting aspect of electric car fires. For this purpose, a series of tests were conducted in a training tunnel Zentrum am Berg on mockups equipped with lithium-ion batteries and two full-scale tests, one on an electric SUV and another on a combustion engine SUV.

In 2023, many passenger car fire tests have taken place. All studies mentioned hereafter were published in 2023 unless specified otherwise. Kang et al. [62] conducted fire tests on three electric cars and a single-combustion engine car. A 300 kW gas burner placed centrally under the car was used for ignition. Additionally, the tests included fire scenarios of battery packs alone for electric cars, mounting a thermal sheet inside the pack. Quant et al.

[63] conducted studies on the toxicity of extinguishing water from electric car fires. Two experiments, one with BEVs car and one with an ICE car, were performed with extinguishing involved. In addition, a reference test of an electric car that had not been extinguished was conducted. A 30 kW propane burner was used to ignite the car. Tramoni et al. [64] conducted fire tests on passenger cars to validate currently used design fires for garage analysis. The tests were conducted on two copies of the Renault Talisman. One study was conducted on a car with an empty fuel tank, and the other on a car filled to 2/3 (33 l). The cars were ignited using a cloth soaked in heptane placed in a tray on the passenger seat. Arvidson and Westlund [65] conducted four fire tests on passenger cars, two BEVs and two ICEVs. The studies aimed to compare the fire progression and extinguishing process using fire sprinklers on ICEVs and BEVs. For ICEVs, gasoline leaked from the car's tank through a small leak into a tray under the car, and was ignited with a torch. For the BEV, a nail piercing the battery and an igniter igniting the fire gases served as the ignition source. Bleye and Suarez [66], as part of the LASHFIRE project, conducted fire tests on passenger cars. The tests included a free burn test of a BEV ignited by a gas burner placed under the car, a first response test in a 3 × 3 car configuration (ro-ro ships arrangement, BEV in the middle set on fire, burner under the car) and a firefighting test inside a built-up space (three cars in an L shape, car at the back ignited from a flammable liquid spill under the car). Hynynen et al. [67]conducted studies on an ICE car and two BE cars. The steel pan simulating a petrol pool fire was used as an ignition source. During the test, at HRR of 1 MW, a sprinkler system was turned on for 30 min, discharging 11 160L of water per test. After this time, the fire was allowed to grow again. Each test resulted in a complete burnout of the car. In 2023, DBI [68], as part of the ELBAS project, conducted fire tests on electric cars to assess the effectiveness of different extinguishing methods at sea. Nine experiments were conducted (seven on Renault Fluence ZE, one on Nissan Leaf, and one on Tesla Model 3). All cars were ignited using Thermal Runaway, which was initiated by a short circuit in the battery. If TR was not initiated, an external source, such as a gasoline burner placed under the car, was used. In 2024, Zhao et al. [69] conducted studies on response strategies to BEV fires caused by thermal runaway. For this purpose, a 400W heating plate was placed under the battery of the car to induce a thermal runaway effect. The selected model had 16 battery modules, with 12 cells each and a maximum capacity of 38,1 kWh. During the study, the car was free-burned in the open air, and windows were lowered by about 10 cm to improve air access to the interior of the car.

4 Data Analysis

4.1 Collected Data from Various Fire Experiments

The basic parameters useful for design that are usually recorded during fire tests include: the heat release rate (HRR); total heat released (THR), and the effective heat of combustion. The HRR is determined based on the mass loss rate (assuming some value of the Heat of Combustion) or through the oxygen depletion calorimetry. An interesting parameter is the peak heat release rate, which defines the maximum momentary heat production in the fire and can be considered as the strongest fire exposure if a transient developing design fire is used. Furthermore, the time after which the peak HRR is reached is usually also recorded (time to reach peak HRR, t_{PHRR}). This variable can be used to approximate the fire growth. However, for several reasons described further in the paper, it has been found difficult to use directly. Representing the fire intensity (HRR) as a variable in a function of time is commonly called the "fire curve". The fire curves can be used directly in fire simulations with zone models or Computational Fluid Dynamics solvers and, in such cases, are referred to as the design fires. The collection of respective fire curves found in the literature after the unification of the data presentation format is shown in Appendix A. The integration of the area under the fire curve provides the total heat released value, representing the total heat released during the duration of the fire. In fire safety engineering, this parameter is used to determine the fire load density by dividing it by the surface area of the fire source.

In practical use of the fire curves in fire simulations, the user routinely defines the production of combustion products. This is accomplished by dividing the HRR by the heat of combustion (H_c) of the fuel and then multiplying the resulting mass flux by yields of products. Commonly, the yields are defined for soot, carbon monoxide (CO) and carbon dioxide (CO_2). As the production of species was often not recorded during the experiments, this review does not investigate them. For simple materials, H_c is determined for individual materials by burning them in pure oxygen in a calorimetric bomb. It is the ratio of the released thermal energy to the mass of the burned fuel. The effective variant of the parameter ($H_{c,eff}$) is determined under conditions of imperfect combustion in the air for a mixture of materials of partially known composition from which the sample is made (in this case, a car). However, as the car is a complex object and a collection of multiple materials that burn simultaneously in different conditions, the determination of reasonable value for $H_{c,eff}$ through individual component testing is challenging. For the purpose of this study, an approximation of $H_{c,eff}$ for entire cars was conducted, measured as total energy released during the test divided by mass lost due to fire (where mass loss data was recorded and published). This means that $H_{c,eff}$ values shown in this paper are related to cars as a whole and may be influenced by, e.g. amount of liquid fuel in the gas tank or modifications done to the cars prior to the experiment (i.e. removal of parts, state at which the car was acquired).

4.2 Separation of the Data into Subsets

In order to perform an analysis of gathered data, some categorisation had to be made. The first criterion was the mass of the car, and the study included arbitrarily chosen categories of:

- small cars with a total mass less than 1400 kg;
- medium cars with a total mass between 1400 and 1800 kg;
- big cars with a total mass higher than 1800 kg.

The cars were not categorised by type (i.e. sedan, truck, van, SUV). If the type of car is important to the fire engineer, a rule of thumb may be that the more recent and heavier cars will be more representative of the SUV segment, while the lighter and older cars may be representative of the sedan segment. The cars were also categorised by drivetrain type, considering primarily two types—Internal Combustion Engine Vehicles and Battery Electric Vehicles. Some of the tests found in the literature involved cars such as Plug-in Hybrid Electric Vehicles and Fuel-Cell Electric Vehicles, but the amount of tests involving them

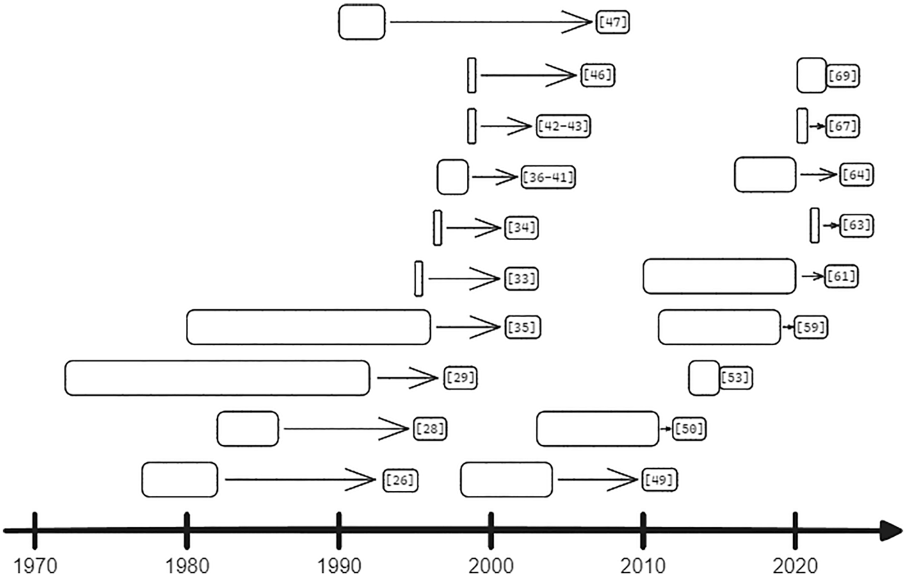


Fig. 3 Timeline presenting the range of years of origin of the cars used in particular research studies and the years of conducting those studies, shown for studies that reported the age of cars

is too small for analysis to be carried out as a separate sub-group (two PHEV and one FCEV). In some of the analysis, the age of vehicles was also accounted for, Fig. 3.

The initial analysis has shown potential differences in the course of the fire depending on the location of the initial fire source. This approach to data analysis was inspired by the concept presented by Morrisset et al. [23], who analysed in detail a course of fire of an upholstered chair. They found providing the time-averaged results for the entire course of the fire challenging. However, after identifying key events in the fire and then relating the measured quantities to the observed fire phases, they were able to provide an improved description of the fire. In their study, the fire was always initiated in the same way and, consequently, went through the same chain of events. In the case of experiments with a much more complex fuel (car), identifying distinct phases of the fire in a generic way is not possible. Consequently, it is impossible to provide any time-averaged information on fires, as the course of events was different in different fire experiments. However, recognising the importance of the fire events in the growth of the fire, identifying some generic events that were observed across many fire experiments was performed. Following this realisation, the fires were grouped by the location of the fire source, based on the assumption that the fires initiated similarly may go through a similar fire propagation. The key events and phases of a car fire are summarised in Table 3.

