The fire safety of car parks

Focussing on structural damage

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by

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Preface

The thesis is written to finish my master degree for my master Building Engineering at the Technical University of Delft. During this master a got interested in Fire Safety Engineering and how this subject is integrated into Civil Engineering. I came in contact with DGMR and together came to the subject to analyse the fire safety of a car park and to focus on the structural damage and how this will be affected due to the changes in the car industry. I would like to thanks DGMR and especially Ir. P. van de Leur to support and help me during this thesis. I would also like to thanks the TU Delft to allowing my the investigated the fire safety of a car park and especially Prof. R.Nijsse, Ir. S.Pasterkamp and Ir. P.Lagendijk for their feedback and support. At last I would like to thank S.Uitenbroek Bsc, who helped me by reviewing this thesis.

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Summary

The focus of this thesis was to investigate the fire safety of a car park in terms of the possible structural damage that could occur in a fire, seen in the light of important changes in the car industry. The car industry is always in development and this has resulted in new energy systems for cars. On the Dutch market six types of fuel systems are today available, petrol, diesel, electric, liquefied petroleum gas (LPG), compressed natural gas (CNG) and hydrogen. Petrol and diesel cars currently constitute a large part of our vehicle fleet. This is going to change rapidly as according to current government planning new diesel cars are not allowed to be sold after 2030, and new petrol cars after 2050. It is largely uncertain to what extent other energy systems are going to take over. Each alternative comes with its own set of fire hazards that needs to be addressed, many of these hazards have been largely neglected until now.

A separate trend in the car industry is the developments in the weight of the car. Goals are set by the car manufacturers to reduce weight which will result in lesser fuel consumption. This could be done by replacing steel with plastic and aluminium. Insofar as this is done with plastic, the total combustion heat of the car increases and the associated fire hazards go up. These material trends are analysed, and it was found that the total combustion heat has increased with 20 % in comparison with cars from the 90s'. Most of the available test data on combustion heat of a car and heat release rate are based on cars from the 90s', more recent data is not available. So the total combustion heat has increased, but it is uncertain what effect this change has on the heat release rate as this not a physical property, the layout of the materials is an important factor. To verify the rate of heat release tests are needed with modern cars.

The peak in the rate of heat release of burning cars is a result of the breakdown of the fuel tank, releasing the fuel which then burns rapidly. For electric cars this is not the case, so the heat release rate of this type of car does not exhibit a 'fuel peak'. The total combustion heat of this type of car was shown to be similar to a petrol/diesel car. The major risk of an electric fire is the continuous reignition of the battery. Due to the heating of the lithium-ion battery a thermal runaway reaction occurs inside this battery. Heat and oxygen are produced in this battery, so a thermal breakdown is a closed fire triangle. There are currently no effective methods to extinguish an electric car battery in an enclosed space. The only option proven effective is to place the car in a water basin and leave it there for 24 hours, a solution difficult to realise in a car park. More research is needed to extinguish these batteries.

Pressurized gas cars bring another set of risks to the car park. Pressured tanks are protected against explosions caused by heating in a fire, as they are equipped with a temperature activated pressure relief device (TPRD). When the device is heated above 120 °C, the device will open and the gas will be released within 100 seconds. Since the car is burning, the gas jet will most probably ignite, resulting in a jet fire up to 20 meters long. There are various regulations on the different type of pressurized gas cars, the aiming direction of the jet is not uniform. A study on the failure of TPRD showed that it failed in 14 of the 90 cases. A disfunction of a TPRD will result in an explosion of the tank with a pressure wave of 10 up to 29 kPa at a distance of 50 meters. That pressure will knock down people to the ground and damage construction elements. A burning pressurized gas vehicle cannot safely be approached by the fire department before the TPRD has released the gas or after the tank has exploded. After either event, the fire department can approach the vehicle as it would a petrol/diesel car. The rate of heat release of these types of cars is similar to a petrol/diesel car, a narrow peak is expected due to the jet fire.

Four case studies were done on car park fires involving traditional gasoline/diesel cars, with a focus on assessing the structural damage. Concrete has spalled as a result of the car fires, in all the four cases, the reinforcement was exposed to the fire. This resulted in faster heating of the reinforcement than anticipated in the design. Debonding between the prefabricated floors and the poured concrete layer has also occurred. Where debonding occurred, the floor cannot carry the load anymore. The debonding damage extends beyond the visible spalling damage. The fire-resistance time of a structure is designed on the basis of exposure to an ISO-curve 834 temperature curve. For a car park, this is also done. The fires in the case studies lasted much

longer than the design fire-resistance time but none of the car parks collapsed. The fire in the King's Dock car park in Liverpool was the most extreme fire that has occurred yet. This open car park was analysed to understand how this fire could develop to such an extent. Due to the event occurring in the Echo Arena near the car park, the car park was almost full. The first assessment period of the fire department took rather long and the fire was attacked after 39 minutes. However, the fire could not be controlled and eventually grew to 1039 cars. The structure itself was similar to other open car parks and this fire could have happened in any other open car parks. There are no indications that cars on alternative fuel systems increased the fire propagation. The spalling of the floor resulted in big holes and even at some places only the reinforcement was left. In the order case studies, columns and beams had spalling damage and reinforcement was exposed but these elements had not failed. As a result of the debonding between the floor layers, floor elements had failed.

Spalling damage of the concrete elements is a serious issue. There is currently not a known concrete mixture that will not spall when exposed to fire, and therefore other methods need to be considered to prevent spalling. Polypropylene fibres could be added to the mixture as an effective method to deal with spalling. However, the only known method to demonstrate performance is to test the mixture in a fire test. There is also an option to keep the fire small by using sprinklers, so-called active protection. Another possible method is to isolate the concrete from heating, passive protection. When the concrete is isolated from the fire, a high fire-resistant time of the structure is achieved. This result in a longer possibility for people to escape and a smaller chance of the failure of concrete elements, lowering the chance of failure. Two passive protection methods are available: fire-resistant coatings and fire-resistant boards. It is unknown how the fire-resistant coatings on concrete will affect spalling behaviour. The fire-resistant boards are investigated a lot, as they are regularly used in tunnels. Rijkswaterstaat, part of the Ministry of Infrastructure and Water Management in the Netherlands, has recently performed tests to verify the needed limit to temperature to prevent spalling. This value has been set at 200 °C. Calculations were performed with a 1D heat transfer model and a model made by Promatect to estimate the needed thickness of the isolation material. The thermal properties published for the board material lead to too conservative results. The properties used by the manufacturer were reverse-engineered from fire tests, these properties are however not available for design calculations using different heating conditions more appropriate for car park fire. It is therefore not possible to accurately estimate the required thickness for a car park.

To understand the probability of the occurrence of a car park fire, statistics were produced with the help of the NEN data provided by Ir. B. Kersten and Ir. D. Jansen. The annual probability of a fire is $7.1 * 10^{-7}$ per m^2, quite similar to a fire in any other occupancy, which has a probability of $4.0 * 10^{-7}$ per m^2. 42 % of the fires included in the statistics developed beyond the first car and 9 % of the fire developed beyond seven cars. Further analysis was made of the variation between an open and a closed car park. It appears that a fire in an open car park has a bigger probability of developing beyond seven cars than a closed car park, contrary to the 'classical truth' that fires in closed car parks are much more difficult to extinguish. Three of the four case studies were closed car parks and developed in much the same manner, a fire propagation time of 13-15 minutes. Only the fire in the King's Dock car park developed much faster.

A sprinkler system is an effective method to keep the fire small in a car park. Tests and fires that occurred in car parks protected by a sprinkler system confirm the idea that the fire is controlled to one car. The sprinkler industry responds slowly to changes, the possibility that the higher plastics content of (traditional) cars requires a change in hazard classification and therefore a higher applied density is only now under discussion within the US standards body NFPA.

The introduction of cars with pressurized tanks and therefore the possibility of explosions and jet fires, challenges the validity of the 'one burning car' concept. An explosion has the potential to damage the sprinkler head and/or the pipes, whereas the much more probable jet fire can ignite neighbouring cars without the sprinkler sprays being able to prevent it. These risks have only begun to be recognised, they have not been studied in any depth yet. Possibilities are to make the sprinkler installation more robust, for example integrating the pipes in the floor. It is also unsure what the effect of a sprinkler on an electric car fire is due to the reignition of the battery. These effects need to be studied to understand the effect of a sprinkler on an electric car fire.

As the different fuel systems introduce new risks to the car park and the intervening fire department, identifying the type of fuel system is of importance. Visibility is poor due to a dense smoke layer, grouping cars in car park seems to be a solution to identify the car. For example, electric cars already are parked near electric loading stations. The cars with a bigger risk of exploding could be placed at the least critical places, for example away from stability elements.

The fire load in car parks has increased and new risks are introduced. Therefore the possibility of more structural damage in case of fire has increased and therefore the probability of a collapse. Various occupancies are situated on top or underneath car parks and the possibility of evacuating these buildings need to be assets. The biggest risks are hospitals and occupancies were people need support to evacuate. For these functions, it is often not possible to evacuate fast, or even at all, and a higher fire-resistant is needed for the structure or the fire should be kept small. Evaluating the risk of evacuation is needed to design a (fire-)safe car park.

Contents

1
Introduction

The fire safety of buildings is gaining more interest in the last few years due to occurred fire. Some examples of fires that resulted in more attention of this field are the King's dock car park fire, 2017 Liverpool, the fire in the Notre-Dame, 2019 Paris and the Grenfell tower, 2017 London. The focus of this thesis is the fire safety of car parks. Most of the available information on this matter is published in the late 90s'. However, vehicles are rapidly changing in material and in powering systems. Occurred fires suggested that the found fire load of a car in the 90s' is no longer valid as the fires were larger than previously assumed.

1.1. Problem statement

As the car park fires are becoming large and the vehicles are changing a new assessment on the fire safety of car park is made. Due to the increase in the size of the fires, the structural damage also increased. Spalling of concrete is one of the main damage occurring in car park fires. Spalling of concrete is still under investigation as it is unknown which parameters play a big role. Spalling of the concrete leads to a smaller cross-section which resulted in faster heating of the reinforcement. All these new factors introduce new risks for a car park fire.

1.2. Research objective

The goal of this thesis is to investigate the developments of car park fires, what is the probability and how many cars were involved. Also, a closer look will be taken to the development of cars, did the potential combustion heat increase and are other fuel systems more likely to park in car parks.

1.3. Research questions

The research question of this theses is, does the change of fuel sources and other innovations in modern cars, influence the structural damage in car parks in case of a fire? To answer this question sub-questions were formulated to research the various elements that have a role in a car park fire.

1. What is the expected structural damage in a car park during a fire in relation to the number of cars involved?
2. What is the expected frequency of a fire in a car park?
3. How to deal/cope with the spalling of concrete for a car park?
4. What is the currently expected fire load in a car park?
5. What are the new risks of electric-powered cars for car parks?
6. What are the new risks of gas tanks in cars for car parks?
7. What are the possible design strategies to make a safe car park?

1.4. Methodology

To asses the structural damage that occurred during a car park fire, multiple case studies will be performed to asses how the fire department dealt with the fire, how the fire could develop and the damage will be evaluated. To asses the frequency of a car park fire, information gathered on the occurrence of car park fire. The other sub-questions will be answered with the help of the relevant literature.

1.5. Relevance

The current regulation is based on research from the late 90s'. Newer research was done in 2010 which suggested the fire load had increased over the years, however in this newer research the cars had the same manufacturing data as the research from the late 90s'. There has not been any research on the combustion heat of cars on more recent models. So this thesis will investigate the potential change of combustion heat of a car. There is also not a lot of research on structural assessments after a car park fires as the focus is often on how the fire department dealt with the fire. Therefore it is interesting to investigate what the resulted damage is and to compare this with the expected damage. The latest information on the probability of car park fires is also from the 90s' and an update will give an insight into the development of this type of fire.

1.6. Limitations

To best method to determine the fire load of a car is to tested perform multiple tests with the help of a calorimeter and a large scale. However, the needed tools to perform these test were not available and therefore only suggestions could be made on this development. The data for the statistics are based on news reports and could therefore fire could have been missed.

1.7. Structure

The first phase of the this Thesis a literature study was performed and relevant developments in the car industry were found. Other important information on regulation, structure of a car park and how the fire department copes with a car park fire can be found in the literature study. To investigated the possible damage in a car park, case studies were done and can be found in the chapter case studies. Statics were made on the available data and can be found in the chapter statics on car parks. Option to deal with spalling can be found in the chapter design options due to spalling. The development in the care industry and the risk of these developments can be found in the chapters, Expected fire load, risk of electric car and risk of pressurised tanks. At last the information is discussed and a general conclusion is made containing recommendations to design a (fire) safe car park.

2

Review of related literature

This chapter gives the state of the art on the development of fires in a car park and on the protection of car parks against fire. A closer look will be taken at the developments in regulations and guidelines and the development in the automotive industry.

2.1. Distinction between car parks

In many jurisdictions a distinction is made between types of car parks, based on the openness of the facade of the car park itself and therefore divides between "open" and "closed" car parks. In an open car park, natural airflow will ventilate the space so that it is similar to outdoors. Therefore, a fire inside an open car park can be considered similar to a fire in the open air, however new insights question this concept. When air cannot flow as easily through the car park it will be categorised as a closed car park.

2.1.1. Open car parks

The distinction between open or closed can be made by calculating the natural ventilation for the car park. When there is enough natural ventilation, the car park is classified as open. NEN 2443 'Parkeergarages en parkeerterreinen' [51] gives criteria to classify the car park as naturally ventilated. The criteria are based on how open the various facades are and on the allowed distance between opposing facades (figure 2.1). In short, in each of the two opposing facades the openings must be 1/3 of the total area or 25 m^2, whichever is larger. The maximum distance between the two facades is 54 m. In this standard, the effects of wind directions or surrounding buildings are not considered. A fire in an open car park is assumed to remain a local fire and flashover conditions cannot occur. Smoke and heat are able to escape through the openings in the facades. When the above mentioned criteria are not met, the car park is categorised as closed. The validation of the natural ventilation concept is receiving more and more criticism. Until recently, a flashover fire in a car park was considered extremely unlikely or even impossible. However, during the fire in the Echo Arena in Liverpool (2018) enough heat was retained in the open car park to cause a flashover fire. Therefore, simply saying a car park is safe due to natural ventilation is highly questionable. The subdivision between open and closed car parks is not as clear as previously thought. The Echo Arena will be part of the case study and a closer look will be taken at the causes of serious development of the fire; the possibility of reoccurrence in the future will also be investigated.

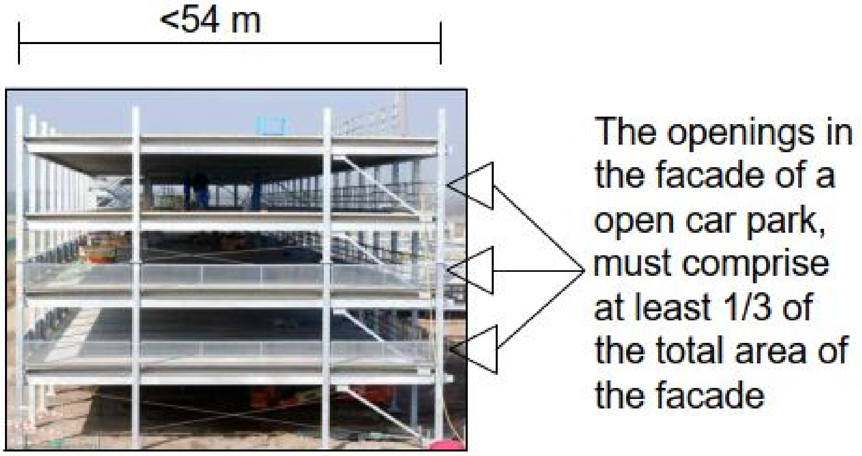


Figure 2.1: Visualisation of the criteria given in NEN 2443 for an open car park [48] [51].

2.1.2. Closed car parks

In a closed car park, heat and smoke are not able to escape naturally and therefore mechanical equipment is needed to provide safe conditions for occupants and emergency services. Two commonly used installations are mechanical ventilation systems and sprinklers. Both methods are explained more thoroughly in the chapter ''Fire protection methods". Fires in a (small) closed car park quickly become oxygen controlled and flashover can occur, although unlikely based on statistics. In the European Union, countries have varying rules and regulations on how to design and construct a safe closed car park, table 2.1. In the USA for example, all closed car parks need a sprinkler when situated underground or buildings are situated on top of the car park. Also, a sprinkler is required when the closed car park is higher than 15 meters [5]. Whereas in some EU countries, a selection can be made between ventilation or sprinkler systems no matter the size of the fire compartment. In Belgium, when the compartment is larger than 5000 m^2, both sprinkler installations and mechanical ventilation are required [56].

Table 2.1: Regulation on closed car parks in different countries [56].

	Area		
	0-1000 m^2	**1000-5000** m^2	**5000** m^2
Netherlands	No ventilation or sprinklers	Ventilation or sprinklers	Ventilation or sprinklers
Belgium	Ventilation or sprinklers	Ventilation or sprinklers	Ventilation and sprinklers
Germany	Ventilation	Ventilation	Ventilation or sprinklers
United kingdom	Ventilation	Ventilation	Ventilation
USA	Sprinklers	Sprinklers	Sprinklers

2.2. Regulations and guidelines in the Netherlands

To design a safe car park, guidelines have been created which provide design tools. These guidelines are not the law and everyone is allowed to deviate from them. These deviations are validated by the authority having jurisdiction on the permit request (the municipality), who usually delegate the specific fire aspects to the regional fire department. Their experts asses the validity of the fire safety concept of a newly designed building. The Dutch Building decree [65] is the major law that needs to be followed in the design. The current building decree states that the maximum area of a fire compartment is 1000 m^2. However, car parks are often bigger and for several reasons designers prefer a single open space. Neither the architect nor the fire department like this idea of dividing the car park in small compartments, since visibility is immensely reduced and so is the safety. Due to the needed walls for creating the fire compartments in a car park, it will take longer to evacuate and the fire department needs more time to localise the fire. Therefore, car parks often deviate from the 1000 m^2 limitation. For these larger compartments safety has to be proven and guidelines were developed that provide tools to provide this proof. This chapter will describe the development in these guidelines and how they should be used.

2.2.1. Dutch Building Decree 2012

In the latest version of the Dutch Building Decree, which dates from 2012 [65], most of the rules are based on the previous version (Building Decree, 2003 [64]). The Building Decree stated that the maximum size of the fire compartment is 1000 m^2 and the distance to exit the fire compartment should not exceed 30 meters [65]. However, when their occupancy ratio is low it is allowed to have a distance of 60 meters. Not a lot of rules are prescribed in the Building Decree relating to the fire safety of a car park. As an exception, fire detection and alarm system is prescribed, depended on the total floor area and the highest floor level. When the highest floor is 1.5 meters below ground level and the floor area is smaller than 1000 m^2, a system with manual call points suffice. If the area exceeds 1000 m^2 full coverage by automatic detectors is required. A type B evacuation alarm (slow whoop sirens) is required in the car park, above 10.000 m^2 this must be a type A system with intermittent siren/spoken word signalling. When the area exceeds 2500 m^2 these installations must be certified [65].

2.2.2. Code of Practice Dutch fire department

To provide guidance for compartments larger then 1000 m^2, the Dutch fire department developed a Code of Practice (Praktijkrichtlijn, 2002) which asks for additional safety provisions for a mechanical ventilated closed car park [49]. The main goal of these regulations was to guarantee the ability for the firefighters to quickly extinguish the fire. The guideline prescribes direct notification of the fire department upon automatic fire detection, localisation of the fire seat to within 1000 m^2, a dry riser connection at each entrance and limiting the maximum travel distance to 30 meters within the car park. When the firefighters arrive on the scene, they want to get close to the fire, without having to find their way through hot smoke over a long distance. The access routes can be used by the firefighters to get near the fire. The travel distance limitation therefore primarily benefits firefighters, but it does also provide additional safety to occupants of the garage when compared to the general 60 meter limit in the Building Decree. The guideline also states that the load-bearing structure of the car park must be fire-resistant for 120 minutes, regardless of occupancy in buildings above the car park. Limited ventilation is prescribed for "after-care". The car park must be clear of smoke within 45 minutes after the fire started. To dimension the ventilation system, an assumption had to be made on the energy release rate of a car and of a row of cars. TNO and EU partners did a study on this matter which resulted in a prescribed a curve that could be used for smoke spread simulations (figure 2.2) [37]. The curve represents three cars of which the cars adjacent to the first car ignite with delay times of 10 and 15 minutes. A further assumption is needed on the time at which the fire service intervenes in the fire development, this was set at 23 minutes (5 minutes detection, 10 minutes arrival at the scene, 7 minutes setting up and 10 minutes for the attack). After a large fire in the Appelaar car park, in Haarlem in 2010, the fire services research institute (Instituut Fysieke Veiligheid, IFV) concluded that this guideline does not result in a fire-safe car park [77] and the guideline was subsequently formally withdrawn.

2.2.3. Code of Practice Rotterdam fire department

In response to the Code of Practice as published by the national fire department, the municipal fire department in Rotterdam created its version of the Code of Practice in 2004 [63]. On top of the earlier mentioned regulations, ventilation is required to assist the firefighters. The ventilation had to create a smoke-free path that allowed the fire department to see and safely approach the fire. With respect to the ventilation system design, the Rotterdam fire department considered that the number of cars burning, when starting an intervention, must be estimated higher than the 'TNO curve'. As the cars parked in the 2004 car parks contained significantly more combustible products than those used in the tests for the TNO curve. Since no newer research was available, they set the number of cars burning at four cars. After the general Code of Practice of the Dutch fire department was pulled back, the Rotterdam Code of Practice lost it is foundation and is not used anymore.

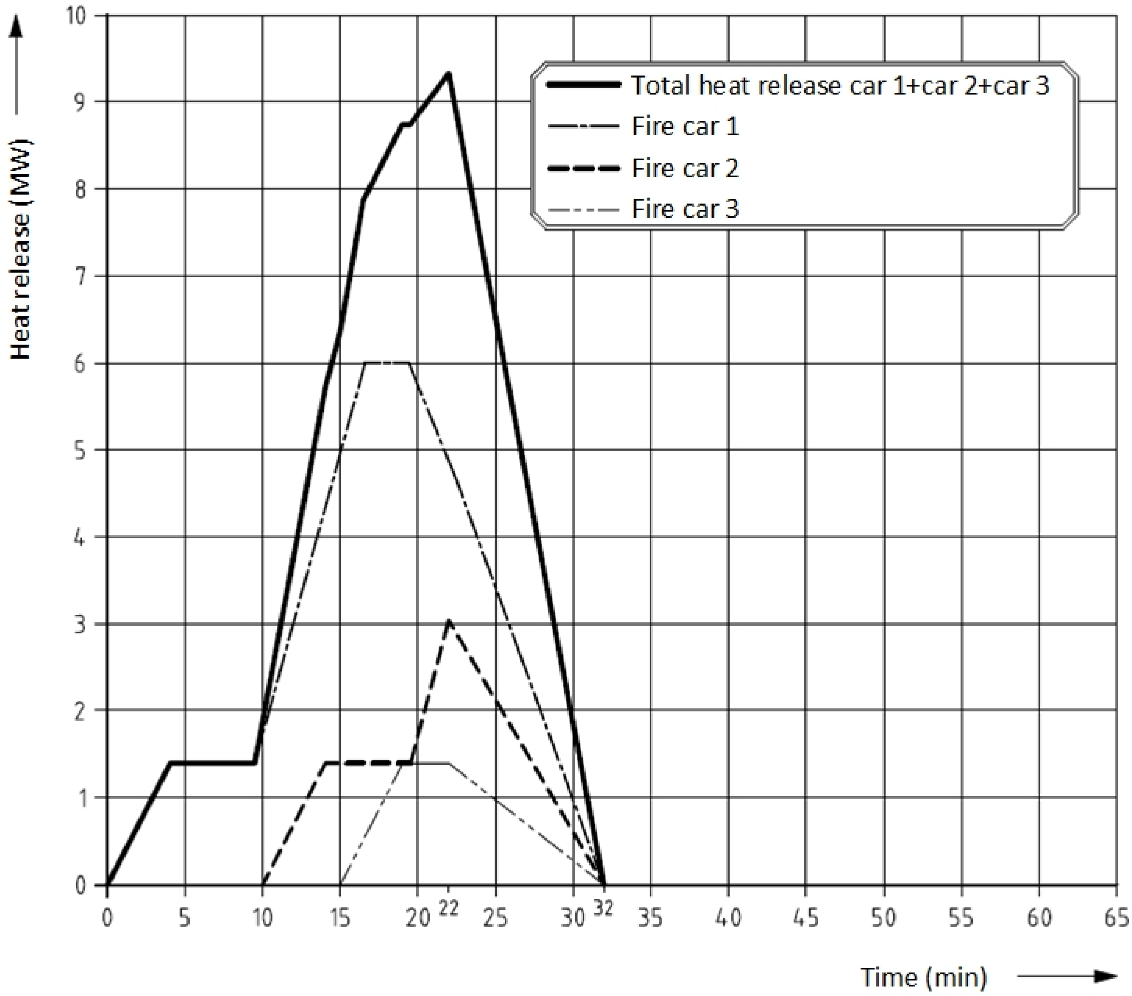


Figure 2.2: The fire load of a single car and three cars based on the TNO and EU partners study [37][50].

2.2.4. NEN 6098

NEN 6098 (Rookbeheersingssystemen voor mechanisch geventileerde parkeergarages 2012) [50] was developed from 2004-2007 to provide tools to better dimension the needed ventilation for a closed car park. That was needed since the Rotterdam Code of Practice left many details either open or treated in an unsatisfactory way. In this standard, a smoke-free access path must be created for firefighters within fifteen metres of the location of the fire. The RHR curve needed to dimension the ventilation is based on the three cars burning simultaneously from the study done by TNO [37], not based on the four cars from the Rotterdam Code of Practice [63]. To prove the smoke ventilation systems delivers a smoke-free path within fifteen meters when the floor area exceeds 2500 m^2 the standard offers two options. Firstly, providing an average air velocity of 1.5 m/s over the smallest cross-section area. Secondly, showing with a Computational Fluid Dynamics model (CFD-model) that even for the most unfavourable fire location the fifteen meter smoke-free access criterion is met (resulting in an air change rate of 30 up to 150 times per hour). For small garages (up to an area of 2500 m^2) the standard suggests, an air renewal rate of ten times per hour. Outside the scope of NEN 6098, it could be used for an open car park. With the help of NEN 1087 (ventilatie van gebouwen) [54] the natural ventilation rate can be calculated and generally this was more than enough to meet the requirements according to the needed ventilation of NEN 6098. The fire department is not keen on designs with smoke ventilation systems and is currently not accepting car parks designed with these systems, due to fires that occurred in closed car parks. However, it is not clear if the fire department could have extinguished these fires if the ventilation system was designed with this norm.

2.2.5. NEN 6060

NEN 6060 (Brandveiligheid van grote brandcompartimenten) [52] provides a general tool allowing the creation of larger fire compartments and has within its scope car parks. The standard relates the allowed fire compartment size to the reliability level of the sprinkler system.

2.2.6. Guideline of 'Bouwen met Staal'

'Bouwen met Staal' published a guideline for open car parks constructed out of steel [2]. This guideline introduces different scenarios based on fire resistance of the load-bearing structure in the fire compartment needed according to the Building Decree [65]. Every fire compartment present in a structure must either comply with a 30, 60, 90 or 120 minutes fire resistance. To which class a fire compartment belongs depends on the ease and speed with which the building can be evacuated as well as the self-rescue capabilities of the occupants. This fire resistance time leads to a fire scenario according to this guideline. A longer fire resistance time means a longer time for a fire to develop, resulting in a higher fire load. The scenarios are shown in figure 2.3, the green areas are 'normal cars' and have a total fire load of 9500 MJ each, which is based on the study done by TNO [37]. In the maximum scenario a vehicle with a higher fire load is introduced, red area (van). To check the steel temperatures, CaPaFi is recommended. Designing a safe car park according to the 'Bouwen met Staal' guideline requires checking the response to fire scenarios at different locations in the car park. Critical locations should be identified based on the layout of the car park. For example, places containing beams with a lot of cars underneath, columns that could be surrounded by cars and corner columns.

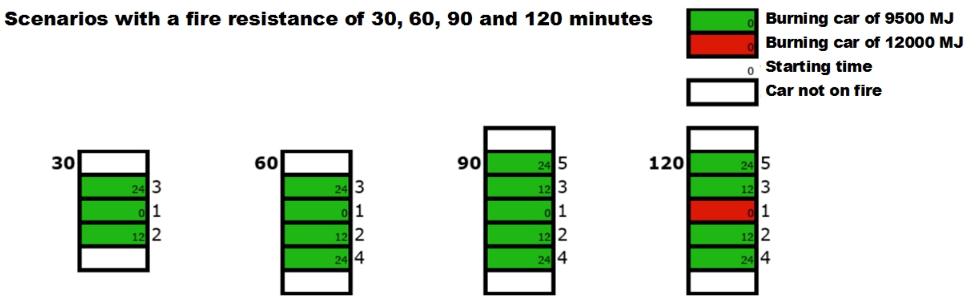


Figure 2.3: The fire scenarios of the Bouwen met Staal guideline. When a longer period is requested a bigger fire scenario could develop and this is incorporated in this guideline [2].

2.2.7. New NEN norm for fire safety design in a car park

NEN started a committee to create a new standard for the fire safety design of a car park. This new standard is currently under development, but already some interesting topics have been discussed. In the European union materials are classified by a curtain fire class A up to F, this material needs to be tested by different test to understand how the material ignites and how fast the fire progress. Fire class A1 and A2 are materials that do not ignite, material that has a fire class B will have a small fire propagation and F is not tested. Any thermal insulation material applied in car parks must have a fire class B certificate, according to the Dutch Code of Practice [49]. According to the Building decree [65] fire class D is needed. However, it was found that these products are sometimes not safe, contributing significantly to fire development in a car park. The new standard therefore requires fire class A2. More information on insulation material will be provided in the chapter "fire suppression systems". In this new standard, the required safety level for a car park is based on how reliably people can evacuate. When the car park is a structure on itself, no other occupancies are connected to the building, the acceptability of collapse is larger and therefore the safety margin can be smaller. If a car park is not self-contained, a division is based on the type of occupancy above it: shops/office, houses or a hospital. In offices and shops people are awake and can generally self-evacuate the building immediately in case an alarm is triggered. For residential function this is not the case, people can be asleep and therefore more time is necessary to escape. The last group entails hospitals (and other curve/care functions), in this specific type of building there are people that cannot escape by themselves because of their vulnerability. Evacuation requires more time or is even not feasible at all.

