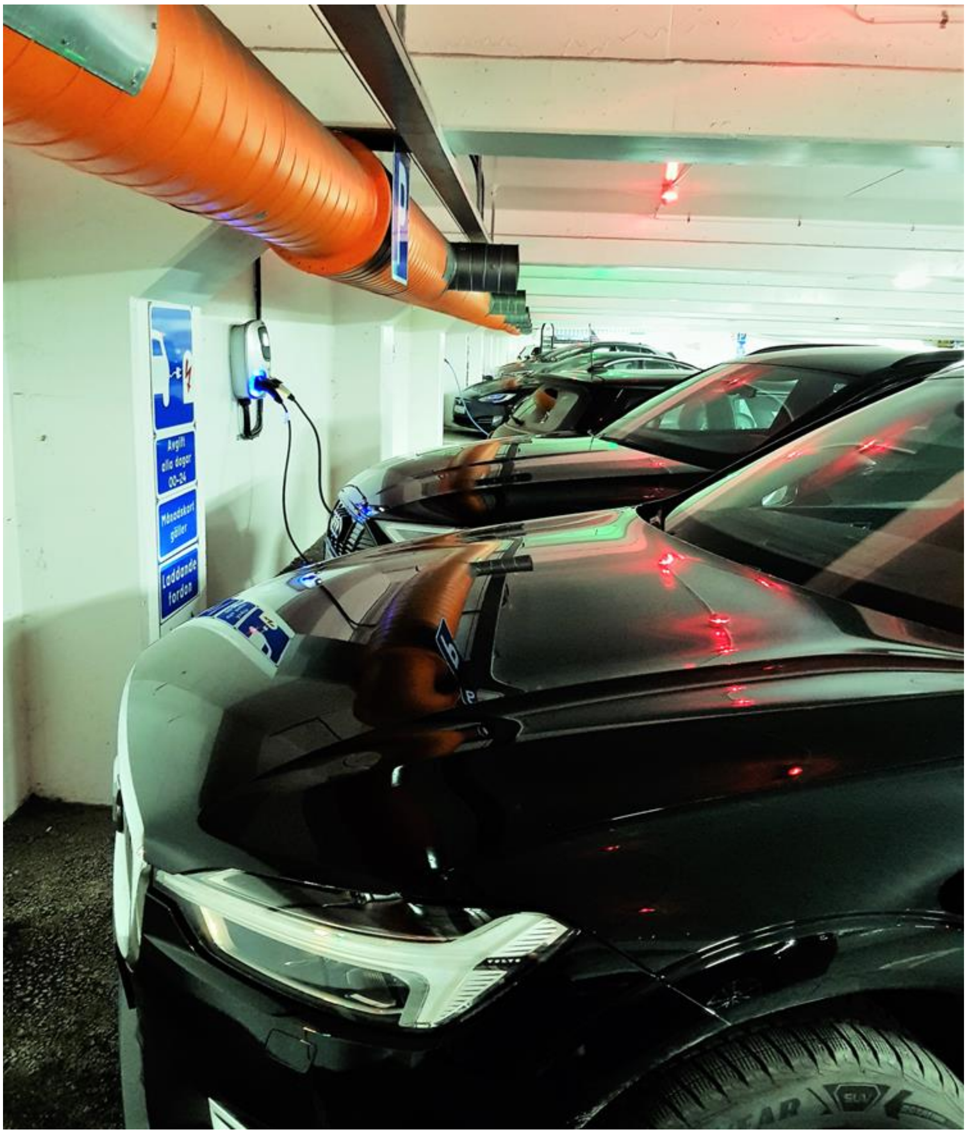
SAFETY AND TRANSPORT
FIRE SAFE TRANSPORT



Electric Vehicle Fire Safety in Enclosed Spaces

Jonna Hynynen, Maria Quant, Roshni Pramanik, Anna Olofsson, Ying Zhen Li, Magnus Arvidson, Petra Andersson

RISE Report 2023:42

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Abstract

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Lately, concerns regarding fires in electric vehicles in enclosed spaces such as in road tunnels and parking garages have been raised and there are indications that parking of electric vehicles may be prohibited in some spaces. For the success of electromobility and the transition from fossil to renewable fuels, it is important to understand the risks and consequences of fires in electric vehicles and to provide technical solutions if necessary, so as not to hinder the widespread adoption of electric vehicles.

In this work, a literature review on fires in vehicles has been conducted. The focus was on fires in enclosed spaces involving electric vehicles. A comprehensive risk assessment of electric vehicle fires was performed using systematic hazard identification. In addition, a workshop with representatives from three Swedish fire and rescue services was carried out to evaluate the emergency rescue sheets/response guides.

The main conclusions are; That statistics regarding vehicle fires need to be improved, as of today the root causes of fires are missing in the data, which could potentially result in non-fact based regulations; The data studied in this work does not imply that fires in electric vehicles are more common than fires in internal combustion engine vehicles; Fires in electric vehicles and internal combustion engine vehicles are similar in regards to the fire intensity and peak heat release rates.

The most effective risk reductions measures on vehicle level, to decrease the number of fires in EVs, could not be defined based on that relevant data on the root causes of fires in EVs are currently not publicly accessible. The most effective risk reduction measures, to limit fire spread, on infrastructure level were the use of fire sprinkler systems, fire detection systems (early detection) and increased distance between parked vehicles.

Key words: Electric vehicle, fire safety, enclosed space, parking garage, vehicle fire, field experience, hazard identification

Cover photo: Anna Olofsson, RISE. Public parking garage in Sweden with charging station for electrical vehicles.

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Summary

Concerns regarding new risks of fires in electric vehicles (EVs) compared to internal combustion engine vehicles (ICEVs) have been raised lately. The concerns primarily relate to fires in enclosed spaces such as parking garages and road tunnels. Consequently, there are indications that some stakeholders want to prohibit EVs from underground parking garages. For the success of electromobility and the transition from fossil-to renewable-fuels, it is important to understand the risks and consequences of fires in EVs and provide technical solutions if necessary, so as not to hinder the widespread adoption. It is also vital that non-fact-based discriminatory treatment of EVs is prevented.

This work has investigated the risks and consequences of fires in EVs with a focus on enclosed spaces such as parking garages and tunnels. The overall goal was to identify differences and similarities between fires in EVs and ICEVs and to propose measures to prevent and mitigate fires in enclosed spaces both at infrastructure and vehicle level. The conclusions and proposed measures have been based on all parts of the study, which included a literature study, a risk assessment based on hazard identification workshops (HAZID) as well as a workshop with personnel from fire and rescue services.

In the literature review, data was collected from three main sources: statistics, scientific journals, and reports along with media reports. The statistics regarding the cause of fire in EVs are limited and many cases are reported as “Unknown”. The lack of knowledge regarding the root causes of EV fires may contribute to discriminatory treatment of EVs.

The HAZID workshops were conducted according to ISO 31000:2018, including hazard and risk scenario identification, comparative risk ranking, and risk evaluation. The risk assessment contained scenario descriptions of how the risk can materialize and considered possible modes of operation of the vehicle. The influence of the operation mode on the incident and its outcome were also considered. A total of four HAZID workshop sessions were performed.

Furthermore, emergency response guides/rescue sheets were evaluated together with representatives from the Swedish fire and rescue services. This was accomplished by sending out a survey as well as through a workshop. Discussions during the workshop pointed out that material and the thickness of reinforced parts used in vehicles should be stated in the emergency response guides/rescue sheets. Among the attending recuse service personnel, there was a desire to increase the use of sprinkler systems, or at least standpipe systems, in parking garages. Finally, a large part of the workshop was dedicated to discussions regarding the electrical safety of EVs during rescue operations. Two anecdotal accounts of electrical shock related to EVs, and rescue operations were shared.

The main conclusions and proposed effective measures from the study are highlighted below. It is, however, important to keep in mind that in 2022 the number of EVs compared to ICEVs on the roads is still very low, and EVs are relatively new. Therefore, the impact of an aging and growing EV fleet on the fire safety and number of incidents is unknown.

The main conclusions from the literature review are listed below:

- The sparse data available does not indicate that EV fires are more likely than fires in ICEVs, rather the contrary by a factor of 8 - 10.
- Fires in EVs share similarities with fires in ICEVs, such as peak heat release rate and total heat release. However, while thermal runaway in EVs is difficult to extinguish, ICEV fires pose the hazard of a high intensity pool fire which can easily spread.
- Case studies and statistics on incidents in enclosed spaces (such as tunnels and enclosed parking garages) for EVs are currently very limited.
- Charging should be performed using the right equipment. Unavailability of charging stations in certain type of garages might lead to that drivers will use non-adequate equipment to charge their vehicles, which could potentially increase the fire risk.
- Sprinkler system design in accordance with EN 12845:2015+A1:2019 for parking garages is adequate, based on field experience and large-scale tests, for passenger vehicles (including both ICEVs and EVs).

The considered most effective risk reduction measures to prevent fire spread in enclosed spaces are listed below:

- Early fire detection either through fixed detection systems or/and through vehicle integrated smart systems
- Sprinkler systems in enclosed parking garages
- Increased distance between parked vehicles (wider parking spots) and increased ceiling heights of parking garages.

The most effective risk reductions measures at a vehicle level, to decrease the number of EV fires, could not be established due to lack of data on the root causes of fire.

1 Introduction

This study was performed by RISE Research Institutes of Sweden on behalf of European Automobile Manufacturers' Association (ACEA).

1.1 Background

Vehicle fires release toxic smoke which besides causing an environmental damage pose risk to human health. In addition, vehicle fires can cause structural damage to infrastructure and the consequence can be severe, depending on factors such as location and fire spread. One recent example of a such an incident occurred at Stavanger airport in 2020, where a car park partly collapsed due to a fire incident. The incident had huge financial consequences, since the airport had to be shut down, in addition to the lost parking structure and several hundred damaged vehicles. [1]

Full scale vehicle fire tests show that there are minor differences between fires in electrical vehicles (EVs) and internal combustion engine vehicles (ICEVs) regarding the produced effluents. However, the intensity of the fire and quantity of emissions will depend on parameters such as the type and size of vehicle. [2] Knowledge regarding similarities and differences between fires in EVs and ICEVs is of great interest since EVs are predicted to dominate the market in the future. In 2021, the sales of EVs around the world doubled compared to the previous year. As the number of EVs is increasing, the number of fires involving EVs are also expected to increase.

Today, commercial EVs are all powered by a class of batteries called lithium-ion batteries (LIBs). LIBs can enter an unstable state called thermal runaway due to external or internal factors such as excessive heating or mechanical damage. During thermal runaway, the temperature inside the battery increases rapidly and toxic and flammable gases are generated from chemical reactions in the cells. In many cases, the gases released from the ruptured cells will also ignite. Fires that start in the traction battery of an EV are rare, but once thermal runaway and fire has started in the traction battery, it is difficult to extinguish. One reason is that the battery packs are usually well protected and hard to reach with the fire suppressant.

During the past years, concerns regarding elevated risks of fires in EVs compared to ICEVs have been raised. The concerns primarily relate to fires in enclosed spaces such as parking garages and tunnels. Consequently, there are indications that some stakeholders for example want to prohibit EVs to park in underground parking garages. For the success of electromobility and the transition from fossil fuels to renewable fuels, it is important that misconceptions related to fires in EVs do not hinder the widespread adoption. It is also vital that non-fact-based discriminatory treatment of EVs is prevented.

1.2 Objectives

In this study, the overall objective was to investigate the risk of fire of EVs, with a focus on enclosed spaces such as parking garages and road tunnels. One goal was to identify potential similarities and differences between fires in EVs and ICEVs. Another goal was to propose appropriate risk reduction measures to improve fire safety for EV fires, based on the risk assessment methodology. Additionally, a goal was to evaluate the requirements on emergency rescue sheet and response guides in the ISO 17840.

1.3 Method

Different methods have been used throughout the study. The methods used included a literature review, data collection, data analysis, numerical fire simulation, risk assessment and a workshop regarding the emergency rescue sheet/response guides.

Data Collection

Field data were collected from three main type of sources:

- statistics
- scientific articles and reports
- media reports

The statistics were collected from the civil contingency agencies in Sweden (MSB), Norway (DSB), and Denmark (BRS). Additionally, statistics from USA, United Kingdom and China were included. Statistics and data from full-scale vehicle fire tests can be found in Appendix A.

Reports and scientific articles were collected by a literature search in the digital scientific archive (DiVA) and by visiting homepages of scientific journals along with screening reference lists in relevant reports. Presentations and publications from the biannual conferences Fires in Vehicles (FIVE) and International Symposium on Tunnel Safety and Security (ISTSS) were examined, and relevant contributions were added to the data collection. Articles from newspapers and media reports were collected by searching through several search engines on the web (Google, Google Scholar, and Bing). Searches at various homepages of newspapers were also performed and relevant articles were added to the data list.

Data Analysis

The collected data were analysed, and a comparison was made in terms of number of occurrence of fires for EVs and ICEVs. The intensity and size of fire were also compared. In cases where several vehicles were involved in the fire, the spread was evaluated in terms of whether it was affected by the energy carrier (EV or ICEV). Other consequences of the fire event such as emissions and jet-flames were also noted. In addition, fires in enclosed spaces and existing fire safety requirements were analysed and discussed.

Simulations

To facilitate the risk assessment related to gas explosions, previous numerical data were collected from published articles, and one additional simulation was performed. More details can be found in the section regarding explosions.

Risk Assessment

A risk assessment was performed by utilizing systematic hazard identification (HAZID) workshops followed by ranking of selected fire scenarios (according to ISO 31000). The risk assessment was based on the aforementioned literature study and engineering judgement from experts within RISE. The risk assessment included three steps: hazard identification, comparative risk ranking, and risk evaluation. The risk assessment included scenario descriptions of how the risk can occur and considered possible modes of operation of the vehicle. Furthermore, it was included how the modes could influence the incident. The workshops considered the fire development, the surroundings where the fire occurs, and the possible outcomes of the fire with and without mitigating measures.

A total of four HAZID workshop sessions were performed, each dedicated to a specific theme. In addition, two more sessions were carried out, dedicated to introduction and debriefing. Each session lasted for 3.5 – 4 hours and they were conducted online. A facilitator led and underlined the scope of each session, and a scribe role was assigned for documentation. During the introduction session, the scope was defined and exemplified, along with descriptions of important terms and assumptions. During the first session, unwanted events for the four themes were defined, as documented in Appendix B, Table A1. Each of the four following HAZID workshop sessions then used these events as starting point for identification of factors affecting the unwanted event, current and potential safety measures, as well as differences between EV and ICEVs. Based on the HAZID and literature study, risk reduction measures were proposed. Before the final debriefing session, all the experts had the possibility to revisit the documentation (Microsoft Excel sheets) produced during the HAZID sessions, to add comments, reflections, and further insights. The risks of the unwanted events were then rated, and the effectiveness of the risk reduction measures were evaluated in terms of mitigated consequences of the scenarios considered in the HAZID sessions. The outcomes and proposed risk reduction measures from the HAZIDs are presented in section 3 and the documentation from the sessions is presented in Appendix B.

Workshop with the Swedish Fire and Rescue Services

The requirements in the emergency rescue sheet and response guides (ISO 17840 series) were studied and discussed in a workshop involving representatives from three Swedish fire and rescue services. Representatives from Räddningstjänst Syd, Södra Älvsborgs räddningstjänstförbund and räddningstjänsten Luleå were present during the workshop.

Prior to the workshop, a questionnaire was sent out, using Utkiken newsletter, to the fire and rescue services in Sweden. Utkiken is a web-based platform that connects over one hundred fire and rescue services in Sweden. Utkiken collects relevant information for the fire and rescue services and connects over one hundred fire and rescue services in Sweden. The goal with the questionnaire and the workshop was to identify if any information is missing in the emergency rescue sheet and response guides. A summary of the workshop is presented in section 4.

2 Literature Study

This section presents the collected data and analyses of the collected data. The number of vehicle fires, root causes of these fires, fire intensity and risk of fire spread have been analysed. Additionally, other consequences of vehicle fires (secondary effects) such as emissions, extinguishing water contamination, jet flames and gas explosions are also covered in this section. Lastly, a brief overview of existing fire protection regulations and field experiences from enclosed fires is included.

Reflections from the data collection and data analysis is later used in combination with result from the hazard identification workshops to reflect upon the risk of fire of EVs and to propose appropriate risk reduction measures.