These identified events have helped us define the sub-categories of fire experiments related to the Origin Of Fire (OOF). For simplification, four main locations for the OOF were defined. These are: (a) fires under the car, i.e. any location underneath the car with a direct attack on the fuel tank or battery of the car; (b) the passenger cabin, which also included fires set up in the trunk of the car (if the trunk was connected with the passenger cabin); (c) fires starting in the engine compartment, and (d) fires started near the chassis, which included any fires set up against or on top of the car chassis or wheels of the car, but not directly attacking the fuel tank of the battery.

Table 3 Key events observed across the investigated passenger car fires

Event	Relevant ignition location	Description of the event
Fire spread over exterior of the car or to the fuel tank/battery	Chassis	Fire spread over external parts of the car – tyres, bumpers, plastic components, cables, piping. Slowly growing, with a potential transition into the car interior, or causing damage to fuel tank/battery
Fire spread to the engine compartment	Engine compartment, chassis	Fire spread into the car engine compartment. Due to low ventilation, this phase was usually connected with prolonged duration and a low peak HRR. Fire may transition into the passenger compartment through the ventilation network
Fire in passenger compartment (underventilated)	Passenger compartment, chassis	Fire that started, or transitioned into the passenger compartment, but with the windows and doors closed and interior of the car is sealed. It consumes the oxygen available and decays. Usually, it leads to damage to the windows
Windows shatter	Passenger compartment	If fire is present in the car's interior, the windshield or side windows may shatter, introducing a new stream of air (oxygen). It is usually connected with the rapid growth of the fire
Fuel tank failure	Under the car	In ICE/PHE car. Observed early in fires with a source located underneath the car, or late when fire originated elsewhere. The release of the fuel stored inside the tank and the resulting fire size is dependent on the amount of fuel used. Usually related to peak HRR and spread of the fire to all parts of the car, followed by quick decay
Battery failure	Under the car	In BEV/PHEV cars. Observed early if the fire was initiated within the battery or the battery was a target of direct fire attack as the initial source, and observed in a later phase if the fire was initiated elsewhere. Usually related to peak HRR. The peak size, duration of the peak and the course of the decay phase may vary depending on the number of cells involved and compartmentation (or separation) within the battery

The events do not happen in order and depend on the location of the fire. The list is based on the author's observations and is not exhaustive

5 Results and Discussion

5.1 Use of Experimental Data as a Design Fire

In a common approach of fire safety engineering, the performance of a fire safety system is evaluated through a comparison of Available and Required Safe Egress Time (ASET and RSET) [70]. In order to determine the ASET component, engineers usually rely on some form of modelling with a variety of tools available, including empirical models [71], zone models, and CFD models. Input to those tools is given in the form of a time-dependent design fire, which is a record of the evolution of the HRR in the function of time. Examples of such design fires are in standards [19] and guidelines [18]. Alternatively, some design approaches [72, 73] use a steady-state approach to a design fire, which is usually referenced as either average or some percentile of peak HRR distribution found in the literature. No matter which approach is used, the design fire can be considered the most important variable in the design [74].

Suppose the design fire is a steady state fire, which size is based on statistical distribution of data. In that case, the outcome may be biased by the incomplete dataset or by comparing incompatible experiments. This is discussed in further chapters. In case of a transient design fire, the engineer decides which experimental results is used as the input to their analysis. It can be argued that no objective 'course of fire of a car' exists, and use of different design fires may lead to different assessments of the system performance. Here, some key differences between fires reported in the literature are highlighted.

First, consider two courses of car fires depicted in Fig. 4: one with a rapid rise to 8,9 MW but short-lived, and another with a lower but sustained heat release. Despite the former having a much higher peak heat release rate, the latter released more total heat and combustion products due to its longer duration. If one was interested in maximum local damage to the car park structure or perhaps the spread of the fire, it could make sense to consider the fire (1). However, if one is investigating the fire load in the structure or bulk emissions into the atmosphere after a fire, the fire (2) has resulted in more heat and combustion products over time. One could argue that if the designer were interested in the evacuation process in the building and picked the fire (2) on the basis that it was a larger fire (measured by the THR), the outcome would be considerably less severe than if the fire (1) was chosen. Here, it is worth noting that non-fire specialised stakeholders (e.g. building authorities) sometimes expect to use *'the worst fire* (highest HRR)' for the *'longest known*

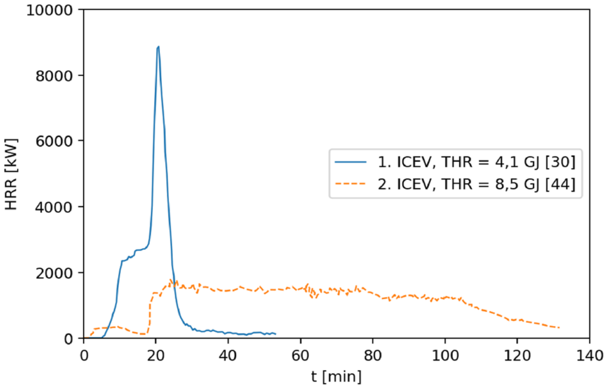


Fig. 4 Comparison between two ICE car fires – one with short duration and high peak, the other with long duration and low peak

fire duration'. However, such a fire (peak HRR maintained for the fire) duration) does not exist in the real world due to the conservation of energy and the constrained amount of fuel in a passenger car. This notion is especially important concerning a common misconception related to the BEV fires presented in mainstream media that the "*electric cars burn more intensely and for a longer period*".

Any attempt to use experimental HRR results directly in a design is burdened with uncertainty related to the complexities inherent to the fuel package (car as a collection of compartments, with a variety of forms and types of fuels) and the diverse methodologies employed to initiate the fire. Different tests may yield different outcomes due to the differences between cars used in the experiments, the state of the cars (new, damaged, and also their age) and the architecture of the test facilities themselves. Finally, as previously mentioned, fires are characterised by the occurrence of various events throughout the fire, such as tank ruptures, battery ignitions, and window breakages.

Figure 5 illustrates the progression of three different fires with closely matching THR values ranging from 6.4 to 6.8 GJ. In this case, the peak HRR values are in a similar range (roughly 6,0 MW to 10,0 MW). However, the peak HRR is achieved at a different time in each of those experiments. If each of the curves were used in a design fire, three sets of outcomes would be achieved. According to the study descriptions, the peak fire intensity coincided with damage to the windows and interior of the car (around the 18th minute in fire 1 and the 40th minute in fire 3), fuel tank rupture (around the 35th minute in fire 2), or ignition of the car's battery (around the 40th minute in fire 3). Observed variability underscores the partly unpredictable nature of car fires, characterised by potentially lengthy incubation and development periods followed by a sudden escalation to maximum power as the fire reaches parts of the car containing substantial fuel reserves (such as the fuel tank, interior or battery). This variability poses challenges for statistically comparing time variations across different studies or definitions of a single reference value of the fire growth rate (in use of so-called αt2 fires, [75]). The subsequent chapters present and interpret the gathered data, taking into account the location of ignition, which impacts the observed progression of fire development.

5.2 Course of Fires with Different Ignition Locations

As previously stated, several key events can be identified during car fires, occurring during both internal combustion engine vehicle and battery electric vehicle fires, Table 3. The list

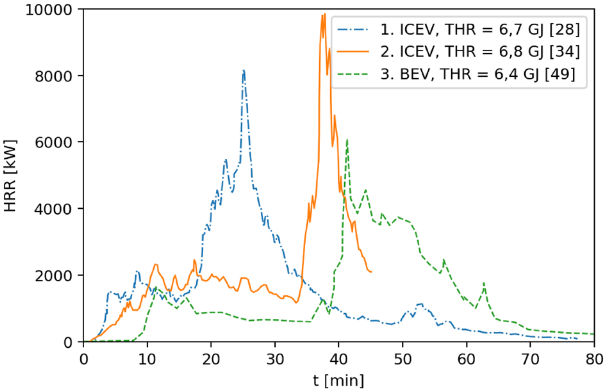


Fig. 5 Comparison between two ICE and one BE car fires with a similar course of events, similar THR and different times to peak HRR

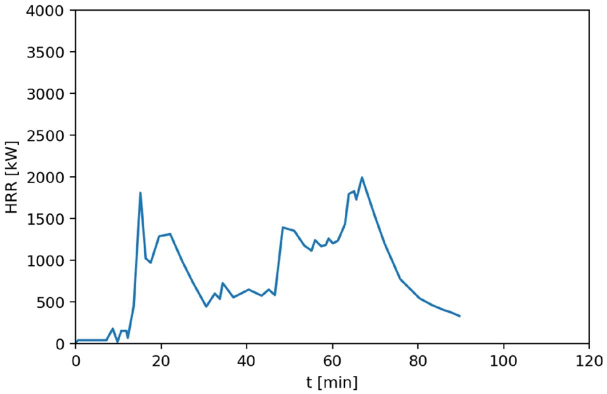


Fig. 6 HRR curve of ICEV weighing 1360 kg with 20l of gasoline ignited from chassis [47]