2.2.8. Regulations in foreign countries

Other EU countries made different assumptions as to the number of cars that will take part in the fire, table 2.2. The table indicates the design fire load for other countries. The main assumption for a smaller fire load with a sprinkler in a car park is due to a smaller likelihood for a fire to propagate to the next car. In America, almost all the closed car parks need a sprinkler installation. According to the table 2.2 there is no clarity on the intensity of the fire load.

Table 2.2: An overview of the design fire load for a car park in different countries. They differ in the number of cars and the peak load [56].

	No sprinklers		**Sprinklers without floor gradient**		**Sprinklers with floor gradient**	
	RHR (MW)	**Number of cars**	**RHR (MW)**	**Number of cars**	**RHR (MW)**	**Number of cars**
Netherlands	9 or 12	3 á 4	-	-	-	-
Belgium	6	2	6	2	4	1
Germany	8	3	3.8	1	-	-
United Kingdom	8	3	4	1	-	-
America	Always use sprinklers					

2.3. Possible fire load in a car park

To verify the fire safety of a structure, an assumption has to be made on the possible fire load in a car park. The fire load is defined as the total amount of combustible material in a certain area, measured in the equivalent mass of wood (kg) or its heat of combustion (MJ) [81]. A fire in a car park differs greatly in comparison with a fire that could occur in a house. When a car is on fire, a high peak in the rate of heat release (RHR) is expected in the first fifteen minutes, therefore the RHR in the beginning phase of a fire is high. Research has been executed to measure the rate of heat release and the total amount of heat during a car fire. During these previously executed experiments car models from the 90s' were used [22] [37], but cars are changing rapidly and new energy sources are developed and incorporated. Not only the engines are changing, more and more plastic material is used in the car [67]. More about these trends in the car industry in the chapter "Car industry in The Netherlands".

2.3.1. Traditional cars

The currently available data on the fire load of a traditional car are mainly based on three studies. First, one reported by TNO and EU partners in 1999 [8]. The second one was reported in 2010 by Building Research Establishment (BRE) [22] and the latest study was reported by the University of Canterbury in 2015 [86]. In these studies, a lot of cars were burned and the heat release rate measured. However, one has to keep in mind that older type cars were used for financial reasons, currently used cars differ in the amount of plastic and type of engine. With the help of the data from these studies, the behaviour of 'traditional' cars during a fire is well known. A problem however, is the non-uniform data obtained by the various researchers. Namely, if two cars of the same type were tested, differences between the obtained data can be observed. A reason for variations in the results is probably the precise ignition scenario: where was the fire ignited, using which ignition source, was there a window (partially) open. Since there is no agreed and documented way to do a car fire test, every study takes its own approach there. During the tests a certain amount of fuel is put in the tank, but in all the research this was different. The amount of fuel in the car is of importance for the peak load, when the fuel tank fails a lot of fuel ignite, resulting in a peak in the rate of heat release. The amount of fuel does not influence the total amount of energy release a lot, most of the heat energy is released due to the plastic material and the fabrics (seats) in the car[22] [73]. To measure the rate of heat release there are two possible methods. The first, and most complex and expensive, one is the use of a large scale oxygen depletion calorimeter that collects all combustion gases and measures mass flow and the amount of oxygen used in the combustion. The simpler possibility is to measure the weight loss of the car during the fire. The first method is much more accurate. In the latter, a rough estimation must be made on the amount of heat release per unit of weight.

2.3.2. Test data for traditional cars

To understand the heat release of a 'traditional' car, tests have been performed over the years. To create a better overview of all the data from the different institutions, a graph was constructed by dr. Mohir [86]. In this graph, a relation is suggested between the total heat release and the curb weight of the car (weight of the car with standard equipment). The data from the TNO and EU partners study is indicated in figure 2.5 by The Joyeux et al... The cars used in the tests are from approximately the same building year, but the main difference is the method used for measuring the heat and could explain the big difference between the data. For the test done by TNO, a calorimeter was used. Shintani et al. measured the weight loss of the car. The data from BRE did not focus on the heat release of a single car and therefore could not be used for this graph. The focus of the BRE study was the fire propagation time between cars and the total heat release of three traditional cars. An overview of all the available data for the peak RHR (or in the table heat release rate) of a car measured with a calorimeter is given in figure 2.5. In this figure the BRE tests are indicated with Shipp et al... Most interesting of this figure is the peak load for a single car. As previously mentioned, the peak RHR which is usually taken in the Netherlands is 6 MW (figure 2.2).

2.3.3. Alternative fuel systems

As a part of the driver to limit the effects of air pollution and the changing climate, new fuel systems have been developed which are increasingly incorporated into newly built cars. Some tests have been executed to determine the fire load of an electric car, for example by DEKRA, a research institution in Germany. From this research, it could be concluded that the total fire load is similar to the fire load of a traditional car. However, there is a substantial danger of reignition [57]. Also, at the Centre Technique Industriel de la Construction

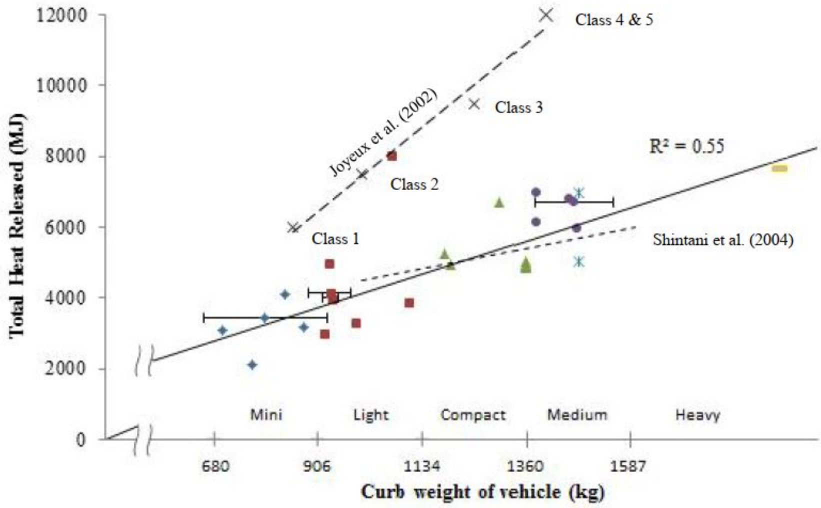


Figure 2.4: The total heat release of the tested cars from the TNO study and the university of Canterbury [86]. The tests show different linear trends.

314

Table 14.1 Large-scale experimental data for road vehicles (passenger cars)

Type of vehicle, model year, test number, longitudinal ventilation (u in m/s)	Tunnel (T) or calorimeter hood (C)	Tunnel cross-section: m^2	Calorific content[a]: GJ	Peak HRR: MW	Time to peak HRR: minutes	Reference
Single passenger cars						
Ford Taunus 1.6, late 1970s, Test 1, NV	C		4	1.5	12	Mangs and Keski-Rahkonen (1994)
Datsun 160 J Sedan, late 1970s, Test 2, NV	C		4	1.8	10	
Datsun 180 B Sedan, late 1970s, Test 3, NV	C		4	2	14	
Fiat 127, late 1970s, $u = 0.1$ m/s	T	8	NA	3.6	12	Ingason *et al.* (1997)
Renault Espace J11-II, 1988, Test 20, $u = 0.5$ m/s	T	30	7	6	8	Steinert (1994)
Citroën BX, 1986, NV[b]	C		5	4.3	15	Shipp and Spearpoint (1995)
Austin Maestro, 1982[b]	C		4	8.5	16	
Opel Kadett, 1990, Test 6, $u = 1.5$ m/s	T	50	NA	4.9	11	Lemaire *et al.* (2002)
Opel Kadett, 1990, Test 7, $u = 6$ m/s	T	50	NA	4.8	38	
Renault 5, 1980s, Test 3, NV	C		2.1	3.5	10	Joyeux (1997)
Renault 18, 1980s, Test 4, NV	C		3.1	2.1	29	
Small car[c], 1995, Test 8, NV	C		4.1	4.1	26	
Large car[c], 1995, test 7, NV	C		6.7	8.3	25	
Trabant, Test 1, NV	C		3.1	3.7	11	Steinert (2000)
Austin, Test 2, NV	C		3.2	1.7	27	
Citroën, Test 3, NV	C		8	4.6	17	
Citroën Jumper van, Test 11, $u = 1.6$ m/s, sprinkler activated after 13.6 minutes	T	50	NA	7.6	NA	Lemaire *et al.* (2002)
BRE Test No. 7, NV	C		NA	4.8	45	Shipp *et al.* (2009)
BRE Test No. 8, NV	C		NA	3.8	54	
Two passenger cars						
Citroën BX + Peugeot 305, 1980s, Test 6, NV	C		8.5	1.7	NA	Joyeux (1997)
Small car[c] + large car[c], Test 9, NV	C		7.9	7.5	13	
Large car[c] + small car[c], Test 10, NV	C		8.4	8.3	NA	
BMW + Renault 5, 1980s, Test 5, NV	C		NA	10	NA	
Polo + Trabant, Test 6, NV	C		5.4	5.6	29	Steinert (2000)
Peugeot + Trabant, Test 5, NV	C		5.6	6.2	40	
Citroën + Trabant, Test 7, NV	C		7.7	7.1	20	
Jetta + Ascona, Test 8, NV	C		10	8.4	55	
BRE Test No. 11 (stacked), NV	C		NA	8.5	12	Shipp *et al.* (2009)
Three passenger cars						
Golf + Trabant + Fiesta, Test 4, NV	C		NA	8.9	33	Steinert (2000)
BRE Test No. 1, NV	C		NA	16	21	Shipp *et al.* (2009)
BRE Test No. 2, NV	C		NA	7	55	
BRE Test No. 3, NV	C		NA	11	10	

Figure 2.5: All the available data on RHR for cars measured with a calorimeter.

Métallique (CTICM) electric cars were tested and the same conclusion was drawn. They even stated that the peak load is smaller for this car type [73]. Due to the possibility of reignition, the duration of the fire is much longer than for a traditional car (up to four hours). DEKRA also measured the amount of water that was needed to extinguish an electric car fire [57], this was approximate 10.000 litre, where a normal car roughly requires 3500 litres. In a real-life situation where a Tesla was on fire in Switzerland, more than 10.000 litres of water was needed to extinguish the fire [41]. This is in line with the result of the test. LPG, CNG and hydrogen fuel systems are fitted with one or more high-pressure tanks. These pressurised tanks create new risks during a fire, such as an explosion or a jet fire. To reduce the possibility of an explosion, these tanks are fitted with a temperature activated pressure relief device (TPRD). When the temperature rises above the threshold of the device, the device will release the gas from the tank within a few minutes, resulting in a high-pressure jet. When the release is triggered by a fire, the gas immediately ignites resulting in a jet fire (figure 2.6). This jet fires occurred closely to 100 % of the fires involving pressurised tanks, the other option is when the TPRD does not operate fast enough, the tank will explode. A jet fire from a burning car has, luckily, not happened inside a car park yet, but it is an important possibility to consider in each design. There are regulations for the direction of the TPRD, for LPG and CNG cars the essence of the regulations is that the people inside the car should be safe. Therefore the jet should be aimed outside the car. The regulations for the TPRD for hydrogen cars is more strict, the jet must be aimed outside the car, but only vertical. The jet must also not ignite the trunk of the car and therefore the most logical option will be downwards, as the hydrogen tank is often situated under the car, or in the trunk. However, with the help of a pipe it could be possible to let the jet aim upwards [75].

Figure 2.6: An overview of jet fires. Figure A is a test of a jet fire of a hydrogen tank [16]. Figure B is a jet fire of a CNG tank on a bus in Wassenaar The Netherlands. This jet had a length of approximately 14 meters and a duration of four minutes [78].

2.3.4. Test data alternative fuel systems

Along with the electric car, CTICM tested LPG and hydrogen cars [73]. In all the tests, first a petrol car was set on fire and after some time the second car caught fire due to fire propagation, where the second car's energy system varied between petrol, hydrogen, LPG and electric. Therefore, in all tests two cars were used. A steel frame was built surrounding the cars and was used to place thermocouples (figure 2.7 A). For the reference cars, case A, two diesel cars were used with a tank of sixty and twenty litres. Both models were produced in the late 90s. For the first car both front and rear window were broken. The fire development of this test can be divided into four phases (figure 2.7B). Phase one is the fire development inside the first car. After twenty-four minutes the fuel tank broke and diesel ignited, resulting in the ignition of the next car phase two. The third phase is the fire development in the second car and after 43 minutes the second tank ruptured, phase four.

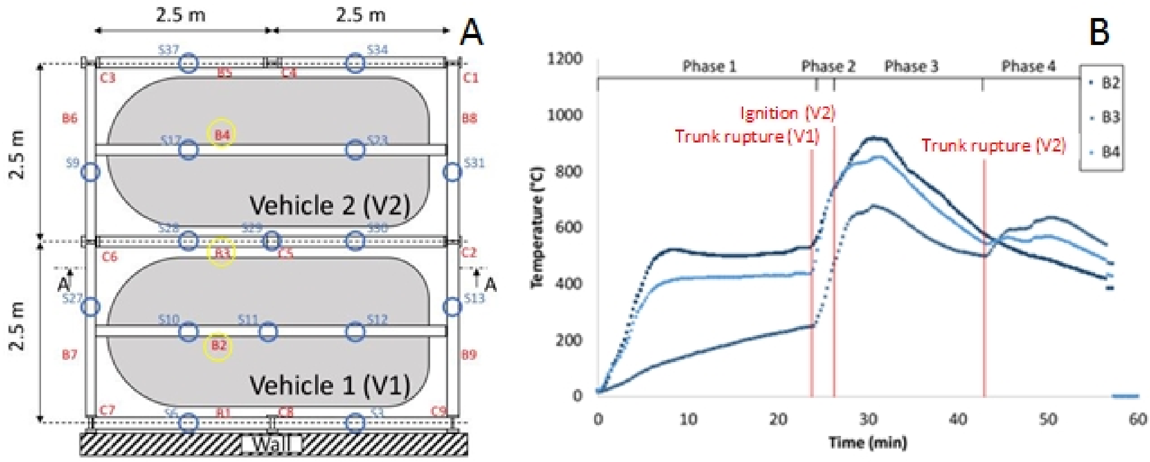


Figure 2.7: Figure A is the used test layout of the CTICM tests on alternative fuel systems. The important thermocouples are indicated with a yellow circle. Figure B is the results of the reference test, case A.

In case B the alternative vehicle had a hydrogen tank of 74 litres equipped with a TPRD with was aimed downwards underneath the car. The second car in this case study had a 20 litres diesel tank both car models were from the 90s. Again four different phases are visible (figure 2.8 A). As previously mentioned, a window of the first car was kept open. However, an increase in heat released occurred in this test when the rear window broke (phase 1). The hydrogen tank starts to purge after 18 minutes (phase 2) and the second car was ignited not long after this point (phase 3). After 32 minutes the diesel tank of the second vehicle broke and the diesel caught fire (phase 4). For case C a CNG vehicle with a 56 litres tank was used. The second car had a 20 litres diesel tank and both models were from the early 20s. This test was very similar to case B (figure 2.8 B). In phase one, two rapid increase in heat release can be seen and these are the result of windows breaking. After nineteen minutes the purge of the CNG tank occurred and resulted in the ignition of the second car, phase two. During phase three the fire developed in the second car eventually failure of the diesel tank after 46 minutes, phase four.

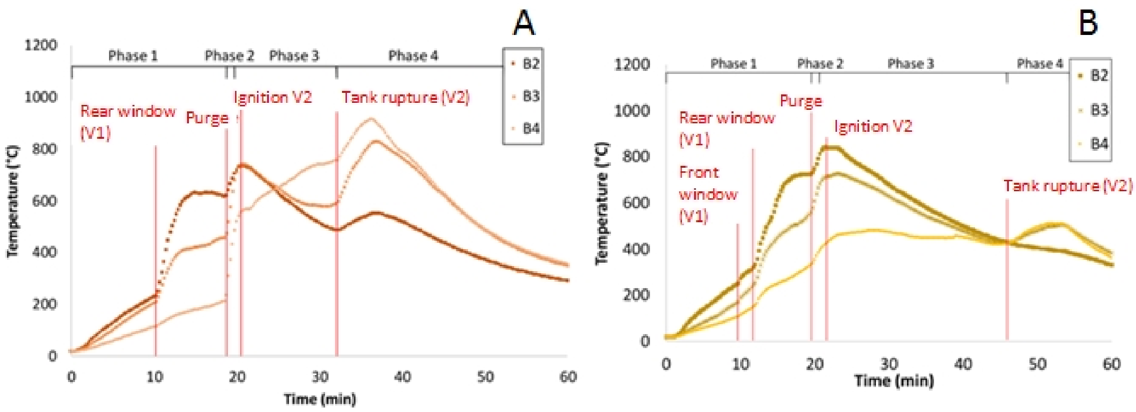


Figure 2.8: Figure A is the test results of case B. Figure B is the test results of case C.

Case D involved an electric and a diesel car with a tank of 20 litres, both from the early 20s. To compensated the weight difference of the electric car with the other cases, eight extra wooden pallets were used which were surrounding the second car. In the fire development of this case, three phases can be seen (figure 2.9 A). The first phase is the fire development in the first car, both front and rear windscreen broke earlier. After eight minutes the second car caught fire, phase two. After 33 minutes the diesel tank ruptured and the fuel was ignited, phase three. The last test, case E, an LPG and a diesel car were used. The LPG car had both a diesel engine of 20 litres and an LPG tank of 36 litres and the car model was from 2016. The diesel car had a 20 litres tank and was from the early 20s. At the beginning of this test, the LPG car did not have front and back windscreen. During this test, four phases were recognised (figure 2.9 B). During the first phase, the fire developed in the first car which eventually resulted in three purges after six minutes. This purges occurred in phase two and after the final purge the second car caught fire after fourteen minutes. During the third phase, the fire developed in the second car which resulted in the rupture of the diesel tank. Also during this phase the diesel tank of the first car ruptured.

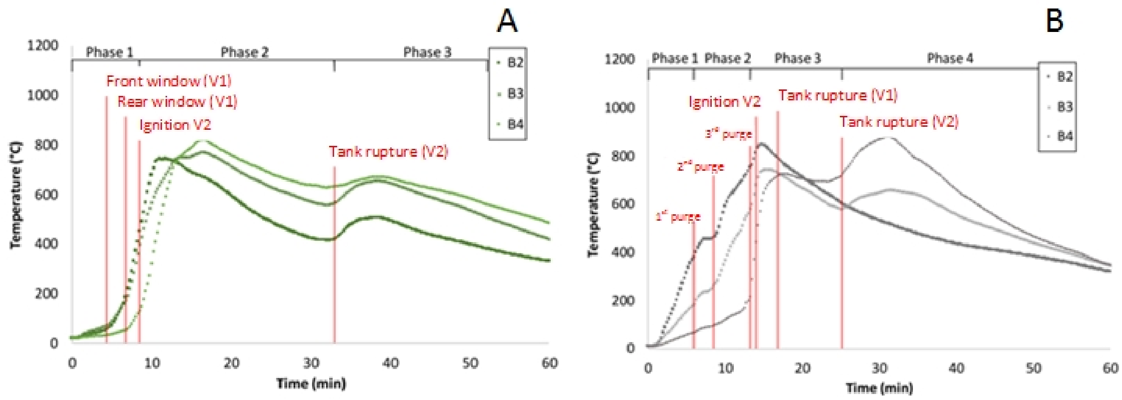


Figure 2.9: Figure A is the test results of case D. Figure B is the test results of case E.

To summaries to above given information, table 2.3 is made. In the reference case, it took longer for the fuel to ignite in the first car. The main deviation between these cars was the location of the tank. A diesel tank is situated under the trunk, the pressurized tanks are situated in the trunk. These pressurized tanks were exposed earlier on in these tests than the diesel tanks. The fire development of the electric car seems also to be faster than the other cars, as it took just eight minutes to ignite the neighbouring car. This car was newer than the other used models and maybe contained more plastic material. The purges of the pressurised tanks do not directly result in the ignition of the next car, however increased the preheating and therefore speed up the process.

Table 2.3: Summary of the test results of the tests done by CTICM.

	Rear window breakage (minutes)	Fuel V1 (minutes)	Ignition V2 (minutes)	Fuel V2 (minutes)
Reference Case A	0	24	26	43
Hydrogen Case B	10	18	20	32
CNG Case C	11	19	22	46
Electric Case D	7	NA	8	33
LPG Case E	0	6-9-13	14	25

2.3.5. Flashover and travelling fire

To start a fire three things are necessary, fuel, oxygen and an ignition source. For a fire to develop into a flashover, after which all combustible materials start to ignite, there should be a hot smoke layer which radiates more than 20 kW/m^2 downwards. This requires enough oxygen and fuel (for example the cars) to develop such a smoke layer. In an open car park, there is enough oxygen available, but the heat will escape and therefore flashover is generally assumed to be unlikely. However, the fire in Liverpool occurred in an open car park which flashed over, a smaller flashover fire occurred in Bristol in 2006, so a flashover does appear to be considered as a realistic possibility in an open car park. In a closed car park, a fire is limited by the amount of oxygen and heat cannot escape so easily, therefore flashover is a real possibility although still extremely rare up till now. A phenomenon carrying its own risks is a "travelling fire". A travelling fire occurs when a fire continues to involve other cars but flashover conditions are not reached. The fire will then travel in the compartment as long as it finds unburnt cars. A travelling fire in a car park, is a fire that moves away from the ignition point, propagating from car to car. When a new car is ignited, on average a previously burning car is burnt out so that at any given moment a limited number of cars is burning. The structure is heated up differently than in a post flashover developed fire. Due to the travelling fire the structure at a certain location is heated slowly, potentially for a long time, before the peak load is underneath that part of the structure, resulting in higher material temperatures and therefore more reduction in strength. Travelling fires are currently investigated because this fire type also occurs in other occupancies than car parks.

2.3.6. Fire propagation

One of the unknowns in the fire propagation, is the time it takes for the fire to move from one car to another. The distance between the cars is a crucial factor. A faster fire propagation will result in higher temperatures, higher intensity but a smaller duration of the fire. The material of the structure has a certain response time before heating up, a shorter progression time leads to a smaller amount of material heating up. On the other hand, a longer fire propagation time will lead to smaller peaks, but a longer average heating of the material itself. The time it takes for a fire to move to the next car is extremely reduced if a jet fire occurs [78]. However, there is not any information available on jet fires in closed environments. There are not any regulations on where the pressure relief vault must aim to and therefore the jet fire could differ in direction per car [87]. TNO has estimated from a limited number of tests that the time it takes for the fire to propagate is twelve minutes [37]. From the experiments conducted by the University of Canterbury, the ignition time for the second car is between four and twenty minutes [86]. These numbers were also calculated by hand and software but the variation between these numbers is big and therefore not yet suitable [86]. A master thesis conducted by B. Mattheus [43] compared the large time differences that were found by TNO and the University of Canterbury and tried with the help of software, to relate the results to car related parameters. However, the program used simplifies parts of the heat transfer and therefore could not produce correct values. Therefore, this subject in car fires is still unclear. To understand fire propagation, exterior parts of a car were investigated by the BRE [22]. The car parts were put under constant heat radiation and the ignition time was measured. From these tests it became clear that the tires and the front bumper ignite first. The tires took 240 and 249 seconds and the bumper 184 and 209 seconds (tested for a radiation of 20 kW/m^2). The tested parts were detached from the car and therefore the real ignition time should be higher than measured. Two other institutions did research on which parts of the car cause the fire to propagate. The first study was done by the Institute of Informatics Slovak Academy of Sciences [40]. They concluded that after a window breaks of the neighbouring car, the car starts to burn. A follow-up research had been done by the School of Safety Engineering, China University of Mining and Technology [14]. The same study was done as the Institute of Informatics Slovak Academy of Sciences did, but cameras were put inside the second car. The images from this camera show that the car is on fire before the window breaks, a lot of smoke is coming out of the ventilation shaft (figure 2.10). However, the fire starts to fully develop after a window broke. With this information, it seems that the fire propagates from car to car due to heating of the wheels or the bumper. These parts seem to catch fire early on. However, the car will not start to burn completely without the breaking of a window due to lack of oxygen in the car itself. Therefore, the relation between the shattering of the first window and the fire propagation is very interesting and can be seen as the major contribution for the fire to propagate.

1 min 3 min 5 min

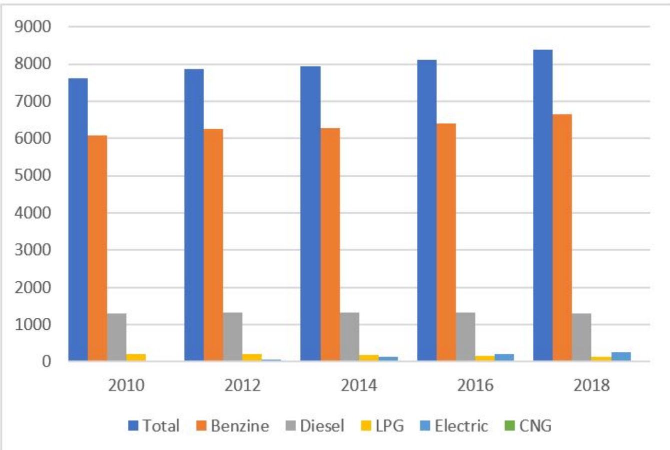
Figure 2.10: Pictures from inside the car during the test. Smoke already visible inside the car when from the outside nothing is visible.

2.4. Car industry in the Netherlands

Greenhouses gases are changing the climate and therefore a more sustainable car is needed. The need for more sustainability leads to a shift in the car industry resulting in a change in the possible cars parked in a car park. Three trends are identified for the Netherlands, innovative fuel systems and an increase in plastic material.

2.4.1. Development in fuel systems

The car industry is changing towards the complete incorporation of 'zero-emission' cars, replacing the old fossil fuel systems that enhance the effects of climate change. Therefore, transitioning from high emission to zero-emission systems. Nowadays, six different types of fuel systems are used in cars for the Netherlands. Namely; petrol, diesel, LPG, CNG, electric and hydrogen. Hydrogen-powered cars are relatively new and only 14 cars were available in 2018 and approximately 140 more were ordered for 2019 [23]. This indicates that this type of car is gaining interest from the public. The main reason why this development is yet slow is the limited amount of gas stations that provide hydrogen gas. The Dutch Central Bureau for Statistics ('Centraal bureau voor de Statistiek', CBS) keeps track on the total amount of cars and which type of engine is used (figure 2.11) [8]. It can be observed that the total amount of cars has been increasing over the last eight years, petrol cars are increasing with the same percentages as the total amount of cars. The total amount of diesel cars increased, however the growth rate is rather small. The amount of LPG cars is decreasing, but the market share of CNG is rapidly increasing. The market share of the electric car is also rapidly growing. The CNG values are not visible in the graph due to the small total number in The Netherlands, that is also the reason why hydrogen cars are not put in figure 2.11. These numbers indicate the change of fuel systems, however the change is still slow. The market share of the pressurised tanks (LPG, CNG and hydrogen) is slowly growing, but future predictions are ambiguous. The market share of electric cars is growing and expect to grow further. The electric car is currently expected to play a big role in our vehicle fleet. In 2019, more than seven % of the new cars have an electric engine [80]. The climate agreement of Paris of 2015 state that the traditional cars are not allowed to be sold after 2028 [46]. Keeping this in mind the market shares of electric, LPG, CNG and hydrogen will only increase more. Although, it is yet not clear which car types are going to develop more and will gain a big market share, already these alternative cars are gaining ground. The result of this trend relating to car parks is a change in cars and therefore a change in the possible fire load. In 2030 it is not allowed to sell diesel-powered cars and in 2050 also petrol cars are no longer allowed to be sold.



Market growth energy systems	Growth rate from 2010 to 2018
Market grow energy systems	
Total	9,85%
Benzine	9,54%
Diesel	1,35%
LPG	-40,13%
Electric	586,59%
CNG	1560,70%

Figure 2.11: Graphical representation of the CBS data of energy sources of the cars in the Netherlands [8]. To make the data more visible everything is divide by thousand.

2.4.2. Plastic content

As mentioned before, more plastic is used in the current manufacturing of cars. A study done by ATkearney [67] provided an insight in the use of plastic in cars (figure 2.12). The tested cars by TNO, BRE and the University of Canterbury originate from the 90s' with a plastic content of 9 up to 13 %. The prognosis is that new cars will have 18 % of plastic, which is roughly double compared to the models from the 90s'. The increase of plastic content leads to a higher fire load per car, resulting in more intense fires.

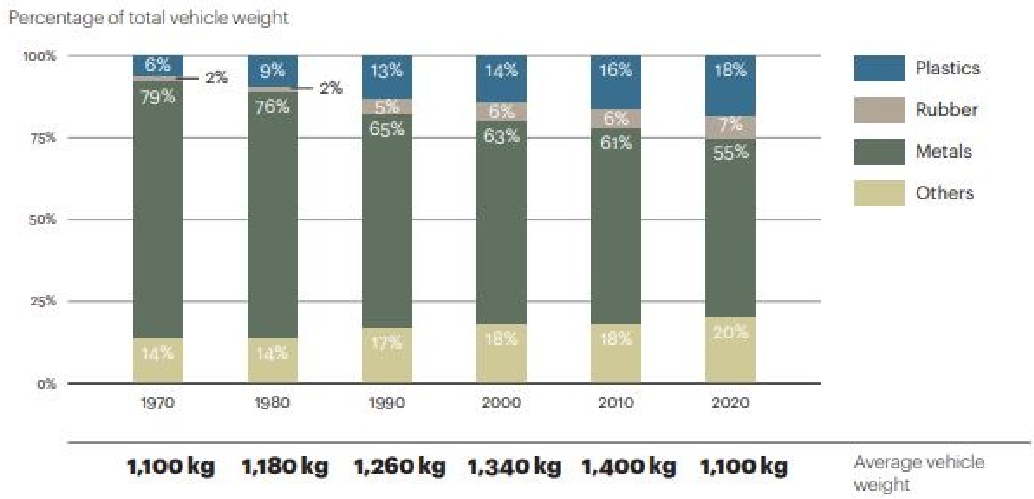


Figure 2.12: Prognosis of the material used in the production of cars [67].