2.1 Vehicle Fires

The occurrence of vehicle fires and vehicle fire incidents found in literature has been analysed from the collected data. Since the total number of EVs is lower compared to ICEVs, the statistical data available are still limited. Furthermore, in many databases the energy carrier of the vehicle is not specified, thus fires in EVs and ICEVs cannot be distinguished. Additionally, reported data does not state if the energy carrier (i.e. battery) caused or was involved in the fire or not. In this section, statistics from Norway, Sweden, Denmark, The United States (US) and China are presented.

Up to date, Norway is the country with the highest proportion of EVs, with 17.3% of the passenger car fleet consisting of EVs at the beginning of 2020. [3] The Norwegian directorate for civil protection (DSB) has studied the fire occurrence of EVs and ICEVs; data is presented in Figure 1. The total number of vehicle fires between 2016 and March 2022 is higher for ICEVs than for EVs (Figure 1b), but no account has been taken to the higher proportion of ICEVs.

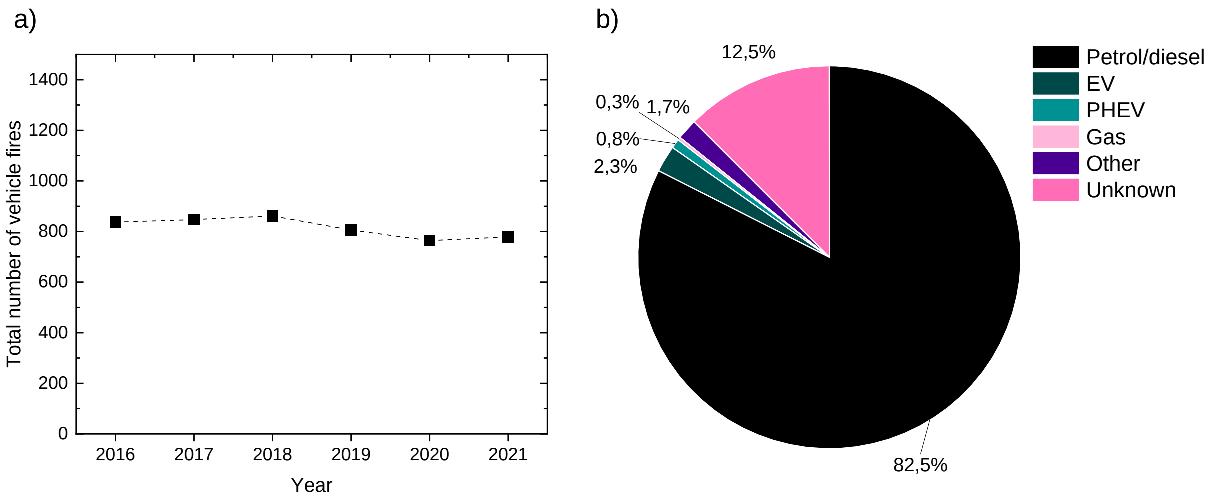

Figure 1. a) Total number of vehicle fires in Norway between 2016 – 2021 and b) total number of passenger vehicle fires in Norway between 2016 and March 2022, divided by the type of energy carrier.

Considering only the data for ICEV and EV fires in Figure 1b, EVs represent 2.7% of the ICEV and EV fires, while they represented 17.3% of the passenger car fleet at the end of the data period. This indicates about a factor 8 lower relative fire frequency of EV than of ICEV. Interestingly, the total number of vehicle fires also shows a slightly declining trend from 2018 and forward. However, this trend might not be due to an increasing proportion of EVs but due the Covid pandemic (2020 – 2021), which might have affected the number of vehicle fires due to the increased number of people working from home and less travels made using passenger vehicles. [4]

In Sweden, the statistics regarding vehicle fires are collected by the Swedish civil contingency agency (MSB). MSB collects data in the IDA database [5] from all incidents that the fire and rescue services attend. A comparison of the relative frequency of ICEV and EV, including plug-in hybrid electric vehicles (PHEVs), fires is presented in Table 1. The relative frequency of EV fires is lower than for ICEVs with a factor of about ten less frequent. One should keep in mind that the EV fleet is younger than the compared ICEV fleet. There are some limitations in the data collected from IDA, namely that the energy carrier is not always specified and that fires initiated "during charging" may also include charging of the 12 V battery of an ICEV.

The proportion of fires reported for electric transportations has increased from 2018 to 2021, most of these fires (78.2%) can be attributed to scooters, kick-bikes, hoverboards and electrical bicycles/motorbikes (see Figure 2).

Table 1. Total number of passenger vehicles in Sweden (2018 – 2020) and the total number of fires per energy carrier [6]

Year	Number of EVs and PHEVs	Number of EVs and PHEVs fires	Relative frequency of fires	Number of ICEVs	Number of ICEV fires	Relative frequency of fires
2018	156 500	8	5 x10-5	4 900 000	3800	80 x10-5
2019	214 500	6	2 x10-5	4 900 000	3400	70 x10-5
2020	308 500	20	6 x10-5	4 950 000	3400	70 x10-5

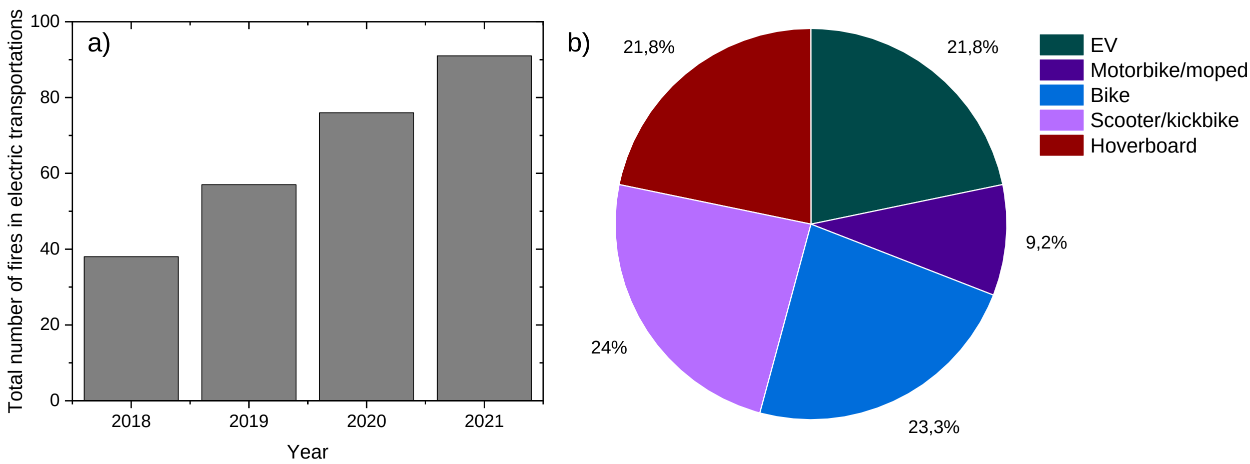

Figure 2. a) Fires in electric transportations in Sweden (2018 – 2021) and b) divided by the type of transportation. [6]

In the statistics from Denmark, fires in charging stations and in the traction battery are identifiable together and the total number of fires are presented in Table 2. In the Danish statistics, the overall number of fires related to fires in power installations in buildings has increased compared to previous years (data studied from 2013). Most of these fires can be attributed to fires in cables but an increase is also seen for fires in charging stations and in the traction battery (Table 2).

In the US, the national fire protection association (NFPA) reports fire statistics, including vehicle fires. [7,8] The US had a total of 1.4 million fires in 2020 and 15% of these were in vehicles (12% in highway vehicles, i.e. 173 000 fires, with 580 deaths and 1500 injuries). The vehicle fires were responsible for 18% of the deaths and 11% of injuries. In 2020, NFPA stated that "*While hybrid and electric vehicles have become more common, existing data collection systems have not yet adequately captured the frequency of fires involving these specific vehicles*." [7]

Additionally, the model year of the vehicles involved in fires (that occurred in 2018) have also been studied by NFPA. Fires due to technical malfunction are more common for vehicles around/or older than 15 years. For newer vehicles (only a couple of years old), collision incidents are the most common cause of fire.

Table 2. Fires in charging stations and vehicle batteries in Denmark per year, number in brackets indicate the total number of fires reported for power installations

Year	Number of fires in charging stations and vehicle batteries in power installations **Buildings**	Number of fires in charging stations and vehicle batteries in power installations **Open spaces**
2016	2 (146)	0 (66)
2017	1 (146)	0 (79)
2018	4 (208)	1 (82)
2019	2 (222)	2 (101)
2020	10 (294)	10 (129)
2021	7 (285)	7 (138)

Data on 100 vehicle fire incidents, see Appendix A, Table A2, involving 122 EVs and PHEVs, were analysed. [6,9] Most of the reported fires occurred when the vehicle was parked (47.5%) or parked and charging (21.3%), see Figure 3. A similar trend was also observed in data collected by the ALBERO project, [10] where 66/113 (58%) of the identified EV and PHEV fire incidents had occurred when the vehicles were parked or parked and charging. This might suggest that parked as well as parked and charging vehicles propose an increased probability of fire. However, to be able to draw this conclusion, the time that EVs are driven compared to the time that they are parked or parked and charging needs to be evaluated. Such statistics could potentially be retrieved from vehicle manufacturers. Furthermore, as seen in Figure 3b the origin of fire (fire root cause) is to a large extent reported as unknown. The large uncertainty of the root causes of fire may hamper the development of appropriate risk reduction measures at a vehicle level.

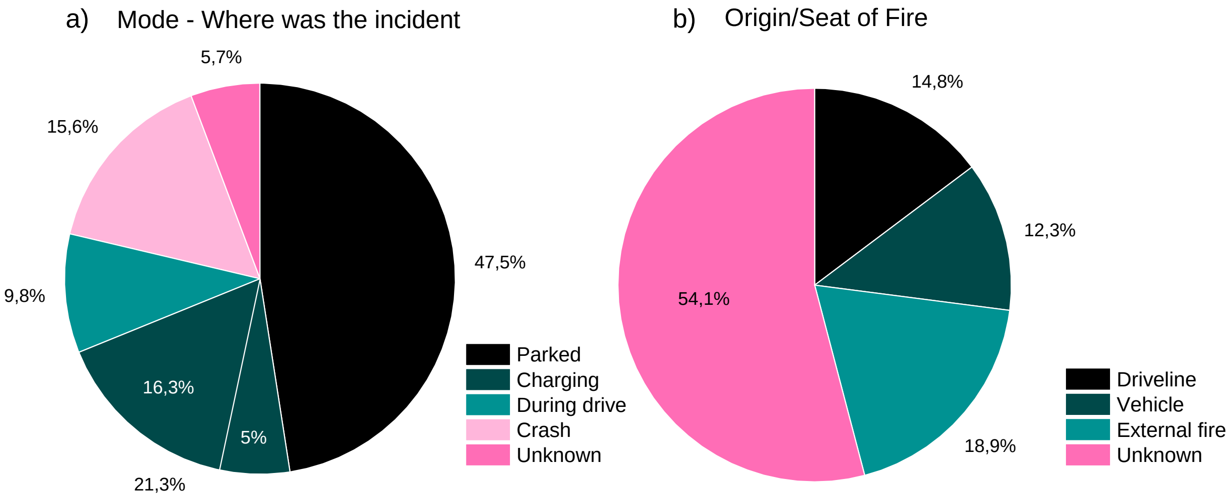

Figure 3. Data on 100 reported EV/PHEV fire incidents, involving a total of 122 vehicles, including where the incident occurred and the fire root cause. The smaller area (5%) in the charging slice represents fires externally ignited while charging (faulty installation, extension cable, wall socket etc.).

Limited statistics from China were retrieved in this project. Vehicle fires reported for the first quarter of 2022 are presented in Figure 4. The data does not distinguish EVs, but they state that out of the total 19 000 vehicle fires, 0.33% were reported for alternative fuel vehicles, [11] these also include gas vehicles. The data analysed does not reveal where the fire incident occurred, neither did it report fires related to collisions or the origin of fire. The most common fire origin was electric faults, but the connection to EVs for these fires is unknown.

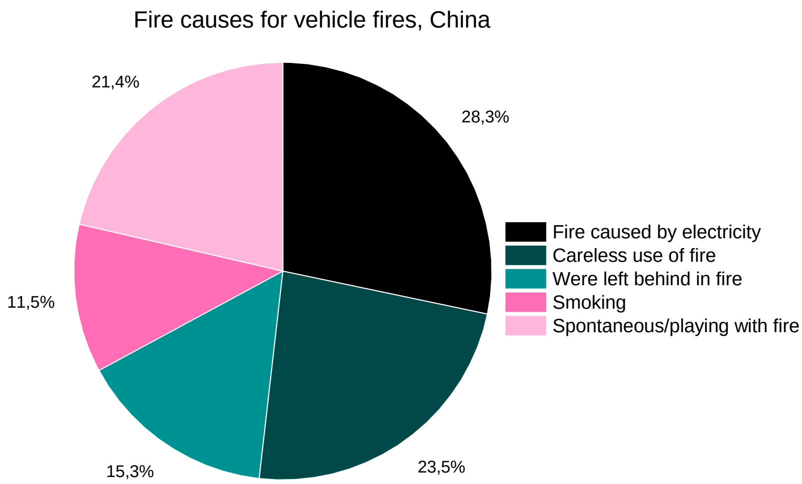

Figure 4. Vehicle fire causes reported for the first quarter of 2022, China. [11]

The main conclusion from the available data is that EV fires are not more likely than fires in ICEVs, rather the contrary by a factor of 8 - 10. However, as EVs are still relatively new and few, it might be that the number of EV fires will increase as the fleet becomes larger and as the fleet ages. Recommendations on more detailed statistics are encouraged, especially regarding the root causes of fires, as well as if the traction battery was involved or not in the fire. In addition, the energy carrier is normally not reported in statistics of vehicle fires, which makes statistical studies difficult.

Fire Causes

In this study, for the HAZID workshop, fire causes have been divided into four subcategories.

- arson
- fires related to the energy carrier (fuel tank or traction battery)
- other parts in the vehicle (e.g., engine compartment, wheels)
- external factors

Arson includes all intentional fires. This subcategory of fire cause is independent of the type of vehicle and the scenario is difficult to predict and prevent. The subcategory, fire related to energy carrier includes the petrol tank for ICEVs and the traction battery for EVs. The third category, other parts in the vehicle, includes fires starting at any other part of the vehicle, e.g., engine compartment, brakes or 12 V battery. Finally, external factors are fires resulting from for example faulty equipment, extension cables, charging stations, not including parts of the vehicle itself.

Regarding the likelihood of fire causes, the subcategories arson and external factors should be similar whether the vehicle is an EV or an ICEV. Fires causes related to the energy carrier will vary if the car is an ICEV or EV.

Intensity of Fire

To compare similarities and differences between fires in ICEVs and EVs, literature values of the peak heat release rate (HRR) and the total heat release (THR) were collected (see Appendix A for references) and are presented in Figure 5.

A vehicle fire typically lasts for 60 – 90 min, has a peak HRR in the range of 1.5 – 10 MW and an average THR of 5.9 GJ. [2] The total chemical energy available in a vehicle will vary depending on the vehicle type and size, and on the materials used to manufacture the vehicle. For example, the trend towards heavier vehicles and use of more plastic [12,13] in vehicle production will increase the chemical energy (total available fire energy). This is also visible in Figure 5 if comparing the peak HRR and THR for ICEV (1), that represents vehicles manufactured before year 2000, to ICEV (2), that represents vehicles manufactured after year 2000.

The collected data shows that there are no significant differences between ICEVs and EVs regarding the peak HRR (maximum intensity of the fire) or the THR (total energy combusted).