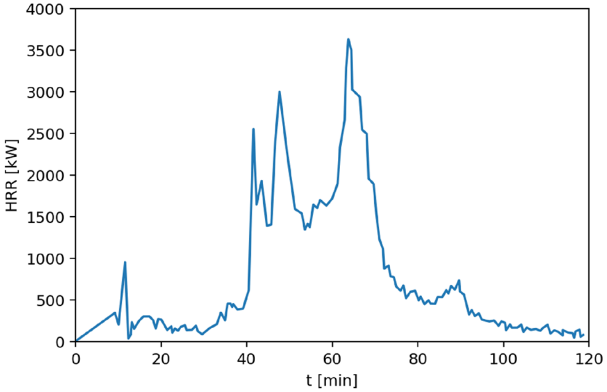


Fig. 7 HRR curve of ICEV weighing 1440 kg with 10l of gasoline ignited from chassis [52]

presented is not exhaustive, and additional events may be observed. This analysis focuses on the collected data based on the events outlined in Table 3 and the corresponding locations of the ignition sources. It is assumed that this initial location may influence the order, frequency, and speed of occurrence of individual events. It is acknowledged that a different sequence of events will be most likely obtained in the case of a test that was initiated from the cabin and another sequence during a test initiated by a pool fire of gasoline under the car. Detailed reports are provided below on the progression of fires initiated at different locations, including the chassis, passenger compartment, and beneath the fuel tank or battery.

5.2.1 Fires Set Up Against the Chassis

Fires set up against the chassis of a vehicle represent design scenarios in which the car fire is ignited from an external source or is a target of fire spread from an adjacent vehicle. An example HRR of a fire set up against the chassis are given in Fig. 6 and Fig. 7. In Fig. 6, a sedan from the 90 s weighing 1360 kg was selected as the test car. During the test, there were 20 L of gasoline in the tank, and the car's windows were closed. In Fig. 7, a minivan from the 90 s weighing 1440 kg was selected as the test car. During the test, there were 10

L of gasoline in the tank, and the car's windows were closed. Fires initiated at this location have been observed to exhibit long incubation periods, and the peak HRR is not achieved until the fire migrates to the fuel tank (first peak on Fig. 6) or to the vehicle interior (peak after 46m45s on Fig. 6, peak after 40 m on Fig. 7). These observations are relevant when one considers a spread of fire between vehicles, as the spread to the chassis of neighbouring vehicle does not yet correspond to a peak HRR of that secondary vehicle. On the contrary, the spread from the offending vehicle must occur to the interior of the secondary vehicle, or the fire must migrate through the internal pathways in the vehicle, similar to what was observed in the experiments detailed below.

In Fig. 6, an HRR curve for an ICEV ignited with 80 g of alcohol gel fuel placed at the right rear splash guard is presented, as described in [47]. Four minutes after ignition, the splash guard was enveloped in flames. At 5m30s, the flame reached the mouth of the filler pipe. By 10 min, flames began to emerge from there. At 13m20s, gasoline leaked, and a large flame formed at the rear of the car. At 15 min, the fire breached the passenger compartment. After 20 min of testing, the rear of the car was engulfed in flames. At 32 min, the rear window shattered, intensifying the fire. Two minutes later, the rear right window broke. At 46m45s, the windshield shattered, dramatically increasing the fire's intensity. Within the next two minutes, all windows broke. After 60 min, the fire reached the engine compartment. By 63 min, it was completely engulfed in flames. Afterwards, the car continued to burn freely. The fire burned out after 90 min.

In Fig. 7, an HRR curve of ICEV ignited with 80 g of alcohol gel fuel placed at the right rear splash guard is presented, as described in [52]. Five minutes after the gel was ignited, the splash guard was enveloped in flames. By the 9th minute, the flames reached the roof height. A minute later, the fire spread to the ceiling of the passenger compartment. About 30 s after that, the passenger compartment filled with smoke, and the flames became invisible. At the 12th minute, the right rear tyre burst. By the 33rd minute, the left rear tyre was ignited. Around the 40th minute, the left rear window shattered, followed by the right rear window and the rear windshield a few seconds later. At 44m50s from the start of the test, flames emerged from cracks in the front windshield. Less than two minutes later, the front windshield was completely shattered. By the 62nd minute, the front of the car was completely engulfed in flames. The fire burned out around the 120th minute.

5.2.2 Fires Initiated in the Passenger Compartment

The fire may originate within the passenger compartment. A 'classic' ignition source used to be the car lighter, and in modern times, the hazards related to the passenger compartment may include fires originating from the car electronics, ventilation or fires of devices charged within the cabin. Example course of two fires initiated in the passenger compartment are shown on Fig. 8 and Fig. 9. For the test presented in Fig. 8, a sedan car weighing 1360 kg was chosen. The tank of the car was filled with 10 L of gasoline and the front left window was left slightly open. The car selected for the test showcased in Fig. 9 was a large family car weighting 1580 kg. The gas tank was empty during this test, and left rear window was left open to the 1/3. In both cases, the initial ventilation conditions in the cabin were altered – the cabin windows were left slightly open. This initial condition is critical, as some experiments carried out with closed windows lead to self-extinction of the fire before the windows of the car shattered [48]. Interestingly, the transition from the passenger compartment to the battery of an EV may be difficult, which is highlighted by the NFPA report: "*The internal battery cooling systems were very effective in delaying the*

Fig. 8 HRR curve of ICEV ignited from passenger compartment [47]

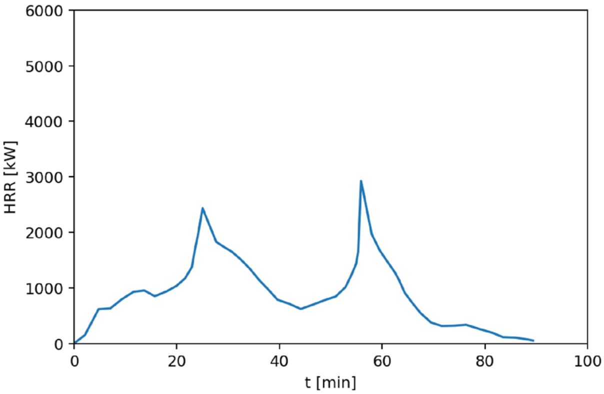
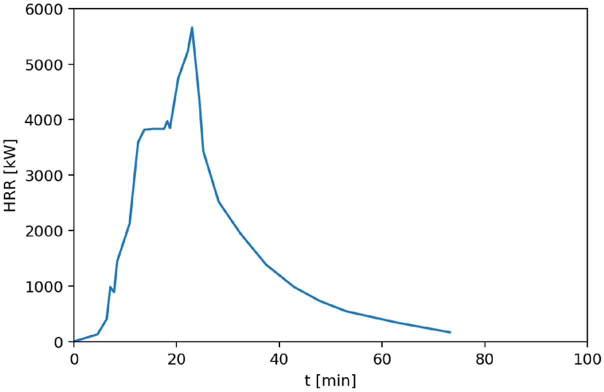


Fig. 9 HRR curve of ICEV ignited from passenger compartment [64]



involvement of battery in fires unless the fire started in battery" [76]. An online repository, evfiresafe.com, provides statistics claiming that batteries were involved in 40% of the EV fires traced by the project [77]. No data is available regarding the possible transition of the fire from the cabin to the fuel tank of ICEV. However, it can be noted that in the passenger cabin fire origin, the peak HRR was observed without the fire transitioning into other parts of the car but usually following a fallout of the windshield. The course of two such fires is described below.

Figure 8 shows a HRR curve of ICEV ignited with 2 l of gasoline spilt on the left front seat, as described in [47]. One minute into the test, the front windshield cracked, and flames began to emerge from it. At 4 min and 30 s, the front windshield shattered due to the temperature, and the fire intensified. Seventeen minutes after the start of the test, flames were visible in the left wheel arch. By the 23rd minute, the fire had encompassed the entire engine compartment. Around the 40th minute, the engine fire significantly decreased in intensity. At 48 min and 30 s, a gasoline leak occurred near the right rear wheel, resulting in both rear tyres bursting. From 55 to 57 min, the fire "raged furiously," as described by the author. The fire burned out at around 85 min.

In Fig. 9, a HRR curve of ICEV ignited with a rag soaked with heptane placed in a 12 cm pan placed at the front passenger seat is shown, as described in [64]. In order to facilitate the ignition, the pan was placed directly under the dashboard, with the seat brought forward. Despite an open window, the fire develops with difficulty. To aid in ventilation, the front passenger door is opened for the first four minutes of the test. The windshield shatters seven minutes after ignition, significantly accelerating the growth of the fire. A minute later, the rear part of the passenger cabin is consumed by fire, and flames emerge through the slightly open rear window. Within the next two minutes, both the rear windshield and the rear right window shatter. The front windows break at the 12-min mark. At the same time, the fire reaches the engine compartment. After 20 min, the fire is fully developed in the front part of the car and spreads to the trunk. By the 23rd minute, the entire car is engulfed in flames. After this, the car burns freely until it burns out.