2.4.3. Development of the average size of a car

The size of a parking spot has not grown over the last decades, however the cars have changed in size. The distance between two parked cars is an important factor for the fire to propagate. A study performed by the European Centre for Mobility Documentation (figure 2.13) [82] gives an insight into the development of weight, width and height of cars. The vehicle width has increased over the years with only a small percentage. In comparison to the cars from the 90s', the width increased with 0.05 meters (three %). Concluding from the test performed by all the research instituted, more weight leads to a bigger the fire load therefore the mass is of importance. Clearly, the total mass of a car did not increase a lot in comparison with the 90s' cars. The same trend for the mass was observed by the study done by ATkearney [67] (in the bottom of figure 2.12 the average mass of a car can be seen). The total volume of the car did increase over the years, however the total weight stayed the same. Therefore, lighter materials must have been used for example more plastics instead of steel or thinner material. The mass did not increase, but this does not mean the fire load did not increase due to the increase of plastic material.

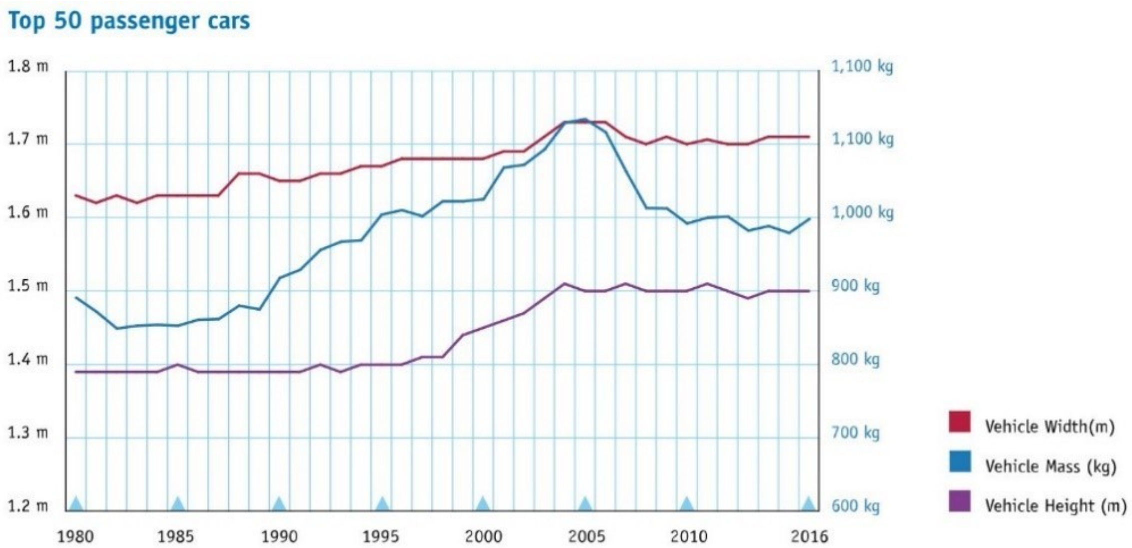


Figure 2.13: A graphical representation of the development of weight, width and height of cars [82].

2.5. Construction materials

For the load-bearing construction material of a car park there are generally two options, concrete or steel. Some car parks are constructed entirely with prefab concrete elements, but there are also car parks which consist of a combination of steel and concrete. For example, concrete floors (hollow core slab, prefab floors, BubbleDeck) placed on steel beams and/or steel columns. Another option is the use of a steel deck floor, a so-called composite floor. All these construction types behave in different ways during a fire and therefore introduce various risks.

2.5.1. Behaviour of steel during a fire

A large amount of information about the material behaviour of steel during a fire is already available. Steel was considered to be 'weak' during a fire and by testing it was shown that steel could survive the fire up to a certain time. Steel may have a reactive coating that will start to foam when heated up. This foam works as an insulation layer and the steel is not heated to critical temperatures. Another option is to make use of fire-proof boards which surround the steel profile and insulate the steel. These methods are so-called "passive protection methods" against a fire. Most studies in the Netherlands, have been executed in cooperation with the company 'Bouwen met Staal' [45]. The organisation has an interest in promoting the use of steel in structures. It published a computer model that gives an insight into the steel temperature during a car park fire, Car-Park-Fire (CaPaFi) model. The effects of a fire on a steel profile result in the weakening of the steel itself. Eurocode 3.2 [10] (figure 2.14B) gives a graph of the relation between the steel strength and the temperature. A generally applied safety level is to prevent the steel heating to surpass 600 °C. Above this temperature, the strength decreases rapidly and the material starts to deform plastically.

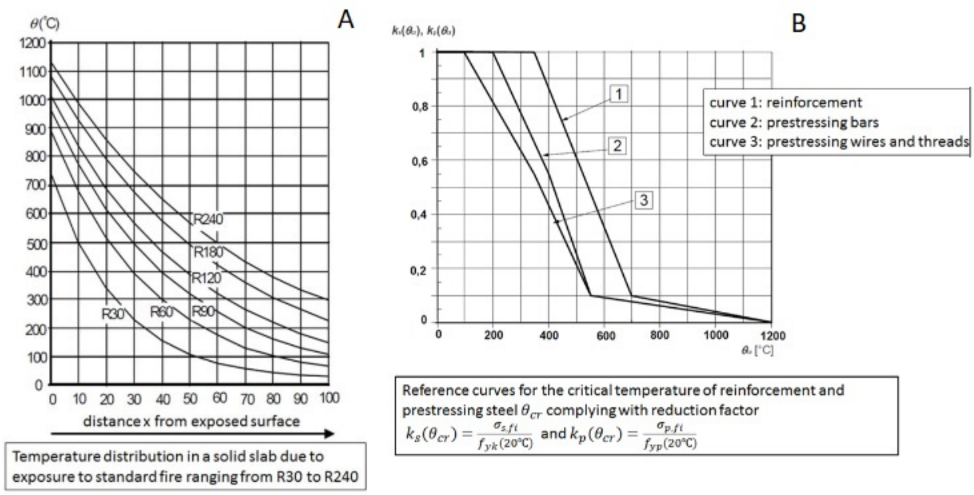


Figure 2.14: Reduction of strength vs temperature according to Eurocode 2 and 3 [9][10]. Figure A indicated the concrete cover needed for the reinforcement of the steel. The lines indicated the amount of time is needed to secure safe escaping of the structure. Figure B shows the strength reduction of the steel at certain temperatures.

2.5.2. Behaviour of concrete during a fire

Until now, there has been less interest in the behaviour of concrete during a fire. Concrete has a high density and a low heat conductivity resulting in the slow heating of a complete cross-section. Therefore, it appears that the behaviour of concrete during a fire is very good (figure 2.14A). Although, the greatest danger of heated concrete is spalling. The definition of spalling is "flakes of material that are broken off of a larger solid body" [58]. Due to this phenomenon, the cross-section of the concrete is getting smaller during a fire. Resulting in a much quicker increase of temperature of the steel reinforcement present in concrete than previously assumed. Stating the fire resistance of a concrete element to be xx minutes without taken into account spalling will give a wrong representation of its safety. The spalling mechanism for concrete is currently investigated by many researchers. It seems that multiple parameters like; water-cement ratio, type of aggregate, compressive and tension strength and loading are playing a big role in this phenomenon. However, in literature even more parameters are mentioned that could play a role. There are some theories that try to predict when a particular type of concrete mixture will spall but there is currently nothing solid. One of this theory is focused on water vaporising in the concrete. This vapour cannot easily escape in the concrete resulting in an increase of stresses, eventually resulting in spalling of the concrete. Another theory is based on micro-cracks and thermal-buckling (figure 2.15 [6]). Due to the cracking, parts of concrete are separated from the larger body. These parts start to buckle due to the compressive load and spall. Spalling of concrete also seems to happen quite often during a fire in a car park [72][77]. In the case studies that will be discussed later, spalling damage is the main damage to the construction elements.

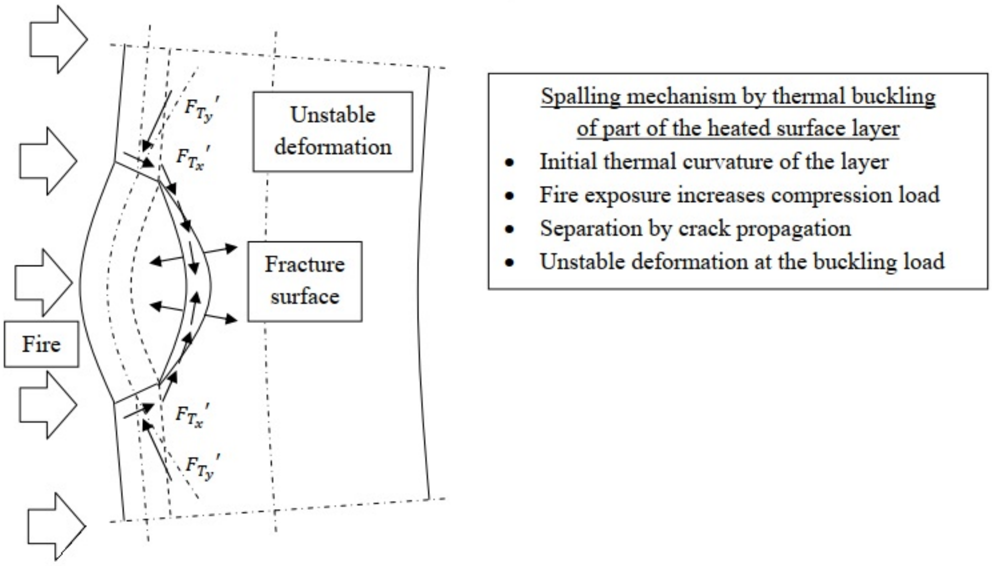


Figure 2.15: The theory of thermal buckling resulting in the spalling of concrete [6].

2.5.3. Dealing with spalling

Eurocode 1992-1-2 (Concrete structures during a fire) has guidelines to deal with spalling of the concrete [9][39]. These regulations only apply for high strength concrete, it was assumed that only high strength concrete was sensitive to spalling. Spalling does not have to be checked when applying normal strength concrete, by law. An overview of what criteria are mentioned in the Eurocode about spalling is given in figure 2.16. High strength concrete is classified as strength higher than C80/95. Silica fume could be added to the concrete mixture to get a higher compressive strength. Something that should not be confused is the moisture content, based on volume it is allowed to have 7% moisture. Based on mass percentage this is 3%, it is the same amount of moisture but expressed in a different manner. Recently performed tests by Rijkswaterstaat and Efectis show that this set of rules does not determine if a concrete mixture will spall or not [21]. Therefore, to investigate this problem more thoroughly, more tests that determine the conditions that cause the spalling of concrete are executed. The Eurocode gives three options to deal with spalling if the concrete mixture will spall: the use of skin reinforcement, fibres (polypropylene) and heat resistant cladding.

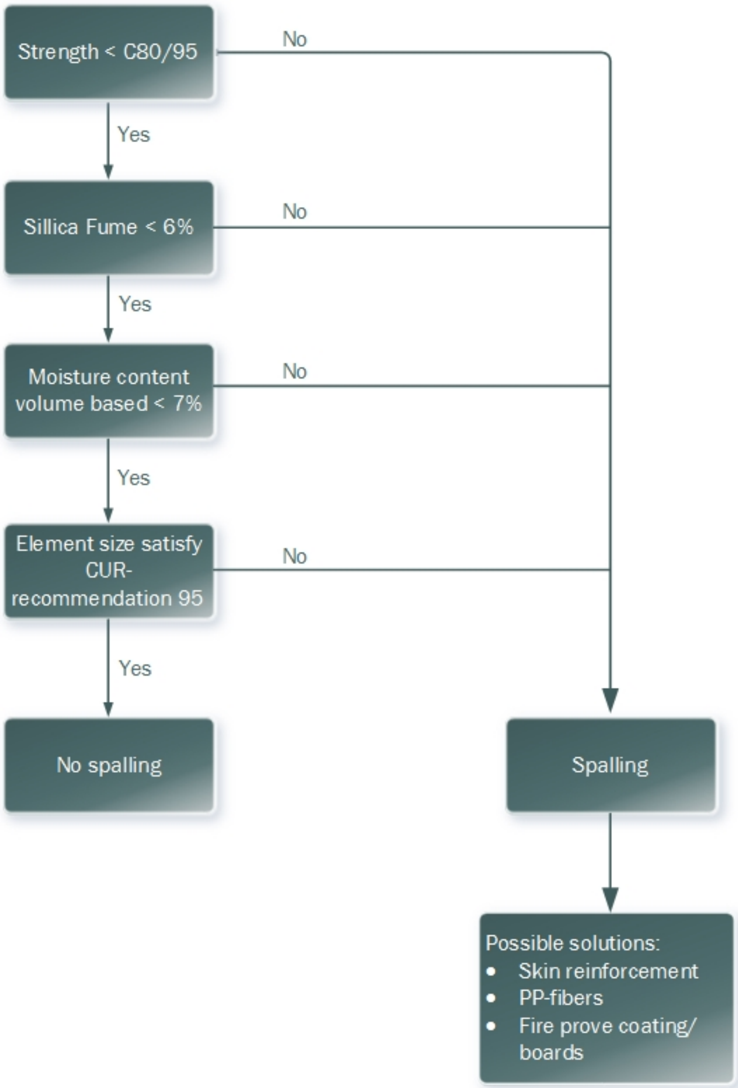


Figure 2.16: Graphical representation of the qualification of the risk of spalling based on the Eurocode 1992-1-2 [9][39].

In performed research that is available in the literature the spalling did not surpass the reinforcement, this was also visible in the RWS and Efectis performed tests [21]. Most of the performed tests were stopped when spalling has occurred and therefore are not tested to see if spalling continues beyond the reinforcement. However, when applying skin reinforcement the idea of spalling not surpassing the reinforcement is applied. Using skin reinforcement, an additional fine mesh is applied on the outside of the concrete with the idea that spalling is accepted to a certain limited, until the skin reinforcement. Therefore, the main steel reinforcement is not affected by the fire [17]. Another way of preventing spalling is by using polypropylene fibres in the concrete mixture. When the concrete is heated these fibres will melt and the moisture pressure cannot develop. The third possible method to prevent spalling is by applying fire-resistant cladding. This cladding will keep the temperature in the concrete below a threshold temperature, usually 200 °C. Below this temperature spalling has not occurred according to the performed tests [21]. This method is generally applied in Dutch tunnels because it is the only method that can be applied after the structure is finished. Another aspect not yet discussed is the trust of the fire department in a structure. In the current situation, the fire department is expected to go inside the car park and extinguish the fire (offensive interior attack). With this risk of concrete falling caused by spalling, the fire department is not likely to enter the car park and the fire load is likely to increase. This can result in more damage and bigger fires. More about this in the chapter ''Fire department".

2.5.4. Wooden car park

There are some general concepts to constructed a (open) car park with load-bearing elements made from wood. Currently, more buildings are constructed with cross-laminated timber (CLT). Research has been performed on the behaviour of CLT subjected to by the ISO-curve. It was found that this product had enough resistance to be applied in structures [13]. The technical university of Munich made a concept on a wooden car park with beech veneer columns and beams and prefab concrete floors [38]. Their main idea was to make a modular car park because it is unclear what will happen to the demand for parking space in the future. Therefore, there is a chance these structures are only needed temporarily. Wooden car parks are not constructed yet and however could happen in the near future.

2.6. Modelling of a structure under a fire load

To understand the behaviour of materials under a fire load, research programs were performed and models were created. The current classification system for the fire resistance of an element is based on the ISO-curve. The ISO-curve is the standard time/temperature curve which is used in the Eurocodes. The curve is based on the burning rate of materials which are generally found in structures. With this curve one can test or calculate the fire resistance of an element. A real fire that occurs is not restrained by any law (apart from the laws of physics) and therefore will not follow the curve, but a conventional assumption is that most of the fires will be less severe. In other words, a certain redundancy is applied in this curve. However, there is still a lot of discussion on this curve, mainly due to extreme fires that resulted in bigger fire loads on the structure.

2.6.1. Natural fire concept

It is allowed to deviate from the ISO-curve, a so-called natural fire concept. In this concept one has to define a realistic fire that could occur. This natural concept is mostly applied when lower fire loads are assumed. The main contributors to a fire in a car park are the cars. As mentioned before, TNO and EU partners developed a fire curve for a single car which was based on tests performed underneath a calorimeter, figure 2.2. NEN6098 gives criterium about the required mechanical ventilation of a car park during a fire [50]. In this norm three cars are on fire before the fire department arrives, so according to this norm no more than three cars are on fire. With the fire load of a single car and the criteria form NEN6098 a natural fire concept can be created. However other guidelines provided other amounts of burning cars, like the Bouwen met Staal guideline [45].

2.6.2. Eurocodes

The Eurocode provides graphs (figure 2.14) for the heating of steel and concrete versus the strength loss. To reach more than 30 minutes of fire resistance of a steel profile, coating or heat resistant cladding is needed. For concrete elements the distance of the surface to the reinforcement (concrete cover) is of importance. Concrete has a very low resistance to tension stresses and therefore reinforcement is placed in the bottom of these elements. If the reinforcement starts to heat, the total resistance of the beam decreases. According to the graph for the concrete resistance (figure 2.14B), more coverage of the reinforcement results in a bigger fire resistance. As mentioned before, due to spalling of the concrete, the reinforcement will be exposed and heat up much faster than this graph indicates.

2.6.3. Zone modelling

Zone modelling is a tool that gives an insight into the behaviour of smoke and heat in an enclosed space. A zone model divides the space into two sections: top and bottom. The top layer is the smoke layer and has a uniform temperature, so all the heat of the fire is equally divided over the top layer. When the total area is large, this uniform temperature of the top layer is not correct. Near the fire the temperature will be far higher than thirty meters from the fire. Car parks are generally very large and low structures and therefore zone modelling cannot be used [36]. Nevertheless, zone modelling is still used for car parks because the calculation speed is fast and a lot of alternative designs can be calculated. The large inaccuracy is than accept.

2.6.4. CFD modelling

To better understand the behaviour of smoke and heat in a car park, a Computational Fluid Dynamics (CFD) model can be made. This model can give a good indication on the behaviour of smoke, but is less precise in the transfer of heat to structural elements. A good understanding of the possibilities and limitations of CFD models is needed to be able to interpret the results. This type of model is commonly used in car parks to design ventilation systems, resulting in the required ventilation and the locations of shafts. It can be used for the heating of members, but the results are not as precise as generally wanted.

2.6.5. CaPaFi

CaPaFi model is created by Bouwen met Staal and can be used alongside their guideline [45]. CaPaFi is a simplification based on a local thermal plume and ceiling jet above each burning car, giving insight in the heating of a steel profile. Due to the simplification of the model, the results of CaPaFi are conservative but can be used as verification of for example CFD models [36]. Additionally, the output of the CaPaFi model is a steel temperature, but one should keep in mind this is at the bottom and not over the complete steel profile [45]. Generally, the steel cross-sections are not only heated from one side. The model is based on a natural fire concept with a maximum of seven cars. This model gives a fast insight into the heating of the steel profile and is generally used to check whether cross-sections are strong enough to withstand the fire for a certain time. When this period is too small, coatings or fire protection boards can be placed.

2.6.6. 1D heat transfer

The CaPaFi model is a so-called 1D heating transfer model, and these models exist for different materials than only steel. DGMR also has a 1D conduction heat transfer model constructed by P. van de Leur. This model contains a variety of materials like steel and concrete. In addition to the CaPaFi model, heat resistant cladding can be added, resulting in a different temperature progression. So, in this model the required thickness of the cladding material can be calculated.

2.6.7. Voltra

Voltra is a 3D program that calculated the heating of the complete cross-section towards a certain fire curve [59]. In advance of the 1D heat transfer programs, a more complex cross-section can be analysed. Also heating from more than one side is possible, resulting in a more realistic calculation. In addition cladding could be added to the cross-sections.

2.7. Fire department

Time is of the essence during a fire, the faster the fire department reaches the fire, the smaller the total damage will be. In addition, the ability to extinguish the fire is bigger when the fire is still small. When the fire brigade reaches the fire, first they must locate the fire, asses how many people are inside the structure and the need to evacuate adjacent buildings. This assessment process takes time but is of the utmost importance. The core values of the Dutch fire department are to rescue the people inside the burning structure and to protect nearby structures from catching fire. Therefore, entering a structure that is on fire, just to limit the damage is something that has a low priority. Even though the main instinct of a fireman (or woman) is extinguishing the fire, new recommendation tactics are formed for a fire inside a construction which contradicts this instinct: the so-called "Brandweer Doctrine" [62].

2.7.1. Response time

In NEN6098 [50], created with the help of fire brigade representatives, the response time of the fire department was set to ten minutes. The fire department starts their offensive attack after fifteen minutes, five minutes being set apart for the assessment process. Based on these times an estimate was made of the maximum number of cars on expected to be on fire, at the time the fire brigade start to extinguish the fire. With this in mind the required flow rate for the mechanical ventilation, for the fire brigade to approach the fire free of smoke, is to be calculated. The 'Centraal Bureau voor de Statistiek' (CBS) has kept track of the response time of the fire department from 2000 up to 2013. It concludes that the response time is more than ten minutes for forty % of the fires (figure 2.17). After 2013 it only kept track of the average response time, which was in 2013 7.4 minutes [7]. The response time consists of four segments, the start time, alarming time, departure time and the travel time. The start time is defined as the time it takes to process the fire alarm to the emergency centre. The alarming time is the time it takes the emergency centre to inform the fire department. This response time increased to 7.9 minutes in 2018 [7], so at least the response time did not improve.

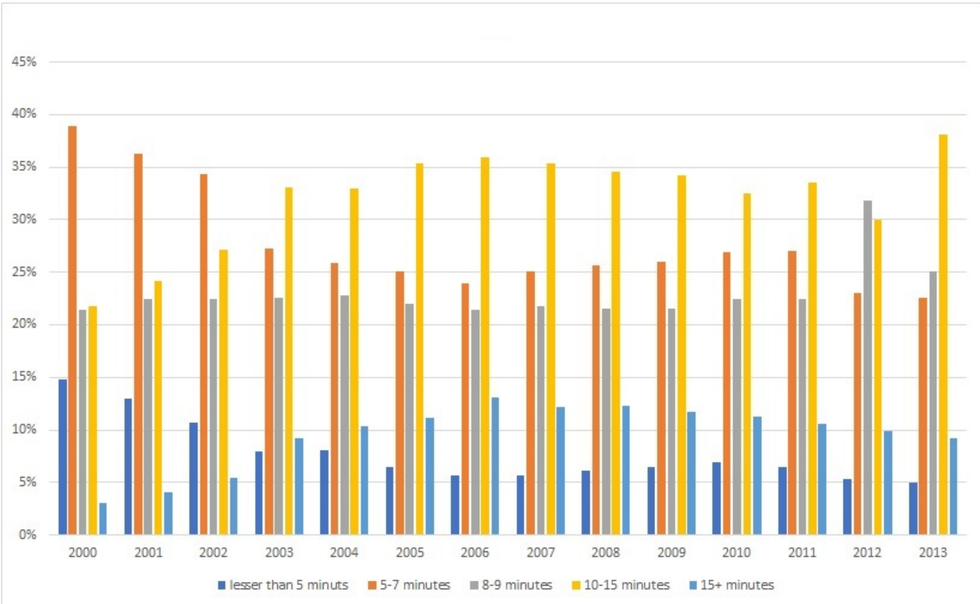


Figure 2.17: Response time of the fire department in the Netherlands from 2000 until 2013 [7].

2.7.2. Methodology of the fire department

In 2014 the Dutch fire department and the 'Instituut Fysieke Veiligheid' (IFV) developed a so-called quadrant model [62]. This model gives the person in charge a method to evaluate the best possible method to deal safely with a fire inside a structure, taking into consideration the safety of the fire brigade. When arriving at the fire, the commander makes an assessment on how big the fire is, its location, the progress of the evacuation, fire compartmentations and the surrounding buildings and other liabilities. After this evaluation there are four possible tactics; defensive exterior attack, offensive exterior attack, defensive interior attack and offensive interior attack (figure 2.18).

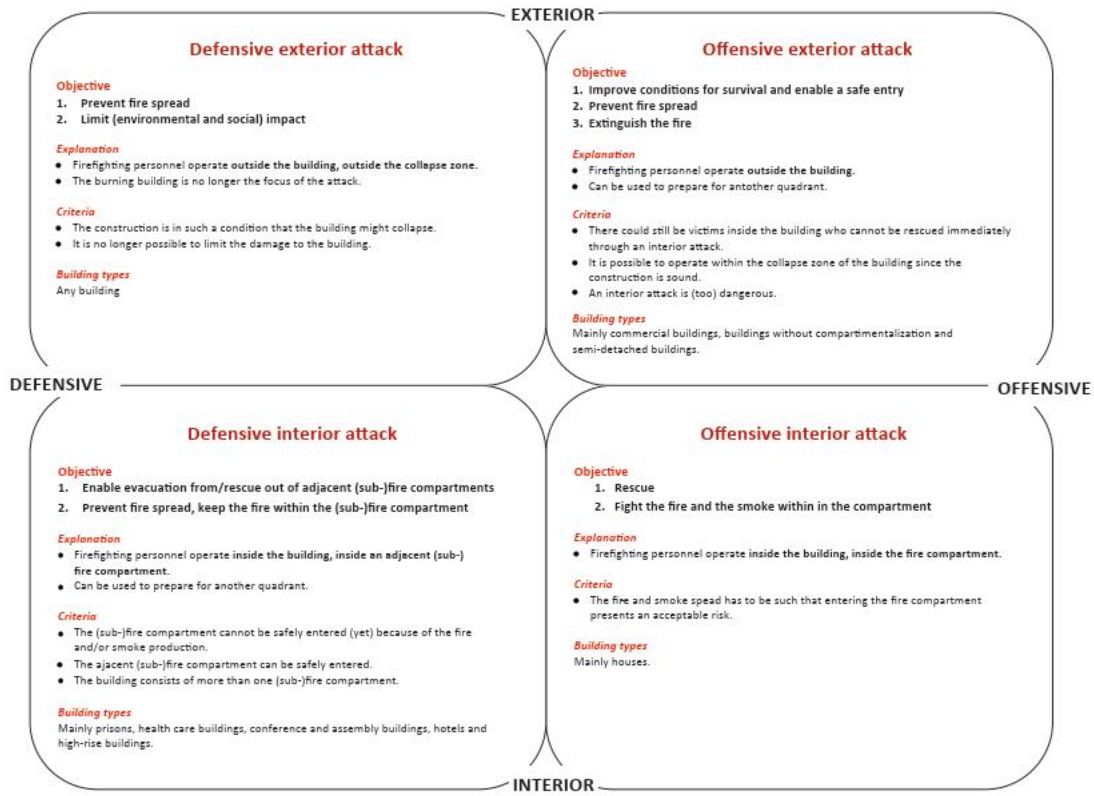


Figure 2.18: The quadrant model made by the Dutch fire department [62].

A defensive exterior attack is undertaken if, the commander deems it is too dangerous to approach the building. All the occupants of the burning structure have already evacuated and the fire department aims its resources at preventing the fire to spread to nearby buildings. This is a worst-case scenario and the structure itself can be considered lost. When an offensive exterior attack is performed, firemen cannot safely operate inside the building. They are still outside but are close to the building. The goal of this tactic is to improve the inside conditions in such an extent that the fire brigade can start an interior attack. It is possible there are still people inside the building, but an interior attack is too dangerous for the firefighters. The third option is the defensive interior attack. The fire brigade is in the building, trying to contain the fire within its compartment of origin: they aim to keep the fire from propagating to adjacent fire compartments. In this tactic the fire itself is not attacked, but the surrounding walls/doors are cooled down. If they succeed in that long enough, the fire will run out of fuel in the fire-compartment itself and eventually will extinguish. This tactic is possible if the adjacent fire compartments are not on fire and the conditions are bearable to be in the building. Sometimes, fireman drills a hole in the wall between themselves and the burning fire compartment. This hole is used to put water in the burning compartment. By drilling this hole, the fire is attack and this part of the tactic can also be considered a defensive exterior attack. The last tactic is the 'classical' offensive interior attack. The fire brigade will enter the fire-compartment which is burning and will start to extinguish the fire. The conditions in this compartment should be bearable enough for the fire brigade to operate. This is only possible when the fire is still relatively small. During an offensive attack the fire brigade is inside a building that has been burning for some time, and are at risk. This tactic will only be used when people are in danger or if the fire is small. Relating these tactics towards open and closed car parks:

Open car park:

1. Defensive exterior attack: this tactic is possible for an open car park and the surrounding buildings will be protected. The car park itself will be considered as lost.

2. Offensive exterior attack: it seems unlikely to be able to extinguish the fire from outside the open car park, it is maybe possible when the car park is not very high and not wide. When this is applicable the adjacent cars can be cooled to prevent the fire from propagating.

3. Defensive interior attack: an open car park is virtually always a single fire compartment, this scenario is then not relevant.

4. Offensive interior attack: this tactic is commonly used in the Netherlands for a car park fire, as historically most car park fires grow only very slowly. However, the conditions in a car park during a fire are often tough. Nobody will be in the car park as the fire department arrives, evacuation is already finished. Adjacent buildings, if any, are assumed to be sufficiently protected against a fire. The main remaining reason for extinguishing the fire in the open car park is to limit the damage. Therefore, it seems unlikely the fire department will risk their lives by entering the car park.

Closed car park:

1. Defensive exterior attack: Often one or more buildings are situated on top of the closed car park. The buildings and car park are a single structure. When this tactic is applied, the fire can grow unchecked. The buildings on top are also treated as lost or depend for their survival on the fire resistance of the load-bearing structure of the car park. It is therefore not a likely successful scenario. However, when everybody is evacuated from all connected buildings this tactic could be applied.

2. Offensive exterior attack: this scenario is impossible for a closed park. The building is closed or situated underground no water can reach the fire from outside.

3. Defensive interior attack: This scenario is not possible. The closed car park is often considered to be a single compartment.

4. Offensive interior attack: the same conditions hold as for an open car park.

These new approaches of the fire department do not result in new tactics for a closed car park. When they consider an offensive interior attack too dangerous, there are no other tactics to control the fire while it is still small. The only realistic option then is a burn out scenario. In other words, the fire can develop to its full potential. This is of course unfavourable and therefore the conditions in the car park should be checked for a possible change in tactics. For an open car park several tactics could be applied, but when they are not aware of people in direct danger within the car park the fire department will not go inside. Unless they are confident they can locate and extinguish the fire, most likely because the fire is still very small. Therefore, the most likely scenario the fire department will apply is an offensive or defensive exterior attack depending on the structural integrity. How this structural integrity can be quantified is not mentioned in this document. Keeping in mind this new approach of the fire department, fires inside a car park will not be extinguished by the fire department as reliably as previously. This will result in bigger and more intense fires resulting in more damage to the structure. A flow chart is presented for the approach of the fire department on fires in car parks, figure 2.19.