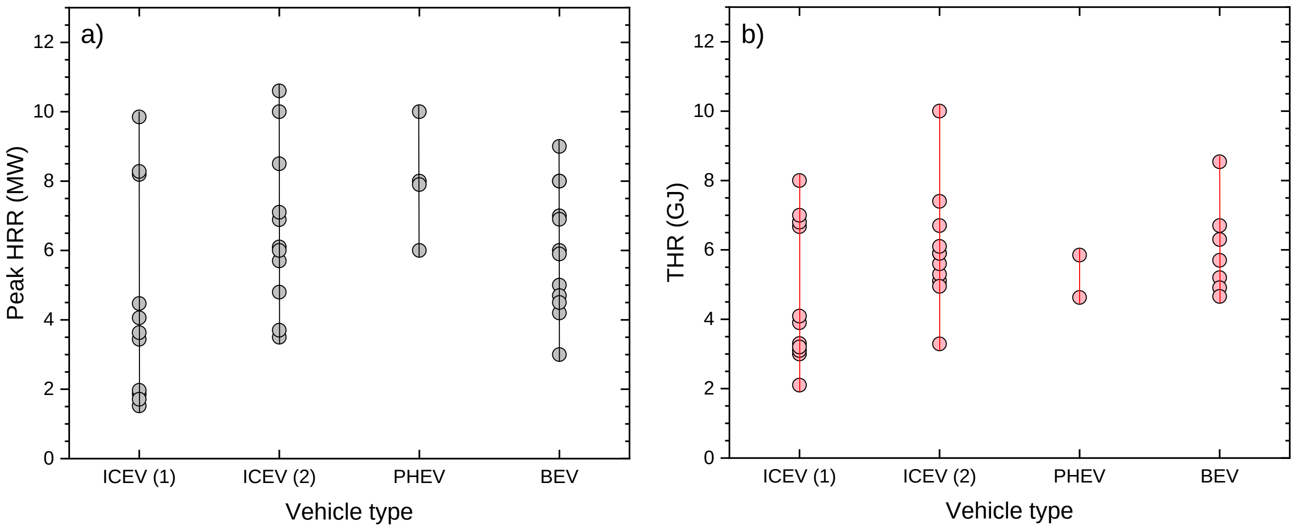

Figure 5. a) Peak HRR and b) THR for ICEVs, PHEVs and BEVs. ICEV (1) represents vehicles manufactured before year 2000 and ICEV (2) vehicles manufactured after year 2000. References can be found in Appendix A.

The Probability of Fire Spread

Current design requirements and recommendations for parking garages assume that the fire will not spread between adjacent vehicles. However, incident reports indicate the fire can spread from one vehicle to the next vehicle in e.g., a parking garage fire. Additionally, regulations regarding fire detection systems varies between different jurisdictions. It is sometimes assumed that people will notice the fire and alert the fire and rescue service or to extinguish the fire with a handheld extinguisher. Previous experiences on parking garage fires show that this is not the case. On the contrary, it usually takes a long time before a fire is detected, which leads to a delay of the arrival of the fire and rescue service.

The probability of fire spread in enclosed spaces is affected by three main factors:

- distance between parked vehicles
- material used to manufacture the vehicles
- ceiling height of the enclosed space

The distance between parked vehicles will depend on the size of the vehicle, the size of the parking spot, as well as of the occupancy of the parking garage, i.e. the density of the parked vehicles. Fire and heat can spread through direct flame/plume contact and through radiation. A shorter distance between the parked vehicles increases the probability for direct plume/ flame contact. Additionally, today's vehicles are generally wider than their previous models. For example, a BMW 3 series was 1.6 m wide in 1992 and 2.03 m wide in 2019. For an increase in width, from 1.6 m to 2.0 m, the distance between two vehicles is reduced from 0.9 m to 0.5 m. The radiation is inversely proportional to the distance squared and consequently, the radiation will increase with a factor of ~ 4. The width of the parking spot will also affect the distance between parked vehicles. In Sweden, a parking spot is generally 2.5 m wide.

The material used to manufacture the vehicles will also affect the fire scenario. For example, the increased use of plastics will increase the fire load and available chemical energy. When vehicle fire requirements were developed in the 1950s, hardly any plastics were used in vehicles. In 1970, 6% of the total vehicle weight was contributed by plastics, and in 2020 it had increased to 18%. [13] This might result in an offset in the fire safety requirements in relation to the vehicles used today. Additionally, the mass and height of passenger vehicles has also increased since the 1990's. [14] The distance between the vehicle and the ceiling in the enclosed space will also have an impact on the fire spread. A low ceiling height (or increased height of the vehicle) will increase the radiation from the ceiling down towards the vehicles and therefore increase the risk of fire spread.

The mentioned factors that enable fire to spread are similar for EVs and ICEVs. One additional risk with ICEVs is the possibility of liquid pool fires. Liquid pool fires can result from rupture of the petrol or diesel tank, due to for example external heating. Liquid pool fires may increase the fire spread and the extent will depend on the amount of fuel, the incline of the flooring and drains adjacent to the vehicle. One case of liquid pool fire spread was found in the literature review and is presented in more detail in section 2.3, Fire Incidents in Parking Garages.

For EVs the possibility of jet flames from the battery pack could potentially contribute to the fire spread. Jet flames are commonly deflected underneath the vehicle and could potentially reach a neighbouring vehicle and cause ignition. However, to the best of our knowledge, specific studies of this phenomenon have not yet been performed. Gehandler and Lönnermark [15] studied jet flames from the thermally activated pressure relief device (TPRD) of compressed natural gas (CNG) tanks for vehicles. The resulting jet flames were 1 – 10 m long depending on design of the TPRD and the incident radiation at 12 m was rather low, 2 kW m^{-2}. Jet flame resulting from an EV are substantially shorter in length and duration, as noticed during vehicle fire tests performed at RISE.

Other Consequences of Fire

Other consequences of vehicle fires are further elaborated in the following sections. Secondary effects include fire emissions, contaminated extinguishing water, explosions and that the vehicle starts to move during a rescue operation.

Emissions

Emissions from vehicle fires contains a variety of toxic gases such as carbon monoxide, hydrogen cyanide, volatile organic compounds, polyaromatic hydrocarbons, hydrogen halides, and metals along with soot particulates. [2,16] These effluents are found in all vehicle fires (both for ICEVs and EVs) and are a direct danger to first responders since inhalation of these gases and compounds can be fatal.

Comparison of emissions from EV and ICEV fires show that hydrogen fluoride, together with some specific metals (such as nickel, cobalt, lithium, and manganese, depending on the battery chemistries) are found in somewhat higher concentrations in the combustion gases from EVs than from ICEVs. [2]

In a previous RISE project, "Fire in new energy carriers on deck, BREND 2.0", [17,18] it was found that the danger of the combustion gases, in an enclosed space, posed no practical difference between EV and ICEV fires. These results were based on computer simulations, where the fractional effective dose (FED) of asphyxiants and the fractional effective concentration (FEC) of irritants were modelled in a ro-ro space. Another conclusion from the conducted simulations was that ventilation was important when it came to the magnitude of the FED and FEC. Values exceeding 0.3 (design value equivalent to when 11 % of the general population will be incapacitated by exposure [19]) were found at all heights in the enclosed space model (without ventilation), while only exceeding 0.3 at the ceiling height in the open space model. It is important to bear in mind that all vehicle fires, regardless energy carrier, pose a danger to human health due to the toxic emissions formed.

Extinguishing Water

Preliminary results from studies performed at RISE in the project "Investigation of fire extinguishing water from vehicle fires, ETOX-2", show that the fire extinguishing water was highly toxic towards aquatic species, for both ICEVs and EVs. The extinguishing water collected from the ICEV fire test was somewhat worse than the water collected from the EV fire test. However, per- and polyfluoroalkyl substances (PFAS) were found in higher concentrations for the LIB tested. Further studies on the existing PFAS substances in LIBs or LIB fires are currently very limited which indicates a need to further validation of these findings.

Explosions

In case of thermal runaway, the traction battery will vent gases. To a large extent these gases consist of carbon dioxide, hydrogen, carbon monoxide and various hydrocarbons. [20] The volumetric percentage of hydrogen in the vented gas varies from a few percent up to 30%, depending on cell chemistry and state of charge. [20,21] Hydrogen is a highly flammable gas, with a wide flammability range and a great laminar flame speed. This poses a potential risk of gas cloud explosion in enclosed spaces. Additionally, the risk of a gas explosion will be affected by the ventilation conditions and the release scenario.

Gas explosions related to large battery energy storage systems have been reported, for example, an explosion on a ferry with battery propulsion [22] and in a stationary battery energy storage system. [23] No reports on explosions due to accumulation of battery vent gases from EVs have been found. The risk of flammable gas clouds is less probable for diesel, petrol, and ethanol vehicles, whilst the risk for gas powered vehicles (if there is a leak) is higher.

In work by Li, [21] a numerical model was developed to obtain blast wave pressures, resulting from the explosion of a hydrogen gas cloud, in a 50 m^2 tunnel. The peak blast wave overpressure as a function of the distance from the cloud centre, for various quantities of hydrogen mixed with air in the tunnel, is presented in Figure 6. The pressure drops rapidly around 20 m from the cloud centre and attenuates slowly along the tunnel. The simulation using 1 kg of hydrogen was performed for this study, whilst the other simulations were retrieved from work by Li. [21]

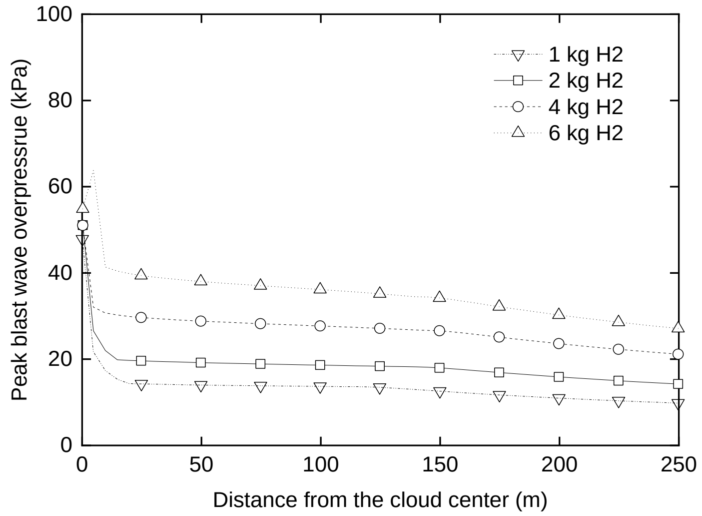

Figure 6. The blast pressure as a function of distance for various quantities of hydrogen gas stoichiometrically mixed with air in a tunnel.

The total amount of vent gas formed, can be estimated to ~ 0.5 L Wh^{-1}. [24] This indicates that a 100 kWh LIB could potentially release ~ 50 kg of gas. The total concentration of hydrogen could therefore be ~ 1.4 kg (1 – 2 kg). For 1.4 kg of hydrogen, the peak blast pressure would end up between 14 – 20 kPa, at a distance of 20 – 50 m (see Figure 6). Notice that the contribution of other vent gases is not considered and may affect the outcome of the numerical model.

For trucks that carry larger battery packs, the explosion hazards could be severe, and should be addressed. Furthermore, the distribution of hydrogen and location of ignition will influence the explosion hazard. The distribution of hydrogen gas is affected by the release pattern, geometry of the enclosed space and ventilation conditions.

Vehicle Starts to Move

A vehicle that starts to move during a rescue operation could potentially result in crush injuries and is a risk to the firefighters and car passengers. This risk is present for both ICEVs and EVs. Firefighters that attend a vehicle fire usually block the wheels of the vehicle before they intervene. Which will decrease the risk that the vehicle would unintentionally start moving. For EVs, that generally are quieter than ICEVs, there could potentially be difficulties to assess if the engine is on or off, especially if the surroundings are noisy.

Fire-Fighting Practises

Recommendations on how to manage vehicle fires in ro-ro spaces onboard ships were developed in the RISE project "Fire in new energy carriers on deck BREND 2.0". [18,25] EVs, H_2 and CNG vehicles were included in the study. Conclusions from this study were that the initial fire in all type of passenger vehicle fires should be handled in a similar way, regardless of energy carrier. In fact, liquid fuels (such as petrol and diesel) are more likely to initiate or contribute to the fire at an early stage (e.g., liquid pool fires) than the alternative fuels. Here, an offensive tactic could be effective, but the personnel that fights the fire needs to be prepared for the fuel-dependent hazards that may occur.

Regarding firefighting intervention, it was concluded that the chance for a successful intervention was higher during the initial fire development for alternative fuel vehicles, given early detection and trained and prepared crew. Initial intervention could be conducted by an unprotected person, a fixed firefighting system (FFFS) or by the fire team onboard.

The preceding project "Fire-fighting of alternative fuel vehicles in ro-ro spaces, BREND" investigated methods and equipment for firefighting with alternative fuel vehicles in ro-ro spaces. [26,27] Further investigations have been made in the project "legislative assessment for hazards of fire and innovations in ro-ro ship environment, LASH FIRE" by conducting full scale fire tests on electric cars with LIBs. In some of the tests, different tools and methods for firefighting were evaluated, for example vehicle fire blanket (Figure 7), handheld devices for cooling and boundary cooling fognail. One of the main conclusions from the drills in LASH FIRE was that drills are very important, to get the crew familiar with the different tools used.

Recommendations for firefighting interventions can also be found in the TUSC handbook. [28] The recommendations found in the TUSC handbook focus on fire interventions in the construction phase of a tunnel/underground construction, but a general conclusion from this handbook is that the development of smoke is one of the major challenges with fires in enclosed spaces. The smoke is accumulated in the tunnel which makes evacuation and intervention more difficult compared to a fire incident above ground.

Figure 7. Firefighters applying a vehicle fire blanket during the fire drills in the LASH FIRE project. Photo by Anna Olofsson, RISE.

2.2 Enclosed Spaces

The enclosed spaces considered within this study include parking garages and road tunnels. Parking garages are further divided into "enclosed parking garage" and "open parking garage". An "enclosed parking garage" is defined as an enclosed building or structure, built above or below ground, where vehicles can ingress/egress only through opening(s). In addition, these spaces require mechanical ventilation. An "open parking garage" is fully or partly built above ground and is naturally ventilated. The code definitions varies but typically, an open parking garage should have uniformly distributed openings on two or more sides with a total open area of at least 20 – 50 % of the perimeter wall area of each floor level.

Road tunnels considered within this study are divided into bi-directional or unidirectional tunnels, where the ventilation system can have either longitudinal or transverse ventilation (Figure 8). For a longitudinal ventilation system, air flows from one end to the other, while for a transverse ventilation system the air flows are transversely transferred from one side to the other through supply and exhaust fans. For a semi-transverse system, only supply fans **or** exhaust fans are in operation. Notice that the locations of supply and exhaust ducts may be different to the schematic drawing (Figure 8), e.g., both ducts may be placed at the upper part of the tunnel.

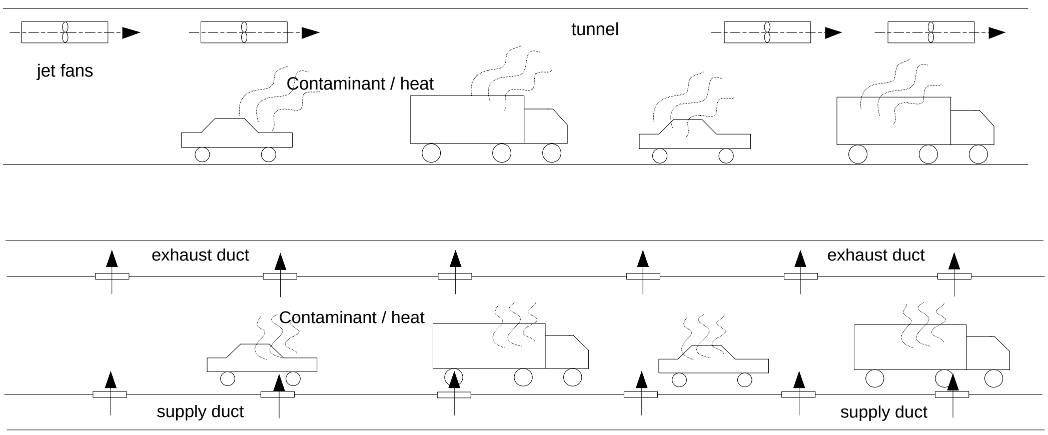

Figure 8. Schematic images of a tunnel with (top) longitudinal ventilation, sideview, and (bottom) transverse (not vertical) ventilation, top view; taken from reference [29].

2.3 Vehicle Fire Incidents in Enclosed Spaces

Vehicle fires in enclosed spaces are further described below, divided into fires in parking garages and fires in road tunnels.