5.2.3 Fires Initiated Under the Fuel Tank or Directly Attacking the Battery

In the recent 10 years, 56% of all experiments in the database and 78% of experiments on BEV included initiation from underneath the fuel tank or a direct attack on the car battery. Arguably, this ignition location should lead to a consistent triggering of the battery (which may be the point of the test), but may not be representative to the real-world fires. Analysing the course of fires initiated from underneath the car, more sharp peaks in the HRR were observed – the peak HRR occurs early and the growth is rapid. This growth is usually connected with either the thermal runaway of the battery (Fig. 10) or damage to the fuel tank and release of the fuel (Fig. 11 and 12). A description of the course of events in a few experiments ignited from underneath the car is given below.

In Fig. 10, a HRR curve for a BEV ignited via battery heating that leads to a thermal runaway is shown, as described in [62]. An electric SUV weighing 1685 kg, with a battery capacity of 64 kWh and fully charged, was chosen as the test car. A heating sheet was placed on a single battery cell to initiate the test. Heating began at the start of the test (0m00s). After 16m32s, an ignitor was activated to ignite the gases produced during heating. Around 21m20s, an internal thermal runaway started. By 24m25s, the first flames were visible at the pack. Within the next 10 min, the entire car was engulfed in flames. At 25m9s, the rear tyres caught fire. Shortly after that, at 26m34s, the car’s trunk ignited. Within the next minute, the fire spread to the rear seats. After another two minutes, the front seats caught fire. At 30m20s, the front tyres ignited. A few seconds later, the fire reached the engine compartment. At 34m43s, the electricity was cut off. Despite that,

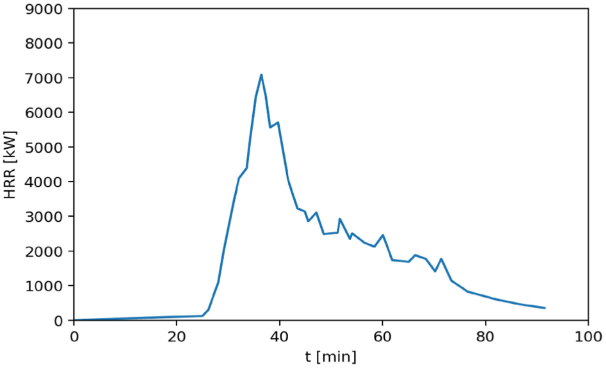


Fig. 10 HRR curve of BEV ignited via heating the battery, leading to a thermal runaway [62]

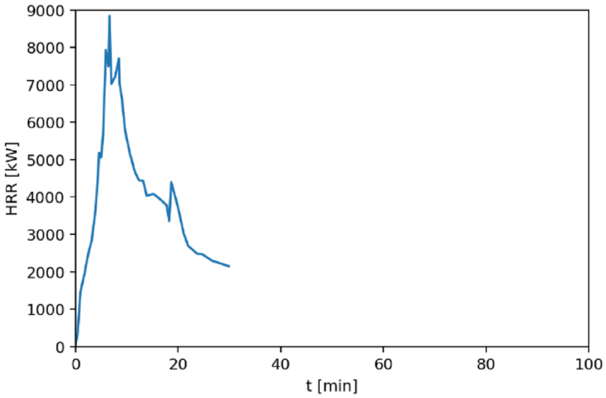


Fig. 11 HRR curve of ICEV ignited with 2 MW burned placed beneath it [53]

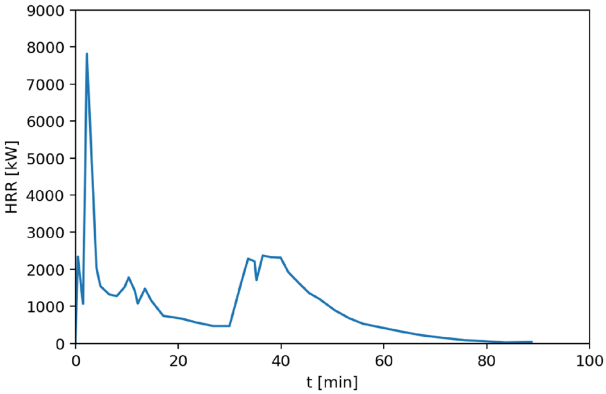


Fig. 12 HRR curve of ICEV ignited with gasoline leak from tank [65]

at 46m13s, the airbags exploded. From 40 to 72 min, a series of thermal runaways were observed progressing from the rear to the front of the car.

In Fig. 11, a HRR curve of ICEV ignited with a 2 MW burner placed beneath it is shown, as described in [53]. The subject of the test was a 2015 Internal Combustion Engine Vehicle weighing around 1350 kg with a full tank of gasoline and all windows closed. For the first two minutes of the test, the burner reached its nominal power of 2 MW. Over the next few minutes, various parts of the car caught fire. Around the 5–6 min mark, the fuel tank ruptured, causing a rapid ignition of its contents. This moment is visible as the peak heat release rate. By the 18th minute, the entire car was consumed by flames. Over the next few minutes, the car burned out.

In Fig. 12, a HRR curve ignited with a gasoline leak from a tank forming a pool fire is presented, as described in [65]. In the study presented, a water spray system was used for the extinguishing process. The ignition method chosen was a pool fire, resulting from gasoline leaking from the car's tank through a 15 mm circular hole into a tray with a thin layer of water. The water layer provided a uniform surface for the fuel to spread freely. The hole was initially closed with a plug, which was removed at the start of the test. As the hole was opened, the leaking fuel was ignited with a torch. At 1m12s from the start of the experiment, with a heat release rate of about 2 MW, water was discharged. The chart shows a sharp HRR peak caused by the burning of a large amount of gasoline, which is quickly suppressed by the extinguishing system. The extinguishing process was activated for 30 min, after which it was turned off. Following the deactivation of the extinguishing system, the fire's intensity rose to about 2,2 MW and maintained this level for just under 10 min. Approximately 90 min after its initiation, the fire had burned out.

5.3 Statistical Analysis of Gathered Data – by Weight and Drivetrain

The rationale for this study was to move away from statistical analysis of car fire experiments, as in most cases, it is difficult to compare them with each other. However, it is acknowledged that such statistical information forms the cornerstone of many design approaches and systems and, within the current design paradigm, is essential for practical fire safety engineering. Therefore, a statistical analysis of the collected database was conducted, focusing on subsets deemed most relevant and considering multiple confidence intervals. If the Reader is interested in performing analysis based on their own criteria, the entire dataset is presented in Appendix B, which allows for statistical analysis in different custom subsets. Here, the analysis was limited to the results from individual cars that were not subjected to suppression in the early stage of the fire. The comparison of HRR, THR, and time to peak HRR by distinguishing the location of the fire source is shown in Figs. 13 and 14. In Fig. 13, the data set is sub-categorised by the vehicle size, while in Fig. 14 by different drivetrains. It must be noted that the results presented in the paper are subject to some error due to the lack of complete knowledge regarding the amount of fuel in the fuel tanks of combustion engine vehicles and the state of charge of electric vehicles. Furthermore, the THR value may be unintentionally skewed by extinguishing the vehicles prior to their burnout.

While this data set does not allow us to form strong conclusions, one can notice that the fires ignited from under the car have the highest peak HRR values and the shortest time to peak. This may be interpreted as a more violent fire development. On the contrary, the fires starting in the engine compartment and chassis lead to the lowest value of peak HRRs, showing a less violent course of the fire. An interesting difference between ignition at the engine and chassis is in the measured time to peak HRR, with the average value for chassis scenarios placed as a high-outlier compared to the ignition at engine compartment

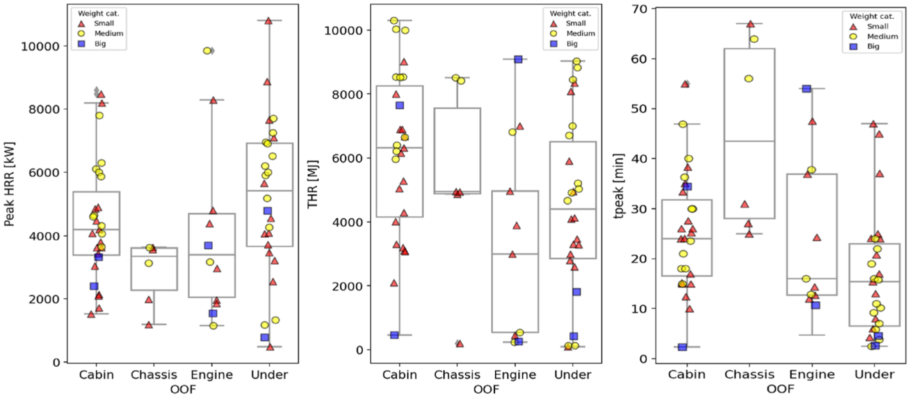


Fig. 13 Comparison of variables in the function of origin of fire, categorisation by weight category