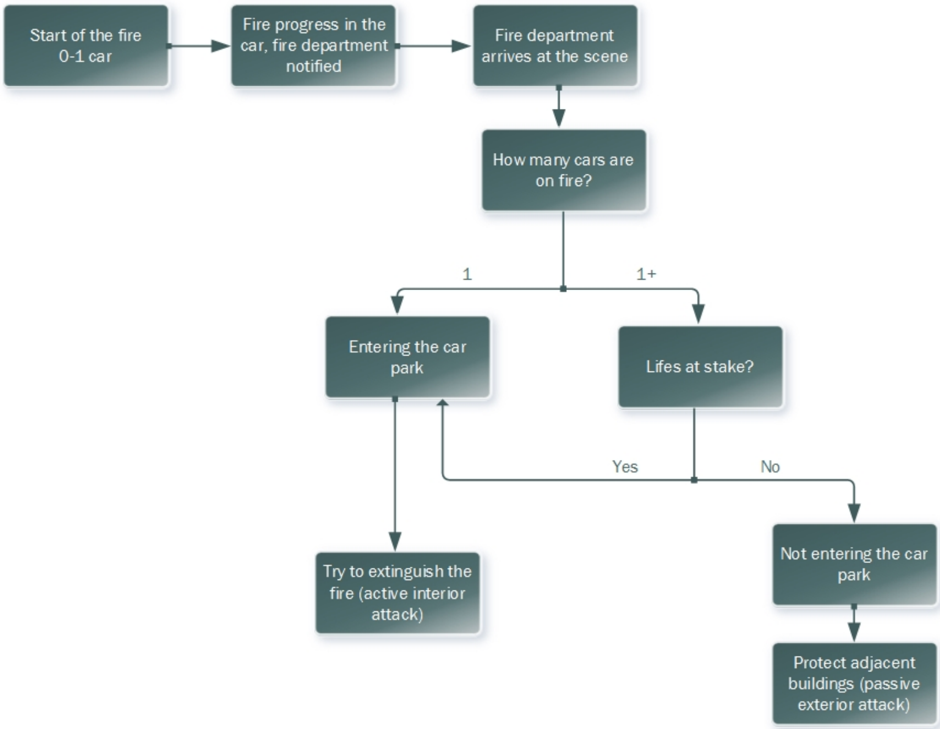


Figure 2.19: Graphical representation of the methodology of the fire department on a fire in a car park.

2.8. Fire protection method

Structural elements are necessary to keep the building in place for at least a certain period during the fire. To achieve a sufficiently high structural safety, active and passive protection methods can be used. An active protection system needs to detect the fire as fast as possible. Possible active systems are the use of mechanical ventilation to clear smoke and provide access to firefighters, or sprinklers and water mist systems to automatically extinguish the fire. These systems need to be maintained, but can also fail in case of a fire. Passive systems are for example the protection of structural elements. The elements can be protected with a fire-resistant coating or by fire-resistant boards. Usually, below a certain compartment size the regulation prescribes a limited passive protection. Additional protection is required if larger fire compartments are desired. Passive systems will be placed during the construction and do not require checking as regularly as active systems.

2.8.1. Smoke control system

Smoke control systems, or mechanical ventilation, have in recent times been used in car parks according to guidelines, for example in the Netherlands NEN6098 [50]. The first guideline for large car park prescribed a smoke control systems to make sure that the car park is cleared from smoke and toxic gasses within 45 minutes after the start of the fire [49]. This principle changed towards a criterium where the ventilation system assisted the firefighters when attacking a fire (interior offensive attack) [63]. The system was designed to create a smoke-free path to the fire source in such a way that the fire department can rapidly and safely reach the fire. After the fire in the Appelaar car park in 2010 [77], it was concluded that these systems did not work when the fire extends to more than three cars, a smoke-free path could not be created [78]. Therefore, the fire department is not very keen anymore on the use of mechanical ventilation to create more visibility. A perfect solution to the problem has not been found yet. It is still unclear if the existing car parks fitted with a smoke control system can still be considered safe enough.

2.8.2. Sprinklers

Sprinklers are often used in larger fire compartments to suppress a fire. In the USA, Germany and Belgium sprinklers are obligated by law for closed car parks at a certain fire compartment size (table 2.2). Sprinkler heads detect the fire and will locally release water. The sprinkler installation will not extinguish the burning car, but it will prevent the fire to propagate to the next car and therefore result in a smaller fire load. A single test is performed with a car fire and a sprinkler by BRE [22] which confirmed earlier tests. It was concluded that the fire was not extinguished by the sprinkler and the fire did not propagate to the neighbouring car. Therefore, the fire load on the construction is reduced to one car. In 2018 in Arnhem, a car caught fire inside a closed car park. This car park was fitted with a sprinkler installation which succeeded in controlling the fire so that only one car was involved. The fire department arrived and extinguished the fire [79]. So, the sprinkler did not extinguish the fire but prevented propagation. This is in line with the BRE test. However, there are some negative aspects. A sprinkler system is a so-called active system and could therefore malfunction in case of a fire. No incident reports on this matter have been found, but this scenario is not inconceivable. Explosions and jet fires associated with fuel tanks in high pressure could damage the sprinkler system and compromise its operation. In case of an explosion, parts of the car or even the pressure wave could blow a sprinkler head or duct away, resulting in loss of pressure over the complete system. Water is then no longer effectively sprayed on the fire area, resulting in a fire that can propagate. Jet fires are virtually inevitable as they result from the operation of the safety valve on the fuel tanks. A big uncertainty is when the sprinkler is operating and a jet fire occurs, will it ignite neighbouring car? Another issue altogether is the turbulence created in the smoke layer, resulting in reduced visibility in the car park [55]. In 2018 tests were done by the University of Eindhoven and Peutz on the cooling effect of a sprinkler system on a smoke layer in comparison with CFD simulations [55]. It was found that indeed the smoke layer is cooled down by the sprinklers and that a higher water flow rate resulted in more cooling. The main conclusion was that CFD software does not predict this phenomenon and therefore cannot accurately be used for calculating the cooling of a smoke layer, the temperatures predicted by the CFD computation are a lot higher than measured [55]. Sprinklers can therefore reduce the fire load on a structure, but it should be well maintained. If the system is damaged, the sprinklers will be of no use.

2.8.3. Mist system

Mist systems are a new method applied in car parks and have a lot of similarities with the sprinkler systems. A big advantage is the lesser turbulence in the smoke layer and therefore a better visibility in the car park itself during a fire [55]. Another positive effect is that less water is needed for a water mist system in comparison with a sprinkler system, to create the same cooling effect and prevent the fire to propagate. Therefore, there will be less water damage in the car park after a fire. Also, the required height (space) needed for a mist system and the number of heads are smaller in comparison with a sprinkler system. This method does not 'attack' the fire, but the smoke layer is cooled down, resulting in a lower temperature in the compartment. Fire propagation will be less likely when the smoke layer is cooled down, but this a theory. No test data were available for mist systems with car fires.

2.8.4. Passive systems

Passive systems are placed during the construction of a car park and do not need to be activated in case of a fire. These systems do not have to be checked after a certain period and therefore cheaper in maintenance than active systems. On the other hand, the damage could occur during the lifespan and this will not be noticed or neglected. The two main passive fire protection systems are fire-resistant coating and fire-resistant boards. When a steel surface must be protected, both methods are commonly used. The coating will be painted on the surface of a steel profile for example in the factory and after placing the elements this coating must be checked for damages. When heated, this coating will start to foam, which will insulate the profile against heating. The materials will lose their strength when heating up. The other option is to use of fire-resistant boards, these will be installed after placing the element on location. Currently, not a lot of concrete elements are protected against fire conditions other than by providing sufficient concrete cover. Previously, spalling was not an issue and therefore concrete elements were assumed to be safe enough. Recently spalling has become a big issue. In tunnels for example the concrete is often protected with boards, to keep the temperature bellow irreparable damage conditions. A generally accepted temperature to prevent spalling is 200 °C. Reactive coatings systems to protect concrete against fire are not widely used but do exist. To prevent heat loss, insulation is put on the ceiling of the car park. Commonly used insulation material is a wood-wool-cement board with expanded polystyrene (EPS). It complies with fire class B according to EN 13501-1 for the assembly. To pass the class B test the material is subjected to thermal radiation with a maximum intensity of thirty kilowatts per m^2 for twenty minutes. The wood-wool-cement board, which by itself obtains class A2, protects the EPS from the radiation. EPS itself will catch fire easily, fire class E or even F. The good fire class B for the assembly does however not translate to an equally good performance on a real scale. Tests have been performed on wood wool cement boards with EPS subjected to a large 2 MW pool fire (figure 2.2). In this test it was found that after 17 minutes the EPS catches fire after the wood-wool-cement boards failed [56]. This system is therefore certainly not recommended for protecting the concrete floor above a car park level. A possible option to prevent the spalling of the concrete floor elements is to improve the insulation. So not only the insulation material is useful as insulation, but also to protect the elements from a fire load.

2.8.5. Reducing oxygen

Another possible method to control a fire is by reducing the oxygen concentration in a car park. Controlling oxygen is a method not yet used in a car park, but may provide more fire safety possibilities, especially if no people are present in the car park. When a car is parked in a stacker car park, the car is moved with the help of machines to a parking spot therefore the people do not have to go inside. So, the available oxygen inside this car park can be reduced, so that when a fire is ignited it is less likely to develop and propagate, certainly not to more than one car. In distribution centres for other goods than cars this technique to reduce oxygen during a fire is sometimes used [47]. The oxygen concentration is reduced, from twenty to thirteen % to obtain a reliable prevention of fire development. The oxygen level is reduced by replacing air by pure nitrogen in the compartment, until the concentration of oxygen has reached the target value. The main disadvantage of this concept is the total amount of nitrogen needed. For a 'normal' closed car park this technique may also be possible when everybody is evacuated. The fire department will check if everybody is outside and check if all the doors are closed. When this is done the fire department will start the machines and will wait for a period. This will reduce the fire damage, the water damage and the firefighters are not in any danger. A serious problem for this alternative is the existence of openings in the surrounding walls and floors, such as doors and cracks. To design this kind of system the NEN-EN 16750 (Fixed firefighting systems - Oxygen reduction systems - Design, installation, planning and maintenance) could be used [53].

2.8.6. Segmentation

Segmentation of the car park can be done, with the help of the Dutch building decree. In the Dutch building decree the maximum allowed fire compartment is 1000 m^2, so the car park is divided into areas of 1000 m^2 [65]. A downside of this concept is that visibility in the car park is greatly reduced. A lot of small compartments are needed resulting in a lot of walls and flexible walls/doors. People inside the car park need more time to find the exits and the fire department needs more time to localise the fire. Therefore, neither the architect nor the fire department like this solution. Another option is making use of flexible fire curtains. These curtains will come down during a fire, keeping the smoke and heat inside the compartment for a certain amount of time. For example, a fire that occurred in a closed car park on Kanaleneiland in Utrecht was equipped with these curtains [76]. The fire department had some big problems with these curtains because they could not reach the fire and therefore needed to demolish the fire curtains (figure 2.20). Therefore, this method is still unfavourable, but could still be applied by keeping the entrance for the firefighters and the escape routes in mind.

Figure 2.20: Fire curtains applied in Kanaleneiland in Utrecht. The fire department needed to demolishes the fire curtains to localise the fire [76].

3
Case studies

In this chapter, a closer look will be taken at car park fires that involved multiple cars and resulted in structural damage. The goal of these case studies is to understand how these fires could develop, what is the relation of the fire to the damage occurred, and how the damage was repaired. This is interesting because it will give insight into the expected damage of a fire and the occurred damage. Not a lot of car parks actually collapse during a fire, the only known case was a car park in Gretzenbach in Switzerland [26]. To extinguish the fire, firemen entered the car park, but the structure failed and five firemen died. The biggest car park fire that occurred up to now is the fire in the King's dock car park near the Echo Arena in Liverpool [72], England. During this fire, hundreds of cars were burning at the same time, nevertheless this fire did not result in collapse. Eventually, the car park was demolished because the structure was damaged beyond repair. Also in the Netherlands, some severe car park fires occurred. For example, the Appelaar car park fire in 2010 [77]. During this fire, 26 cars burned out. The structure was heavily damaged, but the damage of this fire could be repaired. The fires in car parks Markenhoven car park (Amsterdam) [3] and Goudbaard (Bergen op Zoom) [83] will also be used as a case study. Both these fires are well documented, involved multiple cars and resulted in structural damage. There are some additional interesting cases such as the fire in the Lloydstraat Rotterdam. During this fire, the floor elements (hollow-core slabs) collapsed much earlier than anticipated. Even during the cooling down phase, these floor elements continued to collapse. This fire resulted in a broader investigation into the behaviour of hollow-core slabs during a fire, which resulted in new guidelines for their design. This case study will not be used for the thesis, due to the fact that a lot of research is already done on this fire. Other interesting case studies are for example the fire in Monica Wills House, Bristol, UK, 2006, which was probably a flash-over fire and the fire at the Mijnsherenlaan car park (2014) in Rotterdam. For both these cases, documentation was lacking and a case study was not possible. With spalling of concrete, generally, two types of spalling are indented namely explosive spalling and progressive gradual spalling. When explosive spalling occurs a big piece of concrete is released from a solid body with a big force. With progressive gradual spalling small flakes of concrete are falling off a solid body, it looks like concrete is raining. In the case studies the term spalling is used as progressive gradual spalling, the concrete that has spalled are small flakes and this was verified by photo and interviews with people that had asset the damage. In some of the case studies with prefabricated floor elements, the prefab floor came loose of the poured concrete. This has been defined as delamination of the floor as these layers are completely separated.

3.1. The Appelaar car park

The first case study is on the Appelaar car park in Haarlem. The Appelaar car park is an underground car park, and therefore a closed car park, with two levels and was completed in 2007. Each level has an area of 4500 m^2 and therefore equivalence had to been proven to the 1000 m^2 maximum fire compartment size which is stated in the Dutch building decree [65]. The initial fire safety concept contained a mechanical ventilation concept with a capacity of intended to provide a smoke-free access to the fire seat. During the construction of the car park, the LNB-guideline [49] was published which stated that the total volume had to be refreshed ten times per hour. Therefore, the mechanical ventilation was adapted to this guideline and the total capacity was reduced to 20 ACH (air renewal rate). On October 26 2010, a fire occurred which involved 26 cars situated at the -2 level in this car park. In this case study, a closer look will be taken on the fire propagation, how the fire department dealt with the situation and the damage of the construction. Three reports were available for studying this event, 'Nederlands Instituut Fysieke Veiligheid '(NIFV) made a report on the lessons learned by the fire department [77]. Nieman, a Dutch building physics engineering company, made a report to verify the ventilation capacity [68]. Hageman, a Dutch structural engineering company, made a report on the structural damage in the car park [35].

3.1.1. Structure

The main material used for the structure of this car park is concrete. The floor elements and beams are built out of two layers, a prefabricated concrete floor with a concrete layer on top which was poured on-site. The prefabricated floor elements (80 mm) were placed on the prefabricated beam elements (80 mm). On top of the beams 200 mm of concrete was poured and on the floor 120 mm concrete was poured (figure 3.1). The beams are supported with square columns which were cast on-site with a cross-section dimension of 300 by 600 mm. Most of the columns have a grading of C35/45, however there are some columns with a grading of C53/65 (figure 3.2). These are the columns underneath a hotel and therefore carry a higher load.

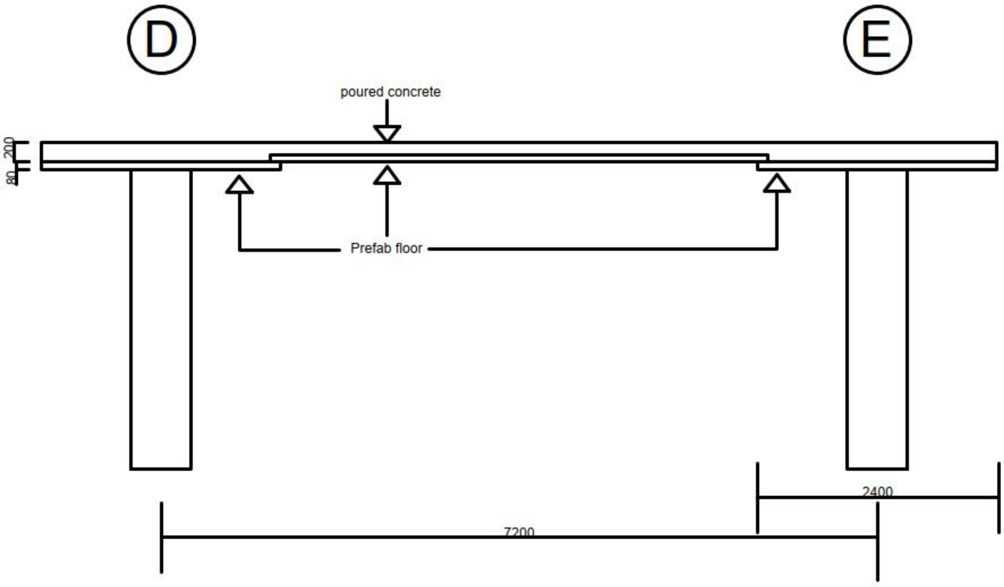


Figure 3.1: A simplistic view of the construction of the Appelaar car park. All the dimensions are given in mm.

3.1.2. Timeline

To get a better idea of the incident itself, a timeline is construed to understand how this fire could progress table (3.1) [77]. In summary, the fire department arrived in less than ten minutes and after thirteen minutes there was a general idea where the fire was and a tactic to attack the fire was determined. When arrived on the -2 floor, locating the exact location of the fire was impossible, the smoke layer was too dense to see anything. This resulted in a fire that could freely progress. Attempts were made to extinguish the fire from staircase A (figure 3.2), however water did not reach the fire. Due to the fire being able to develop freely, conditions in the car park became untenable (after 99 minutes in the timetable) for the firefighters and they had to pull back. After 129 minutes mobile ventilation equipment was deployed, after which the fire could be localised. In total it took 419 minutes (almost seven hours) to extinguish the fire. The time it took for the fire to propagate could not be conclusively determined with the available information. After thirteen minutes there is already a lot of smoke and possibly two cars are on fire. Eventually, 26 cars were involved in the fire resulting in structural damage to the car park. The repairs took four months and the car park was closed for this period.

Table 3.1: Timetable for the fire that occurred in the Appelaar car park [77].

Time	Progression (Minutes)	Action
19:50	-	An automatic fire alarm warns the emergency centre, the start of the fire is probably 2 á 3 minutes earlier.
19:57	7	Two fire trucks arrive at the scene.
20:03	13	Team one and two try to localise the fire, there is a lot of smoke on the -2 floor and both teams regroup outside the car park. The exact location of the fire was not found. Fire is classified as average.
20:14	23	Fire is classified as a big fire.
20:19	28	A third team arrived, team two is trying to locate the fire and team one is looking to other ways to enter the car park.
20:30	39	There is a global idea where the fire is located, however trying to extinguish the fire from exit A (figure 3.2) with the basic equipment was unsuccessful. Therefore heavier equipment is requested.
20:37	46	The fire is classified as a very big fire.
20:44	53	A fourth team arrives.
21:00	69	Bigger equipment, deluge canon, was used in the global direction of the fire from exit A (figure 3.2).
21:30	99	Change in tactics, from offensive tactic towards a defensive tactic. The visibility is very low and it is too hot.
21:32	101	It is assumed that only a limited amount of water has reached the fire.
22:00	129	The fire is located.
23:18	207	The ventilation equipment in the car park is used to improve visibility.
00:07	278	Extra ventilation equipment is requested.
00:45	316	First attempt to extinguish the fire. Possible due to improved conditions in the car park. This attack had to be stopped because the conditions were still unbearable.
01:45	376	Second attempt to extinguish the fire.
02:28	419	The fire was extinguished.

3.1.3. Overview of the car park

To gain a better understanding of how the fire department tried to attack the fire, figure 3.2 [35] can be used. Staircase A and B are used by the fire department to extinguish the fire, however they have not used the staircase in the left upper corner, staircase Z. This staircase was not equipped with a dry riser and therefore not part of the fire department access points. The mechanical ventilation system in the car park started directly when the fire detection systems went off, resulting in a ventilation direction from left to right. Therefore staircase A and B are 'downwind' and this could explain the bad visibility for the firefighters. If the staircase in the upper corner was used, the firefighters would have had the wind blowing in their back and possibly a better visibility. The red box indicated the area where the structural damaged was located. The exact locations of the 26 cars that burned down were not reported. However, in the red box twenty-four parking spots are located. So it seems likely all these spots were filled and two other cars were located in the row above. Photos are available showing that the cars located in the most left row are undamaged, at least not burned. During the fire, the mechanical ventilation system pushed air from the left shaft towards the right shaft. Therefore it seems likely the fire started on the left side of the red box and propagate to the right side of the red box. An enlarged image of the red box can be seen in figure 3.3.

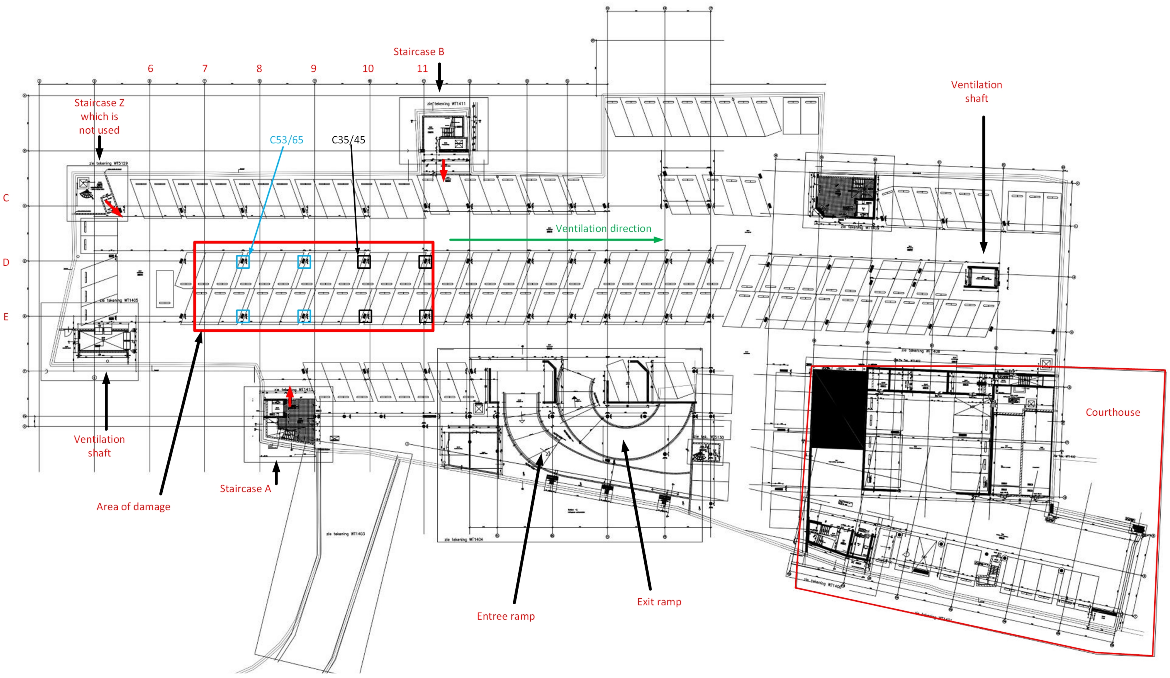


Figure 3.2: A floor-plan of the -2 level of the Appelaar [35]. Gridlines are indicated on the left and top side of the figure. The red box indicates the location of the structural damage. Entree locations of the car park are indicated, the red arrow shows the access door to enter/exit the staircases. Two ventilation shafts are indicated and the air flows from right to left. The strength class of the damaged columns are indicated. On the right side of the figure, the car park for the courthouse is separated from the Appelaar car park.

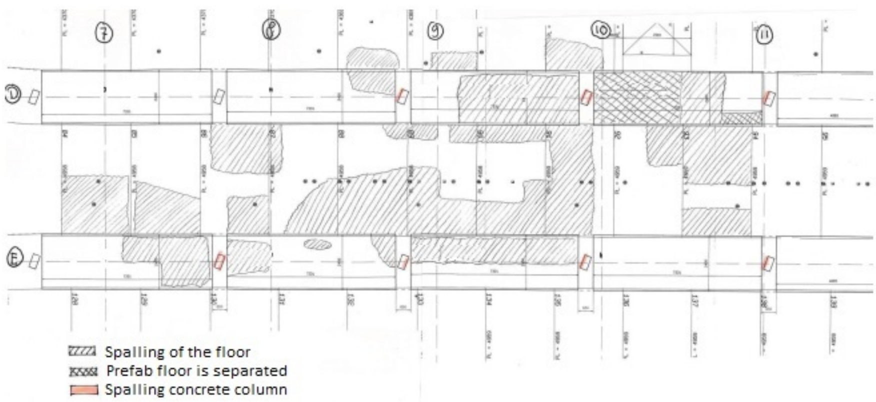


Figure 3.3: Enlargement of the area with structural damage of the Appelaar car park (red box, figure 3.2). The spalling damage is highlighted.

3.1.4. Structural damage

The structural damage was investigated by Hageman, a Dutch consultancy company. They assessed the damage caused by the fire and advised on how to repair the damage. In the red box (figure 3.2) eight columns and two beams are located. On seven of the eight columns spalling occurred (figure 3.3). Spalling also occurred on the beams and floor elements. Between gridline ten and eleven in the floor element, the reinforcement came down and was hanging from the ceiling. Also in figure 3.4 A and B the severity of the spalling can be seen, a lot of reinforcement is visible and therefore directly exposed to the fire. In addition to the spalling damage, debonding between the beam had occurred between gridline ten and eleven. The prefab elements have no connection with the poured layer of concrete and were hanging from the ceiling. To assess if the reinforcement was affected by the fire, samples were taken from a beam (gridline D between nine and ten (figure 3.3) and pulling tests were done to test the tensile strength. In this beam two types of reinforcements were used varying in diameter, 8 and 16 mm. The 16 mm reinforcement was slightly reduced in strength. However, the strength of the 8 mm reinforcement was reduced by 40 %. The 8 mm reinforcement had less cover than the 16 mm in the beam. To verify how much the concrete strength was reduced, four samples were taken from the columns between row nine and ten. So, two samples are outside the damaged area and two inside the red box. The concrete samples outside the damaged area had a strength far greater than the design value. At the columns with spalling damage, the strength at the surface is reduced to 34,4 N/mm^2 and 40 N/mm^2, so below the 45 N/mm^2 design value. In the core the measured strength is 47 N/mm^2 and 52 N/mm^2. The maximum spalling depth on the columns (column at gridline E-11) was 30 mm and locally some reinforcement was visible (figure 3.4).

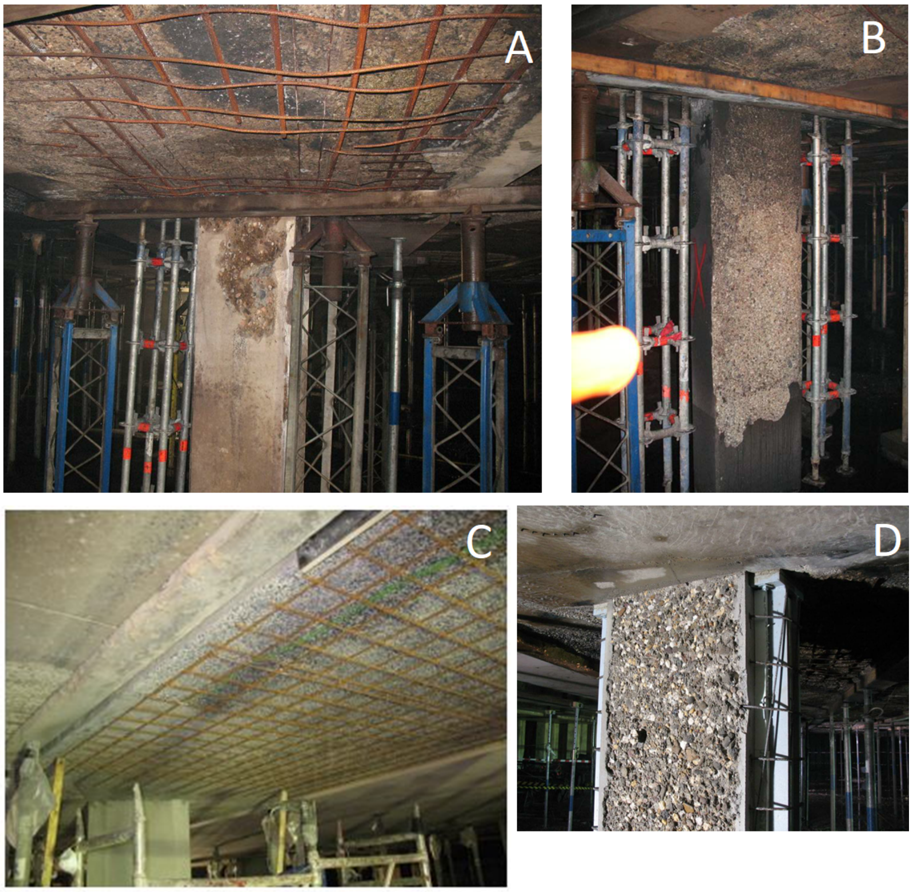


Figure 3.4: An overview of the damages and repairs in the Appelaar car park. Figure A shows spalling damage of the beam, the reinforcement is exposed. Figure B shows spalling damage of the concrete column, reinforcement is not visible. Figure C shows how the beam is repaired, an extra steel mesh applied. Figure D shows how the column is repaired, two extra steel columns are placed on both sides.

3.1.5. Capacity

Before the fire, the columns between gridline nine and ten (figure 3.3) had a capacity of 4200 kN. To calculate the strength capacity for the columns after the fire, a homogeneous spalling depth on all sides of 25 mm was assumed. A strength capacity of 3210 kN was found. This is smaller than the design load of 3660 kN on these columns. However, due to the strength loss in the concrete caused by the heating, the actual capacity will be even lower than 3210 kN. It is not clear how deep the columns are heated, therefore a more exact calculation cannot be made. Concrete samples were not taken from columns near row nine, this would also be interesting because another type of concrete is used. The strength loss could be completely different, however in the report the same assumptions were made for these columns. The spalling depth is also not very different between this row of columns. Most of the spalling damage of the floor occurred near the supports. Therefore the reduction in strength in the middle of the span will be small. Near the connection, the upper reinforcement is not affected and therefore there is also enough capacity to deal with the negative moment. However, to secure the integrity of the floor elements a new steel mesh is needed which needs to be covered with a new layer of concrete.