Fire Incidents in Parking Garages

The number of fires in parking garages in Sweden between 2005 – 2019 are presented in Figure 9. The number of fires show a small increase over the years; the reason behind this increase is unknown. Additionally, three accident investigations of underground parking garage fires in Sweden have been studied in detail. A conclusion drawn from these investigations is that the environment for the fire and rescue service attending underground car park fires is harsh, especially due to thick smoke and long access routes. All three reports indicate that structural damages were found (concrete spalling) which could potentially impose a great danger. In work by Terlouw, [14] where statistics on car park fires and spread between vehicles were covered, the fires developed beyond the first vehicle in 42% of the incidents studied. Terlouw also noted that major structural damage was common and concluded that the fire will most likely spread much faster in an open car park compared to an underground garage due to the availability of air as well as wind. [14]

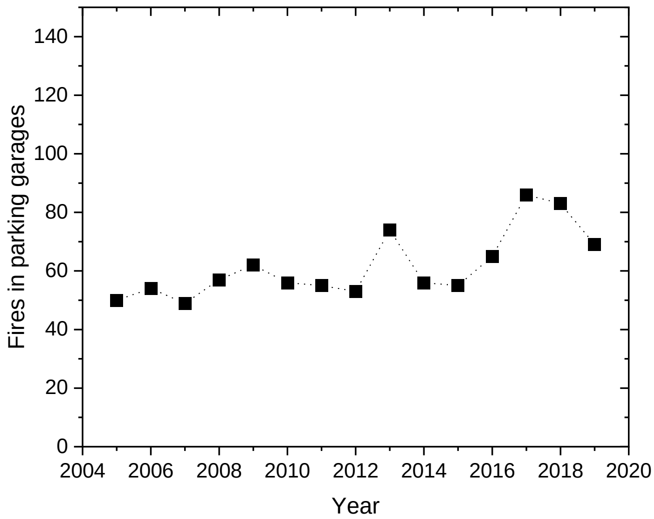

Figure 9. Number of fires in parking garages in Sweden between 2005 – 2019. References can be found in Appendix A.

Statistics on car park fires in the UK are presented in Figure 10. The data indicates that the total number of fires is higher for multi-story parking garages above ground than for underground parking garages. The extent of damage was although similar for the two groups. The reason for the large extent of damage in 2014/15 could not be found (Figure 10b). For 2017/18 the large extent of damage could be coupled to the fire at King's Dock, Liverpool, which resulted in 1 400 destroyed vehicles, and took 36 hours for the fire and rescue service to control. The car park was an open car park consisting of six floors, with natural ventilation. According to the fire investigation, the fire started in a Range Rover (ICEV) and spread to nearby cars. After ~ 1.5 hours the fire spread to another floor through the drainage system (liquid pool fire). The structure was completely damaged but did not collapse.

Another major car park fire is the fire at Stavanger airport in Norway. [1] The fire brook out in an Opel Zafira (ICEV) on the 7th of January 2020 and the vehicle was parked on the ground floor. Not long after the fire started, it spread to over 10 vehicles and subsequently also to the first floor. Accident investigations show that the wind conditions aided in the rapid fire spread. After approximately 2 hours, parts of the car park collapsed. The incident at Stavanger airport resulted in a huge financial loss since the airport had to be shut down and several hundred vehicles were damaged.

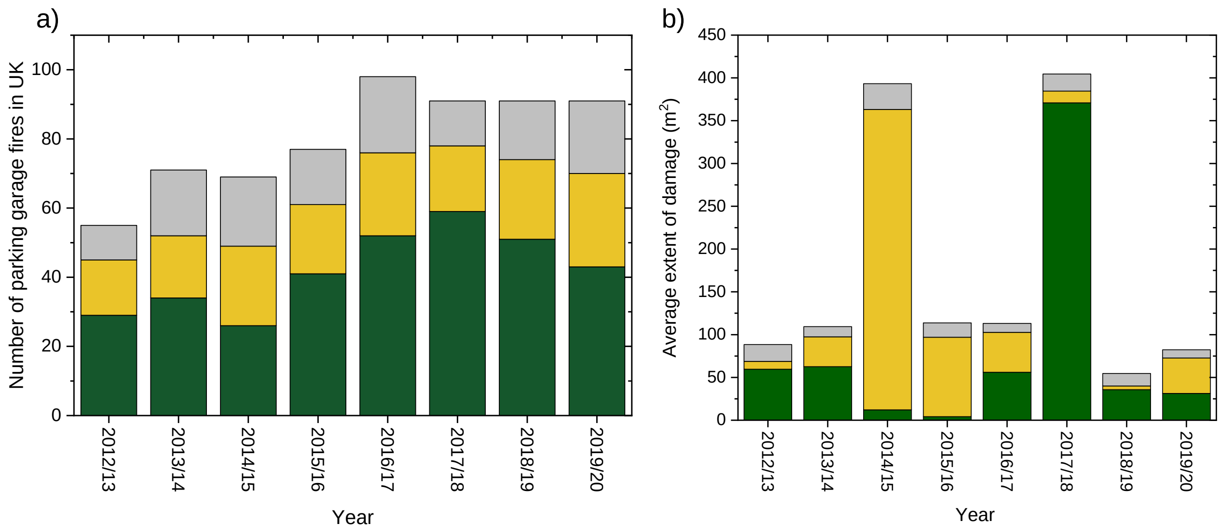

Figure 10. a) Number of parking garage fires in UK between 2012 – 2020 and b) average extent of damage in m^2 for green – multi-story garages, yellow – underground garages and grey – "other". Reference can be found in Appendix 1.

Fire Incidents in Tunnels

A study from PIARC presents tunnel fire statistics from 12 countries. [30] The statistics show that the fire rate of heavy goods vehicles (HGVs) appears to be higher than for other types of vehicles, and the ratio lies between 1 and 4.

Fire statistics from Austria show that most fires (90%) are caused by vehicle defects and around 10% of the fires were caused by collisions. The rate of fires caused by vehicle defects was 3 – 6 times higher for HGVs than for passenger vehicles based on Australian and French data, and 1.5 – 2 times in Norway.

Casey [31] analysed fire incidents from 16 Australian urban road tunnels, equipped with low-pressure water-based fire suppression system. Vehicle defects were pointed out as the key cause of fires and the portion of fires caused by collision was even lower than reported in the statistics from Austria. Unknown causes of fire were reported for 28% of the incidents. For tunnel fire incidents, where the tunnel was equipped with a fire suppression system, the time from fire detection to re-opening of the tunnel was less than 4.2 hours (except for the Burnley tunnel incident in 2007). [32] This could be regarded as a positive sign for installation of water-based fire suppression systems in tunnels.

Bai et al. [33] analysed 156 tunnel fire incidents, mostly incidents in China, which resulted in the statistics on fire origin and cause in Figure 11. They concluded that a majority of tunnel fires in China occur in summer; tunnel fire accidents are more frequent in economically developed areas in China as well as in the mountainous areas in western China; long tunnels and very long tunnels experience more fire accidents, which occur mostly at tunnel entrance/exit (within 200 m from portals); most tunnel fires are caused by spontaneous combustion of vehicles (vehicle defects) and traffic accidents; consequences of tunnel fires include casualties, vehicle damage, damages to tunnel structure and facilities, and traffic interruption. Around 36% of the fire incidents were caused by a traffic accident (or collision). For vehicle fires caused by vehicle defects, the locations of ignition sources mostly involve the engine and tires.

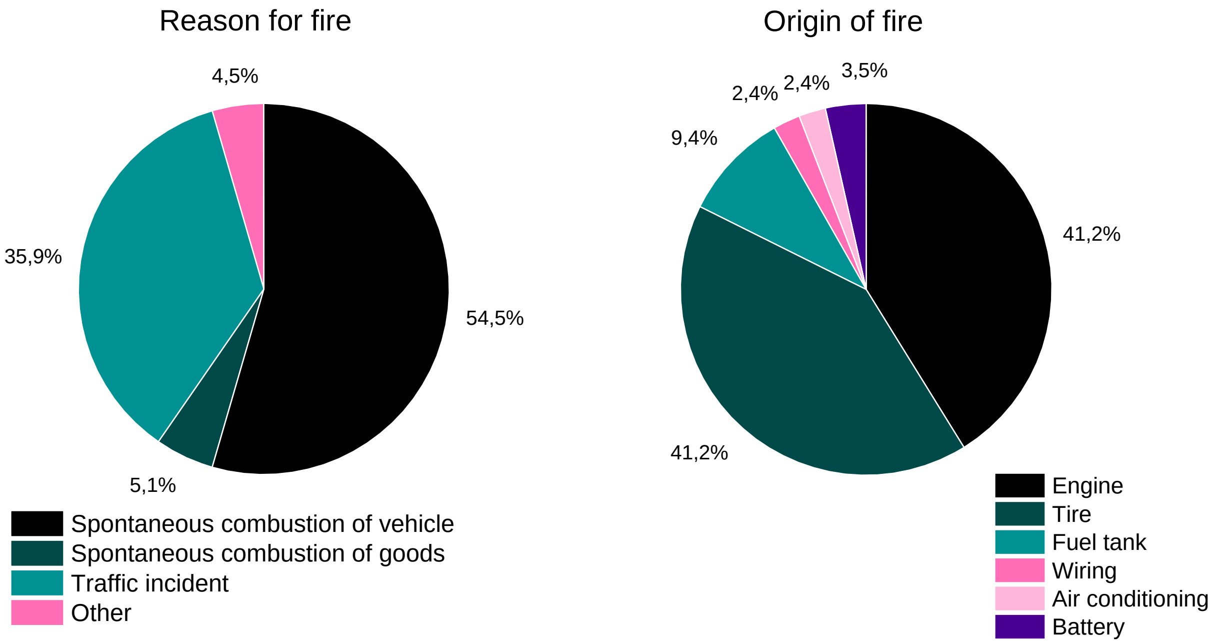

Figure 11. Reason for fire and origin of fire from 156 tunnel fire incidents, data taken from reference [33]

Major Fire Incidents in Tunnels

Major fire incidents (before 2015) with catastrophic consequences in road tunnels were reported by Ingason et al. [29]. Most of these catastrophic fire incidents in road tunnels were caused by collision involving at least one HGV (or tanker). Ventilation was found to be a key influencing factor, as it plays a role in how the flame spreads over the initial vehicle(s) and towards neighbouring vehicles.

Tunnel Fire Incidents Related to Electric Vehicles

Fire incidents related to EVs in road tunnels are scarce. A plausible reason for this could be that EVs still represent a small number of the overall passenger vehicle fleet. Some incidents related to EVs are described briefly below.

On 26 July 2022, a Tesla Model 3 caught fire in a tunnel in China. The car was destroyed, and the tunnel became full of sooty smoke on the downstream side. The driver reported that debris/parts from the wheels of a truck ahead of the vehicle detached and hit the vehicle chassis. [34]

On 26 Aug 2022, an electric bus caught fire while driving in Wusong tunnel in Tongling, China. Fortunately, there were only two passengers on the bus, and they were evacuated safely. The fire was extinguished by a fixed fire suppression system on the vehicle, probably designed for such purpose. The operator of the bus mentioned that such incidents have occurred several times. [35]

2.4 Existing Fire Protection Requirements

Rules and regulations regarding the fire safety in parking garages and tunnels varies between countries and are extensive. In the following sections a brief overview of some of the requirements for fire protection in road tunnels and parking garages are presented. Additionally, existing requirements for charging infrastructure is further described.

Requirements for Road Tunnels

Swedish requirements for fire protection of road tunnels can be found in The Swedish Transport Administration document regarding construction of tunnels, TDOK 2016:0231 ("Krav Tunnelbyggande") [36] and in law 2006:418 regarding safety in road tunnels. [37] The law is ratified through The Swedish Transport Agency's regulation on safety in road tunnels TSFS 2019:93. [38]

According to TDOK 2016:0231 tunnels shall be divided into a Tunnel Class: TC, TB, or TA, where the tunnel class TA comes with the most requirements. The classification is dependent on the tunnel length and the dimensioned year-round traffic. A tunnel in class TA shall have a shutdown option, fire detection system, evacuation alarm, variable lane signals, camera surveillance, alarms for security and traffic incidents, traffic control system, traffic information system, traffic management system, monitoring functions and enhanced fire protection. However, TDOK 2016:0231 gives the construction contractor options to make certain changes and additions to specified requirements. The extent of fire protection measures in a road tunnel shall be based on an investigation of the tunnel's safety in use, which shall be done during an early phase of the design.

Above-mentioned requirements are based on Swedish regulations and recommendations. International regulations for fire protection and life safety for road tunnels can be found in the National Fire Protection Agency standard NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways. [39] In NFPA 502, tunnels are categorized in a different way compared to in Sweden with, tunnels less than 90 meters (category X) to tunnels with a length of 1000 meter or longer (category D). Category B, C and D need to meet all the requirements in the standard. According to NFPA 502, tunnels in category B, C and D shall have at least two independent means for detection and localization of the fire. An automatic fire detection system shall be installed.

Tunnel Construction

For tunnels in Sweden where the main load-bearing system consists of surrounding rock, no verification of the load-bearing capacity in case of fire is required. The load-bearing capacity of tunnels that may flood in the event of fire (submerged tunnels) or cause nearby buildings to collapse (overlays) must be verified by testing or calculation. The fire intensity in tests and calculations shall be according to the standardized hydrocarbon time-temperature curve in SS-EN 1363-2:1999. [40] The duration of the fire exposure shall be at least 180 minutes (3 kap. 10 §, TSFS 2019:93). According to the internationally recognized NFPA 502 standard, protection of structural elements in a tunnel shall be designed to prevent progressive collapse of primary structural elements. For this purpose, another time-temperature curve is referenced, namely Rijkswaterstaat, which is more severe than the hydrocarbon curve used in the Swedish regulation. The functional requirements for structural elements according to NFPA 502 are, in addition to life safety, (1) to support fire fighter accessibility (2) to minimize economic impact, and (3) to mitigate structural damage.

Construction parts that form the boundary between a traffic space and a space that is part of an evacuation route shall be designed to at least withstand the standard/cellulosic time-temperature curve (less intense than the hydrocarbon curve) for 60 minutes (3 kap. §12, TSFS 2019:93).

In tunnels where transportation of dangerous goods is permitted, there must be a drainage system that can lead away flammable or toxic liquids. The drainage system must prevent fire, flammable liquids, and toxic liquids from spreading in the tunnel tube and between the tunnel tubes (3 kap. 21 §, TSFS 2019:93).

Tunnel Ventilation

For tunnels longer than 1000 meters and with a traffic flow[1] higher than 4000, there are requirements for mechanical ventilation (3 kap. 15 §, TSFS 2019:93). Transverse or semi transverse ventilation should be used in tunnels with bi-directional flow and in tunnels where dense queuing is expected. If longitudinal ventilation is used in these tunnels, a risk analysis must be carried out and be the base for if/which risk reducing measures need to be applied (3 kap. 15 §, TSFS 2019:93). The ventilation system in these tunnels shall be able to direct the gases emitted from a fire and the exhaust system shall be functionable in fire scenarios. This means that the equipment used should withstands temperatures that can be expected from fire gases.

In accordance with NFPA 502, emergency ventilation systems shall be developed to use the tunnel ventilation system as much as possible. The purpose of the emergency ventilation system is to remove and control smoke and hot gases from fires in the tunnel.

Rescue Operation and Evacuation

Regarding accessibility for the fire and rescue service, it is stated in the Swedish requirements that "*A tunnel must be designed so that the emergency services are given the opportunity to carry out efforts to save life, property and the environment*" (B.3.8 TDOK 2016:0231). Additionally, according to the Swedish Law Safety on road tunnels (2006:418, 12 §), it is required that the operator of tunnels longer than 500 meters to has a yearly safety practice (involving the fire and rescue services, the Police Authority, and the tunnel operator safety coordinator).

Emergency phones and handheld fire extinguishers shall be available in tunnels. The distance between fire hydrants must be a maximum of 250 meters (3 kap. 35 §, TSFS 2019:93). According to NFPA 502, the distances between portable extinguishers shall not exceed 90 meters. Fire hydrants must be arranged near the tunnel mouths.

The distance between evacuation routes shall not exceed 500 meters, which is in line with the allowable distance defined in European Directive on minimum safety requirements and mentioned in PIARC Road Tunnels Manual. [41] PIARC highlights the importance of self-rescue of people in a tunnel fire incident. To mitigating the consequences of the incident, people need a quick access to a safe zone, which is not affected by smoke.

Sprinkler System Design in Road Tunnels

In most countries, installation of fixed firefighting systems (FFFS) is not specified by national tunnel regulations. Therefore, these installations could be considered as an

[1] Traffic flow is defined in TSFS 2019:93 as: dimensioning year-round traffic with vehicles, calculated per tunnel tube.

additional safety measure to handle specific risks or to compensate for insufficiencies in tunnel design and/or other fire safety equipment. Road tunnels in Australia, New Zealand, and Japan (for certain length and traffic flow) however, require installation of water-based fire protection systems.

There are no European standards for the design and installation of sprinkler systems in road tunnels, but PIARC has published practices and recommendations for FFFS in road tunnels. [42] According to the recommendations by PIARC, there is no single deterministic method for determining the water application rate for a FFFS, as this is a choice combining current practice, large-scale testing and/or engineering analysis. It is also argued that the water application rate depends on the fire protection objectives. In some countries, such as Japan, the water application rate is pre-defined and varies from 2.5 – 12 mm min^{-1}. [42]

According to NFPA 502, a fire hazard analysis shall be conducted to determine both the design parameters of a water based FFFS and the type of fire detection and activation scheme to be employed. The fire hazard analysis should address the anticipated vehicle types, their content, ease of ignition and re-ignition of fuels, anticipated fire growth rate, anticipated maximum heat release rate of a fire and expected fire duration time.