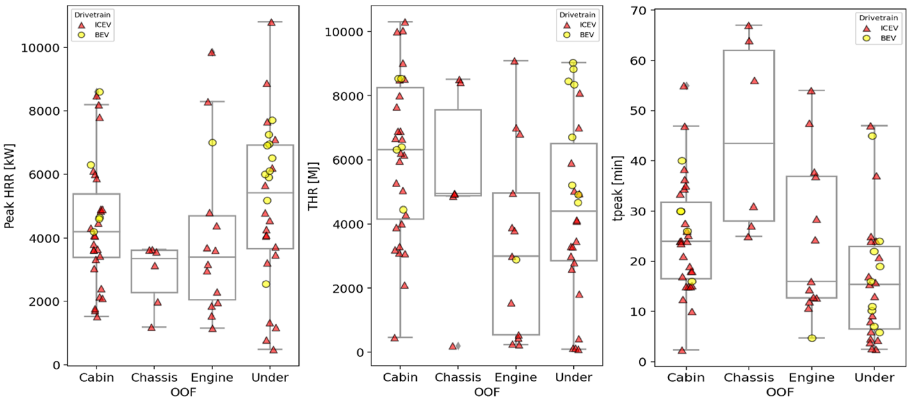


Fig. 14 Comparison of variables in the function of origin of fire, categorisation by drivetrain type

scenarios. In the case of fires initiated in the cabin, large variability in all three investigated variables was noticed, notably with the highest average THR value.

Due to the large scatter in the results, a further categorisation by size and drivetrain was performed, as shown in Tables 4 and 5, respectively. The tables present values of peak HRR, time to peak and THR. The average, median, and 5th, 95th, and 99th percentiles of the fires in the database are reported. Based on the total burning time, mass loss rate (where available)

Table 4 Simple statistical analysis of chosen fire parameters distribution in the database, by the mass of the car

	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Small			
Average	4232	25,22	4516
Median	3716	24,10	4217
5th percentile	1488	7,80	408
95th percentile	8521	48,25	8119
99th percentile	10,580	65,63	8943
Standard deviation	2320	13,69	2149
Medium			
Average	5296	21,64	6293
Median	5900	18,00	6670
5th percentile	1243	4,60	167
95th percentile	7860	52,36	10,020
99th percentile	9690	63,33	10,278
Standard deviation	2065	15,26	2953
Big			
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

Table 5 Simple statistical analysis of chosen fire parameters distribution in the database, by the type of the car

	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
ICEV			
Average	4148	22,80	4386
Median	3700	19,90	4112
5th percentile	1179	3,62	189
95th percentile	8521	48,48	9221
99th percentile	10,635	64,95	10,254
Standard deviation	2354	14,22	2752
BEV			
Average	5959	21,57	6951
Median	6100	20,50	6700
5th percentile	3705	6,58	4578
95th percentile	7970	41,75	8910
99th percentile	8562	44,81	9023
Standard deviation	1481	11,42	1677

and HRR measurements, an approximation of the average effective heat of combustion for a car was calculated, which is given in Table 6. Additional tables for subsets related to the ignition location are presented in Appendix C.

5.4 Statistical Analysis of Gathered Data – by Date of the Tests

Additional statistical analysis was performed with distinction into decades of performed tests to ensure relevancy for modern fire safety engineering. For this purpose, three categories were created: tests performed before 2000 (including); tests performed from 2001 to 2010 and tests performed after 2011 (including). The comparison is presented in Fig. 15. It can be observed that after 2011, almost all tests were performed with the use of two origins of fire (cabin, under), and a previously common origin in the engine compartment was almost entirely omitted. Another observation is that tests conducted in the last decade are characterised by higher values of peak HRR and THR and shorter time to peak, compared to previous decades. The meaning of that is not unambiguous. On the one hand, it can mean that newer cars are capable of causing larger fires. However, it may also be an artefact of how the testing is performed (more tests ignited from underneath, researchers have access to better safety systems so they can manage larger fires). Further analysis of this topic is needed.

To ease the analysis of the presented results, a statistical analysis was conducted, and the findings are shown in Table 7. A noteworthy decrease in the average and median values of HRR and THR in the second interval is accompanied by an increase in the time to peak HRR value. This change may be due to the fact that, between 2001 and 2011, ignition methods in the engine compartment and on the vehicle body were more widely used. With these methods,

Table 6 Approximation of the average effective heat of combustion

Effective heat of combustion [MJ/kg]	
Average	25
Standard deviation	7

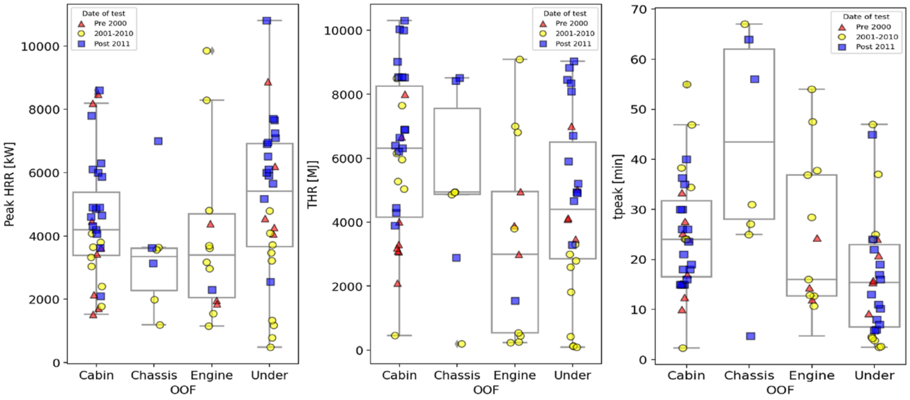


Fig. 15 Comparison of variables in the function of origin of fire, categorised by the decade of test

Table 7 Simple statistical analysis of chosen fire parameters distribution in the database, by the decade of test

	before 2001	2001—2010	2011 and after
Peak HRR [kW]			
Average	4361	3263	5623
Median	4167	3332	5882
5th percentile	1663	932	2463
95th percentile	8580	6890	8080
99th percentile	8854	9722	10,582
Standard deviation	2357	1985	1864
Time to peak HRR [min]			
Average	18,80	26,99	22,27
Median	16,40	25,00	18,50
5th percentile	9,80	2,54	5,91
95th percentile	29,05	54,60	49,95
99th percentile	33,14	65,99	63,26
Standard deviation	6,77	17,65	14
THR [MJ]			
Average	4315	3444	6770
Median	3954	3150	6795
5th percentile	2775	130	3111
95th percentile	7250	8202	10,014
99th percentile	7955	9037	10,275
Standard deviation	1586	2859	2232

fires generally took more time to reach peak HRR. However, when analysing HRR values from this period, consistent measurement results were observed across all vehicle ignition methods. Additionally, it was noted that most THR measurements during this period fall in the lower half of the scale, which is the opposite of the trend observed for the subsequent period. The values obtained in studies conducted after 2011 are higher for both HRR and THR, with the time to reach peak HRR falling between the values from previous periods.

Comparing data from studies conducted after 2011 and considering the division of vehicles into ICEVs and BEVs, a preference for the ignition method for each type can be observed. ICEVs were primarily set on fire using the cabin method, while in studies involving BEVs, the method of ignition from under the car was mostly used, as presented in Fig. 16. Additionally, analysing the peak HRR chart shows that studies conducted using the ignition from underneath method exhibit similar values for this parameter. In contrast, studies where the ignition point was located in the cabin show a much wider range of measured peak HRR values. It is also worth noting that the average peak HRR is significantly higher for vehicles ignited using the method from underneath. However, when looking at the THR, it can be observed that the range of its values is similar for both methods, with a tendency for higher results in the cabin ignition method. The average value of this parameter is similar for both main ignition methods, which indicates a consistent amount of combustible material in the tested vehicles. Analysing the obtained results, it can be concluded that in studies conducted after 2011, the method of vehicle ignition had a greater impact on the test results than the type of vehicle being tested.

6 Conclusions

In this research, a systematic literature review on passenger car fire experiments was performed to obtain the most complete database on the performance of passenger cars in fires to date. Through a systematic review of the Scopus, Web of Science and Science Direct repositories, 11 studies were identified. Additionally, using the citation mining approach and from the proceedings of the Fires in Vehicles conference, another 33 papers were found. Finally, 44 documents were discovered, encompassing 148 individual fire experiments. These experiments were then sub-categorised by the mass of the car (small, medium, large) and the type of the drivetrain (ICEV, BEV). The focus was on the Heat Release Rate, Total Heat Release as well as the peak value of HRR and the time at which it was observed. The effective heat of combustion was also investigated in experiments, that besides oxygen depletion calorimetry has also provided mass loss rate measurements and estimated at a value of 25 MJ/kg (± 7 MJ/kg).