3.1.6. Repairs

To be sure all the concrete, that lost its strength due to fire, is removed a high-pressure water jet is used. After the removal of the weakened concrete, a new steel mesh is applied on the floor and beam elements (figure 3.4 C). This mesh is covered with a new layer of concrete. The bent reinforcement was not removed but bent back as good as possible. The concrete columns were also blasted and extra steel columns were needed at both short sides (figure 3.4 C). These extra steel columns were small steel profiles and are connected to the column by adding a layer of concrete to make it one big column. The cost to repair this car park was 2.8 million euros and the car park was closed for four months. Therefore the total cost of this fire will be even higher due to lost revenue [18].

3.1.7. Conclusion

The goal of this case study was to gain inside the fire propagation, how the fire department dealt with the situation and the damage to the construction. Due to poor visibility, fire propagation cannot be analysed. When the fire department arrived there is already a lot of smoke, but it is not clear on how many cars are on fire. The fire department was fast at the Appelaar car park, however locating the fire took a very long time. Based on the used entree points this seems logical because they are all downwind. It took more than two hours before the fire department localised the fire and start to attack the fire. Staircase Z was not used by the fire department as it was not indicated as a fire entrance, although it some logical when searching the fire all possibilities will be explored. The fire was located after two hours, so the concrete elements were completely exposed during this period. The construction was designed to survive a fire of 90 or 120 minutes, this was not clear on the based information. Therefore the expected damage was the failure of multiple floor elements, beams and columns, but no elements had failed. Therefore the expected damage was bigger than occurred. The columns lost a lot of capacity and were damaged beyond the required capacity, resulting in the need for extra steel columns. The floor elements had a lot spalling damaged, however the steel on the most critical places was hardly effected. To secure integrity these elements needed a new mesh with a fresh layer of concrete. This case study indicates that spalling damage is likely to occur and can have a depth beyond the reinforcement. To gain more insight in the capacity of the concrete columns a more detailed analyse was needed of the concrete samples, as the exposed surface of the concrete showed strength reduction. Now it is not clear to what depth the concrete was heated.

3.2. Markenhoven

The Markenhoven car park is a large car park, 250 meters long and 50 meters wide, with two floors near the centre of Amsterdam. The car park was constructed in 1995 and there were some guidelines available to design a fire-safe building, but not very explicit for car parks. In 2007 a new assessment was made on the fire safety of this car park. Based on this assessment the car park was implemented with an automatic alarming system with direct notification to the emergency centre. The car park has two fire compartments per floor which are divide with a type of flexible firewall, resulting in two fire compartments of 5000 m^2 and 6500 m^2. The first floor (level -1) is designated for residents, the lowest floor (level -2) is used by visitors. On top of the car park, stores and housing were situated (figure 3.5). On 8 January 2013, a fire occurred in this car park involving five cars and took more than six hours. The fire occurred after the fire in the Appelaar, which was under investigation at that moment. Therefore, this fire was also investigated by the fire department as it also took rather long to deal with this fire. Due to these investigations, the fire is well reported and it was possible to make this case study. In this case study, a closer look will be taken on how this fire could develop, how the fire department dealt with the fire and the structural damaged will be analysed. For this case study two reports are available, a fire incident rapport made by the fire department "Amsterdam-Amstelland" [4]. The second report is an analysis of the structural damage by Hageman [29].

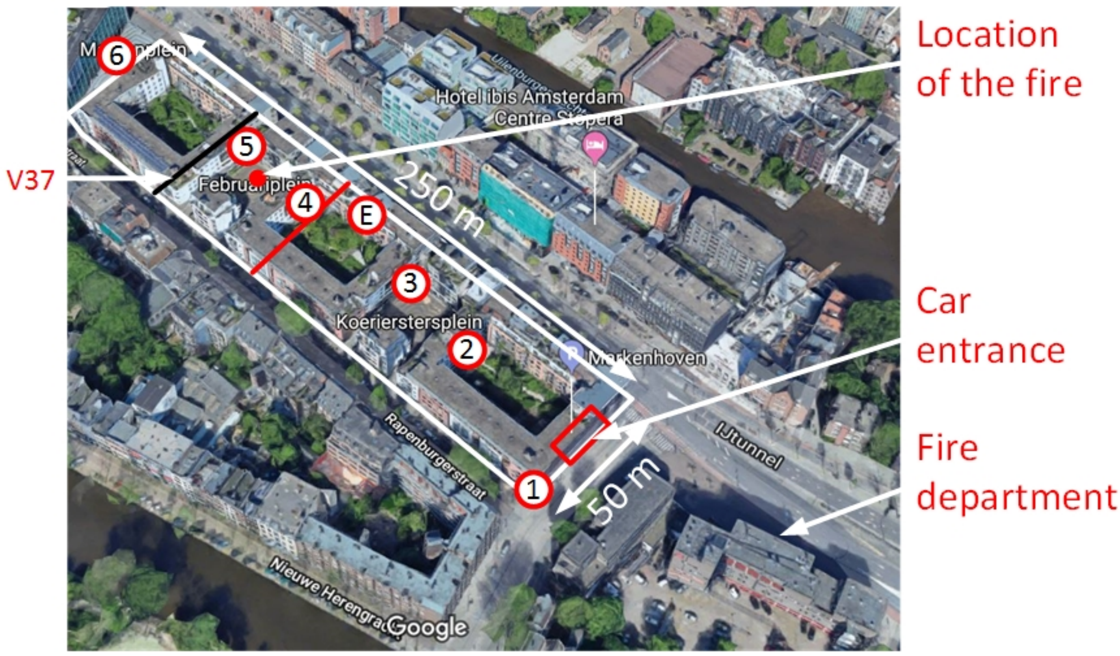


Figure 3.5: A bird's eye view of the buildings on top of the car park. The white lines indicate the outline of the car park. The red line indicates the flexible separation wall between the compartments. The numbers indicated the location of entree locations for the fire department. V37 is a gridline and is used as a reference for the close up for the damage [28].

3.2.1. Structure

The structure of the Markenhoven car park contains mainly concrete elements (figure 3.6). The floor and the beams exist of two layers, a prefab concrete floor of 60 mm and layer of concrete is poured, with a thickness of 190 mm at the beams and 130mm on the floor. The columns were cast on-site and are round with a diameter of 540 mm. The columns near gridline V37 (figure 3.7) have a bigger diameter as these columns carried part of a building. The columns in the damaged areas only carried the square (Februariplein) [29].

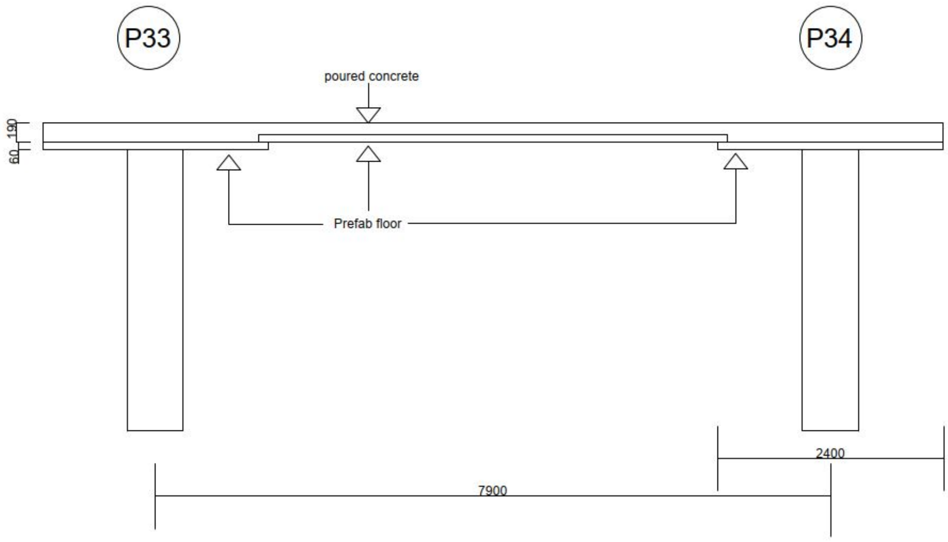


Figure 3.6: A cross-section of the structure of the Markenhoven car park between gridlines P33 and P34.

3.2.2. Timeline

To create a better idea of the development of the fire, a timeline is constructed (table 3.2). In this timeline, important events on how the fire department dealt with the fire and possible reports on the size of the fire will put in the timeline. With this timeline a closer look will be taken to the fire development, the time it took to ignite the neighbouring cars. The fire was caused by a car driving into the car park, while already on fire [4]. At the time of entering smoke was already visible underneath the vehicle on the CCTV footage. The automatic fire alarm noted the fire and the fire department was at the scene in seven minutes, which is rather fast. The fire station was less than 100 meters away (figure 3.5). It took more than an hour to localise the fire mainly due to the thick smoke layer. Eventually, the fire was found and an interior offensive attack was performed. This attack took multiple hours but eventually the fire was extinguished [4].

Table 3.2: A timeline for the fire in the Markenhoven car park [4].

Time	Progression (Minutes)	Action
14:02	-	A car drove into the car park and smoke is already originating from the car.
14:03	1	The car is parked.
14:05	2	Flames are visible from the car on the CCTV footage.
14:06	3	Fire is detected by the automatic fire alarms.
14:08	5	Fire trucks are requested by the emergency centre, this is the so-called alarming time.
14:10	7	First fire truck arrives at the main entrance of the car park.
14:11	8	Owner of the vehicle is standing at the main entrance, the firefighters try to walk with the owner to the car. The fire doors have closed (red line (figure 3.5)). When opened, there is a lot of dense smoke in the fire compartment and the fire cannot be seen. The owner was sent back to the main entrance.
14:14	11	Other teams that have arrived and the surrounding exits are entered to see if the fire can be localised. There are various fire exits and residence entrances. The residence entrances are locked and the superintendent of the car park does not have the key.
14:17	14	The fourth team arrived at the car park and the fire is categorised as average.
14:19	16	The team at the fire door moves inside the fire compartment containing the fire, to localise the fire. However, they cannot find the fire and move back. The firefighters did not have a thermal camera with them.
14:22	19	Another team tries to localize the fire form exit E. They cannot find the fire and the attempt is aborted.
14:48	45	Fire categorised as big fire, more teams are requested.
15:01	58	The source of the fire has still not been found, however large amounts of smoke escaped from emergency exit 5.
15:03	60	Fire categorised as very big fire.
15:10	67	An attempt is made by the firefighters to localise the fire from emergency exit 5 with the help of a thermal camera. The fire is located and an interior offensive attack was planned from this exit.
19:21	318	The fire is extinguished.

3.2.3. Overview of the car park

The car park consists of two storeys, beneath ground-level, and has two fire compartments per storey. The fire occurred on the first storey in the last compartment in relation to the main entrance. The fire compartments were divided by a flexible steel wall, which closed during a fire. In this car park, no additional equipment was situated to help the firefighters or to suppress the fire. The ventilation in the car park had an air renewal rate of four times, which was used to clear the car park form the exhaust fumes. The location of the fire is indicated in figure 3.5, near emergency exit 5. The fire was 45 meters away from the fire separation wall (red line). Above the starting point of the fire, a square is located instead of buildings. Smoke was exiting the car park through emergency exit 5 which was eventually the staircase that was used to start an offensive interior attack. A total of five cars were involved in the fire, which results in the burndown of four cars and one car only partial burned (figure 3.7) [4]. One of the cars moved during the fire and this is indicated in figure 3.7. There were cars near the burned cars that were not involved in the fire. Without the fire department, the fire would have extended and more damage would have occurred to the structure. The fire department arrived rapidly at the main access point of the car park, however due to the large size, many entree points, smoke development and not bringing a thermal camera with them the localise the fire it took rather long. According to the timeline the fire was located after an hour and therefore the fire could freely develop until this moment. So, the fire propagated to five cars in roughly an hour which seems to be in line with the guidelines of "Bouwen met Staal" which indicates four cars are on fire after an hour. However, the car park was not full and the fire skipped some open spaces. The vehicle that is parked on the intersection of V37/P33 was also near the source of the fire. It seems logical this car would also have been involved in the fire but this is not indicated in the available reports. Possible explanations could be the ventilation direction, which is unknown and the car nearest to exit five would have been extinguished first. Maybe the fire propagated already to the next car (intersection V37/P33), but no car window had broken and so the fire inside the car could not develop.

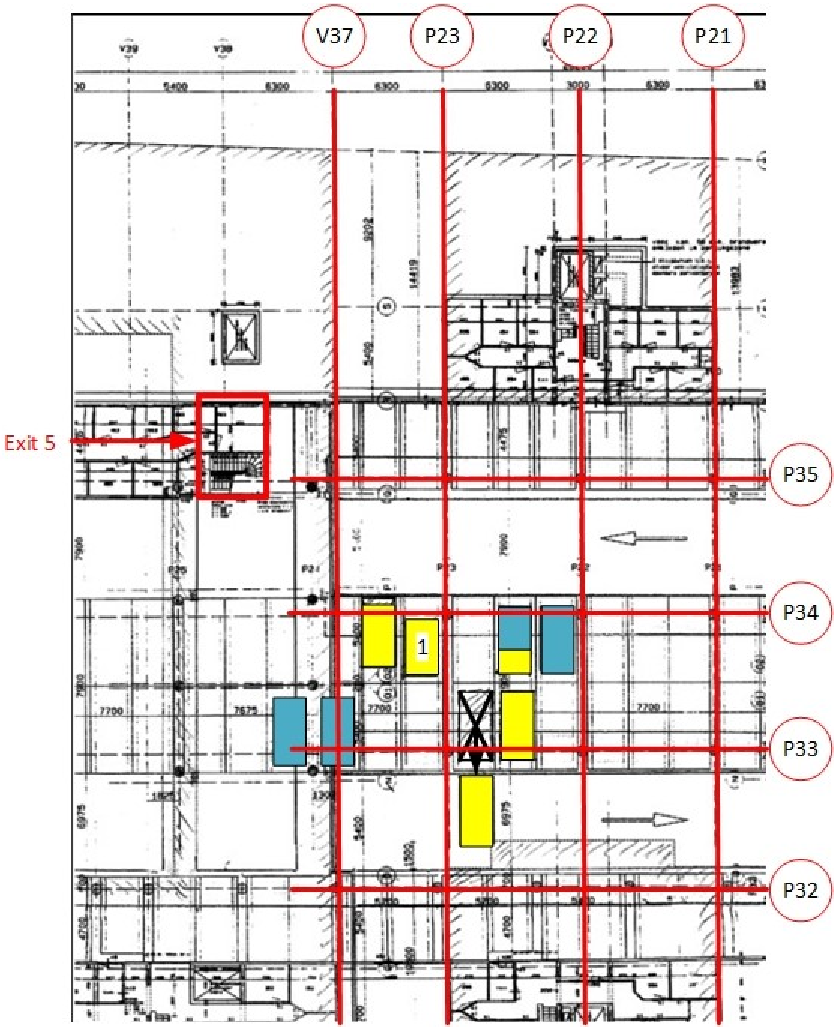


Figure 3.7: An overview of the cars that were involved in the fire. The yellow blocks are completely burned down, the blue blocks are unburned cars. Number one is the first car. The gridlines are highlighted, P21 up to P32 and V37. Exit 5 is also indicated in the upper left part of the figure [29].

3.2.4. The structural damage

The fire resulted in structural damage between grid-line V37-P22 and P34-P33 (figure 3.8). To verify the strength of all the concrete elements after the fire, a Schmidt hammer is used. This tool is a rebound hammer and measures the concrete compressive strength. The design strength of all the concrete elements was B35 (C28/35) [29]. All the concrete columns showed no visible damage, spalling had not occurred. To verify the strength reduction of the columns an unaffected column was measured (P20/P33). A compressive strength was found of 34 N/mm^2, which is slightly less than the design value. Two columns, P22/P33 and P23/P33 were tested and a compressive strength was found of 25 N/mm^2 and 30 N/mm^2. The columns had a maximum strength reduction of 28 % (at the surface) and with the help of the Eurocode figure for concrete heating (figure2.14), the surface temperature was around 400 °C. This would result in a reinforcement temperature of

100 °C (20 mm concrete cover), so the reinforcement was hardly affected and did not lose any strength. The prefab floor showed a lot of damage caused by spalling, near the edges of the floor elements and in the middle of the beams. The spalling damage on the floor occurred at locations where the parked cars had burned. In the P23-P22 and P34-P33 field 3.8), the damage was so severe that the reinforcement was hanging from the ceiling, because the complete 60 mm prefab floors were gone. To measure the concrete strength reduction of the floor elements, again the Schidthammer was used. First, the strength of a reference sample was measured, a prefab floor between P20 and P21. This element had a compressive strength of 62 N/mm^2. Two locations near the spalling damage were measured and a compressive strength of 40 N/mm^2 and 60 N/mm^2 was found. Respectively, the strength reduction is 30 %, however the lowest measured value is bigger than the design value of 35 N/mm^2. Therefore, the heated concrete is still stronger than the needed capacity. Additionally, the exposed reinforcement strength was measured. Six samples were taken and were pulled until failure. Of these six samples, only one sample showed a strength reduction of 10 %. This sample was also bent due to the fire indicating severe heating of the steel. A bigger strength reduction was expected, as steel was directly exposed to the fire.

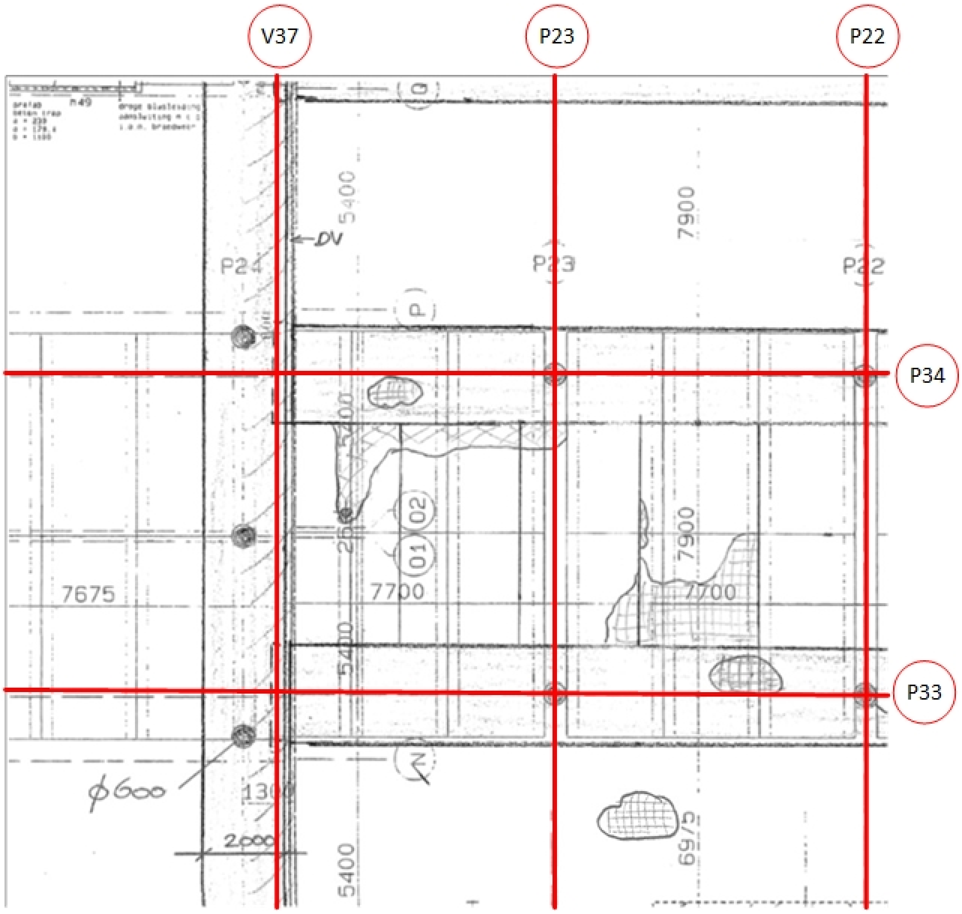


Figure 3.8: Overview of the structural damaged, the highlighted areas are spalling damaged. Between P22-P23 and P34-P33, the reinforcement of the floor was hanging from the ceiling.

3.2.5. Capacity

The columns had a design load of 1264 kN. To capacity of these round concrete columns with a diameter of 540 mm is 4275 kN, far greater than the design load. It is assumed the heating at 20 mm in the column is 100 °C, therefore concrete is also not affected after this point. So, assuming this 20 mm layer is damaged and has no capacity left, the capacity is 4000 kN. This is still sufficient. The prefab floor was completely gone and the reinforcement is completely exposed. Therefore the floor has failed and has no capacity left. Other construction parts keep the floor up. The beams are hardly effected and the original capacity has not changed after the fire.

3.2.6. Repairs

The columns were hardly affected by the fire in this car park and are not repaired. So, only the floor elements and beams are repaired. The first step to repair the floors (between gridline P34 and P33) is to remove all the weakened concrete with the help of a water jet. The exposed steel needs to be bent back as much as possible, and a new reinforcement mesh was applied on the floor elements. A new layer of concrete is used to secure bonding, and a concrete cover of 25 mm on the new reinforcement is needed. On the other location where spalling damage had occurred, only a new layer of concrete is necessary. No repairs were needed on the columns as the total strength capacity of the columns was enough.

3.2.7. Conclusion

The goals of this case study were to investigate how the fire could develop, how the fire department dealt with the fire and what was the structural damage. The fire propagated to five cars in one hour, which seems to be in line with the performed test of TNO and EU partners [37] and the BRE [22]. Which stated the fire propagated to the next car in eight to twelve minutes. The fire department arrived rapidly at the Markenhoven car park with help of the direct notification of the alarming system, however localising the fire took more than an hour. Mainly due to a lot of smoke development, rather big compartments with a lot of possible emergency exits and not having a thermal camera. Also, no additional equipment like ventilation was installed in this car park that could have helped the fire department. The five cars that were involved in the fire only damaged a small part of the structure, the columns had no severe damage. The prefab floor was affected a lot by the fire and even completely gone at certain locations, the floor elements have failed. It is not clear what the design fire resistance time was, however a concrete cover of 35 mm was applied indicating a fire-resistance time of R90/R120. Therefore it seems likely these elements would have failed.

3.3. King's Dock car park

The King's Dock car park was situated in Liverpool and was mainly used as a car park for the Echo Arena. The car park is surrounded with buildings (figure 3.9), however on the south and east sides, the apartment blocks are only five meters away. The car park had six storeys and was constructed with prefabricated concrete elements. The construction was a so-called portal frame, all the connections were moment resistant. The floor elements are prefabricated TT slabs and are prestressed. The car park is a so-called 'open' car park and due to the large openings in the facades a natural ventilated is assumed. The fire department demanded firefighting shafts, due to the surrounding buildings and therefore poor accessibility for an offensive external attack. These shafts have a higher fire resistance than a regular staircase and provide a safe access route for the fire brigade. The total floor area is 24000 m^2, resulting in a capacity of 1600 cars. The facade openings were covered with a steel mesh and at the north side banners were placed on this mesh. Different from other car parks, cars could park on the ramp itself. The fire occurred on 30 December 2017, during a horse show that was held in the Echo Arena. To situate the horses, the ground floor of this car park was used for stables. This results in a reduced capacity of 1400 cars and was almost full before the fire occurred. For this case study three reports are available. A significant incident report that describes how the fire department dealt with the fire and investigated how the fire could develop to other levels [72]. The second report is a list of emergency calls and when fire trucks left the stations [25]. The last report is the incident report, this report investigated the initial car and if there was any criminal activity involved [61]. A structural assessment report is not available as it was not safe to enter the car park. However, there are some details available about the structure [71]. The goal of this case study is to understand how this fire could develop to such an extent and if this is possible for other open car parks.

Figure 3.9: The surroundings of the Kings Dock car park in Liverpool. The white buildings surrounding the car park are only 5 meters away. The red building on the north side is a hotel. The big building on the west side is the Echo arena [28].

3.3.1. Structure

The structure exists of prefab columns, beams and TT slabs. TT slabs are commonly used in car parks as this floor has a low self-weight and a relatively big span. These TT slabs are prestressed so a very thin web can be used (figure 3.10). These slabs are put on prefabricated beams and with the help of corbel connected to the columns. A deck floor is applied on the floor, however it is unknown if this deck floor had any structural function or not. The needed fire-resistant level by law was fifteen minutes. However, when looked for product information of these TT slabs, the lowest fire resistance mentioned in the tables is sixty minutes based on the ISO-curve. However due to spalling, it is unclear how long these elements could have survived the fire. The four cores of the car park are made with concrete and had a higher resistant against the fire. Staircase one and two were firefighting shafts and had a fire resistance of 120 minutes. Staircase three and four had a fire resistance of 90 minutes.

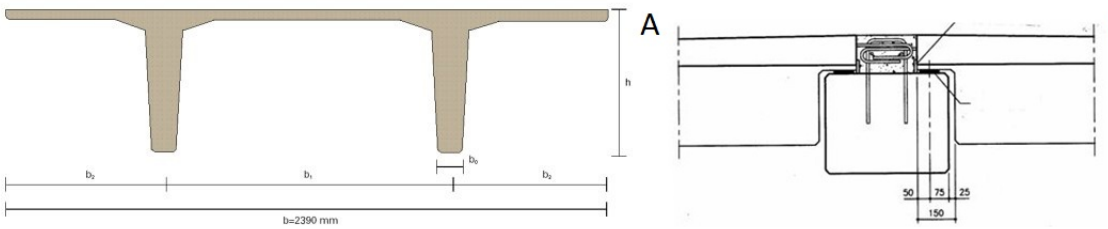


Figure 3.10: Figure a is a general lay-out of a TT slab. Figure B is a general method to connected TT slabs to a prefabricated beam.

3.3.2. Timeline

A timeline is constructed of the incident to get create insight into the fire development and on how the fire brigade dealt with the fire, table 3.3. In summary, the alarming time for this fire was rather long (13 minutes). An automatic alarming system was not installed in the car park itself, there were only manual operating systems near the staircase. However, smoke detection systems were installed in the staircases. The fire department needed seven minutes to arrive at the car park which is rather fast, however it took an extra eighteen minutes before the fire was attacked. This assessment period took probably longer due to the stables from the event resulting in a busy environment. Therefore, the total time the fire could freely develop, before the firefighters attack the fire, was almost forty minutes. It is not clear how many cars are on fire at that moment, the only indication is that multiple cars are on fire on level three at 17:01. Half an hour after the fire department started the offensive interior attack the fire involved thirty cars. With the help of the CCTV, the fire on level four can be seen after 82 minutes. Due to smoke development, the images of the CCTV were not very clear therefore it is possible that the fire already moved earlier to level four, however at 17:52 flames were visible. The fire on level four developed rapidly involving ten cars in just 36 minutes. Eventually, the firefighters had to pull back due to unbearable conditions and the fire could freely develop resulting in a fire on almost all the levels of the car park.

Table 3.3: Timetable of the fire in the King dock car park [72].

Time	**Progression (Minutes)**	**Action**
16:29	-	With the help of the CCTV, the starting time of time fire can be determined. Smoke is visible from a car on level 3.
16:37	8	The fire is fully developed and flames are visible from the car on the CCTV.
16:42	13	The emergency centre is alerted of a fire by a phone call.
16:43	14	First manual fire signal, someone has pushed the window of the manual system. The first fire truck left the station.
16:45	16	Due to the event in the Echo arena, there was a fire event team. This team arrive at the car park, however are not equipped to deal with such a fire.
16:50	21	First fire truck arrives at the car park.
16:56	28	After a global inspection on the ground level, staircase two (figure 3.11) was used to localise on which level the fire was. A team proceed to level three and observe that multiple cars are on fire.
17:01	33	The team in the car park moves back to make a plan with the other teams
17:08	39	The first attempt to attack the fire was done with twelve firefighters and three main jets. Staircase two was used to reach the third floor.
17:35	65	New teams arrived at the car park and start to attack the fire from staircase one.
17:40	70	Reported by the firefighters, thirty cars are on fire on level three. Fire is only in row two and three.
17:52	82	From the CCTV, the start of the fire on level four can be determined, flames are visible. However, the fire could have occurred earlier as there was a lot of smoke.
18:07	97	Firefighters on level 3 could see the cars on level 4 trough the floor. They could also see the other team on the same floor on the other side of the fire, indicating good visibility.
18:21	111	Teams for staircase two pulled back due to unbearable conditions. The firefighters reported when pulling back concrete is failing from the ceiling on level three.
18:28	118	A team arrived at level four using staircase one, reports that ten cars are on fire.
18:38	128	Teams from staircase one are pulled back. All teams are pulled back and a defensive tactic is used. The focus was on protecting the adjacent flats.
2nd January 07:45	Almost 36 hours	The last fire truck left the scene, the fire is extinguished.