In a report by the Federal Highway Association, visits to several tunnels in Australia and New Zealand were made to study the use of FFFSs. [43] The water application rate was typically 10 mm min^{-1} in new tunnels (with zone lengths of ~ 25 – 30 m) and in tunnels retrofitted with FFFS, the water application rate was ~ 6.5 mm min^{-1}. Detection of incidents typically relied on a closed-circuit television (CCTV) camera system with both trained operators and automatic video incident detection (AVID). For all tunnels visited, heat detection systems were used as back-up. The AVID systems or the operator viewing the CCTV were the first to detect stopped vehicles or fires. Typically, a spacing of about 60 m between cameras was desired to enable the identification of the location and nature of the incident. Several incidents were documented where the operation of the FFFS controlled or extinguished fires in passenger cars or trucks.

The Swedish recommendation for fire protection measures in road tunnels (TSFS 2019:93), recognizes the use of FFFS. If such a system is installed, an evaluation shall be made to determine the impact on the: drainage system, stratification of the air in the tunnel cross-section in the event of a fire, the ventilation system, the tunnel's monitoring and control system, as well as their relationship with the fire detection and alarm systems.

Requirements for Parking Garages

Swedish requirements for fire protection of parking garages can be found in the national Building Code (BFS 2011 with amendments until BFS 2020:4). Fire protection of buildings in Sweden has its basis in the type of building and what the building will be used for. Buildings are divided into building classes based on the protection needs of the building. These needs shall consider fire scenarios, possible consequences of a fire and the complexity of the building (e.g., number of floors and function of the building). Garages with more than 3 floors give the highest classification and hence stricter requirements. The building code also utilizes alternative design, which means that fire protection can be analytically designed using for example computer simulations to verify the level of fire protection.

In NFPA 88A, Standard for Parking Structures, [44] requirements for parking structures are included. NFPA 88A is used internationally and therefore provide an international outlook on fire protection of parking garages. Requirements from NFPA 88A are described further in the coming sections.

Garage Construction

According to BFS 2011:6 (amendments BFS 2020:4), [45] garages must be designed so that the risk of fire or explosion due to the presence of flammable or explosive gases is limited. Garages addressed in the Swedish building Code are those larger than 50 m^2. In the Swedish building code, it is stated that for parking garages with large floor area and parking garages with more than 2 floors are required to design the fire protection with performance-based design. This means that the complexity of the structure and of the fire protection may be high and needs to be validated through a specific assessment. It is therefore difficult to state generic fire protection requirements for parking garages. Four criteria shall be particularly considered in the assessment:

- if external extinguishing intervention cannot be carried out
- if internal rescue intervention can be complicated
- if the feared consequence in case of collapse is very large
- if the evacuation process can be associated with great difficulties

The fire load in a parking garage for passenger cars is generally assumed to be 800 MJ m^{-2}. Construction parts that form the boundary between the garage and other spaces should be designed to withstand the passage of flames, fume, toxic gases, radiant heat, and temperature for a period of 60 minutes (EI60) while exposed to the standard/cellulosic time-temperature curve. Parking garages (also applied for other large buildings) cannot cover too large floor areas due to the risk of fire spread. This is normally assessed by evaluating the need for fire compartmentation and/or a sprinkler system. From the Swedish building code, it is listed that without a fire detection system or an automatic firefighting system (i.e. a sprinkler system) the area can be 1250 m^2.

According to NFPA 88A (2023) open parking garages are permitted to be of unlimited area if both of the following conditions are met:

1) the height does not exceed 25 m
2) the horizontal distance from any point on any parking level to an exterior wall opening on a street, an alley, a courtyard, or other similar permanent open space does not exceed 60 m.

Garage Ventilation

Open parking garages are naturally ventilated through openings uniformly distributed in the perimeter of each floor. Open parking garages are not required to have mechanical ventilation according to NFPA 88A (2023). Mechanical ventilation is however required for enclosed car parks. The capacity shall be 300 l min^1 per m^2 of floor area. This capacity shall be maintained during normal operation.

Rescue Operation and Evacuation

Generally, parking garages must be designed to allow satisfactory evacuation in case of fire. The same is valid for rescue operations, parking garages must be designed so that rescue operation can be carried out with satisfactory safety.

Regarding evacuation, it is often ordinary evacuation routes, such as doors and staircases that shall be used as escape routes. They are often designed for the number of people that will use them. A parking garage intended for various sorts of public events where many people are expected to park/pick up their cars at the same time needs to have larger dimensions.

Sprinkler System Requirements for Parking Garages

Some jurisdictions require sprinkler systems in enclosed parking garages, whilst those that meet the code definition of ‘open’ traditionally have not been required to be sprinklered. The newest 2023 edition of NFPA 88A, Standard for Parking Structures, requires sprinklers in all parking structures, including open parking garages. The 2021 version of the International Building Code (IBC) has also included more stringent requirements that now require open parking garages greater than 48,000 ft^2 (4 460 m^2) to have a sprinkler system. [46]

In September 2022, the Dutch government introduced a regulation that requires, with some exemptions, automatic sprinklers to be installed in parking garages larger than 1 000 m^2 (equal to about 40 cars) and which are below “sleeping risks” (residential buildings). The new requirement has been introduced because modern cars present a greater fire load and because fires more readily extend to multiple vehicles before the fire and rescue service can intervene. [47,48] In June 2022, the Belgian government published a law introducing requirements for sprinklers to be fitted in large underground parking garage. [49]

Sprinkler System Design in Parking Garages

EN 12845:2015+A1:2020 [50] provide the minimum requirements for the design and installation of automatic sprinkler systems. Fire hazards similar to “car parks” fall under the classification Ordinary Hazard Group 2 (OH2). A wet-pipe or pre-action system should be designed for a water discharge density of 5 mm min^{-1} and an area of operation of 144 m^2 (whereas a dry-pipe system should be designed for 180 m^2).

Wet-pipe systems are designed for applications where the temperature is maintained above freezing and employ sprinklers attached to a piping system containing water under pressure.

Dry-pipe systems are used in spaces subject to freezing temperatures. These systems employ automatic sprinklers attached to a piping system containing air or Nitrogen under pressure. The activation of one or more sprinkler permits the water pressure to open a valve, known as the dry-pipe valve. The water then flows into the pipework and out of the opened sprinklers. There is a time delay of up to 60 s from the activation of the first sprinkler until water is discharged. Pre-action systems are similar to a dry-pipe systems; however, water is also held back by an electronically operated valve connected to a fire detection system. Pre-action systems are commonly used for areas where there is a danger of serious water damage because of impact or broken piping.

NFPA 13 provides the minimum requirements for the design and installation of automatic fire sprinkler systems. [51] In the 2019 edition of NFPA 13 the hazard “Automobile parking and showrooms” is classified as Ordinary Hazard Group 1 (OH1). However, in the 2022 edition of NFPA 13 “Automobile showrooms” is classified as OH1 and “Automobile parking garages” is classified as Ordinary Hazard Group 2 (OH2). The reason for the reclassification is a concern that the hazard classifications in the 2019 edition were inadequate. Automobile design has continuously been evolving and now modern vehicles contain significantly more plastics than older cars, hybrid/electric drive cars pose a different risk and the distance between cars is close in parking garage, which promotes fire spread. [52]

The wet-pipe system design for automobile parking garages is 8.1 mm min^{-1} over an area of operation of 140 m^2 per NFPA 13 (2022), which results in a minimum total water demand of at least 1 134 l min^{-1}. This is 58 % higher than the minimum total water demand of 720 l min^{-1} in EN 12845:2015+A1:2019 and 33 % higher than the minimum total water demand of 854 l min^{-1} for an OH1 design.

The European Fire Sprinkler Network (EFSN) has published a position paper on sprinkler systems in parking garages that holds EVs. [53] The paper concludes that sprinkler systems can prevent fire spread between vehicles, and that this also applies to EVs. The fire and rescue service can then approach the scene to complete the fire extinguishment. The position of EFSN is also that the design hazard category should remain OH2 under EN 12845, in the absence of evidence that this hazard classification does not provide adequate fire protection.

Directives Regarding Charging Infrastructure

According to Directive 2014/94/EU [54] “Member States should ensure that recharging points accessible to the public are built up with adequate coverage, to enable EVs to circulate at least in urban/suburban agglomerations and other densely populated areas, and, where appropriate, within networks determined by the Member States. The number of recharging points should be established considering the number of EVs estimated to be registered by the end of 2020 in each Member State.” The directive says that one charging point per 10 EVs would be appropriate.

“Recharging points accessible to the public should be installed, in particular at public transport stations, such as port passenger terminals, airports or railway stations. Private owners of electric vehicles depend to a large extent on access to recharging points in collective parking lots, such as in apartment blocks and office and business locations. Public authorities should take measures to assist users of such vehicles by ensuring that the appropriate infrastructure with sufficient electric vehicle recharging points is provided by site developers and managers.”

This directive will in many cases mean that there will be a large introduction of newly installed charging possibilities. In Sweden, Boverket (BFS 2021:2) [55] has stated that parking lots of more than 10 spots, within a heated building, or immediately adjacent to a heated building, with a building permit issued later than March 2021 should be equipped with charging infrastructure for EVs. From 2025, this will also be applied retroactively for buildings with more than 20 parking spots. In many cases, one charging possibility per parking lot is anticipated. BFS 2021:2 states the type of connector that should be used and accessibility for disabled people but not much more.

Charging stations needs to fulfil the EU Directive 2014/35/EU, so called Low Voltage Directive (LVD). [56] The LVD requires that the charging station should be safe against electric shock and fire. In the LVD, it is up to the producer to certify that the product meets these requirements. In general, there is no specific requirement that needs to be fulfilled, but for many products the producers tend to reach some consensus what needs to be fulfilled in form of certain standards etc. This can include harmonized standards such as EN IEC 61851-1. [57]

Currently there are no requirements on inspections of charging stations. One could expect that over time, these can be prone to computer viruses, cyber-attacks, but also that cables and connectors will get damaged/worn or corroded over time. Damaged equipment could result in low contact and thus heat produced, which could potentially increase the risk of fire. For consumer safety, regular inspections of charging stations and validation of charging meters needs to be developed and could be a route for improving the safety. These measures are especially useful for public charging, when paying to charge your vehicle, for example charging in public parking garages.

2.5 Field Experience in Enclosed Spaces using Sprinkler Systems

In the following sections field experiences regarding fires and sprinkler systems in road tunnels and in enclosed spaces, such as underground parking garages, are summarized.

Fire Suppression Tests in Road Tunnels

There have been many small- and large-scale fire suppression tests exploring system type and system design for road tunnels. A history of large-scale tunnel fire suppression tests was given by Li and Ingason. [58] Small- and intermediate-scale tunnel fire suppression tests were also reported by Ingason et al. [29] A few examples are given below.

Water mist systems have been promoted as an alternative to traditional water spray systems and in recent years several extensive large-scale tests have been conducted. The tests show that the systems' advantages are primarily through cooling of hot gases and preventing the spread of fire to neighbouring vehicles. [59]

Large orifice water spray sidewall nozzles may be used to reduce the number of nozzles installed and to reduce the system operating pressure. A deluge system concept was tested in five large-scale fire tests with an additional test that incorporated automatic sprinklers. [60] The fire protection objective of the system was to prevent fire spread to a target positioned 5 m downstream of the fire and to ensure that the fire did not exceed 30 MW in size. These objectives were met in all the tests conducted.

Field Experience of Sprinkler Systems in Road Tunnels

There are some field experiences with FFFS in road tunnels, such as the fire in the Burnley tunnel in Melbourne, Australia on 23 March 2007. The accident occurred when a truck stopped in the slow lane due to a punctured tire. The tunnel control centre activated a closed lane signal and reduced the tunnel speed limit. Despite this action, a series of collisions occurred. One of the trucks involved in the incident burst into flames causing a large fire and explosions. [32] The fire size was limited to less than 20 MW thanks to rapid operation of the deluge water spray system.

Japan’s first water spray system was installed in the Kobotoke Tunnel on the Chuo Expressway in 1968. Between 1989 and 2012, 4 – 21 fire accidents occurred each year, resulting in a total of 283 fires. Of the total number of tunnel fire accidents, 132 were in AA grade tunnels, i.e. tunnels with the highest safety measures. Water spray systems were used 75 times, 55 times during vehicle malfunction fires and 20 times for accident induced fires. Application of water started on average 5.4 minutes after the fire initiated, the average spray time was 24.7 minutes, and the average time taken for the fire and rescue service to arrive was 24.8 minutes. [61]

Based on field experience and fire tests it appears that the sprinkler systems are adequate to control fires in both passenger cars and HGVs. Large-scale fire tests show that the advantages of deluge water mist systems are primarily through cooling of hot gases and preventing the spread of fire to neighbouring vehicles. Independent of the type of system, the design is typically based on fires in HGVs. The system design is thereby concluded to be adequate also for passenger cars. Electric buses and trucks may pose a fire challenge like, or in excess of that in regular buses or trucks, but no systematic research on this has been identified.

Experience of Sprinkler Systems in Parking Garages

There have been several projects simulating fire in parking garages and in ro-ro spaces on ships to evaluate the fire sprinkler performance. Fire test and sprinkler experience in parking garages are further described in theses sections.

Fire Tests Simulating Fires in Enclosed Spaces

In 2007 and 2008, BRE in United Kingdom conducted several multi-vehicle full car fire tests in a parking garage mock-up, having a floor area of 12 x 6 m and a ceiling height of 2.9 m. [62] The report concludes that the sprinklers are effective in limiting a fire to a single car, which supports findings reported verbally by the fire and rescue services.

In 2009, BRE performed a single automatic sprinkler test, using a two-car stacker configuration. [63] It was concluded that automatic sprinklers at the ceiling contained the fire to the lower car; it allowed some spread to the vehicle above but prevented it from becoming fully involved.

VdS Schadenverhütung has published several fire test methods for water mist fire protection systems. The test results from assignment tests at RISE are usually proprietary, but some test results have been published with permission from the client. [59] For these tests, the ceiling height was 3.0 m, and the cars were manufactured in the late 1990s. The average gas temperature at the ceiling was at most ~ 150 °C. The surface temperatures on the part of the body facing the centremost car on both target cars were measured with four thermocouples welded to the steel body. The average surface temperature at the bodies of the adjacent cars peaked at ~ 100 °C. Several test series show that water mist is comparable in performance to traditional sprinkler systems, although the distance between the nozzles is often higher and water flow rates lower.

RISE has also conducted sprinkler tests in the project “Legislative assessment for safety hazards of fire and innovations in ro-ro ship environment” (LASH FIRE) [64] with the aim of developing sprinkler system design and installation guidelines for ro-ro vehicle spaces on maritime vehicle carriers. [65] These spaces differ from underground parking garages in some respects: the number of vehicles per square meter is higher, larger vehicles are found in some areas and the ceiling heights are typically lower. The large-scale performance validation tests proved that a system is activated at an early stage with few operating sprinklers, fire spread between vehicles is prevented or delayed and ceiling gas temperatures are reduced.

RISE has also conducted fire suppression tests in the LASH FIRE project comparing ICEVs with EVs. Questions have arisen whether the manually operated water spray deluge systems (denoted 'drencher systems') on board ro-ro cargo ships are able to control a fire in an electric vehicle and if the design of the system in terms of water flow rates needs to be increased. The results from the large-scale tests with ICEVs and EVs have not yet been officially published in any report but have been presented at the Conference of fire safety at sea (CFIS) 2022. The overall conclusion from the tests was that a fire in an EV does not seem to be more challenging to control than a fire in an ICEV for the drencher system design given in current international recommendations.

Field Experience of Sprinkler in Parking Garages

A total of 3 096 parking garage fires (in buildings) were reported in United Kingdom during 1994 – 2005. [62] Of these, 1 592 (51.4 %) fires started in a vehicle. In 162 of the fires, an automatic sprinkler system was present, Figure 12. In 61 (37.7%) of the fires, the sprinkler system did not activate, probably since the fire was too small or that the fire was extinguished by fire and rescue services actions. In the fires where the sprinkler system activated, it can be concluded that the fire was extinguished or controlled in almost all cases (Figure 12).