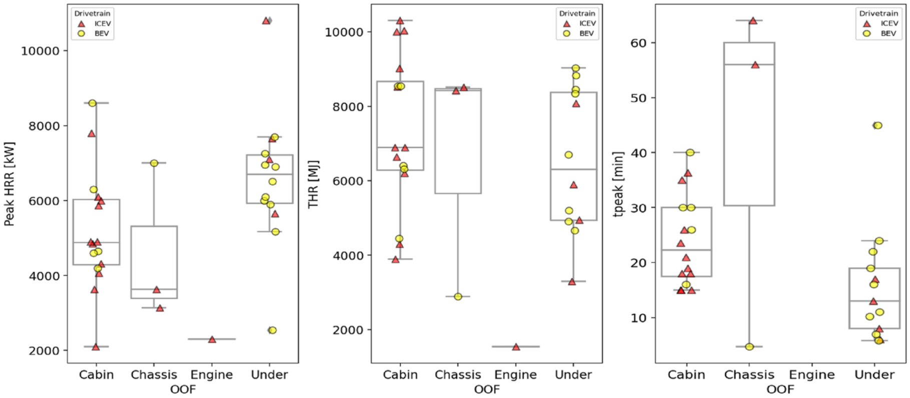


Fig. 16 Comparison of variables from test preformed since 2011 in function of origin of fire, categorised by drivetrain type

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. After defining the confidence interval and choosing the data sub-set (all cars, by size or type, by specific ignition location), the values could be useful as general guidance for the design of car parks.

In terms of the time evolution of the fires, an in-depth analysis of the collected HRR curves revealed that the 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 to fire safety. Proposal of a single design fire based on some averaging approach may not be feasible. In such case, after an analysis, a "*most onerous but probable*" design fire candidate may be proposed based on the results of chosen experiments. However, determining the general best candidate experiment within the database was not possible.

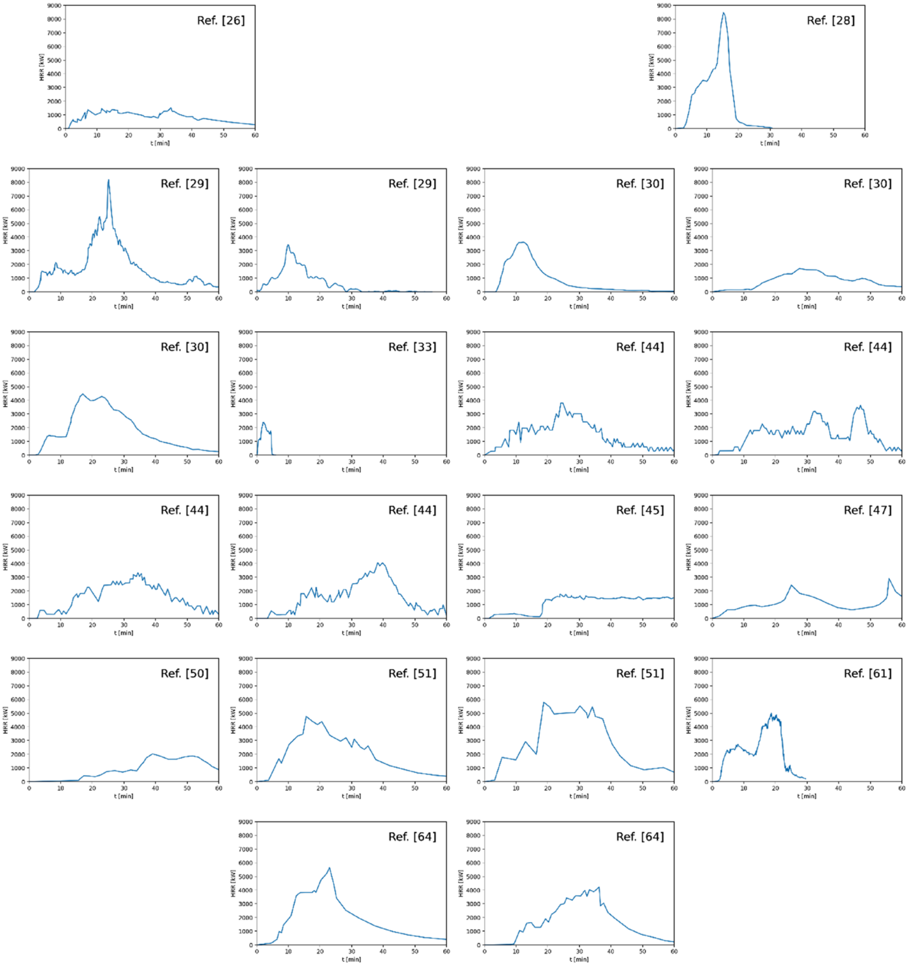
For research purposes, by recognising the inherent variability in car fire scenarios and adopting a case-by-case methodology, the researchers could craft scenarios that can better address the diverse challenges posed by different ignition sources, car configurations, and environmental conditions. This individualised approach enables the development of targeted solutions that account for the specific context of each fire event, where a generic design fire will not be viable. This approach requires further studies on the course of fires within cars, as well as a description of the transitional events in such fires. As this lies in the research domain, an approach like this is not suited for current design applications.

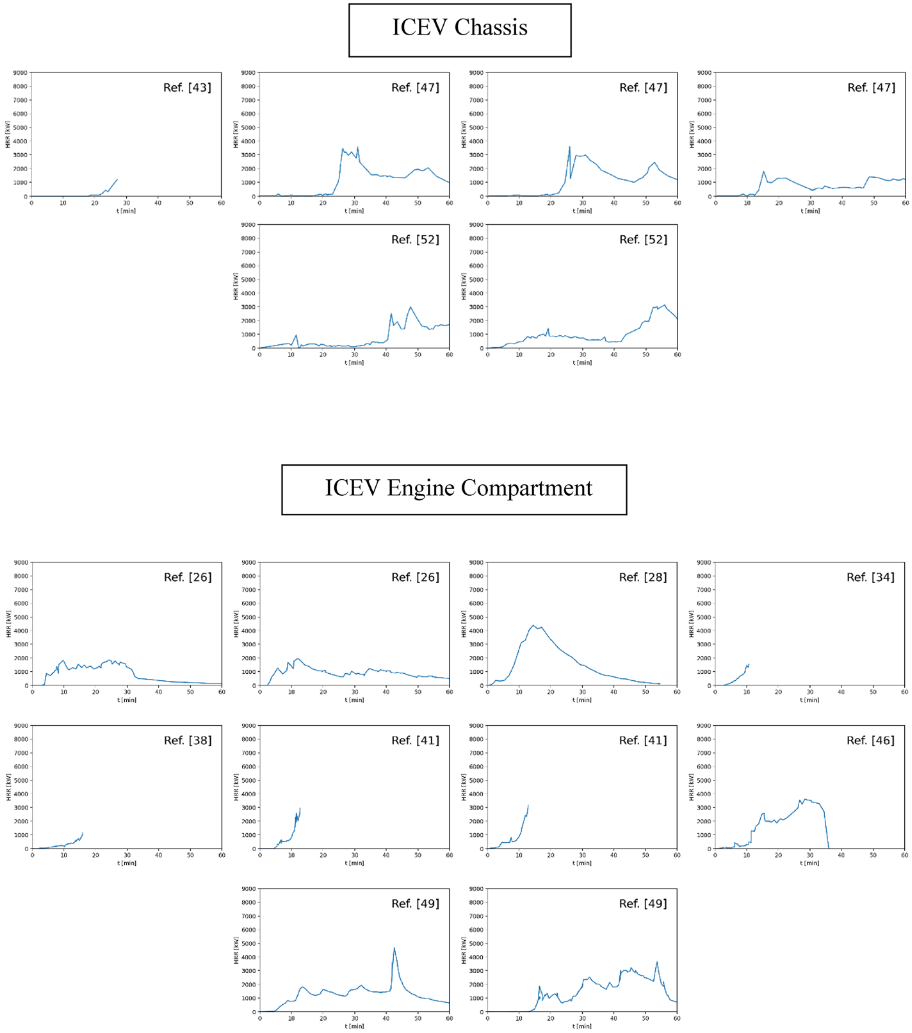
The diversity in fire progression is a challenge for an unbiased design fire choice for fire safety of car parks. It is recognised that the growth of the fire, besides the already mentioned inherent properties of cars, is also determined by the heat flux feedback from the parking structure, as well as the ignition of the neighbouring cars. Such factors are rarely included in the literature studies, and the ones with setups closest to real car parks were experiments by TNO [31] carried out in a real car park and experiments carried out by the BRE [49] performed in an enclosed compartment. With this in mind, there is a clear need for more studies on fires in cars in setups that are more representative of actual car park structures. Furthermore, the use of the ignition of the car from underneath is questionable, as an ignition mode that accelerates the growth of the fire and leads to a higher peak HRR that may not correspond to natural fires of cars. Future studies need to balance out the ignition location, to provide a more complete image of the course of car fires. Finally, the database contains almost solely fires of single cars. Little is known about the behaviour of secondary and further cars, which may be subject to higher heat fluxes and simultaneous ignition in multiple locations on the car. The definition of multi-car design fires requires further large-scale testing.