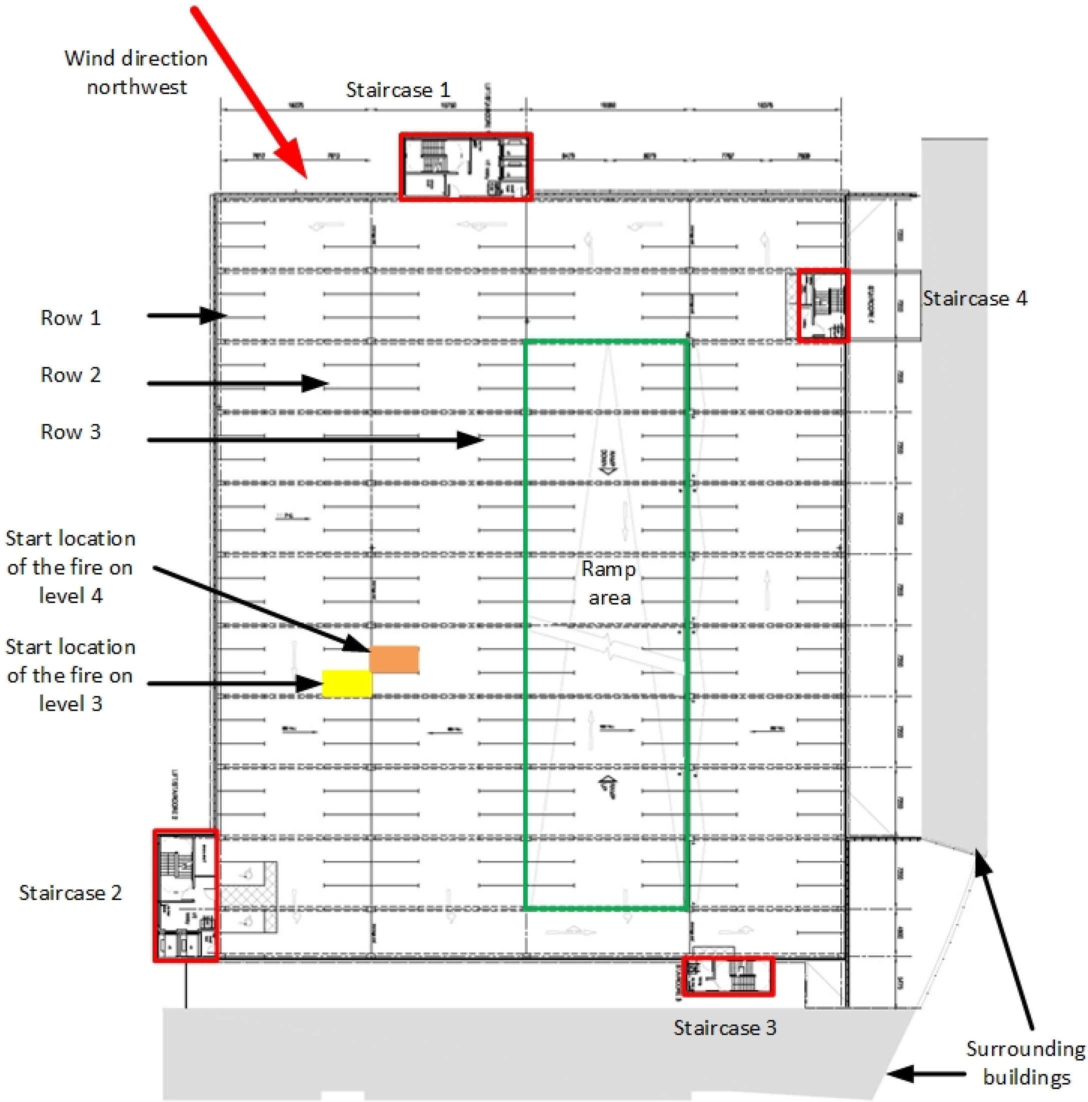


Figure 3.11: Floor plan of the car park. Staircase one and two are firefighting shafts, three and four are regular staircases. The ramp area is indicated with a green box.

3.3.3. Fire propagation

With the help of the CCTV and the communication between the firefighters, the development of the fire can be determined. At 16:29, smoke is visible from the car. After the owner had parked the car at 16:27, he walked around the car looking for something. Later he explained he was smelling something that was burning and was controlling the car. The car could not be checked after the fire because it was unsafe to move any vehicle in the burned structure. However, fireworks and vandalism can be ruled out with the help of the CCTV. Also, foul play by the owner can be ruled out, as there are not lawsuits against the owner of the car. So, the most logical explanation is a (technical) malfunction inside the car. The car was an older type Range Rover and had a petrol engine. The car had a Ministry of Transport (MOT) certificate, in Dutch 'APK'. Range Rovers are large cars and therefore the fire load of the first car was probably high. Due to the smoke and the not very useful position of the CCTV camera, the time before the neighbouring cars caught fire, cannot be determined. However, flames are visible from the car after eight minutes, so it took roughly eight minutes for the fire to develop to an 'one car' fire. The next indication of the size of the fire is at 17:40 and thirty cars are on fire. So, in 62 minutes the fire developed from one car to thirty cars which is rather fast. As a general car burns forty minutes, the first cars will not have been on fire anymore. However, it is not very clear of this thirty is an exact number or a rough estimation. The fire is only located in row two and three (figure 3.12. Using these boundary conditions every 8 minutes four new cars caught fire.

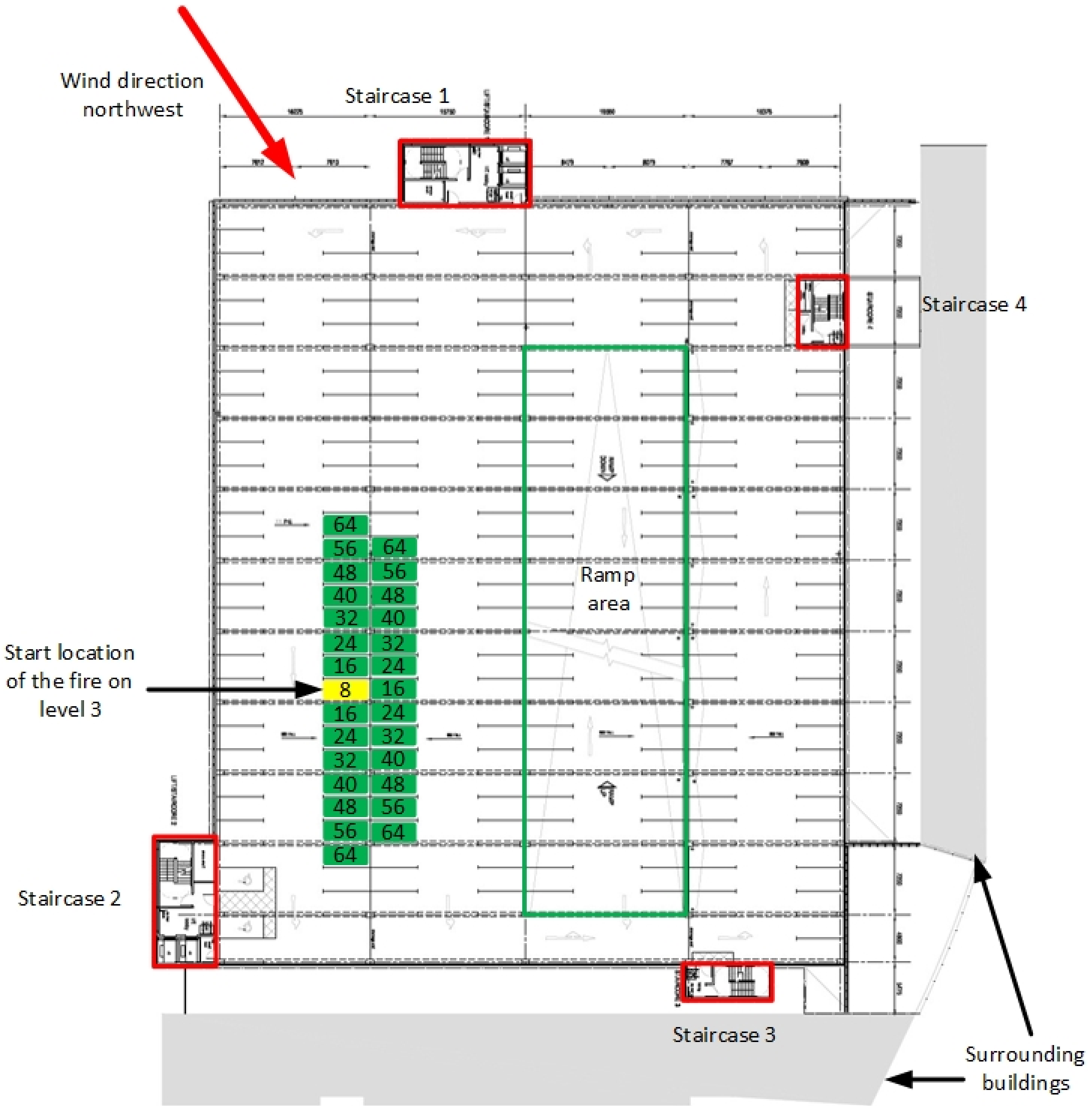


Figure 3.12: A rough estimate on the possible fire propagation on level 3. The numbers in the coloured boxes indicate the time it took to ignite the car. In total 28 spots are coloured, indicating that more places in row two and three were on fire after 62 minutes.

The fire propagated to level four after 82 minutes. In the reports, this fire propagation is highlighted and concluded that the fire propagated due to the drainage pipes. The drainage system was directly above the starting point of the fire and exists mainly out of plastic, the corners were made from thin aluminium. The plastic pipes were completely melted during the fire, melted plastic could be seen on the ceilings. However, it seems unlikely this was the main route the fire could spread upwards. The upwards fire propagation occurred after eighty minutes. Plastic would have melted between 100 °C to 260 °C. These temperatures would have been reached much earlier in the fire. Also at 18:07, 91 minutes, the fire brigade standing on level three reported the could see cars from level four through the deck. Indicating a large gap in the floor of level four, which is the result of spalling. Therefore it seems likely spalling damage was also present after 82 minutes and some small holes in the floor let to the fire propagation to level 4. At 18:28 firefighters arrive at level four and report that ten cars are on fire. In 36 minutes, the fire on level four developed in a ten car fire. This faster development was mainly due to the high intensity of the fire on level three. Also, the floors lost their integrity and smoke and heat could easily move upwards, resulting in a fast fire development. The fire department had to pull back due to unbearable conditions and not long after the firefighters started the defensive exterior attack, some kind of flash-over occurred. Eventually, 1039 cars were involved during this fire resulting in a complete burn-out car park.

3.3.4. Damage

Due to the total damage, it was not possible to do a structural assessment in this car park (figure 3.13). Multiple TT slabs have such severe spalling damage and only the reinforcement was left. Not only the TT slabs had spalling damage, over the full height of the beam spalling damage can be seen. On these beams the reinforcement is visible as the corners have spalled. At 18:07, fire is progressing for 97 minutes, the firefighters could see through the floor from level 3 to level 4, so the TT-slabs were completely gone. Due to spalling, it seems logical holes have been formed in these elements and smoke and heat could escape upwards. This would explain the total time it took for the fire to propagate to level four. The TT slabs were prestressed, and this could have influenced the severity of the spalling damage. Also, the beams were rigidly connected, this would have resulted in obstructed deformation and therefore higher internal stresses. The four cores, which had a higher fire resistance, were hardly affected by the fire and secure the stability. Staircase one, two and three are outside the car park, no cars could park near a wall of the staircase and therefore the exposure of these wall to the fire is less severe. Not only the floor elements had spalling damage, on many columns the reinforcement is visible. In addition to the damage of the car park itself, the adjacent building has also damage, the facade was burned and some parts fall (figure 3.13). Luckily the fire did not propagate to this building.

Figure 3.13: The damage in the car park self and on the surrounding buildings. Figure A, B and C show spalling damage in the car park. Figure D shows damage to the adjacent building due to the fire in the car park.

3.3.5. Visibility

The car park was categorised as an 'open' car park. So, smoke and heat could easily escape the car park. The car park is surrounded by buildings and therefore not a lot of wind could have flown in the car park. The wind direction of the car park was northwest and there was a lot of wind during the fire. Firefighters who attacked the fire from staircase two were obstructed by the wind, had poor visibility and had to pull back after 18:21. The teams that attacked the fire from staircase one had the wind in their back and had better visibility. This can also be concluded from the timeline as the firefighters at staircase two had to pull back earlier than at staircase one.

3.3.6. Conclusion

The construction of the King's Dock car park is not very different from any open car park in The Netherlands. The main deviations are the improved staircases to firefighting shafts and the possibility to park on the ramps. The improved staircase helps the fire department to access the fire, they had a secure route to leave in case anything happened. The parking on the ramps could have influenced the fire propagation, however this had no role in the first hours of the fire. It could have played a role in the fire propagation downwards, as burning fuel could run down on these ramps. However, with the current information the fire propagation downwards cannot be explained. The surrounding buildings are close to the car park and would have blocked the airflow and escape of heat and smoke. The wind direction was northwest, not fully blocked by the surrounding buildings. It was reported that the teams attacking the fire form staircase one had good visibility, indicating a good airflow. The response time of the fire department was rather long due to the initial alarming time took thirteen minutes. Also, the global inspection took long due to the event happening in the Echo arena, resulting in a fire that could freely develop for the first 39 minutes. Ultimately, the fire could not be controlled and the floor elements failed, the firefighters had to pull back and more than 1000 cars burned out. The structure needed by law to have a fire-resistance of only fifteen minutes. However a TT-slab had a minimum theoretical resistance of 60 minutes, also the columns would have a concrete cover and would also have a higher fire resistance than this fifteen minutes. Due to the duration of the fire a collapse of the car park would have been expected, but the staircases were hardly effected and kept the car park in place. The fire propagation in this car park is faster than previously assumed, the LNB guideline [63] and the ’Bouwen met Staal’ guideline [45]. However, there are no indication alternative fuel systems had played a role in the early stages of the fire propagation, suggestion the idea of an increased heat energy of the car itself.

3.4. Goudbaard

The Goudbaard car park is located in Bergen op Zoom and is situated underneath a residential building. The car park was privately owned, only the people that lived in the housing above could use the car park. The car park and the houses were finished in 2011. The size of the car park is roughly 2000 m^2. The car park is naturally ventilated, one of the sides has a gabion (steel cage with stones, figure 3.14), air can 'freely' flow between the stones. No additional ventilation systems were present in the car park. The fire detection system was connected to a direct notification of the fire department, it is unclear if contained smoke or thermal detectors. For this case study there are five reports available, an assessment report of the fire by the fire department [44], SGS Intron made three assessment report on the materials [34] [33] [32] and a structural assessment report made by ABT [31]. On 26 October 2015 at 04:45 am a fire occurred in this car park which involved seven cars. The fire was investigated as arson and one person was eventually convicted for this crime. The goal of this case study is to gain insight into how this fire could develop, what is the relationship with the fire and the occurred damage, and how this damage was repaired.

Figure 3.14: Figure A is an overview of the building and the surroundings. The damaged area is indicated with the red box and the complete car park is indicated with a blue box [28]. Gridline U is used as a reference line for other figures. Figure B is the Goudbaard car park from the side. The steel gabions with the stone can be seen on this figure, smoke damage can be seen on these gabions [44].

3.4.1. Structure

The construction was built with prefabricated concrete columns and prefabricated floors, with a few steel beams and concrete-filled steel columns to support the access balcony (figure 3.14) [31]. The concrete columns in the car park have a dimension of 1000 by 250 mm at axis three and at axis six the columns have a dimension of 1100 by 250 mm with a strength class of C28/35. The floor exists of two layers, a prefabricated concrete floor of 80 mm C50/60 which was prestressed with eight tendons with a diameter of 9.3 mm. On top of this prefabricated concrete floor, a layer 170 mm of concrete is poured and coupled reinforcement (koppelwapening) is applied resulting in a big span. On top of the car park houses are situated, resulting in high loads on the columns. Between axis six and seven (figure 3.15), the entree balconies are located and steel profiles were placed which are supported situated at gridline seven with a steel column filled with concrete.

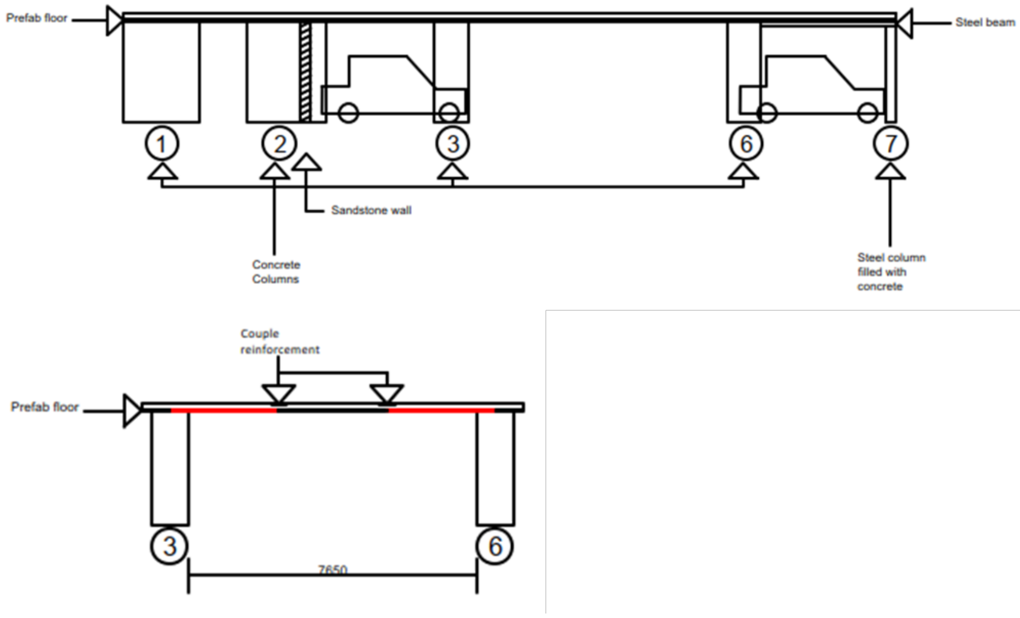


Figure 3.15: A cross-section of the Goudbaard car park.

3.4.2. Timeline

With the help of the available documents, a timeline of the fire in the Goudbaard car park was constructed (table 3.4) [44]. In summary, the fire was detected by an automatic detector and signalled directly to the emergency centre. Seven minutes after this signal the fire department arrived with two trucks, which is rather fast. A global idea of the location of the fire is formed after 15/16 minutes. Due to the apartments situated on top of this car park and the severity of the fire, it was decided to start the evacuation directly. Commonly the evacuation is already proceeding before the fire department arrived, however the alarming system of the car park was not 'connected' with the house above and so the residents were not alarmed of the fire. Connecting these alarming systems is not standard in The Netherlands. Therefore, the evacuation is started late and assistant of the fire department was needed, resulting in a split of resources. The police department also assisted the evacuation. Due to the layout of the building, a lot of smoke reached the entree balconies resulting in entrapped people in their house. A fire truck with a ladder was needed to evacuate the people that could not exit their houses, resulting in an evacuation that took a long time and lesser resources to deal with the fire. The teams that attacked the fire used an interior offensive attack and an exterior offensive attack. From photos made by bystanders, it can be seen that the fire department tried to get water through the gabions. After 167 minutes the fire brigade controlled the fire, it is not clear how long it took to extinguish the fire after the sign 'brandmeester' as there is no documentation after this point.

Table 3.4: The timeline for in the fire in the Goudbaard car park [83] [44].

Time	Progression (Minutes)	Action
04:45	-	The emergency centre is alerted by an automatic alarm system of a fire in the car park at the Goudbaard in Bergen op Zoom.
04:46	1	Two fire trucks are sent to Goudbaard 1.
04:52	7	Two fire trucks arrive at Goudbaard 1. From the start it was clear that the fire was in the car park.
05:00	15	Firemen enter the car park and classify the fire as average, the car park is filled with smoke. Multiple cars are involved in the fire. The firemen exit the car park to discuss the possibilities.
05:01	16	Fire classified as a large fire, the houses on top of the car park must be evacuated. Three teams start to attack the fire, offensive interior attack. One team start the evacuation with the help of the police.
05:11	26	Due to smoke development, parts of the access balcony cannot be entered, residents cannot exit their houses. Therefore, a fire truck with a ladder was used to assist the evacuation, to evacuate people from the balconies.
05:15	30	The fire is classified as very large.
05:19	34	Two new fire trucks arrive at the Goudbaard and start to assist the evacuation.
05:39	54	Eighty to a hundred residents were evacuated and are standing near the building.
05:45	60	The decision was made to increase the number of units as the fire was more complex than normally expected for this building type and the evacuation was not yet finished.
06:02	77	Unit 5 arrives.
06:17	92	Unit 6 arrives. Both units are needed to assist evacuation.
06:30	105	The evacuation is finished, it is not clear if all the teams start to attack the fire from this point.
07:32	167	Fire is under control, 'brandmeester'.

3.4.3. Damage

After the fire multiple structural assessment were done [31] [34] [33] [32]. After the first assessment, the damage was considered to be beyond repair and demolishing a part of the building was taken into consideration. The residents of the apartments on the leftmost part of the construction, above the location of the fire, could for a long time not enter their houses, as it was considered not to be safe. Eventually, Ervas International repaired the damage and the car park and houses could be used again. A lot of spalling damage occurred during the fire, multiple floor elements and columns had severe spalling damage (figure 3.16). The spalling damage occurred nearby places were the cars had burned. The spalling depth on the floor was between 20 and 40 mm (table 3.6). However, not a lot of reinforcement was visible. The only location where reinforcement was visible was between gridlines S-T/7-6. For the columns the spalling damage had a depth between 25 up to 50 mm and a lot of reinforcement was visible (table 3.5 and 3.17). Columns at S-3 had the most spalling damage on all sides, the short sides 30-40 mm and the long sides 50 mm (figure 3.17). This column had the most damage and was considered to be the weakest. To gain more insight into the strength reduction of the concrete that did not spall, bore samples were taken. With the help of epoxy and a microscope the microstructure was analysed and an indication of the maximum temperature can be estimated (table 3.5). The exposed sides after spalling reached a temperature of 350 °C. From the RWS test spalling starts at 200 °C [21], however this concrete started to spall after 350 °C +. On columns were spalling had not occurred, the maximum reached temperature was 150 °C. In addition to the concrete samples, steel samples were taken. The samples from the columns show that the reinforcement was not affected by the fire. In the floor elements, the tendons were slightly affected by the fire, there was a two % loss in strength. The steel beams and columns were also tested. The columns had a fire-resistant coating, however it was unknown what the fire resistance was of this coating. After testing samples of the columns, the material properties slightly changed, lower stiffness and a higher strength, but are still safe. The steel beams were protected by fire boards and again it is unknown what the initial fire protection time was. However, the same result was visible as the steel columns.

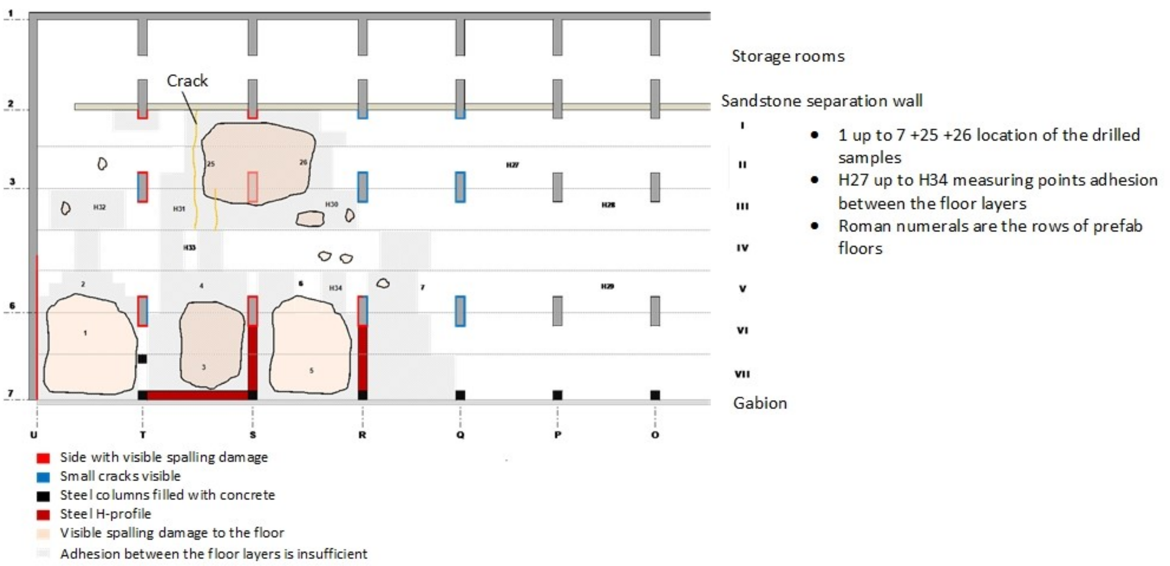


Figure 3.16: Overview of the damage in the Goudbaard car park [33].

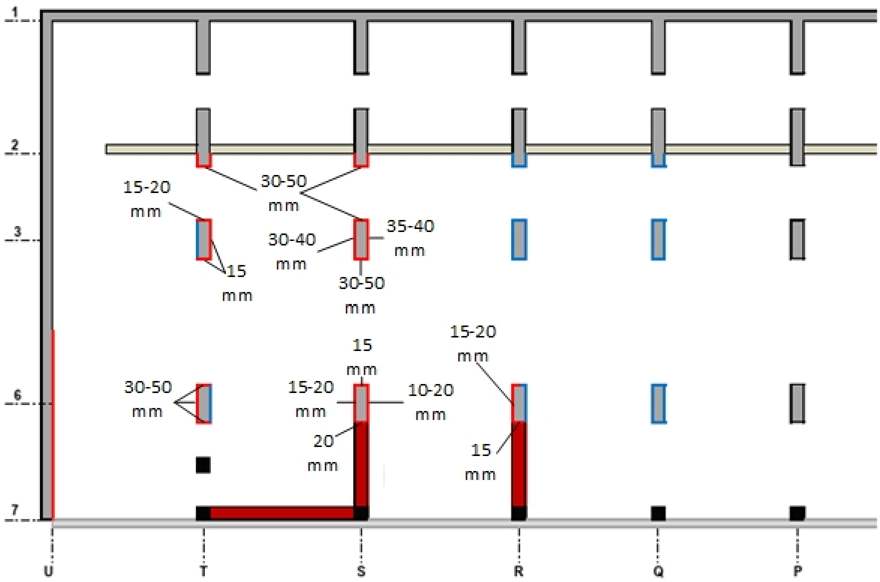


Figure 3.17: Overview on the spalling depth on the columns in the Goudbaard car park [32].

Table 3.5: The temperature profile of different columns based on drilled samples [32].

Location	Temperature development left side	Temperature development right side
T/6	No spalling Up to 40 mm: 105-150 °C	Spalling 30-35 mm 40-55 mm: 250-350 °C 55-75 mm: 105-150 °C
S/6	Spalling 5-15 mm 15-35 mm: 250-350 °C 35-55 mm: 105-150 °C	No changes in the micro structure
R/6	No changes in the micro structure	Spalling 10-15 mm 15-40 mm: 250-350 °C 40-45 mm: 105-150 °C
Q/6	No changes in the micro structure	No changes in the micro structure

Table 3.6: The temperature profile of various locations of the floor based on drilled samples [32].

Location	Spalling depth (mm)	Temperature development
U-T/ 7-6	2-20	Up to 20 mm: 250-350 °C Up to 35 mm: 105-150°C
U-T/ 6-3	None	Up to 45 mm: 105-150°C
S-T/ 7-6	8-35	Up to 40 mm: 250-350 °C Up to 80 mm: 105-150 °C
S-T/ 6-3	None	Surface below 105 °C
R-S/ 7-6 (sample broke)	20	Up to 80 mm: 250-350 °C
R-S/ 6-3	None	Up to 80 mm: 105-150 °C
Q-R/ 6-3	None	Surface below 105 °C

Table 3.7: Percentage debonding between the floor layers. The Roman numbers indicate which floor element and can be seen on figure 3.16 [32].

	U-T (%)	T-S (%)	S-R (%)	R-Q (%)	Q-P (%)	P-Q (%)
I	0	60	75	100	0	0
II	0	75	80	80	0	0
III	60	85	100	50	0	0
IV	20	45	0	50	0	0
V	70	85	70	0	0	0
VI	100	100	100	0	0	0
VII	100	100	100	0	0	0

3.4.4. Debonding

Not only spalling damage occurred during the fire. The grey areas in figure 3.16 are locations were debonding between the floor layers had occurred (table 3.7). The debonding of the floor was detected with the help of sonar equipment. The debonding occurred around the spalling damage however the debonding area is much larger. The field reinforcement of this floor is located in the prefabricated floor as result of debonding the floor layers are no longer connected and cannot carry any load.

3.4.5. Capacity

Some of the structural elements were heavily damaged, so an analysis is made on the capacity of these elements. The columns had some severe spalling, the maximum spalling depth is not uniform over the whole surface. Therefore, in the calculation an assumption was made on the uniformity of this spalling (table 3.8). At first only spalling is considered, the exposed surface is not affected by the heat. All the columns have enough capacity. The most severe one, S3, was further analysed. From the temperature profiles, it follows that 20 mm beyond the spalling damage a temperature of 250 °C was reached. For the calculation is was assumed all this concrete has lost its strength, a worst-case scenario. When this is applied the capacity of the column is still high enough. The floor elements had some severe spalling damage above the car and the prefab floor heated up to 350 °C at 40 mm. Also, debonding occurred between the layers and multiple prefabricated floor elements were completely separated. These elements had failed during the fire and have no capacity left. The reinforcement was hardly affected by the fire, however it is not clear how much of the prestressing is left. Therefore, it is impossible to calculate the capacity for this floor.

Table 3.8: The capacity of the damaged columns.

	T6	S6	R6	T3	S3	R3	S3*
North spalling depth (mm)	35	15	0	20	40	0	60
East spalling depth (mm)	0	15	0	15	40	0	60
South spalling depth (mm)	35	20	15	15	40	0	60
West spalling depth (mm)	40	15	20	0	40	0	60
Area (mm^2)	216300	234300	249550	226775	156400	250000	114400
Fed (kN)	4038	4374	4658	4233	2919	4667	2135
Design load (kN)	1207	1286	1286	1999	1999	1999	1999
Unity check	0,30	0,29	0,28	0,47	0,68	0,43	0,94

3.4.6. Repairs

The first stage of the repairs was done with a pressurised waterjet [31]. With this jet, the weakened concrete is blasted off the surface. For example columns S3 of the original 250 mm width, only 50 mm was left after blasting. To repair the columns an extra steel mesh was applied and a new layer of concrete is applied to restore them to the original dimensions. The repairing of the floor was more tricky, due to the fact the floor was prestressed. For the calculation for the floor it was assumed the prestressing force was gone, the steel was downgraded to regular reinforcement. After cleaning the floor elements an extra mesh was applied and at least a 20 mm cover of concrete was needed on the new mesh. Due to the downgrading of the steel, extra reinforcement was needed to deal with the negative moments at the joints. So, on the top side of the floor carbon fibre reinforced polymer (CFRP)-bars were moulded in the floor to deal with this moment.

3.4.7. Isolation material

In this car park EPS with Herakliet panels were as used as thermal insulation between the car park and the apartments. From pictures after the fire, it is clear that this material caught fire. However, it is not clear what the influence of this material was to the fire development. From the pictures it can be seen that beyond the damaged area Herakliet has fallen on the ground. This could indicate that the fire developed in the EPS, however there is also the possibility the fire department pulled the Herakliet down to check if there was no fire in the EPS.

3.4.8. Conclusion

The fire department arrived very rapidly and the location of the fire was clear from the start. Due to the smoke development, the fire department needed to assist the evacuation and therefore needed to divide their resources. It took almost three hours to control the fire and seven cars were completely burned down and two cars were burned. There was a lot of structural damage, floor elements had failed due to complete debonding. The columns had some severe spalling damage but had enough capacity to keep the building standing. The building was designed to resist a fire of 120 minutes so the expected damaged was greater than occurred. An assessment of the fire propagation was not possible with the information from this case study.