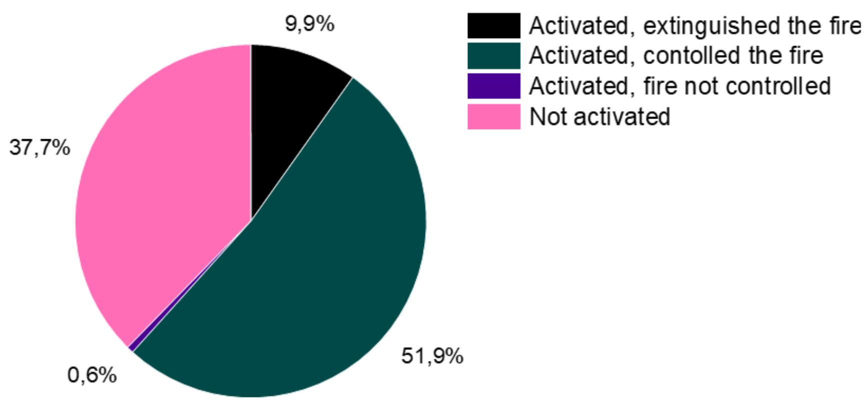

Figure 12. Parking garage fires in United Kingdom (1994 – 2005) where a sprinkler system was installed (activated or not during the fire) and the outcome of the fire.

There are some recently reported cases with fires in sprinklered parking garages that involves EVs. In the first case, an EV fire was started deliberately on September 1, 2020, in the Netherlands. The sprinkler system controlled the fire, which did not spread to the battery pack. The parking garage and other vehicles were undamaged. [66]

Shortly after 3 am on November 21, 2021, there was a fire in the underground parking garage Marienplatzgarage in Ravensburg, Germany. According to initial information, an EV parked on the first level and connected to a charging station was probably the cause of the fire. "The sprinkler system and other fire protection devices worked extremely well", according to the press spokesman for the Ravensburg rescue service. Three other vehicles, two charging stations, several lights and cables and the concrete ceiling were damaged by the heat.

In 2014, there was a serious fire in the same underground parking garage, which resulted in closure for six years and a restoration for several million euro. The garage was reopened in 2020, now fitted with an automatic sprinkler system. [67] Overall, the property damage was estimated to €370,000 and the value of the damaged vehicles to €120,000. [68]

The overall conclusion is that the sprinkler system design in accordance with EN 12845:2015+A1:2019 for parking garages is adequate, based on field experience and large-scale fire tests. It is expected that a sprinkler system can prevent fire spread between vehicles. Based on fire tests, fire sprinkler suppression tests and a limited number of actual fires in sprinklered parking garages, it is likely that this conclusion also applies to fires involving EVs (passenger cars).

3 Risk Assessment

Experts from various fields of expertise participated during the HAZID workshop sessions. Experts with in-depth knowledge and experience from fire safety, fire protection, first response manual intervention, fire engineering, tunnel safety, material chemistry, chemical engineering, emissions from vehicle fires, battery fire safety, laboratory fire testing and vehicle risk assessment, participated in the HAZID workshop sessions.

During the workshop sessions, risks were investigated from different perspectives, by identification of unwanted events, possible secondary effects, and respective failure pathways. The workshop sessions also included a comparative risk ranking of the risks identified. Finally, the currently existing safety measures were addressed, and potential additional safety measures were identified. Special considerations were given to potential preventive and mitigative actions for vehicles, for infrastructure and for manual intervention/first response.

3.1 Risk Evaluation Criteria

For risk evaluation, several criteria were discussed. While the most common risk evaluation criteria are likelihood of event and severity of consequence of unwanted events, there may be several other criteria which gives a more holistic picture of the hazard and its associated risk, for example: the fire development, size of fire and fire spread; type and size of vehicle; size and state of charge of the LIB and the distance to other vehicles and ceiling height in the enclosed space. Additionally, the interplay between the aforementioned factors and the surrounding environment might also affect the outcome of a hazard and its associated risk.

A qualitative approach was chosen to evaluate unwanted events under each HAZID theme. For likelihood of occurrence, special emphasis was given to the likelihood of occurrence of fire spread. Followed by this, it was matched against the severity of consequence. The severity of consequence was determined by a cumulative ranking based on extent of fire spread together with damage to the infrastructure. For example, if the unwanted event was an EV fire arising from a collision in a tunnel, then the likelihood that the fire spreads to adjacent vehicles was discussed with respect to the impact of the consequence on the load bearing infrastructure, casualties caused, unavailability of the tunnel etc. The scales of likelihood and severity of consequence that were used for estimations during the HAZIDs are presented in Appendix B.

3.2 HAZID Workshops

The inputs considered for the HAZID workshops were derived primarily from the literature study. The assumptions and definitions for "enclosed spaces" are described in section 2.2. Four different HAZID session with different themes were carried out.

1) Arson
2) Collison of EVs in tunnels
3) EV fires in enclosed car parks when the origin of fire is external. Vehicle is parked or parked and charging.
4) EV fires in enclosed car parks when the origin of fire is the vehicle. Vehicle is parked or parked and charging.

In all HAZID sessions, the starting point for the discussions was based on the surrounding environment, the origin of the fire and the mode of the vehicle.

HAZID Theme 1: Arson

The first theme considered was arson. The surrounding environment considered was multiple carports, open and enclosed parking garages. This was done to be able to make a comparison of the severity of consequences, effect of the fire spread due to either open or enclosed spaces, ceiling heights, available FFFS systems in public garages both open and closed, and relevant safety measures between EV and ICEV scenarios. Origin of fire in the arson theme by default implied an external source. The mode of operation that was considered relevant for this theme was a parked vehicle. Road tunnels were excluded from this part since the event of arson in a road tunnel is unlikely.

Discussion

At present there are no requirements to install ventilation, fire detection, or sprinkler systems in carports. However, there is a requirement on safety distance for adjacent buildings to a carport. The discussions indicated a need to further investigate if sprinkler systems and/or fire detection systems could be beneficial for carports to reduce fire risks in the future, where the latter would probably be easiest to implement. Sprinkler systems and fire detection systems are regarded as risk reduction measures for infrastructure. Additionally, these measures will have positive effects on the first response, since such infrastructure risk reduction measures will likely reduce the response time by earlier detection, and/or early-stage containment of fire reducing the fire spread etc.

For open and enclosed parking garages, there are requirements for fire protection systems, but they vary, between countries and depending on the size of the parking garage, in terms of unit area or vehicle capacity. No other significant difference was identified in terms of the overall risk of an arson fire. Both were assessed as high-risk events with medium to high likelihood of fire spread and medium to high severity of consequence.

According to the statistics analysed, open parking garages may be subjected to a higher risk of fire spread, due to the exposure of wind conditions. On the other hand, closed parking garages are subjected to higher risk of toxicity from smoke, which makes them more challenging and complex for the rescue operations.

Risk Reduction Measures

Potential risk reduction measures particularly for infrastructure were discussed. This mainly included the need for installation of fixed systems, such as sprinkler systems, ventilation systems, particularly for enclosed underground parking garages, and fire detection systems. Additionally, reducing the size of fire cells was discussed as a measure to mitigate severe outcomes. All these measures are well-known and are applied for some types of parking garages already. Additionally, jet fans were brought up as an example to reduce smoke in evacuation routes. Negative effects of jet fans are the high speed which can influence the fire scenario and thus the fire spread.

HAZID Theme 2: Collison of EVs in Tunnels

The second theme considered was collision of EVs in tunnels. For the surrounding environment, different types of tunnels were considered: unidirectional tunnel and bi-directional tunnel. Various types of ventilation systems in the tunnels were also considered, namely, longitudinal ventilation and transverse or semi transverse ventilation. The origin of fire in this theme was the energy carrier or other parts of the vehicle (e.g., brakes, engine, cabin). An origin of fire external to the vehicle was not considered relevant. The mode of operation, that was considered for the discussion, was active driving of the vehicle. Clearly, the fire spread, toxic emission of gases, gas explosion, impact on the load bearing infrastructure and availability of the tunnel were relevant factors affecting the consequences in this theme.

Discussion

Fire spread to multiple vehicles after a collision in a tunnel was estimated to be a low likelihood event, although high in severity and therefore was assessed as medium to high-risk event. Typical risk factors considered were prevailing ventilation conditions, length of the tunnel and whether it is a unidirectional or bidirectional traffic flow. In a unidirectional tunnel, less severe collisions are more likely as all vehicles are driving in the same direction, compared to bi-directional tunnels where head-on collisions are possible. Most collisions, however, do not lead to fire and there are no highlighted differences in relative frequency of fire in case of collision between EV and ICEV.

Typical risk factors considered were passenger injury, unavailability of the tunnel, prevailing ventilation conditions, extent of damage to load bearing structures and accessibility of the tunnel.

Another distinct unwanted event considered under this theme was fire during active drive when the EV is being driven in a tunnel or in an enclosed parking space. The likelihood of an EV catching fire during active driving through a tunnel was estimated as a low likelihood event. The likelihood between EV and ICEV may vary since brakes and the engine compartment are designed differently. These events indicate a higher likelihood for ICEVs, but statistics for EVs are still scarce.

The likelihood of explosion following a collision, caused by accumulated flammable gases, was ranked very low in terms of likelihood of event, whilst the severity was ranked high. The reflection was that if the EV has a high state of charge, it increases the probability of immediate ignition and thus no explosion.

Risk Reduction Measures

The focus of the discussion was on potential risk reduction measures to mitigate the severity of outcomes from a collision followed by an explosion.

When FFFS are installed in tunnels, the drainage of sprinkler water needs to be considered in the design. However, in work by Held et al., the effect of thermal runaway on the contamination of infrastructure was investigated. The decontamination after an EV fire was not considered more difficult or costly compared to after an ICEV fire, neither did they experience any corrosion on the infrastructure. [69]

Escape routes, portable fire extinguishers and emergency telephones were highlighted as risk reduction measures both from a tactical as well as an infrastructure perspective. Explosion hazards related to vented gas from the traction battery are not covered clearly in the legal requirements. Further simulations or modelling work could be beneficial.

Another clear mitigation measure is surveillance that detects interruption or sudden stop in traffic flow. In many big cities and in longer tunnels with high occupancy, these measures exist. Further investigations on the need for legal requirement related to surveillance in tunnels was highlighted.

HAZID Theme 3: EV Fires in Enclosed Car Parks, When the Origin of Fire is External. Vehicle is Parked or Parked and Charging.

The third theme considered was EV fires in enclosed underground car parks when the vehicle is parked or parked and charging. Here the origin of fire considered is external. According to the literature study the origin of fire in enclosed parking garages, when the vehicle is parked and charging, is mostly unknown due to incomplete data. The fire external to the vehicle, included fires in charging stations, electrical sockets, external charging adapters, in other adjacent parked vehicles or fires related to other stored material (such as tyres, garbage etc.). To allow for a more comprehensive discussion, EV fires in above ground car parks when the vehicle is parked or parked and charging was also considered.

Discussion

In open and enclosed parking garages, the fire spread depends on the capacity and occupancy of the parking garage. The estimated likelihood of a fire to initiate in a vehicle due to an external fire was judged low. According to the literature study, the data regarding this topic related to EV is limited but in some cases the root cause has been attributed to a non-compliant assembly of powertrain (home built).

A higher likelihood of fire was found for other 2-3-wheeler light electric vehicles (such as kick bikes, electric bikes etc.). The consequence of such fire was ranked low. However, the fire may spread to an EV if the light electric vehicle is parked or parked and charging in the garage adjacent to an EV. A potential risk reduction measures to prevent and mitigate the event is to not allow charging or storage of light electric vehicles adjacent to EVs.

Another unwanted event identified was fire in adjacent storage rooms (rubber tyres, garbage etc.). This was estimated as a high-risk event, owing to the severity due to the increased amount of chemical energy. The likelihood of such event was estimated as low for larger public car parks where storage is commonly not allowed but medium likelihood for small parking garages (such as car parks connected to housing cooperatives). Lack of awareness was attributed as one of the main causes behind these kinds of unwanted events.

Furthermore, fire in an electrical socket or adjacent electrical installation was identified as a medium risk event, owing to the risk of fire spread to EVs when they are parked and charging. Non-compliant connectors, poor quality cables, lack of maintenance of electrical installations and sockets were identified as common causes of fire.

Risk Reduction Measures

A potential risk reduction measure is better awareness on the need for maintenance of electrical installations. This could be achieved by routine inspections. In addition, design guidance which enforces design compatibility, which does not allow incompatible charging equipment to be connected to EVs.

From an infrastructure perspective, installation of sprinklers and/or fire detection system was discussed and seen as the most effective measure, especially for enclosed parking garages. A less costly solution could be to introduce fire curtains for compartmentalisation of parking garages. For fire localisation, drones or robots could be used, especially in enclosed parking garages, to ensure safer firefighter accessibility. Drones or robots powered by thermal imaging could be regarded as an effective complementary tactical measure in fire detection and localisation.

Furthermore, to prevent fires in enclosed spaces, parking garages should not be used as storage or garbage holds.

HAZID Theme 4: EV Fires in Enclosed Car Parks, When the Origin of Fire is the Vehicle. Vehicle is Parked or Parked and Charging.

The final theme considered was EV fires in enclosed parking spaces when the origin of fire was the vehicle. The mode considered here was a parked or parked and charging vehicle. According to the literature study the data is still limited. Fire in EVs, explosions, arcing, flooding of vehicles due to extreme weather events were some of the unwanted events that were discussed within this theme.

Discussion

Fires that origin and spread from one EV to an adjacent EV, while it is parked and charging in an enclosed car park, can be severe depending on the extent of the fire spread. As highlighted in the HAZID, it is likely to find several parked vehicles in an enclosed car park but comparatively less likely to find several vehicles that are parked as well as charging. Even if parking spaces for charging are often grouped together, it is still relatively much more common with parking spaces without charging capability.

Despite that the data is still limited, the likelihood of fires in EVs while parked and parked & charging were assumed to be similar to that of EV fires during active drive.

The unwanted event of an explosion of an EV while it is parked and charging, was rated low in likelihood of occurrence but was deemed as a high severity event. It was also noted that explosion related to EV fires overall has not been well defined in accident reports or accident literature.

The unwanted event where gases are released from the battery of an EV without immediate ignition was rated medium in likelihood of occurrence but was deemed as a high severity event. Given the number of reported incidents, special consideration was given to the lack of currently existing risk reduction measures. This consequently indicates a need for potential risk reduction measures.

Arcing between EV and charging plug was rated low in likelihood of occurrence; however, it was assigned a high severity of consequence, considering that an enclosed surrounding environment could have multiple adjacent EVs parked and charging. Risk factors considered in the discussion were the quality of connectors, fuses, overloading and overheating.

Another unwanted event is flooding of the charging station or EV. This was rated medium to high in likelihood of occurrence, considering the increase in the number of EV fires reported caused by extreme weather conditions, as well as the overall increase in number of charging stations installed for EVs. The severity of the consequences of the event was rated high. Moreover, lack of current risk reduction measures to mitigate this event makes it even more important to consider potential risk reduction measures to mitigate the outcomes of the event.

Risk Reduction Measures

Based on the HAZID discussion, an increased distance between parked and parked and charging EVs is a proposed risk reduction measure. Safety recommendations with respect to number of EVs parked in per unit area to indicate safe capacity were also discussed as a risk reduction measure. A technological solution could be based on artificial intelligence (AI) and machine learning (ML) to aid safer parking distances and guide the EV to a specific spot. The software of the vehicle is empowered by an AI program and ML which is based on safety distances as well as type and size of EV that is subjected to be parked. The purpose is to keep fire safe distance and fill the farther spots first to mitigate fire accidents arising from EVs.

Charging stations can be addressed both as a potential preventive as well as a mitigative measure for infrastructure. Better planning of the positioning of charging stations, regarding fire spread, was given special emphasis. By strategical placement of charging stations, fire spread between EVs can be prevented. This measure can also be expected to improve the time required for the first response tactical teams to arrive at the location of the accident and begin firefighting. Furthermore, introduction of quality assured/compliant charging stations was a clear recommendation. Gas detection adjacent to charging stations could be introduced as another measure addressing infrastructure. Regular inspections of the charging stations to avoid using worn equipment could be introduced as a preventive measure. In addition, design which ensures compatibility could be introduced to prevent inappropriate equipment to be connected to charge EVs.

Regarding measures to prevent arcing between EV and charging plug, there is a need to make compliant and standard connectors, connections and charging stations accessible. More precisely, the HAZID discussions highlighted that a lack of proper charging stations (that comply with voltage, connection, connectors, and similar design compatible recommendations) could lead to an increase fire risk due to the use of incompatible equipment.