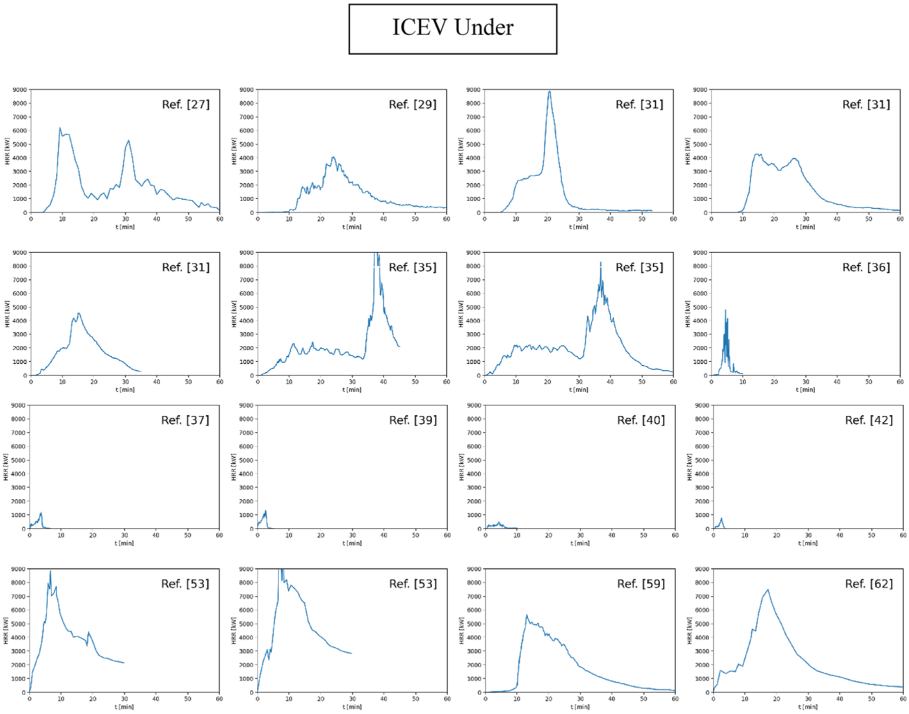
Appendix A

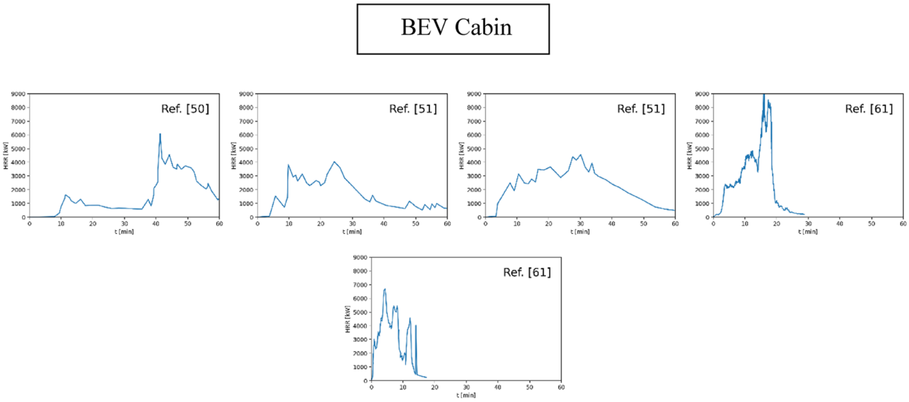
HRR curves extracted from fire the tests in reviewed literature.

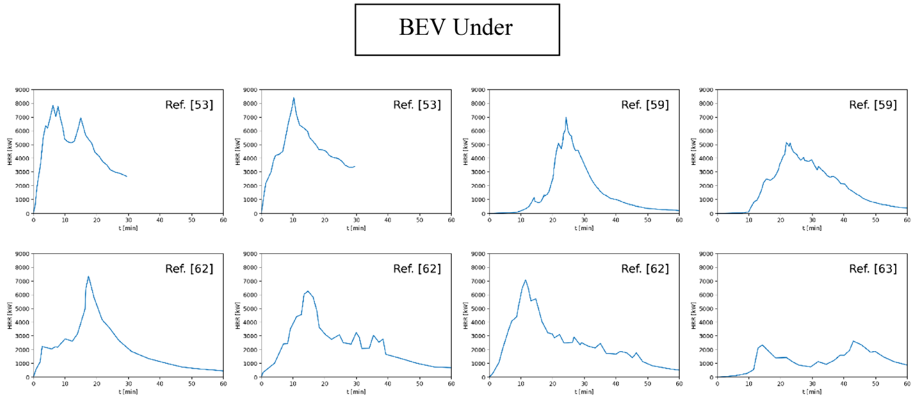
ICEV Cabin




ICEV Chassis
Ref. [43]
Ref. [47]
Ref. [47]
Ref. [47]
Ref. [52]
Ref. [52]
ICEV Engine Compartment
Ref. [26]
Ref. [26]
Ref. [28]
Ref. [34]
Ref. [38]
Ref. [41]
Ref. [41]
Ref. [46]
Ref. [49]
Ref. [49]
HRR [kW]
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
t [min]
0
10
20
30
40
50
60


ICEV Under
Ref. [27]
Ref. [29]
Ref. [31]
Ref. [31]
Ref. [31]
Ref. [35]
Ref. [35]
Ref. [36]
Ref. [37]
Ref. [39]
Ref. [40]
Ref. [42]
Ref. [53]
Ref. [53]
Ref. [59]
Ref. [62]
HRR [kW]
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
t [min]
0
10
20
30
40
50
60


BEV Cabin
Ref. [50]
Ref. [51]
Ref. [51]
Ref. [61]
Ref. [61]
HRR [kW]
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
t [min]
0
10
20
30
40
50
60



Appendix B

Fire test results database.

Driv-etrain	Mass [kg]	Peak HRR [KW]	Time to Peak [min]	THR [MJ]	Mass loss [kg]	Mass loss [%]	Hc,eff [MJ/kg]	OOF	Date	Source
ICEV	1102	1972	12	3900	176	15,97	22,16	Engine comp	1994	26
ICEV	918	1859	24,3	3000	143	15,58	20,98	Engine comp	1994	26
ICEV	990	1521	33,4	3300	141	14,24	23,40	Cabin	1994	26
ICEV	1780	6206	9,2	7000	N/A	N/A	N/A	Under	1994	27
ICEV	930	4390	14,4	4957	N/A	N/A	N/A	Engine comp	1995	28
ICEV	933	8482	15,2	4008	N/A	N/A	N/A	Cabin	1995	28
ICEV	757	3439	10	2100	138	18,23	15,22	Cabin	1997	29
ICEV	955	2150	24	3080	145	15,18	21,24	Cabin	1997	29
ICEV	830	4063	24,1	4090	184	22,17	22,23	Under	1997	29
ICEV	1303	8188	25,2	6670	275	21,11	24,25	Cabin	1997	29
ICEV	695	3630	12,4	3100	100	14,39	31,00	Cabin	1998	30
ICEV	1067	4470	17	8000	270	25,30	29,63	Cabin	1998	30
ICEV	893	1710	27,6	3200	108	12,09	29,63	Cabin	1998	30
ICEV	872	4549	15,4	3466	139	15,94	24,94	Under	1999	31
ICEV	1780	4270	15,8	5028	201	11,29	25,01	Under	1999	31
ICEV	927	8872	20,8	4134	165	17,80	25,05	Under	1999	31
ICEV	2232	2405	2,3	459	N/A	N/A	N/A	Cabin	2001	33
ICEV	1848	1545	10,7	254	N/A	N/A	N/A	Engine comp	2001	34
ICEV	880	3469	24	2800	141	16,02	19,86	Under	2001	35