4

Results

4.1. Conclusion for the case studies

To create a general conclusion on the case studies, a comparison is made between them. This resulted in some similarities between the cases. For example, the spalling behaviour of the concrete only occurred near a burning vehicle. But spalling will occur due to car-related fires. In all the cases the fire department was delayed by events occurring near the fire, resulting in a longer period before the fire was attacked. Not in all the case studies, all the needed information was available. For example, the fire investigation reports of the King's Dock fire were very detailed, however they stopped immediately after the fire brigade had pulled back. For the Goudbaard car park, the focus of the fire incident report was on the evacuation and not on the fire. Therefore, not all the case studies could be used to answer all the research questions.

4.1.1. Fire propagation

The first goal for these case studies was to determine the extent and speed of fire propagation of these fires: How far did the fire propagate and how much time did it take to ignite the next car. In the Appelaar car park visibility was poor from the staircases the fire department used. Therefore, the number of cars on fire was not reported in this fire incident report, they could not have seen any cars. For the Goudbaard car park incident report the number of cars on fire was also not reported, however the focus of this report was not on the fire but on the evacuation. In the Markenhoven car park, the fire propagation is clearer, five cars were on fire after an hour. But the car park was not full, two of the three nearby parking spots were empty near the initial car. If all the parking spots would have been filled, a bigger fire would have occurred in this first hour. However, the fire did propagate beyond these empty spots. Often, a car park will not be full and therefore this fire is a realistic scenario to occur. So, due to the empty parking spots the fire developed slowly, but still resulted in five cars after an hour. The fire in the King's Dock car park developed from one car to thirty cars in just 62 minutes. This open car park was almost full, close to the initial car all the parking spots were occupied. The fire department started their attack on this fire after 39 minutes, but the fire kept growing after this point. So, with the interference of the fire department, the fire grew to thirty cars. A member of the fire brigade reported that every thirty seconds a new car caught fire, which indicated conditions close to flash-over. A general understanding of an open car park is that heat and smoke can easily escape, resulting in a fire that the fire department can deal with. However, it seems that due to its open character the fire can develop faster, beyond a point where the fire brigade can deal with the fire. Comparing the King's dock car park and the Markenhoven car park, the fire propagation of the King's dock car park fire was much faster. The variation in lay-out could explain this difference. The Markenhoven car park is a closed car park and did not have a very strong ventilation system (the installation capacity had an air renewal rate of four times per hour needed for exhausting fumes). The King's dock car park was completely open and had access to an unlimited amount of air. The cars that could have parked in the King's dock car park were newer, the fire in the Markenhoven car park was in 2013, the King's Dock fire in 2017. With this data, it seems likely that a fire propagates faster in an open car park than in a closed car park. Comparing the data on these fires before the fire brigade started a successful attack and assuming the Markenhoven as a baseline, there is a clear relationship between the time and number of cars for closed car parks (table 4.1.

Table 4.1: A summary of the data found from the case studies for the fire propagation. The Markenhoven car park fire is used as a baseline, the standardised columns are divided by the number of burned-out cars or the time before the fire department successful attacked this fire. The propagation time is calculated as the number of burned-out cars divided by the time before a successful attack was done.

	Cars (standardised)	Time before the fire department successful attack (standardised)	Propagation time (minutes)
Markenhoven car park	1.0	1.0	13.40
Goudbaard car park	1.4	1.6	15.00
Appelaar car park	5.2	5.6	14.46
King's Dock car park	208	322	2.07

4.1.2. Behaviour of the fire department

For the Appelaar car park, Markenhoven car park and the Goudbaard car park, the fire department arrived very quickly due to the alarming system in the car parks that gave a direct notification to the emergency centre. However, this quick response did not result in a fast extinguish of the fire. In each case study another aspect that played a large role, in the Appelaar car park visibility was poor, Markenhoven car park was large and had a lot of entry points and for the Goudbaard car park a lot of capacity of the fire department was needed for the evacuation. In chapter 2.7 it is described that the fire department has changed its approach to car park fires and will only enter a car park if people are in danger and not to prevent any damage. This will directly lead to an increase in the average damage in the car park during a fire. In for example the Goudbaard car park, the fire department would have used all their resources towards the evacuation of the houses and probably, in the end, the building would have (partially) collapsed. To improve the current situation, it seems useful to connect the fire alarm in the car park with the buildings on top, resulting in a faster evacuation. The main downside is false alarms, people will be evacuated for nothing. A possibility is a two-step approach, if two different types of sensors will detect a fire, the above alarms will go off.

4.1.3. Occurred damage

In all the cases studies a lot of damage occurred, mainly spalling of the concrete. Resulting in completely different heating of the concrete structural elements than assumed. However, in the case studies the expected damage is far greater than the resulted damage to the structure (table 4.2). Car parks situated underneath a building need a fire resistance time of 90 up to 120 minutes, the Appelaar car park fire and Goudbaard car park fire took much longer and did not result in a collapse. The fire resistance time is not the duration that a structure is likely to survive a real fire. It is more an indication to compare different structures. In these case studies, some structural elements failed which were mainly floor elements due to debonding. The spalling of concrete is a serious issue, it is not clear in how fast the spalling propagated. The only thing that can be concluded on spalling is, it will occur, in the immediate surroundings of a burning car. Also, the structure elements, even when taking account of spalling, can still fulfil the fire resistance time it was designed for. Not only spalling damage occurred in the case study fires, debonding between the floor layers was the main reason these had failed. The three Dutch case studies were all built with a prefab floor and a layer of poured concrete. In all three cases debonding had occurred between these layers. The King's Dock car park fire resulted in a different scale of damage, the complete car park burned down. However, the designed fire resistance time of this structure was 15 minutes. The elements used in this structure would have a higher fire resistance time than these 15 minutes. But a collapse would still have been likely due to the duration of the intense fire. Also, in this fire the structure survived beyond the design fire resistance time, but could not be repaired.

Table 4.2: A overview of the occurred and the expected damage of the case studies.

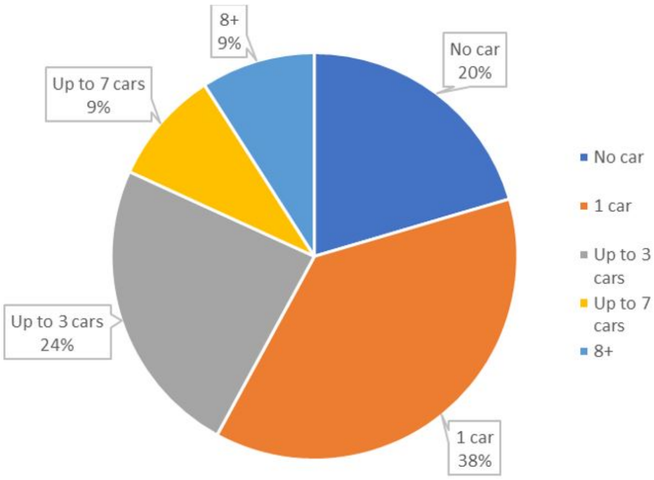
	Designed fire resistance time (minutes)	Start of a successful attack (minutes)	Duration of the fire (minutes)	Amount of cars (-)	Expected damage	Resulted damage
Appelaar car park	90	376	419	26	Failure of the structure.	Multiple elements had severe damage. One beam element has failed.
Markenhoven car park	90	67	318	5	Structural damage.	Exposed reinforcement. Structure hardily effected.
Goudbaard car park	120	105	167	7	Failure of the structure.	Much structural damage, floor elements have failed. One column almost failed.
King's Dock car park	15	-	21603	1039	Failure of the structure.	The structure is completely damaged, but did not collapse.

4.1.4. Repairs

In all the three Dutch case studies the car park could be repaired, damaged concrete was blasted off and new steel meshes and concrete was applied.

4.2. Statistics on car park fires

To gain an insight on the likelihood of fires occurring in car parks, a study was done for the newly formed committee for the NEN guideline for a parking garage, which is led by Ir. D. Jansen and Ir. B. Kersten. The study focused on how many cars were involved in the fire, the classification of the car park (open or closed) and available equipment in the car park. If the fire does not grow further than one car, the fire department is sometimes not called and these fires will not reach the news. Most of the data were found in news reports and therefore not all the fires are in this study. Therefore, the likelihood of a fire in a car park is probably larger in reality than these numbers suggest, and at the same time the probability of growth beyond one car is smaller. In figure 4.1 an indication is given for the number of cars on fire during a car park fire in the Netherlands. There are fires in car parks that did not involve any cars for example, a garbage fire. In the pie-chart these fires are indicated with 'no car' (figure 4.1). Concluding from this figure, 42 % of the fires develop beyond the first car.



Data for public owned car parks (2006-2016)	
Number of fires in public car parks	53
Total area of public car parks	7500000 m^2
Years	10
Chance of a fire per m^2	7,1 E-07 m^{-2}
Chance of a fire being bigger than three cars	0,18
Chance of a fire bigger than three cars per m^2	1,3 E-07 m^{-2}
Chance of a fire being bigger than seven cars	0,09
Chance of a fire bigger than seven cars per m^2	6,3 E-08 m^{-2}

Figure 4.1: The probability of a fire in a car park. Based on the fires in car parks from 2006 up to 2016.

To understand the probabilistic of fire in any type of structure, the Eurocodes provide numbers that indicate the annual probability per m^2, Eurocode 1991-1-2 + C1 Appendix E [11] of a fire leading to the fire service being called. For car parks, such a number was first calculated in 1999 in New Zealand [42], but more recent data is not available. It is interesting to compare the annual probability of a fire per m^2 for the Netherlands with the data found by NEN. The total number of car parks in the Netherlands is unknown. A lot of car parks are privately owned (car parks underneath housing or companies) and nobody keeps records on these car parks. Research has been done to discover the number of public car parks. Spark, a research company in the Netherlands that does research relating to parking, performed this research for the Dutch government in 2014 [70]. They found that there are 500 public car parks in the Netherlands. In the statistics of NEN, a distinction is also made between public and private car parks. To determine the probability of a fire per m^2, only public car park fires were considered. This corresponding total number of fires in a public car park is 53 between 2006 up to 2016. To determine the total size of all public car parks, an average is calculated for the car parks described in the NEN statistic and multiplied with the total amount of car parks, the total area is $7.4 * 10^6$ m^2. This results in a probability of a car park fire of $7.1 * 10^{-7}$per m^2. This is very close to the number published in the Eurocode 1, NEN-EN 1991-1-2 + C1, for the probability of a fire per to be $4 * 10^{-7}$ per m^2. Table 4.1 also shows the probability of fires involving more than one car. According to the statistics, it seems that the probability of a fire inside a car park is just almost so big as the probability of a fire in any other building.

4.2.1. Variation between open and closed car parks

With the available information on the car park fires in the Netherlands, a difference between open and closed car park fires can be analysed (figure 4.2). From these pie-charts, it can be concluded that the probability of a fire without any car involved in a closed car park is bigger than an open car park. In closed car parks, garbage containers or storage units are often located resulting in a bigger chance of a 'no car' fires. The chance of a '0-1 car' fire is roughly the same for both categories of car parks. Of most interest is that large fires seem to have been a bigger probability of occurring in an open car park than in closed car parks, as the probability of an '8+' fires is three times as big. Possible explanations for this large difference could be the amount of available oxygen, available equipment for the firefighters, for example dry riser and firefighter entrance.

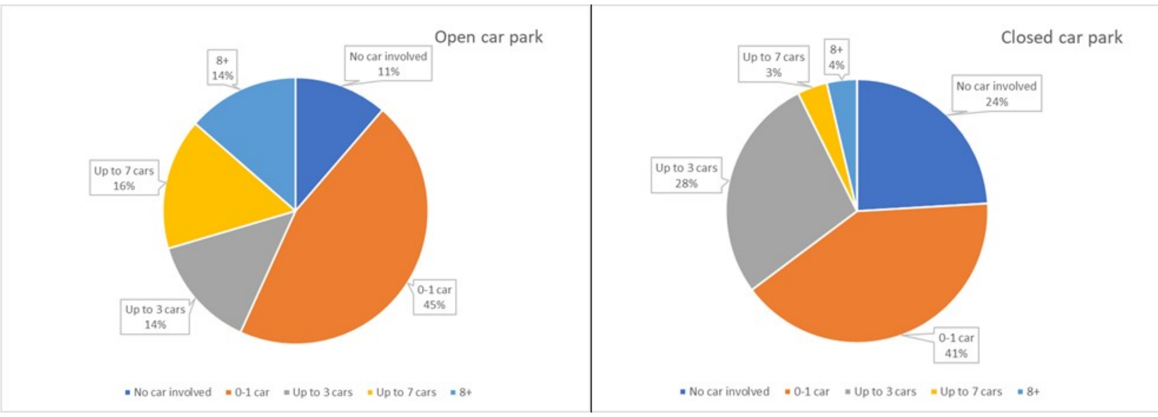


Figure 4.2: Open and closed car park fires split from each other. For the open car parks 43 fires have occurred and for the closed car parks 54 fires.

To proceed to a further analysis on the fires that occurred in closed car parks, a comparison is made on what kind of equipment was installed in the closed car park (figure 4.3). The category 'mechanical ventilation' is ventilation equipment to support the fire brigade in dealing with the fire; this could be an LNB [63] or a NEN 6098 [50] ventilation. However, the purpose of an LNB designed ventilation system is for the after-care, clearing the car park from smoke after the fire. Both systems therefore have another role in case of a fire, only the available data is not making a division between them. The 'nothing' category does not directly mean there is no equipment installed. This category has no sprinkler or mechanical ventilation but could contain dry-risers and fire detection systems. The 'nothing' and the 'mechanical ventilation' category have some similarities, both have two big fires. Also, the same number of fires proceeded beyond the first car. Figure 4.3 suggest that car parks installed with mechanical ventilation equipment have the same results as car park without any equipment. However, mechanical ventilation was needed to prove equivalence to the 1000 m^2, therefore a car park with this equipment is always large and these should at least be as safe as a compartment of 1000 m^2. On the contrary, the car parks without equipment are not necessary 1000 m^2. There are car parks of very large size without any equipment installed, like the Markenhoven car park which had compartments of 6500 m^2. So, it is not clear with this information if mechanical equipment helped the fire brigade to extinguish the fire. With the new fire tactics [63], the fire brigade will enter less often or even not at all the car park anymore (chapter 2.7) and therefore mechanical ventilation equipment will have no further use. There are not a lot of fires that occurred in a car park with sprinklers, however this data suggested the same as the BRE research [22], i.e. that a sprinkler can limit the fire to a single car.

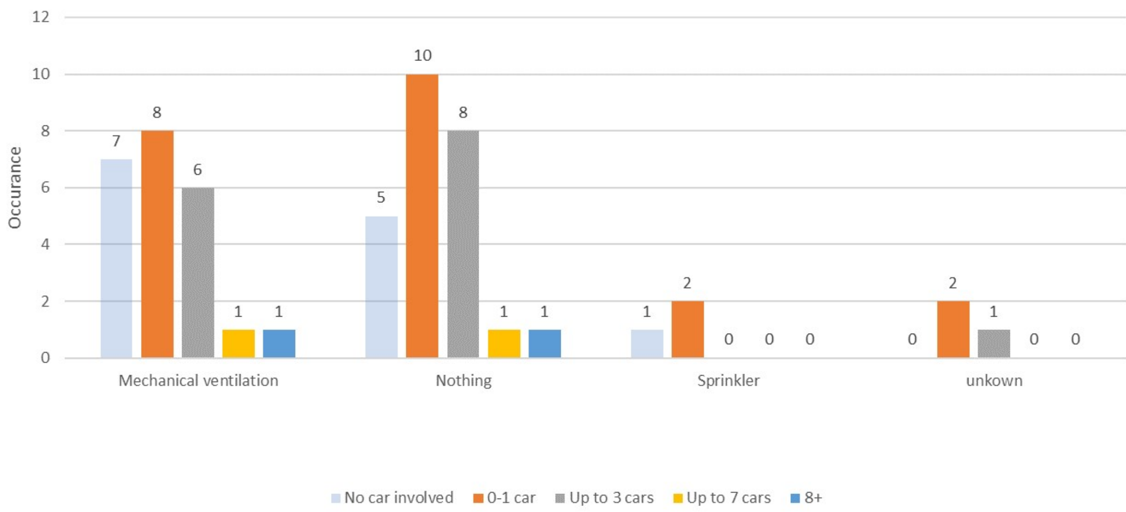


Figure 4.3: Fires that occurred in closed car parks, categorised on the installed equipment.

4.2.2. Size of compartments in the car park

It would have been interesting to see what the influence of compartment size was on the occurred fires. However, the available data on the size of the car parks was incomplete and had some large assumption. Therefore it was decided that with the available data it is not possible to make any statistic on compartment size in relation to the car park fires.

4.3. Design options due to spalling

From the case studies, it became clear that spalling of concrete is a serious issue. Currently, there is no concrete mixture that could guarantee spalling will not occur. Therefore there are two possible options, preventing the fire to reach spalling temperatures or to protect the concrete. Protecting the concrete is a so-called passive system and will be further analysed in this chapter. The active systems were already discussed in the literature study (chapter 2.8).

4.3.1. Heat resistant cladding

To gain more insight into the possibilities of heat resistant cladding material, a 1D heat conduction model was provided by DGMR and the performed calculations were compared with calculations provided by Promat. To validate the difference and similarities between the models, the same insulation material and fire curve was used, Promatect-H and ISO curve 834. Promatect-H is a product generally used to protect steel and concrete against a fire. In these calculations, the thickness of the Promatect was variated and the time it took before the concrete surface reached 200 °C was noted (figure 4.4). This 200 °C is also used to design the heat resistant cladding for tunnels. Of course for tunnels an RWS curve is used instead of the ISO curve, but the big difference in the thermal shock will be prevented due to heat resistant cladding. From these calculations, it can be concluded the variation between both models is large. The 1D heat model by DGMR is purely based on physics and the thermal properties (conductivity, heat capacity, mass density) of the isolation material are derived from pure 'building physics' measurement methods. The model by Promat is very similar, but the calculations were made using thermal properties determined in fire tests where a large number of non-conduction phenomena occur: moisture migration and evaporation, gaps opening between boards, cracks due to mechanical deformation, for example. The thermal properties used by Promat in the calculation are chosen such that the calculation fits the measurements. Moisture will have a positive effect on the heating of the concrete, it will slow down the heating. However, the cracking and deforming of the isolation material will have a negative effect on the heating of the concrete. Figure 4.4 suggested that the positive effect of the moisture is much larger than the negative of the thermal behaviour of the cladding material.

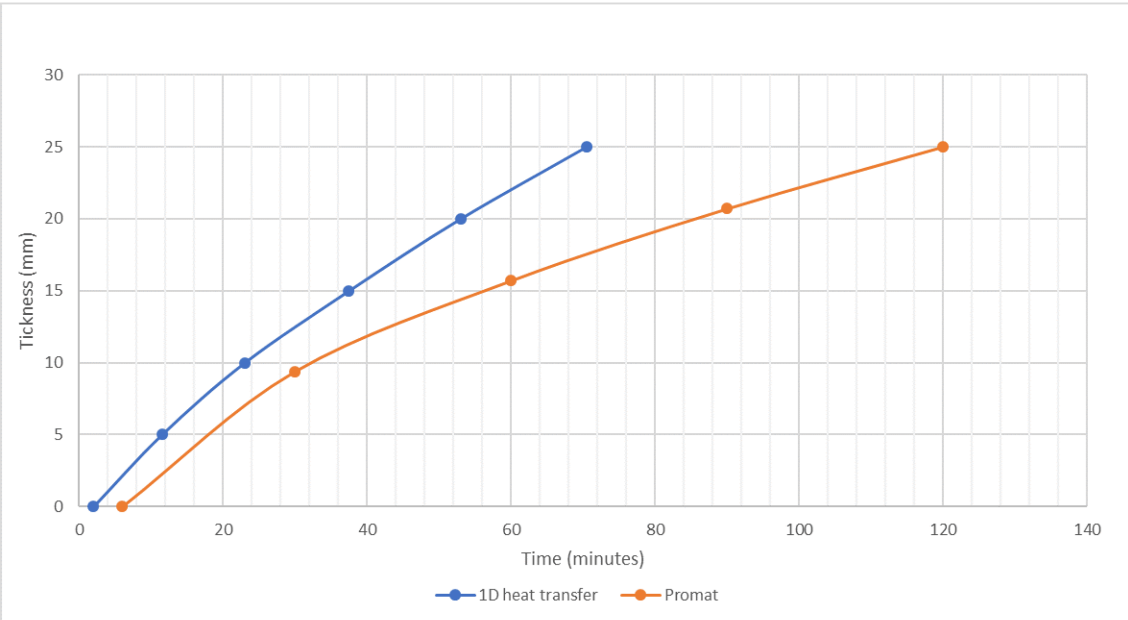


Figure 4.4: The time it took to reach a temperature of 200 °C at the surface of the concrete for both models.

4.3.2. Heat resistant coatings

Another possibility to passively protect the concrete is using a heat resistant coating. Multiple heat resistant coatings for concrete are currently on the market. These coatings will foam and form an insulation layer, like the steel coatings. However, no information was found how long it will take before the concrete is heated beyond this coating layer to 200 °C. Of importance, what will happen to the coating when the surface of the concrete will spall? Therefore, with the available information it is unknown how heat resistance coatings for concrete will perform due to spalling.

4.3.3. Fibres

As there is no spalling free concrete mixture, there is an option to add fibres to the mixture. Various researches are done on the matter, resulting in a mixture of results. Not all type of fibres are useful and the percentage of fibres has a big influence on the spalling ratio. Due to the fact the spalling mechanism is not fully understood, the effect of the fibres is unknown. Polypropylene fibres are the commonly used fibre type and not only used for the spalling of concrete as in increased the tensile strength and reduced the shrinkage [69].

4.3.4. Composite steel deck floor

A composite steel deck floor consists of two elements, a steel plate and on top of this deck a layer of concrete is poured. This steel deck is only a millimetre thick and in case of a car park fire will not isolate the concrete. Therefore the concrete is heated up fast and spalling will occur, however the concrete cannot move due to the steel deck. So the concrete will spall but will still isolate the reinforcement. The main uncertainty is the spalling force and therefore the chance it will go through the steel deck. During this thesis, two car park fires occurred in car parks with this type of floors. In Bordeaux France, 32 cars burned down in a closed car park as a result of arson. The fire took in total more than 18 hours, but from the pictures the floor elements had not failed. Some spalling had occurred on the concrete beams, but the floor seems to be intact [27] (figure 4.5A). The other case was in Cork Ireland, in an open car park were 45 cars burned out and the fire lasted more than four hours. The composite steel deck floor survived the fire, however the castellated beams were damaged too much and the car park is currently demolished [20](figure 4.5B).

Figure 4.5: The damage of composite floors as result of a car park fire. Figure A is the damage of the fire in Bordeaux [27]. Figure B is the damage of the fire in Cork [20].

4.4. Expected fire load

One of the trends in the car industry is the increase of plastic material (chapter 2.4.2). To further investigate the effect of this increase on the total combustion heat of a car, two studies are down on the material development of cars in the last 40 years. With the found information on the change in total combustion heat a closer look will be taken to possible development in the heat release rate of a car.

4.4.1. Total combustion heat of cars

The plastic content and the weight of passenger cars have increased until 2013 but is expected to decrease until 2020. The expectation for the next years is that these trends will continue [12]. The European Commission of mobility and transport performed a study on the positive effects of the weight reduction of cars on the CO2 consumption and the possibilities to reach the climate goals, less weight of the car results in a smaller fuel consumption of the car. To reach these goals the weight of the car should be further reduced and multiple vehicle companies have goals to reduce the weight of a vehicle with more than 100 kg in 2030 [12]. Possibilities to reduce the weight of the car include a smarter use of materials, for example using 3D printers. Another option is to replace steel with other materials. Two options to replace the steel are aluminium and strong plastics like carbon fibre reinforced polymers and both are commonly used. When steel is replaced with aluminium, there is no change in the total heat of combustion, however when changed to plastic the total heat of combustion is increased. From the McKearney study [24] (figure 2.12), the growing rate of plastic content in a passenger car can be seen. Processing this information with the weight of the car, figure 4.6 could be made. Plastic is a collective term for various materials. The main plastics in the car industry are polypropylene (PP), polyethylene (PE) and polyurethane (PUR). On average 63 % is polypropylene, 20 % is polyethylene and 17 % is polyurethane as used in a car [24]. The 'others' category is rather large it contains, for example, the car battery, glass and liquids.

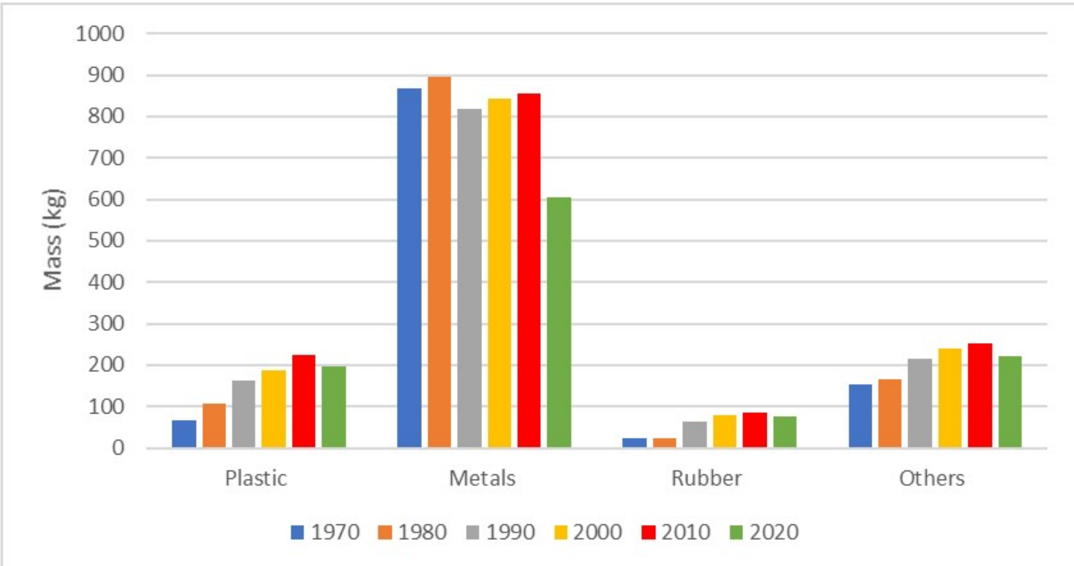


Figure 4.6: The development of different materials in passengers cars over the last years.

The total potential heat release of various materials is measured and tested over the years by different companies and expressed in MJ/kg. The most relevant materials are put in table 4.3 [66] [74]. With this information and the amount of kg of material in an average passenger car, the total combustion heat of a car can be calculated (figure 4.7). A peak in combustion heat is reached in 2010, but a downward trend can be seen for 2020. The curve of the heat release rate of CaPaFi is based on the research of TNO and EU partners (chapter 2.5.1). In this research car models from the '80s and '90s were ignited and the change in mass and the heat were measured. The heat release curve was the upper limit of the tested cars. Comparing the 2020 combustion heat with 1990 combustion heat an increase of 20 % can be seen. The combustion heats found are not the real expected values, as the group 'others' is rather large. This group contains materials which will also influence the combustion heat. Therefore, the numbers are not exact but give a good indication of how the trends in the car industry affect the total combustion heat. During a fire, the car will not burn down completely, some materials inside the car will not ignite. From the performed test by TNO and EU partners [37], roughly 70 % of the total combustion material will ignite during a fire.

Table 4.3: Combustion heat of various materials [66] [74].

	Combustion heat (MJ/kg)
Polypropylene	41,4
Polyethylene	41,6
Polyurethane	24,6
Metals	-
Rubber (tire)	27
Nylon	39
Polyester	24

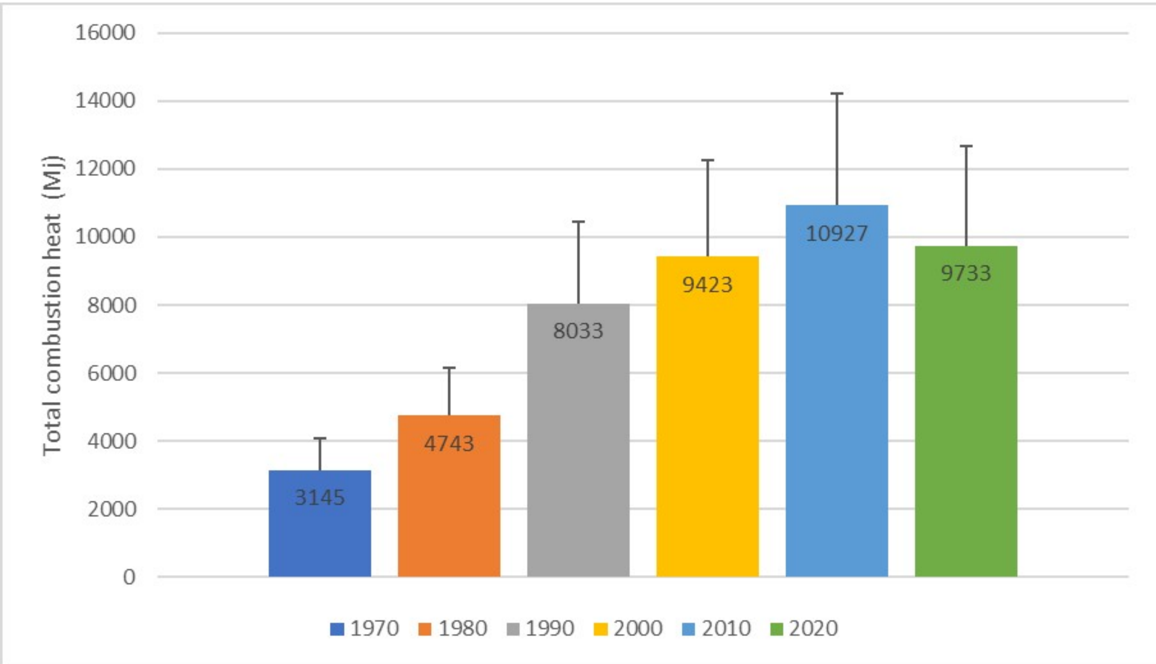


Figure 4.7: The development of the total combustion heat of a passenger car. An error bar is applied for the ‘other’ material group as it is not clear what percentage will release heat.