Concerning risk reduction measures to prevent flooding of the charging station or EVs. A potential infrastructure risk reduction measure is raised platforms for charging stations to delay water submersion but more importantly to allow easier drainage of water. As a tactical risk reduction measure, advice and more detailed recommendations on how to tow away submerged EVs and on how to handle EVs following a flood was proposed. This scope could be included in the design phase of EVs where ACEA can possibly play an influential role on guidance & recommendations.

3.3 Firefighting Practises

Concrete guidance from this study is that rescue operations with EVs are mostly similar as for ICEVs. Trapped smoke is the main challenge in enclosed spaces and ventilation will most likely play an important role for the rescue operation and for evacuation purposes. It is necessary for the emergency personnel and operators of tunnels to have the knowledge to make an appropriate risk analysis for different fire scenarios that can occur.

Vehicle fire blanket could be used for preventive purposes, to mitigate fire spread to an adjacent vehicle, and during post extinguishment, to hinder re-ignition and to contain gas emissions. However, these fire blankets have not yet been fully validated in terms of efficiency compared to already existing practises.

A thermal imaging camera is a very good tool and almost a necessity for access in complex structures, this was highlighted in the SP Report "Risks associated with alternative fuels in road tunnels and underground garages". [70] The use of drones and robots for fire localisation and detection, especially in enclosed parking garages, could ensure better accessibility for the firefighters. Drones or robots installed with thermal imaging cameras could be regarded as an effective complementary tactical measure in fire detection and localisation. These can also be used to gather more information which could be used to decide upon which firefighting tactic that should be utilized.

4 Workshop with the Fire and Rescue Services

A workshop regarding the Emergency Rescue Sheet and Response Guides (ERG) was held digitally, with representatives from three Swedish fire and rescue services on the 25th of November 2022. Question and answers from a survey circulated beforehand were used as basis for the discussions. The results from the survey are presented in Figure 13. Additionally, to the questions presented in Figure 13, two more questions were asked in the survey:

1. Do you have any additional suggestions/questions regarding/related to the ERGs?
2. Is there anything else (techniques/information missing) that you would like to point out, related to fires in alternatively fuelled vehicles?

As to summaries the answers presented in Figure 13, all firefighters that answered the survey knew about and had used the ERGs. The main reason for using the ERGs varied but in most of the cases (34.6%) they were used to obtain information regarding hazardous material. The ERGs were also considered clear in respect to color-coding, font and information used/supplied. Regarding the two additional questions asked in the survey, the following answers were given (translated from Swedish):

"Safety distances regarding of gas-powered vehicles should be included" [71]

"How to handle damaged batteries should be included"

"How to extinguish a battery fire and how to/not to approach a battery fire"

"There should be standardized attack point for connecting fire hoses to the battery pack, so that water can be directly injected to the pack"

"The possibility to use fog nail"

"What type of reinforcement that is used in the vehicle"

"Sometimes recommendations of equipment that is not available for the fire engine are made"

"It would be great if we could know the burn time of the pack in the car"

"Charging stations and connected parking lots should be design so that the fire cannot spread to adjacent vehicles or buildings"

"Cutting zones should be included"

"There should be a possibility to ground the vehicle to avoid electric shock"

"The potential risks of electric shock should be included".

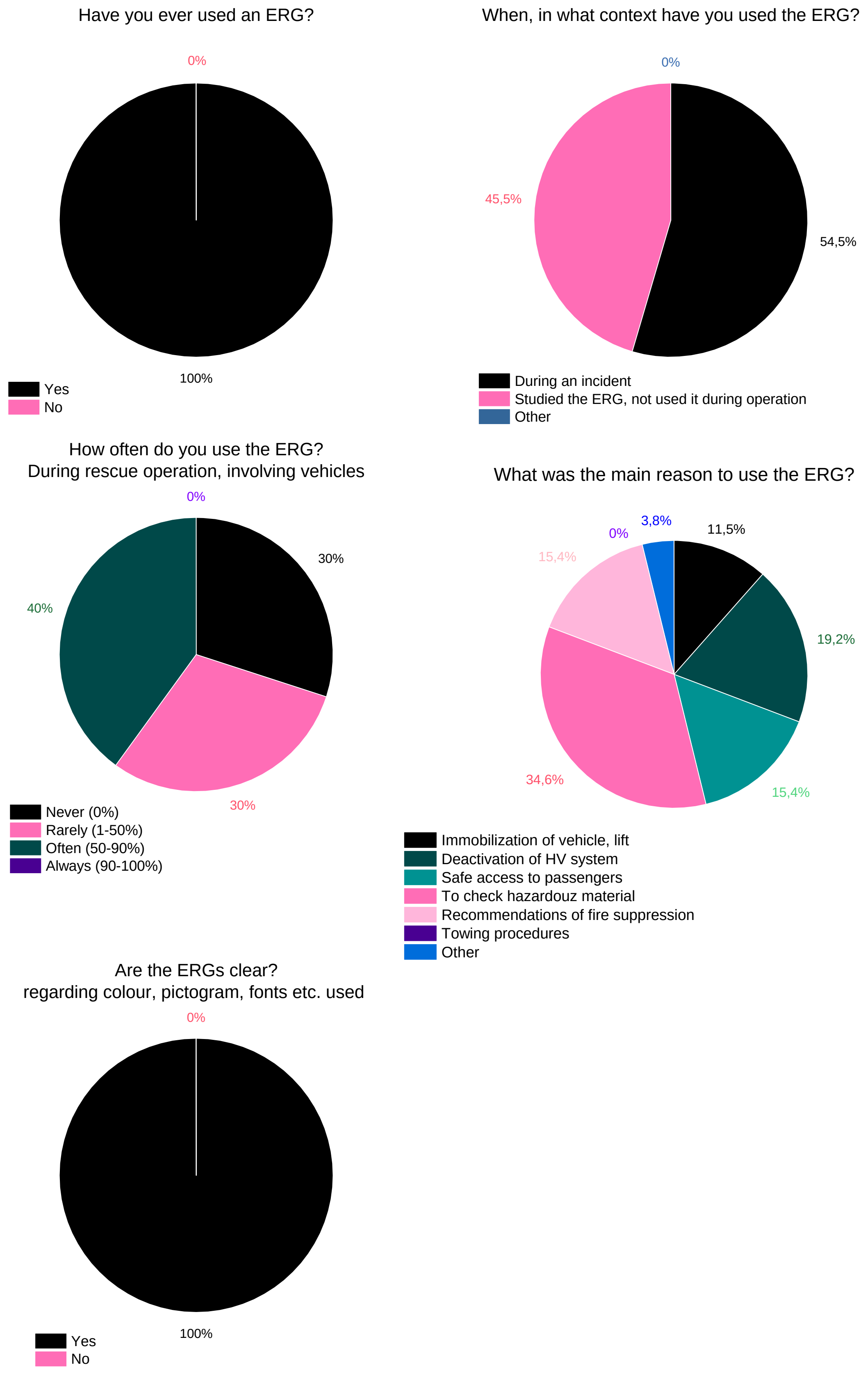

Figure 13. Answers to the survey that was sent out to the fire and rescue services in Sweden.

4.1 Workshop Discussions

Since the ISO 17840 standard does not cover "the rescue process" or "information related to education and training for rescue teams" some of the answers were out of scope but were still included in the discussion and are presented below for completeness.

Regarding tools and equipment, discussions were held regarding the cutting zones and the reinforced parts of the vehicle. It was pointed out that it is very important that the material specifications and the thickness of the reinforced parts should be specified. Especially if carbon fibre components have been used in the vehicle, as this poses a great health risk for the firefighters. Additionally, the information regarding the use of prying tools is currently very limited regarding EVs and the following question was asked "*Can prying tools be braced against the battery pack/flooring of the vehicle, or will it damage the integrity of the pack?*".

The use of fog-nails for the battery pack is most often not recommended in the ERGs. However, questions arouse regarding the use of fog-nails in the engine compartment of the EVs. Is there a risk associated due to damaged HV cables, which could result in electric shock?

A wish to standardize the equipment recommended in the ERGs in line with the equipment used on the fire engines was made.

Sprinkler systems were discussed, and consensus was reached that the regulations are lagging. "*There is a great difference to attend a fire were there has been a sprinkler system active, the working conditions, in all aspects, are much better when sprinklers have been activated*". There was a wish to increase the use of sprinklers, or at least standpipe systems, in parking garages.

A large part of the workshop was dedicated to discussions regarding the electrical safety of EVs during rescue operations. Two anecdotal accounts of electrical shock related to EVs, and rescue operations were shared. Note, that further information such as incident reports regarding these incidents where not collected. The first experience included a crashed vehicle where the contactors were damaged, and the safety features had failed, which resulted in an electric shock for one of the fire fighters. The second experience involved a bus that was stuck in the snow, the driver had spun the wheels for some time before the fire and rescue services arrived. When the tow truck operator performed work around the wheels it resulted in an electric shock and the tow truck operator had to be taken to the hospital. A concern for new car manufacturers and their safety systems was expressed. Additionally, the need to be able to earth/ground the vehicle was expressed. More information regarding the risk related to charging, fires and application of water was enquired.

Lastly, it was brought up that the end chain, such as tow-truck operators and vehicle-workshops, needs more education regarding EVs. "*There is a lack of knowledge, sometimes we see crashed EVs being stored inside of vehicle workshops with no safety zones around them.*" Additionally, the recommendation of discharging battery packs using water baths (and salt) found in some of the ERGs was heavily criticized.

5 Conclusion

This section presents the main conclusion from the conducted study.

5.1 Literature Study

The data available today does not indicate that fires in EVs are more likely than in ICEVs, rather the contrary by a factor of 8 - 10. However, as EVs are still relatively new and few, it might be that the number of EV fires will increase as the fleet becomes larger and as the fleet ages. Recommendations on more detailed statistics are encouraged, especially regarding the root causes of fires, as well as if the traction battery was involved or not in the fire. In addition, the energy carrier is normally not reported in statistics of vehicle fires, which makes statistical studies difficult.

Collected data from large-scale vehicle fire tests show that there are no significant differences between fires in ICEVs and EVs regarding the peak HRR (maximum intensity of the fire) or the THR (total energy combusted). The total chemical energy available in a vehicle varies depending on the vehicle type and size, and on the materials used to manufacture the vehicle. It is interesting to note that the time until reaching the peak HRR is often shorter for ICEVs than for EVs, due to rupture of the fuel tank and release of a large amount of chemical energy in a short duration of time. However, the fire initiation plays an important role regarding the time until and the magnitude of the peak HRR.

Factors that Determine Fire Spread

The probability of fire spread in enclosed spaces is affected by three main factors:

- distance between parked vehicles
- materials used to manufacture the vehicles
- ceiling height of the enclosed space

The factors that enable fire to spread are similar for EVs and ICEVs. One additional risk for ICEVs is the possibility of liquid pool fires. Such fires may result from the rupture of the petrol or diesel tank, for example due to external heating. Liquid pool fires may increase the fire spread, the extent of which depends on factors such as, the amount of fuel, the incline of the flooring and drains adjacent to the vehicle.

For EVs, the possibility of jet flames from the battery pack could potentially contribute to fire spread. Jet flames are commonly deflected underneath the vehicle and could potentially reach a neighbouring vehicle and cause ignition. However, to the best knowledge of the authors, specific studies of this phenomenon have not yet been performed. Compared to jet flames from gas tanks, such as a CNG tank, jet flames from EVs are substantially shorter (in length and duration), as noticed during several large-scale vehicle fire tests performed at RISE.

Vehicle Fires in Enclosed Spaces

Since publicly available data on EV fires in tunnels and parking garages are limited, conclusions regarding fires in enclosed spaces were mostly based on statistics and field experiences related to ICEVs.

Accident investigations from fires in enclosed parking garages in Sweden conclude that an important difference when attending to a fire in an enclosed and an open structure is the environment for the fire and rescue services. For fires in enclosed car parks, the environment is harsh due to thick smoke and generally long access routes. Structural damages (concrete spalling) were found in all the cases studied, which all involved multiple vehicles on fire, and can potentially impose a great danger to the firefighters. In another study, it was concluded that in 42% of car park fires the fire spread from the initial vehicle to an adjacent vehicle. Fire will most likely spread much faster in an open car park compared to an underground garage due to the availability of air as well as wind. Additionally, the data studied indicated that the total number of fires is higher for open multi-story parking garages than for enclosed parking garages. The extent of damage was although similar for fires in the two groups.

Vehicle Fires in Tunnels

Statistics and field experiences studied in this work showed that the catastrophic fire incidents often involved heavy goods vehicles (HGVs), and that most fires were caused by vehicle defects. For causes related to vehicle defects, the location of ignition most often involved the engine or tyers/wheels. The rate of fires caused by vehicle defects was 3 – 6 times higher for HGVs than for passenger vehicles. Additionally, between 10 – 30% of the fire incidents were caused by a traffic accident (or collision).

For tunnel fire incidents, where the tunnel was equipped with a fire suppression system, the time from fire detection to re-opening of the tunnel was less than 4.2 hours. By contrast, the past catastrophic fire incidents in tunnels, without fire suppression systems, showed that this duration could be several months to several years, mainly due to the fire spread between vehicles and its impacts on tunnel structure and equipment. This could be regarded as a positive indication for installation of fixed fire suppression systems in tunnels.

Sprinkler System Design and Field Experiences from Parking Garages using Sprinkler Systems

Requirements for sprinkler systems in parking garages vary, and can depend on floor area, other functions in the building and can also be a subject for a risk analysis if the building is complex (i.e. risk for fire and rescue intervention, many floors, other functions above the garage).

The overall conclusion is that a sprinkler system design in accordance with EN 12845:2015+A1:2019 for parking garages is adequate, based on field experience and large-scale tests. It is expected that a sprinkler system can control a fire and prevent fire spread between vehicles. Based on free-burn fire tests, fire suppression tests and a limited number of actual fire incidents in sprinklered parking garages, it is likely that this conclusion also applies also to fires involving EVs (passenger cars).

5.2 Risk Assessment

A summary of the distinct unwanted events identified and assessed from respective HAZID sessions are presented in Figure 14.

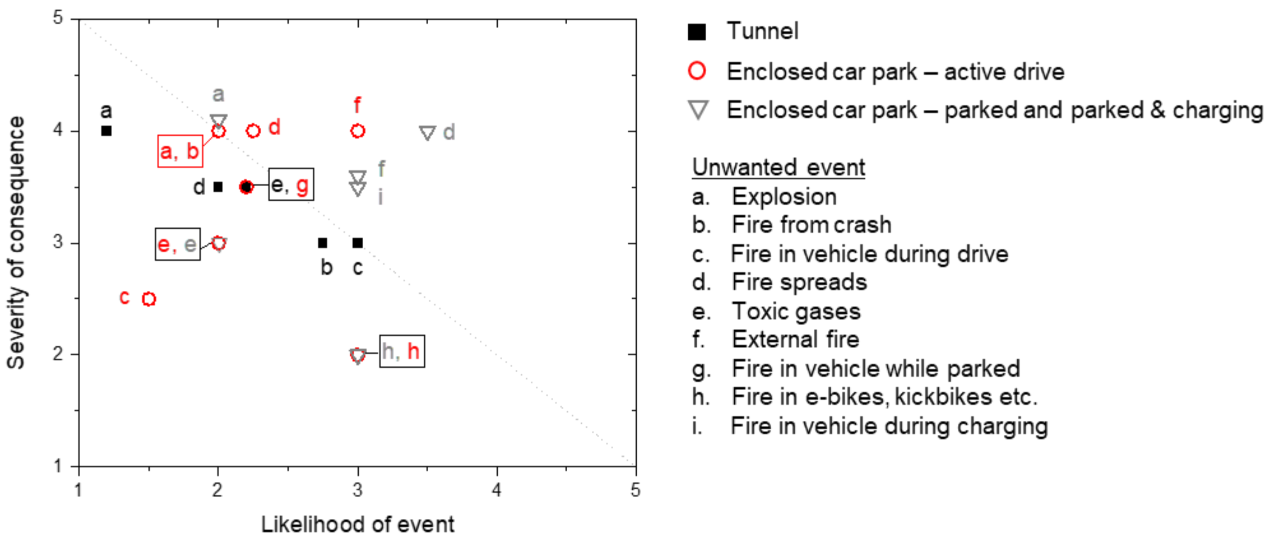

Figure 14. Summary of the likelihood of event and severity of consequence from the scenarios discussed during the HAZID workshop sessions.

5.3 Current and Proposed Risk Reduction Measures

Risk reduction measures on vehicle level are difficult to assign without having the root causes of the fire. Here, more statistics are needed to propose appropriate risk reduction measures on a vehicle level. A summary of potential risk reduction measures for infrastructure is presented in Table 3.