Driv-etrain	Mass [kg]	Peak HRR [KW]	Time to Peak [min]	THR [MJ]	Mass loss [kg]	Mass loss [%]	Hc,eff [MJ/kg]	OOF	Date	Source
ICEV	820	4088	25	3300	131	15,98	25,19	Under	2001	35
ICEV	1382	8283	36,9	7000	255	18,45	27,45	Engine comp	2001	35
ICEV	945	3716	37	3000	151	15,98	19,87	Under	2001	35
ICEV	1454	9854	37,8	6806	262	18,02	25,98	Engine comp	2001	35
ICEV	1025	3221	47	2600	164	16,00	15,85	Under	2001	35
ICEV	1848	4797	4,6	421	N/A	N/A	N/A	Under	2002	36
ICEV	1649	1181	3,8	130	N/A	N/A	N/A	Under	2002	37
ICEV	1738	1161	16	233	N/A	N/A	N/A	Engine comp	2002	38
ICEV	1454	1337	2,5	131	N/A	N/A	N/A	Under	2002	39
ICEV	1382	484	4,3	90	N/A	N/A	N/A	Under	2002	40
ICEV	1182	2973	12,7	445	N/A	N/A	N/A	Engine comp	2002	41
ICEV	1470	3173	12,9	540	N/A	N/A	N/A	Engine comp	2002	41
ICEV	1920	780	2,6	1816	N/A	N/A	N/A	Under	2003	42
ICEV	1380	1189	27,1	199	N/A	N/A	N/A	Chassis	2003	43
ICEV	1182	3801	24,1	5280	165	13,96	32,00	Cabin	2004	44
ICEV	1920	3332	34,4	7648	N/A	N/A	N/A	Cabin	2004	44
ICEV	1380	4073	38,3	6144	192	13,91	32,00	Cabin	2004	44
ICEV	1470	3650	46,9	5960	186	12,65	32,04	Cabin	2004	44
ICEV	N/A	1780	24	8500	N/A	N/A	N/A	Cabin	2004	45
ICEV	N/A	3618	28,4	3800	N/A	N/A	N/A	Engine comp	2006	46
ICEV	1360	3633	25	4860	221	16,25	21,99	Chassis	2009	47
ICEV	1360	3560	31	4950	225	16,54	22,00	Chassis	2009	47
ICEV	1360	3039	55	5040	229	16,84	22,01	Cabin	2009	47
ICEV	1360	1990	67	4930	224	16,47	22,01	Chassis	2009	47
ICEV	1197	4800	47,5	N/A	N/A	N/A	N/A	Engine comp	2010	49
ICEV	1815	3700	54	9084	370	20,39	24,55	Engine comp	2010	49
ICEV	1275	2100	35	4300	195	15,29	22,05	Cabin	2012	50
BEV	1520	6300	40	6400	291	19,14	21,99	Cabin	2012	50
ICEV	1128	4850	15	6890	192	17,02	35,89	Cabin	2012	51
ICEV	1404	6100	18	10,030	275	19,59	36,47	Cabin	2012	51
BEV	1501	4650	30	8540	279	18,59	30,61	Cabin	2012	51
BEV	1122	4200	26	6314	212	18,89	29,78	Cabin	2012	51
ICEV	1440	3630	64	8515	N/A	N/A	N/A	Chassis	2013	52
ICEV	1440	3141	56	8420	N/A	N/A	N/A	Chassis	2013	52
ICEV	1440	4062	21	8526	N/A	N/A	N/A	Cabin	2013	52
ICEV	1096	7100	6	3290	274	25,00	12,01	Under	2016	53
ICEV	1344	8800	8	4950	336	25,00	14,73	Under	2016	53
BEV	1475	5900	5,8	4910	295	20,00	16,64	Under	2016	53

Drivetrain	Mass [kg]	Peak HRR [KW]	Time to Peak [min]	THR [MJ]	Mass loss [kg]	Mass loss [%]	Hc,eff [MJ/kg]	OOF	Date	Source
BEV	1448	6000	7	N/A	333	23,00	N/A	Under	2016	53
BEV	1650	6900	10,2	4660	363	22,00	12,84	Under	2016	53
ICEV	936	4900	15	6890	192	20,51	35,89	Cabin	2018	55
ICEV	1564	7800	15	10,000	262	16,75	38,17	Cabin	2018	55
ICEV	1404	6000	18	10,300	275	19,59	37,45	Cabin	2018	55
BEV	1501	4600	30	8540	278,5	18,55	30,66	Cabin	2018	55
ICEV	1200	3627	26	9018	N/A	N/A	N/A	Cabin	2019	58
ICEV	1326	5650	13	5900	252	19,00	23,41	Under	2020	59
BEV	1562	5170	22	6700	400	25,61	16,75	Under	2020	59
BEV	1584	6950	24	5200	247	15,59	21,05	Under	2020	59
BEV	N/A	6100	N/A	N/A	N/A	N/A	N/A	Under	2022	61
BEV	N/A	7000	4,7	2893	N/A	N/A	N/A	Engine comp	2022	61
BEV	N/A	8600	16	4454	N/A	N/A	N/A	Cabin	2022	61
ICEV	N/A	2300	N/A	1540	N/A	N/A	N/A	Engine comp	2022	61
ICEV	N/A	4900	19	3892	N/A	N/A	N/A	Cabin	2022	61
ICEV	1320	7660	17	8080	N/A	N/A	N/A	Under	2023	62
BEV	1685	7250	11	9030	N/A	N/A	N/A	Under	2023	62
BEV	1540	6510	16	8450	N/A	N/A	N/A	Under	2023	62
BEV	1655	7700	19	8830	N/A	N/A	N/A	Under	2023	62
BEV	1170	2550	45	8340	240	20,51	34,75	Under	2023	63
ICEV	1580	5864	23,6	6640	310	19,62	21,42	Cabin	2023	64
ICEV	1540	4319	36,3	6207	296	19,22	20,97	Cabin	2023	64

Appendix C

In-depth statistical analysis of gather data.

Result by the size of car and the location of the ignition source.

Small			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Cabin			
Average	4011	24,95	5208
Median	3716	24,65	5160
5th percentile	1663	11,80	2835
95th percentile	8262	42,48	8255
99th percentile	8469	54,25	8972
Standard deviation	1927	11,19	1949
Chassis			
Average	2593	37,53	3735
Median	2775	29,05	4895

Small			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
5th percentile	1309	25,32	898
95th percentile	3622	61,60	4947
99th percentile	3632	66,68	4950
Standard deviation	1043	17,15	2042
Engine Compartment			
Average	4046	24,63	3860
Median	3682	19,35	3900
5th percentile	1887	12,18	956
95th percentile	7412	44,85	6591
99th percentile	8231	47,34	6975
Standard deviation	2194	13,42	2166
Under			
Average	5094	22,05	4157
Median	4088	20,80	3466
5th percentile	1724	5,32	1596
95th percentile	9643	45,80	8184
99th percentile	10,731	46,93	8331
Standard deviation	2716	13,34	2160

Medium			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Cabin			
Average	5335	27,88	8114
Median	5257	26,80	8533
5th percentile	3835	16,35	6071
95th percentile	7125	43,80	10,179
99th percentile	7760	46,71	10,293
Standard deviation	1217	10,08	1610
Chassis			
Average	3386	60,00	8468
Median	3386	60,00	8468
5th percentile	3165	56,40	8425
95th percentile	3606	63,60	8510
99th percentile	3629	63,98	8515
Standard deviation	245	4,00	48
Engine Compartment			
Average	4729	22,23	2526
Median	3173	16,00	540
5th percentile	1362	13,21	264
95th percentile	9186	35,62	6179
99th percentile	9814	37,67	6768
Standard deviation	3716	11,08	3029
Under			
Average	5662	11,58	5427

Medium			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Median	6103	9,70	5200
5th percentile	1282	3,35	131
95th percentile	7770	22,70	8910
99th percentile	7892	23,92	9023
Standard deviation	2020	6,48	2714

Big			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Cabin			
Average	4203	19,14	4991
Median	3332	19,00	4454
5th percentile	1905	5,04	1146
95th percentile	7860	32,32	8330
99th percentile	8556	34,28	8490
Standard deviation	2436	10,49	2878
Engine compartment			
Average	3633	24,45	3514
Median	3618	19,55	2893
5th percentile	1696	5,60	511
95th percentile	6340	50,16	8027
99th percentile	6960	53,77	9021
Standard deviation	1870	19,16	3034
Under			
Average	3892	3,60	1119
Median	4797	3,60	1119
5th percentile	1182	2,70	491
95th percentile	5970	4,50	1746
99th percentile	6092	4,59	1812
Standard deviation	2264	1,00	698

Results by the location of the fire and the type of the drivetrain.

ICEV			
Cabin			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Average	4238	24,30	5969
Median	3932	23,80	6176
5th percentile	1728	10,60	2345
95th percentile	8091	44,75	10,023
99th percentile	8460	54,39	10,280
Standard deviation	1893	11,52	2575
Chassis			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]

ICEV			
Cabin			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Average	2857	45,02	5312
Median	3351	43,50	4940
5th percentile	1389	25,53	1364
95th percentile	3632	66,25	8491
99th percentile	3633	66,96	8514
Standard deviation	941	17,71	2785
Engine compartment			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Average	3818	25,63	3463
Median	3173	20,15	3400
5th percentile	1391	11,42	245
95th percentile	8911	50,43	7938
99th percentile	9797	53,79	9015
Standard deviation	2490	14,50	2888
Under			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Average	4569	15,56	3346
Median	4179	14,20	3295
5th percentile	736	2,59	124
95th percentile	9161	38,50	7162
99th percentile	10,702	46,49	8025
Standard deviation	2734	12,09	2261
BEV			
Cabin			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Average	5670	28,40	6850
Median	4650	30,00	6400
5th percentile	4280	18,00	4826
95th percentile	8140	38,00	8540
99th percentile	8572	39,88	8540
Standard deviation	1633	7,74	1545
Under			
	Peak HRR [kW]	t_{PHRR} [min]	THR [MJ]
Average	6103	17,78	7015
Median	6305	16,00	7520
5th percentile	3729	6,28	4748
95th percentile	7498	36,60	8960
99th percentile	7688	44,50	9026
Standard deviation	1376	11,38	1751

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