To verify the above calculation a second analysis is performed. A research was done on the material content of a light-duty vehicle for 1995 up to 2014 [60]. This data was used because it was more detailed, the category ‘others’ is smaller. The main difference in a light-duty vehicle with a passenger vehicle is the maximum curb weight. Light duty vehicle means that all the vehicles have a mass below 4600 lbs (2086 kg). So, this includes passenger cars, but also minivans and pick-up trucks. The same steps are done as for the previous analyses and the same trend can be seen for the total combustion heat (figure 4.8). A peak in combustion heat can be seen between 2010-2011 followed by a decline. This data gives also an insight into the increase of aluminium in cars, it almost doubles over ten years. The total heat release varies a lot between both analyses, in 2010 for the first analysis 11000 MJ and the second analysis 9600 MJ. Possibilities for this difference are how well the car was assets and the minivans and pick-up trucks contain more steel than a passenger car.

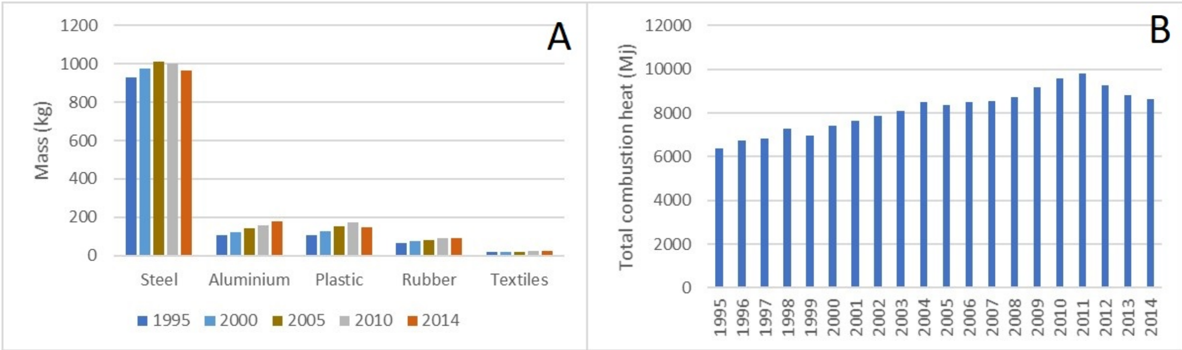


Figure 4.8: Figure A: The material trends of a light-duty vehicle between 1995 up to 2014. Figure B: The total combustion heat of a light-duty vehicle between 1995 and 2014.

4.4.2. Expected fire load

The fire load of a single car for the CaPaFi model [45] is based on the TNO and EU partners research [37]. This rate of heat release was the upper limits of the performed test. However, due to the increase of plastic the available fire load has increased. The used cars in this research were models from the '90s and an increase of 20 % in fire load was found for cars in 2020. Therefore, this rate of heat release for a car is no longer the upper limit, however still useful as there has not been any newer experimental research data on this matter. This 20 % increase can result in two different scenarios, based on the location of the newly added plastic. If this new plastic material is at the surface of the car, these plastics can directly start to ignite which will result in a direct increase in the heat release rate. So to visualise this, the rate of heat release is multiplied with 1.2 (figure 4.9). The other possibility is the plastic material is not at the surface but deeper in the car, for example in the frame. These new plastic materials will not have any influence at the start of the fire, however the total fire load is increased. Therefore, the HRR is integrated and this is multiplied with 1.2. As there will be no change in the starting phase, the HRR is only adapted after the peak value to reach this new integrated value. In figures 4.9 and 4.10 twenty cars are used to visualise a certain maximum heat release. The real scenario will be in between these two options, a part of the new plastic will be at the surface and a part will be deeper inside the car. Therefore, both options are extreme. In option 1 the peak is increased by 20 % and in option 2 this peak increases with 14 %, so the variation between the scenarios is not that large. Both integrals are the same, the total heat is increased with 20 %. Of importance in this calculation is the fire propagation time. In the 'Bouwen met Staal' guideline [45] and the NEN6098 [50] the fire propagation time is set on twelve minutes and this number is also used for the calculations. The fire propagation could be faster than twelve minutes, however when looked to the data from the case studies for the closed car parks there are no indications the fire developed faster. This heat release rate will not occur in a single place as it needs to travel in the car park to ignite new cars. A single structural element will not be exposed to an unlimited number of cars. In most cases, a structural element will be exposed to two or three cars.

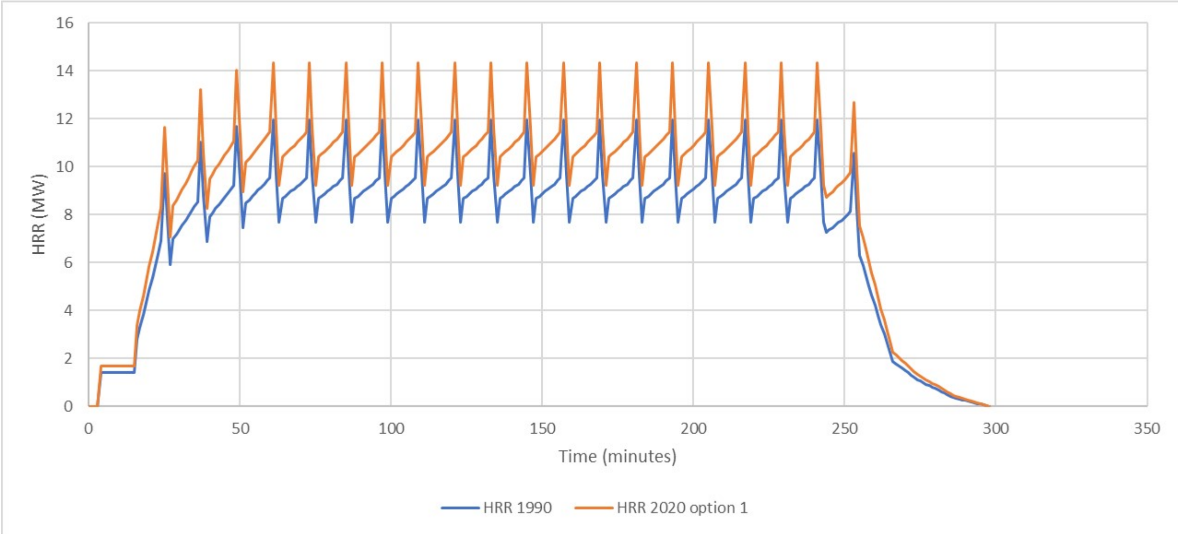


Figure 4.9: The original HRR in 1990 and option 1 for the HRR in 2020. In option 1 the original RHR is multiplied with 1.2.

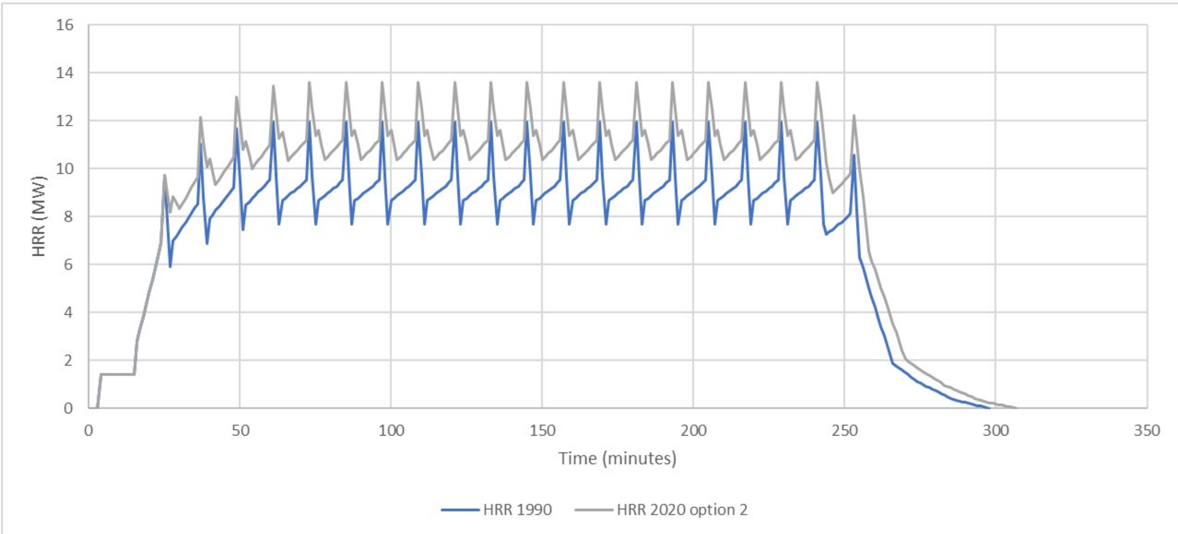


Figure 4.10: The original HRR in 1990 and option 1 for the HRR in 2020. In option 2 the integral is multiplying by 1.2 and the HRR is adapted after the peak to reach this new integral value.

4.5. Risk of electric cars

To power a car on electricity, a large battery is needed. The currently most used battery packs in a car are lithium-ion batteries. The big issue of this batteries is when on fire the number of resources and time needed to extinguish are large. The most effective way to deal with such a fire is to place the burning electric car in a big container with water and leave it there for several days [1]. This is not possible if the car is parked in a car park. Therefore, these electric car fires are a big issue in an enclosed space, simply drawing water from a dry riser is not effective enough. Due to the heating of this battery, a thermal runaway is started deep within the battery. Using a fire triangle to analyse this thermal runaway, oxygen is released by the overheated cathode and heat is produced by the electrolyte. The other parts in the battery can be considered as fuel, so a thermal runaway is a closed fire triangle: it does not need oxygen from the surrounding air to continue burning [84]. The batteries in cars are currently in development and safety mechanism are put in place in this battery to prevent a thermal runaway or to stop one. One of the mechanism is placing barriers inside the battery to separate different compartments [15]. By dividing the battery in smaller compartments the total amount of fuel is reduced and therefore if a thermal runaway occurs the duration will be smaller. If an electric car is on fire, a thermal runaway is a very likely scenario.

4.5.1. Fire scenarios with an electric car

When an electric car is on fire, the battery will be heated and a thermal runaway is likely to occur. The thermal runaway is the reason why the electric car keeps reigniting. Stopping a thermal runaway is not that easy and the only option is to cool down the battery package. If a thermal runaway does not occur there are two possible scenarios: a) the battery will not be involved in the fire and b) an explosion. A few explosion have occurred with battery packages [30], the explosion is unfavourable as it could result in an explosion of 0.4-9 MJ. This explosion could result in a shockwave pressure of 37 kPa at 50-meter distance of the source [85]. The shockwave is strong enough to damage the structure and to blow people to the ground. These explosions are currently investigated [30] as the goal of the engineers is to prevent them from occurring.

4.5.2. Extinguish an electric car

The only available option proven effective to extinguish an electric car fire, when the battery is on fire, is to submerge it completely in water. This has already been used as a tactic by the Dutch fire department. The car is lifted and placed in a container filled with water, and the car is left there for at least 24 hours. If the burning car is parked in an enclosed car park, this is not an option since lifting the car into a water-filled container is not possible. Therefore, there are currently no effective methods to effectively deal with an electric car fire in an enclosed environment. If the fire service succeeds in extinguishing the burning car and the battery continues to reignite, the fire service is forced to stay and keep the unburnt parts of the car wet or covered in foam, otherwise the fire may grow again and propagate to other cars. The fire service might consider allowing the car to fully burn out; then, the battery fire may be allowed to reignite as it is not capable of causing propagation by itself. Towing the burning car out of the car park does not seem feasible, except when after the burnout the fire is limited to the reigniting battery. In both cases, the solution is relevant only if either the fire service or a sprinkler system has limited the fire to one or a few cars. Only then is the concept of dealing with one or a few carcasses with reigniting batteries realistic.

4.5.3. Dealing with an electric car

The electric car is gaining a bigger market and is expected to take a big role in our future vehicle fleet. Therefore the likelihood of these cars to park in the car park is increasing and introduces new risks concerning fire safety. The electric car has approximately just as much total combustion heat no board as any other car. The main difference is the peak HRR that occurs in fuel cars when the fuel tank fails and the fuel ignites; this peak is not expected in an electric car. Therefore, to efficiently and successfully deal with this type of fire it useful the fire department knows what type of vehicle is on fire. As visibility is poor in case of a fire, it may be useful to separate vehicles in a car park. Placing all the electric vehicles in one area will support the fire department by making decisions on possible tactics. It still however, does not deal with how to extinguish the fire. If proper equipment is available it is possible to equip the car park with these. Another positive effect of grouping the electric cars is the possibility to place them at a low-risk location. Possible locations could be in an open car park on the roof. Steering this type of car to park at certain places is not that hard, many car parks have electric charging stations. Most of the electric cars will park at these charging stations. Grouping the cars can be seen as a passive protection method. A sprinkler installation will probably keep the fire to the original electric car like a normal car and the electric car fire will be not a risk for the sprinkler installation. However, if explosions are more likely to occur than this will compromise the sprinkler installation and possibly damage the system to such an extent it is no longer useful. There are also some concerns about the use of a sprinkler installation on an electric car fire. As a result of the reignition of the battery more water is needed to control the fire. The NFPA 88A, the American code to design a sprinkler, is recurrently revising this standard. One of the changes is to enhance the amount of water that is needed for a sprinkler in a car park [5].

4.6. Risk of pressurised tanks

In the Netherlands there are currently three types of fuel systems with pressurised tanks, Liquefied petroleum gas (LPG), Compressed natural gas (CNG) and hydrogen gas. In the literature study, it was found for the Netherlands that these types of cars do not have a big market (chapter 2.4.1). However, it is expected that hydrogen-powered vehicles will grow in market share. The various gases need a different working pressure, LPG cars have a pressurised tank of 32 bar, a CNG tanks have a pressure of 200 bar and a hydrogen tank has a working pressure of 700 bar. LPG is heavier than air and in case of leakage these gases will drop to the ground. Hydrogen and CNG are on the other hand lighter than air and will move upwards. In case of a fire, three possible scenarios can occur, a jet fire, tank rupture resulting in a fireball and a gas cloud explosion.

4.6.1. Jet fires

By law it is required to install a temperature activated pressure relief device (TPRD) on pressurized tanks. This TPRD is a safety mechanism that in case the tank pressure exceeds 1.5 times the working pressure or the temperature reach 120 °C will start to release the gas. The aiming direction varies for the different gases (chapter 2.3.4). By releasing the gas before the tank wall fails by weakening, an explosion of the gas tank is avoided, so the release of gas is the most favourable outcome. In case of a fire, the 120 °C barrier will be reached and the TPRD will release the gas when functioning properly. Since the heating is caused by a fire in the car, most likely the gas will catch fire directly when exiting the TPRD resulting in a jet flame. The release speed depends on the opening size and the (working) pressure. A general diameter for this TPRD is 5 mm, however a piece of rubber is placed inside the tube resulting in a diameter less than 3 mm. The length of the jet flame is important for the fire propagation to adjacent objects and the safety of fire department personnel. Two different models were used to anticipate the possible length of the jet (table 4.4). In case of a hydrogen tank, a maximum jet flame length of 22.7 meters is expected, for a CNG tank 18 meters and for an LPG tank 11 meters [85]. So, when a jet is aimed from the side of the car towards an adjacent car, this jet will very likely ignite the next car. Maybe even the car beyond the adjacent car, given the length of the flame. There are cases where a TPRD has failed in case of fire, but also cases where the tank failed before the TPRD could operate. The pressurized tank is not heated uniformity and the tank wall weakens enough for the tank to shear, leading to the immediate release and an explosion. An investigation was done on the malfunction of TPRD in case of a fire and in 14 of the 90 cases the tank exploded [19].

Table 4.4: An overview of possible jet lengths for different gases and diameters. To different mathematical models were used to estimate the length of the jet fire [85].

	Diameter (mm)	HRR (MW)	Jet length Delichatsios (m)	Jet length Lowesmith (m)
LPG (32 bar)	2.5	1.9	5.4	3.7
	5.0	7.6	11	6.2
CNG (200 bar)	2.5	7.0	7.3	6.0
	5.0	34	18.0	10.8
Hydrogen (700 bar)	2.5	27	11.4	9.9
	5.0	108	22.7	16.6

4.6.2. Gas cloud explosion

If a TPRD starts to release the gas without it being ignited, the released gas could form a cloud and when ignited a very big explosion could occur. A gas cloud explosion has not yet been reported in a car park or a tunnel and is not likely to occur. Hydrogen and CNG gases will rise upwards and will ignite due to the hot smoke layer, therefore a cloud cannot be formed. LPG will move downwards and a cloud can be formed. The expected energy release and the strength of the shock wave of a gas cloud explosion can be seen in table 4.5. An explosion with a force of 5-7 kPa will throw people to the ground, windows will break and construction elements will be damaged [85]. So, when a gas cloud explosion will occur people in small proximity will die and the building will be severely damaged, maybe even collapse. It is not very likely in case of a fire the released gas of a TPRD will not catch fire, however another possible scenario is the leakage of a pressurised tank and a fire occurring in another vehicle. Therefore, sufficient ventilation in a car park is needed to prevent a cloud.

Table 4.5: An overview of the energy release and shock wave due to a gas cloud explosions [85].

	Energy (MJ)	Overpressure at 50 m (kPa)	Overpressure at 100 m (kPa)
LPG (32 bar, 10-50 kg)	1.4-11	30-600	30-223
CNG (200 bar, 10-50 kg)	0.5-200	15-780	15-730
Hydrogen (350, 2-6 kg)	0.2-0.7	19-38	18-36

4.6.3. Explosion of the tank

When a TPRD is not functioning in case of a fire, the pressure inside the tank will increase and the tank will start to decay. The tank is often made of some sort of plastic, in case of a fire these tanks will start to melt. This process will eventually lead to the failure of the tank and the gas will be released rapidly through cracks eventually leading to an explosion. This fast release of energy will lead to a high-pressure wave which will result in structural damage (table 4.6).

Table 4.6: An overview of the energy release due to an explosion of the pressurised tanks for different gases [85].

	Energy (MJ)	Overpressure at 50 m (kPa)	Overpressure at 100 m (kPa)
LPG (32 bar, 10-50 kg)	2-14	10-16	7-11
CNG (200 bar, 10-50 kg)	5-26	15-29	10-20
Hydrogen (350, 2-6 kg)	5-18	10-15	7-11

4.6.4. Temperature activated pressure relief device

Pressurised tanks have introduced new risks to the car park structure. Due to the small percentage of vehicles with a pressurised tank these new risks did not yet realise into actual incidents in a car park. With the expected increase of hydrogen-powered cars due to the climate goals, these cars will park more often in a car park, resulting in a bigger probability. The most likely scenario is a jet fire, however it is unknown in what direction the TPRD is aimed to. Having uniformity in this direction, preferable vertical, a better risk assessment could be made for the fire propagation. When aimed horizontal towards the next car, this car will ignite. Aimed vertically, there will not be a direct contact of the flame with the next car. However, a lot of energy is released and this could speed up the fire propagation. More uniformity on the TPRD direction will also help the fire department in dealing with these types of vehicles, however unlikely as the regulation of TPRD is global. In case of a fire the firefighters cannot see what type of vehicles is on fire and due to the possibility of the TPRD aiming horizontally a proper distance is needed between them and the vehicle. In other words, approach a pressurised car is not possible before a jet fire, as jet could have a length of 20 meters.

4.6.5. Extinguish a pressurised car

When the TPRD functions a jet flame is expected with a length up to 20 meters. Approaching such a vehicle before the TPRD has been activated is quite hazardous since activation cannot be predicted certainly not from a distance, and when it happens the extremely hot jet flame is established within tenths of a second. The fire services can only safely approach a burning car with a pressurised gas tank if the TPRD has activated and the jet flame has died down. If the TPRD does not activate, the tank is almost certain to fail at a certain point, leading to an explosion. This means they must maintain a safe distance of tens of metres to the burning car. After the jet or explosion had occurred the fire department can approach the car only if it did not ignite a neighbouring car with a pressurised tank, starting the same waiting process. In practical terms, if the fire services know or suspect that more than a negligible fraction of parked cars runs on pressurised gas, they should leave the fire to its fate as they cannot be expected to risk their life approaching the burning car or cars.

4.6.6. Dealing with a pressurised car

Due to the bad visibility in a car park as a result of a fire, the fire department cannot see what type of car they are dealing with. With the possibility of a jet fire having a length of twenty meters going in any possible direction a safe distance is needed between them and the cars. To create a better idea of what type of car is on fire, grouping them in a specific area could help the fire department. After the jet has occurred the fire-fighters can approach the fire as a normal car fire. A sprinkler installation will be damaged due to the explosion of the pressurised tanks or the resulted blast waves. The damage could vary from damage sprinkler head up to damaged pipes. If the sprinkler system is damaged, water will not reach the fire and will not contain the fire.

5 Discussion

To achieve the climate goals [46], changes are needed in various industries. The car industry is one of these industries where a lot of changes are happening. This has resulted in various fuel systems that are now available, however five years from now different fuel systems may be available. As car parks are generally built to last more than a few years, these trends should be followed and anticipated. The market share of electric cars is growing strongly and is possibly taking a big role in the near car fleet. Pressurized gas vehicles currently have a market share of 1.5 % in the Netherlands, so there is a relatively very small chance these cars will catch fire. It is unknown whether these types of vehicles will grow substantially in market share. Therefore it is unsure how big the risks of pressurized tanks in car parks will be in the future. The data used to analyse the trends in the total combustion heat of cars are based on average material development for passenger cars and light-duty vehicles. The average mass of a car has changed over the years. One option to explain this is the development of lighter materials in a car, it is also possible people tend to drive smaller cars. Also, by using the average development it is unsure what possible peak loads could be. For example, a smaller car could have a higher content of plastic in comparison to an SUV. This could result in a smaller deviation of total combustion heat between a small and a large car. The car industry has set goals to make a car lighter, so less fuel consumption is needed per kilometre. It is unsure how these goals will be achieved, the most obvious option is replacing steel with lighter material. However this could be done with aluminium and plastic, so it is unclear how this development will affect the total combustion heat of a car and the heat release rate. The maximum interface concrete-insulation temperature, 200 °C, to perform calculations for the heat-resistant cladding material is based on tunnel tests with an RWS curve. This heat progression of a car fire is different than by an RWS curve. Also, concrete elements in a car park can be heated from multiple sides, for example a concrete column can be heated on four sides whereas a tunnel segment can only be heated at one side. Heating from multiple sides will also affect the conditions of the cladding material and this effect is unknown. The need for car parks is a subject not discussed in this thesis, but of importance. Self-driving cars are in development and are currently used. When these cars are fully functional somewhere in the future, car parks may no longer be needed in cities as there is a possibility the car drives home or to a location outside the city. Temporary car parks are currently used and built as the demand for parking spots near dense areas is unknown due to the self-driving car.

6 Conclusion

The research question of this thesis is: does the change of fuel sources and other innovations in modern cars, inuence the structural damage in car parks in case of a fire. To answer the research question, sub-questions were formulated to answer the main questions.

The first sub-question relates to fires in car parks that have occurred and asks what type and level of damage were found in these car parks. To investigate what damage is caused by a fire located in a car park, four case studies were executed. From these case studies, it can be concluded that the most significant damage is caused by the spalling of concrete. As a result of the spalling, the reinforcement was exposed to the fire and heated up much faster than assumed, resulting in a faster strength reduction. Spalling of concrete is a serious issue and bare concrete will spall due to a car fire. Another type of damage that had occurred with the prefabricated floors is the debonding between the layers. The prefab floor with the reinforcement detached from the poured concrete layer and was hanging from the ceiling, so this element has failed. This floor type is currently under investigation by Dutch authorities as it is not certain if the floor was correctly connected in the first place. Although significant constructional damage can be caused by a fire, the collapse of a car park was rarely observed. When comparing the fire-resistance time and the fire duration time, much larger damage was expected. To note is that the fire-resistant time is based on the ISO-curve 834 and not a car fire and the fire-resistant time is only an indication to compare structures. The King's Dock car park is the largest car park fire that has occurred worldwide. This open car park was a standard open car park, there was no large variation in the construction with any other open car park. Therefore, this fire could have occurred in any open car park. It should surprise no one if that kind of extremely large fires becomes much more common.

The second sub-question is how frequent a fire in a car park occurs in The Netherlands. The annual probability on a fire was found to be $7.1 * 10^{-7}$ per m^2, quite similar to a fire in any other occupancy, which has a probability on $4.0 * 10^{-7}$ per m^2. The probability that a fire can progress in a fire involving more than seven cars is 9 % and this percentage is expected to grow as a result of the new approach of the fire department and the increase of total combustion heat of a car. A closer look was taken to the outcome of occurred fires between an open and a closed car park. There was no measurable difference observed between the probability on a fire occurring in an open car park and the probability on a fire occurring in a closed car park. Although, it seems that fires in open car parks seem to have a higher probability to develop to more cars, this contrary to the 'classical truth' that fires in closed car parks are much more difficult to extinguish.

The third sub-question is, what are options to deal with the spalling of concrete. From recent tunnel tests involving exposure to the RWS-curve, it was found that, generally, keeping the concrete under 200 °C spalling is not occurring. The previous design criterion for design a tunnel was a concrete temperature of 380 °C, so this design criteria has changed. A fire for which the RWS-curve is designed for is not likely to occur in a car park, however the same damage type is observed in a car park. A possible passive method to protect the car park and to deal with spalling is by using heat resistant cladding material. This method has been tested extensively and it is possible to isolate the concrete in such a manner to keep the temperature under 200 °C for 120 minutes with a thickness of 25 mm Promatect-H. Other possible methods are using fibers in the concrete mixture or apply a fire-resistant coating, both methods are currently under investigation. There are currently no regulations on the use of fibers on concrete and the only current method to be sure is to test the concrete mixture. For the heat-resistant coatings it is unsure what will happen if spalling occurred.

The fourth sub-question related to the expected fire load in a car park. An analysis of the trends in the car industry was performed and it was found that the total combustion heat per car has increased with 20 % in comparison with the cars from the 90s. However, it is unsure how materials in cars will develop. Expected is that the plastic content will increase and the total weight of the car will decrease. The heat content of a car has increased, however it is unknown how fast this heat will release over time. That is not the result of a simple inventory: the only possible method to know whether the HRR increased, is to carry out systematic new fire test series with modern cars. So far, these have not been done, so the expectation that the increased plastics content leads to more intense fires is not more than an informed expectation.

The fifth and six sub-questions related to the risks of electric, LPG, CNG and hydrogen cars in a car park. The danger of the currently popular lithium-ion battery is the reignition as a result of thermal runaway. This thermal runaway is by itself a closed fire triangle. The only current option to extinguish an electric car is to place the battery underwater. However, when a car is parked in a closed structure, lifting a car is not possible. Therefore, there is currently no effective method to deal with such a fire in a car park. This should be further investigated. Alternative options are for example covering the car in a dense foam or covering the burning car by a fire blanket. LPG, CNG and hydrogen-powered cars are equipped with pressurised tanks. These tanks are equipped with a TPRD and the aiming direction varies per car. A jet fire could reach a length of 20 meters and therefore is likely to speed up the fire propagation, defeating the primary benefit of a sprinkler system if present. If the tank is heated unevenly or if the TPRD malfunctions, explosions can be expected with blast pressures reaching of 10 up to 29 kPa. This will blow people to the ground, damage the structure and even the sprinkler system.

The electric cars have the same fire load, but there are yet no effective methods to extinguish the battery fire in an enclosed space; just letting it be for one or two days is unattractive. The pressurised tanks bring new risks to the car park. The fire department cannot safely approach such a car before the jet has not occurred, as the jet will have a maximum length of 20 meters and if the TPRD failed an explosion will occur. The fire department needs to keep its distance and this will result in an increase in fire load on the structure as the fire can freely develop. It is likely a sprinkler cannot control the fire in the event of a jet fire that inevitably occurs when the TPRD activates in a burning pressurized gas car; in the less likely event of the tank exploding the sprinkler system can easily be damaged and fail. Therefore studies are needed into the danger of pressurised gas cars in sprinkler protected car parks.

Due to the spalling of concrete, the reinforcement will heat up faster than anticipated. However, the fire department extinguished these fires (except the King's Dock car park). The cars are still in development and the fire department will less often extinguish fires in car parks resulting in an increase of the total heat that will be released in these fires and enlarging the risk of collapse. The King's Dock car park fire was anticipated to be impossible. However, the structure was a normal open car park where a single car fire expanded to the complete car park. Therefore, such fires are likely to occur and will occur more often.

In summary, the fires in car parks seem to have increased in fire load as resulted in the increase of total combustion heat and the new approach of the fire department. Due to the spalling of concrete the probability on the failure of the concrete elements has increased and there are two possible methods to reduce this chance, isolate the concrete or limited the fire (sprinkler installations). Taken into consideration the new risk of the alternative fuel system, the probability of collapse has also increased as a result of an explosion and jet fires. The explosion will directly affect the structure and jet fires will speed up the fire development. As there are some big uncertainties on the effectiveness of a sprinkler installation on an electric car and the redundancy against an explosion, the only option left is to isolated the concrete.

6.1. Recommendations

- Identifying the car type that is on fire is important as the various fuel system have different risks. As visibility due to smoke is poor, the cars cannot be seen. Therefore placing cars at a certain position dependent on the fuel system will help the fire department to estimate the risk. Easy to do while a fuel system has a very small market share, less practical otherwise.
- To guarantee the integrity of the concrete passive, protection methods need to be applied. A well tested option is fire-resistant boards.
- The composite steel-concrete floor is a good option to use in a car park. The steel will not prevent the spalling of the top layer, however the concrete cannot go anywhere. This spalled concrete will still protect the reinforcement.
- Sprinkler installations can control the size of the fire to one car, however this has not yet been verified for electric, LPG, CNG and hydrogen-powered cars. These cars introduce new risks that could compromise the complete sprinkler system and allow a fire to spread to full involvement. Therefore the sprinkler installations need to be tested and optimized for these types of cars. If a pressurised tank will explode, the sprinkler system may be damaged but to what extent is unknown. The possible damage should be analysed, and a more robust design may be needed.
- The total amount of combustion heat in a car has increased, but a downward trend has started some years ago. To verify the influence of this on the heat release rate, tests should be performed with the newer cars.
- New tactics should be developed on how to deal with an electric car fire in an enclosed space.
- As the likelihood of large fires in car parks is increasing, a larger probability of safe evacuation is needed of buildings that are underneath or on top of car parks. To support a fast and safe evacuation, an effective detection system in the car park is needed and an alarm signal should be lead to occupancies on top or underneath the car park. A distinction should be made between types of occupancies: in an office or commercial occupancy, people are awake and mobile, they can leave the building fast. In a residential building, people could be sleeping and more time is needed to evacuate, requiring a reliable detection system and sufficient and safe escape routes. The biggest risks are hospitals and occupancies where people need support to evacuate. For these functions, it is often not possible to evacuate fast, or even at all, and a higher fire-resistance is needed for the structure or the fire should be kept small. Evaluating the risks of evacuation is needed to design a fire-safe car park.

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