Early detection is key to reduce the severity of consequences of the fire. As fires in EVs are more difficult to extinguish than fires in ICEVs, preventive measures and early detection of the fire should be prioritized. Preventive measures are aimed at reducing the occurrence of fires (safe design), for example by limiting thermal propagation in the battery pack or by a battery management system and thermal management system which enables quick detection and management of events that are outside the safety window of operation. For the vehicle, early detection of vent gas, voltage fluctuations and/or temperature could potentially be coupled to the car alarm or an eCall which could reduce the time of fire detection, enabling a quicker response to the fire. From the workshop with the Swedish fire and rescue services, technical solutions that enable water injection into the battery pack were suggested as a risk reduction measure. However, if this is practically feasible, was out of the scope. Additionally, extinguishing lances were out of the discussion since the risk of electric shock was highlighted as a high-risk event.

Table 3. Summary from the four HAZID workshop sessions, unwanted events, and the risk reduction measures on infrastructure, currently existing and potential, preventive as well as mitigating are presented below.

HAZID workshop session	**Unwanted event**	**Risk reduction measures (infrastructure)**
Fire in parking garages Carport, open above ground car park, enclosed underground car park	Arson	Fire detection system, FFFS, wider parking spots, reduction in size of the fire cells, jet fans/ventilation to combat smoke
Collision of EVs in Tunnel	Explosion	Fire/traffic flow interruption detection systems, FFFS, escape routes, portable extinguishers, emergency calling systems, ventilation to combat smoke
	Release of toxic gas	
	Fire	
	Fire during active driving	
EV fires in enclosed car parks when the origin of fire is external *to* the vehicle. Vehicle is parked or parked and charging.	Fire in electrical socket/adjacent electrical installation	Fire detection systems, FFFS, wider parking spots, handheld extinguishers, maintenances and inspections of electrical installations, safety rounds, “safe by design” to prevent the use of improper equipment for charging, fire curtains, AI/ML enabled parking allocation to ensure safe distances between vehicles
	Fire in 2–3-wheel light electric vehicles	
	Fire due to spill of flammable liquid	
	Fire in adjacent storage room	
	Fire in adjacent vehicle	
EV fires in enclosed car parks when the origin of fire is the vehicle. Vehicle is parked or parked and charging.	Fire during charging	Fire detection systems, FFFS, wider parking spots, handheld extinguishers, maintenances and inspections of electrical installations, safety rounds, “safe by design” to prevent the use of improper equipment for charging, fire curtains, AI/ML enabled parking allocation to ensure safe distances between vehicles
	Explosion	
	Release of toxic gases	
	Arcing	
	Flooding of car park causing fire in EV	

5.4 Firefighting Tactics

Regarding firefighting tactics, concrete guidance from this study is that rescue operations with EVs are similar to ICEVs.

Trapped smoke is the main challenge in enclosed spaces. Since ventilation, both natural and mechanical, plays an important role in fire scenarios, it is therefore critical to have an improved awareness on risks and opportunities with ventilation, i.e., when to use it as a firefighting tactic or when it might lead to a secondary side effect causing a greater risk. Such knowledge is likely to influence the outcome of the firefighting, rescue operation and evacuation. Therefore, it is necessary for the emergency personnel and operators of tunnels and parking garages to have enough knowledge to make an appropriate risk judgement applicable to different fire scenarios that might occur.

Drones are used in wildfire surveillance and may also be applicable in vehicle fires in enclosed spaces. The use of drones and robots for fire localisation and detection, especially in enclosed parking garages, could ensure better accessibility for the firefighters. Drones or robots installed with thermal imaging cameras could be regarded as an effective complementary tactical measure in fire detection and localisation. These can also be used to gather more information which could be used to decide upon which firefighting tactic that should be utilized.

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Appendix A. Data on vehicle fires

Data on vehicle fires have been collected from different countries and sources, with focus on EV. Table A1 presents EV and ICEV fire test data and Table A2 presents data collected on EV fire accidents.

Table A1. Data collected on EV and ICEV fire test data, where green rows mark data for EV

Ref	Type of vehicle	Vehicle year	Li-ion battery	Amount of fuel/ SOC	ignition	THR (GJ)	Peak HRR (kW)	Mass loss (kg)	Radiat./ temp.	Gas/ prod. meas.	Sim./ modelling	Cell/Module/ Pack tests performed	Other
[2]	ICEV, diesel	2011	n.a	44 L	external fire	5,9	5700	252	Temp.	y	Yes - smoke movement garage	y	
[2]	BEV	2019	NMC pouch	80%	external fire	5,2	7000	247	Temp.	y	Yes - smoke movement garage	y	
[2]	BEV	2016	NMC prismatic	80%	external fire	6,7	5000	400	Temp.	y	Yes - smoke movement garage	y	
[72]	BEV		330V, 50Ah	100%	cabin	6,3	4200	212	Temp.	y	n	y	
[72]	BEV		355V, 66,6Ah	100%	cabin	8,54	4700	279	Temp.	y	n	y	
[72]	ICEV, diesel				cabin	6,89	4800	192	Temp.	y	n	y	
	ICEV, diesel				cabin	10	6100	275	Temp.	y	n	y	
[73]	4xTrailer mock-up	n.a.	n.a.						Temp., gas	n	n	y	
[74]	ICEV	1998		0	cabin		3500		heat flux	y	n	n	flame height
[74]	ICEV	1998		0	cabin		6000		heat flux	y	n	n	flame height

[75]	ICEV			45	simulated pool fire - burner		1000 0+	Temp.		n	y	
[75]	ICEV			45	simulated pool fire - burner		8500	Temp.		n	y	
[72]	Small PHEV				simulated pool fire - burner		8000	Temp.		n	y	
[72]	Large PHEV				simulated pool fire - burner		1000 0	Temp.		n	y	
[72]	BEV			100%	simulated pool fire - burner		8000	Temp.		n	y	
[72]	BEV			85%	simulated pool fire - burner		8000	Temp.		n	y	
[72]	BEV			100%	simulated pool fire - burner		9000	Temp.		n	y	
[76]	ICEV	2008		100 mL	engine comp. space			Temp., heat flux		n		fire spread
[77]	BEV (Nissan Leaf)	2011		100%	left rear soft bumper	6,4		heat flux	n	n		
[77]	ICEV (Honda Fit)	2003		10 L	left rear splash guard	4,2		heat flux	n	n		

[2]	ICEV (Toyota Sedan)		10 L		5,1		
[2]	ICEV (Nissan minivan)		10 L		5,3		
[2]	ICEV (Subaru station)		10 L		5,6		
[2]	ICEV (Toyota minivan)		10 L		5,9		
[2]	ICEV (Toyota luxury sedan)		10 L		7,4		
[78]	BEV2	”new”		electric resistance heater		y	time to escape
[78]	PHEV2-1	side impact		electric resistance heater		y	time to escape
[78]	PHEV2-2	front impact		electric resistance heater		y	time to escape
[78]	BEV1	front impact		electric resistance heater		y	time to escape
[78]	PHEV1	front impact		electric resistance heater		y	time to escape

[78]	HEV3	”new”			electric resistance heater				y			time to escape
[79]	PHEV battery (A)	battery only	4.4 kWh	100%	external fire			Temp, heat flux	y	n	y	electrical measurements, firefighting tactics, water
[79]	EREV battery (B)	battery only	16 kWh	100%	external fire	0,72	700	Temp, heat flux	y	n	y	electrical measurements, firefighting tactics, water
[79]	PHEV battery A	mock up	4.4 kWh	100%	external fire			Temp, heat flux	y	n	y	electrical measurements, firefighting tactics, water
[79]	PHEV battery A	mock up	4.4 kWh	100%	external fire			Temp, heat flux	y	n	y	electrical measurements, firefighting tactics, water
[79]	PHEV battrey A	mock up w interior	4.4 kWh	100%	external fire			Temp, heat flux	y	n	y	electrical measurements, firefighting tactics, water
[79]	EREV battery (B)	mock up	16 kWh	100%	external fire			Temp, heat flux	y	n	y	electrical measurements, firefighting tactics, water
[79]	EREV battery (B)	mock up	16 kWh	100%	external fire			Temp, heat flux	y	n	y	electrical measurements, firefighting tactics, water

[79]	EREV battery (B)	mock up w interior	16 kWh	100%	external fire				Temp, heat flux	y	n	y	electrical measurements, firefighting tactics, water
[80]	12 vehicles each floor	63x63 m car park 4 story							Temp.	n	n	n	steel temperatures, stress-strain curves, deflection etc.
[75]	ICEV	2015		full	propane burner - pool fire	3,29	7100	274	Temp, heat flux	y	n		Electrical measurement
[75]	EV	2014		100%	propane burner - pool fire		6000	333	Temp, heat flux	y	n		Electrical measurements
[75]	EV	2013		85%	propane burner - pool fire	4,91	5900	295	Temp, heat flux	y	n		Electrical measurements
[75]	ICEV	2013		full	propane burner - pool fire	4,95	10800	336	Temp, heat flux	y	n		Electrical measurements
[75]	EV	2013		100%	propane burner - pool fire	4,66	6900	363	Temp, heat flux	y	n		Electrical measurements
[75]	PHEV	2013		full/ 85%	propane burner - pool fire	4,63	6000	308	Temp, heat flux	y	n		Electrical measurements
[75]	PHEV	2014		full/ 100%	propane burner - pool fire	5,85	7900	445	Temp, heat flux	y	n		Electrical measurements

*	BEV no Battery, free burn	2020/2021		no fuel storage	external fire	5	2500	240	Temp.	y	n	y	water run-offs
*	ICEV, sprinklered test	2020/2021		40L	external fire	6,1	3700	309	Temp.	y	n	y	SPRINKLERED TEST, water run-offs
*	BEV, sprinklered test	2020/2021	50kWh, 216 cells in 18 modules	90%	external fire	5,7	3000	327	Temp.	y	n	y	SPRINKLERED TEST, water run-offs
*	Battery pack, sprinklered test		50kWh, 216 cells in 18 modules	90%	external fire	0,8	2400	75	Temp.	y	n	y	SPRINKLERED TEST, water run-offs

*Tests conducted January 2022, data not yet published

Table A2. Data collected on EV fire accidents, where coloured rows mark vehicles which were parked upon fire initiation

Year	Type of EV	Reference	Comment
2008	Toyota Prius	9	A Toyota Prius caught fire due to spontaneous ignition while in transit. This vehicle was converted to a PHEV. The main reason could be an improper assembly of bolted joints with electrical lugs inside the battery pack, which triggered the overheating and thermal runaway of the battery cell.
2011	Chevrolet Volt	9	A Chevrolet Volt spontaneously caught fire almost three weeks after the crash-test exercise
2011	Tesla Model S	9	In Merida, Mexico, a Tesla Model S caught fire at high-speed driving through a roundabout and hit a wall and a tree
2012	Nissan GTR	9	A Nissan GTR crashed and caught fire. The fire was caused by electric arcs created by the short-circuiting of high voltage lines, which ignited the vehicle’s combustibles (interior materials and around 75% of the power batteries

2012	Toyota Prius/Fisker Karmas	9	After Hurricane Sandy flooding, a Toyota Prius Plug-in Hybrid and 16 Fisker Karmas caught fire while being parked in a marine. The fire was caused by saltwater expansion into the electrical system, its corrosion, and finally—a short circuit in the unit
2013	Mitsubishi-iMiev	9	A Mitsubishi i-MiEV caught fire at the Mizushima battery pack assembly while being charged
2013	Tesla Model S	9	A Tesla Model S caught fire after the vehicle hit debris while being driven on a highway. Flames began coming out both of the fronts at the end of the car. Extinguishing the fire with water obtained from outside of the car was unsuccessful because the fire reignited underneath the vehicle. Water given directly to the burning battery extinguished it finally.
2013	Tesla Model S	9	A Tesla being driven in Murfreesboro, Tennessee, caught fire after it struck a tow hitch on the roadway that caused damaged beneath the vehicle
2014	Tesla Model S	9	In Toronto, Canada, a Tesla Model S caught fire while parked in a garage, but it was not charged
2016	Tesla Model S	9	in Norway, A Tesla Model S caught fire while being charged by a Tesla Supercharger. The fire grew up slowly, and the owner managed to unplug the car. Tesla suggested a short circuit in the vehicle’s distribution box as the direct reason for the fire.
2016	Tesla Model S90D	9	In France, A Tesla Model S 90D caught fire during a promotional test drive. The vehicle started burning spontaneously and was destroyed within 5 min. Tesla suggested a “bolted electrical connection” that was “improperly tightened” under the production process, causing the fire.
2017	Tesla Model X	9	in California a Tesla Model X lost control over an embankment and struck a garage, starting a fire that completely damaged the car
2017	Tesla Model S	9	In Austria A Tesla Model S crashed on a concrete barrier at a motorway, which initiated the fire in the battery at the front of the vehicle. The fire was described as extremely severe with a lot of toxic gas production
2017	VW-e Golf	9	in Germany, a VW e-Golf caught fire in a high-voltage battery space; after initial cooling, the firefighters moved the vehicle into a water container

2018	Kia Optima Hybrid	9	A driving Kia Optima Hybrid spontaneously caught fire, and the whole car started to burn just 30 s after it started. The causes were electrical in nature but not determined in detail.
2018	Panamera E-hybrid	9	A Panamera E-Hybrid burst into flames while being plugged into a household outlet for charging
2018	Lifan 650	9	A Lifan 650 ignited and was completely lost as the fire could not be extinguished in time. The fire initiated spontaneously under the car, in the battery space. During the fire, several small explosions and significant emissions of toxic black smoke were noticed
2018	Porsche Panamera	9	A Porsche Panamera caught fire and exploded while its battery was being charged. The reason was an improper installation and working of the charging system
2018	Tesla Model S	9	A Tesla Model S hit a wall, causing the battery pack to ignite. The battery reignited twice, requiring it to be extinguished three times in total
2018	Tesla Model S	9	In Switzerland, A Tesla Model S caught fire after the vehicle hit the guard-rail on a highway
2018	Tesla Model S	9	in California, a Tesla Model S started to smoke while being parked in the street and flames started shooting out from under it. Firefighters were able to extinguish the fire effectively, and the cabin was left unaffected.
2019	Tesla Model S	9	A Tesla Model S caught on fire being parked in a garage. The same car caught on fire again two months later (on April 8th), while it was under investigation.
2019	Tesla Model S	9	in Florida, A Tesla Model S burst into flames just after it crashed into a tree, was effectively extinguished, and repeatedly caught fire after being brought to the car park used by police.
2019	Tesla Model X	9	A Tesla Model X was completely burned in the middle of a frozen lake; during the fire, numerous small explosions were noticed, and firefighters arrived about 30 min after the fire began, which appeared to be too late.
2019	Tesla Model S	9	in China, A Tesla Model S caught on fire and exploded in an underground car park; in total, five cars were damaged by the fire.

2019	Outlander	9	An Outlander caught fire after immersion in saltwater.
2019	Tesla Model S	9	A Tesla Model S spontaneously caught on fire while not plugged in, with smoke observed near the rear right tire.
2019	Tesla Model S	9	A Tesla Model S in Hong Kong caught on fire while parked.
2019	Tesla Model S	9	in Belgium, A Tesla Model S burned down while supercharging.
2019	Tesla Model 3	9	in Russia, A Tesla Model 3 hit a truck on a high-speed road and subsequently burned down
2019	Tesla Model x	9	in England, A Tesla Model X from 2017 burst into flames while charging. The fire ignition was confirmed in the battery pack, and it was caused by an impact on one of the battery pack modules.
2019	Kona Electric	9	In Canada, A Kona Electric caught on fire while being parked in a residential garage in Montreal. The car was not plugged in. The fire triggered an explosion and caused damage to the attached structure.
2019	Kona Electric	9	in south Korea, a Kona Electric caught fire while charging
2019	Kona Electric	9	in south Korea, A Kona Electric burst into flames while being charged in an underground car park. The vehicle was completely destroyed
2019	Tesla	https://driving.ca/auto-news/news/tesla-spontaneously-combusts-in-shanghai-parking-garage	Tesla spontaneously combusts in garage
2019	Porsche Panamera	9	in Portugal, a Porsche Panamera E-Hybrid caught fire after hitting a pillar of a bridge
2020	Porsche Taycan	9	in Florida, a Porsche completely burned while parked in a residential garage
2021	Chevrolet Bolt	https://www.nbcwashington.com/news/local/northern-virginia/electric-vehicle-sparked-fire-at-virginia-home-did-235k-in-damage-officials/2663744/	Fire started while charging

2021	Tesla model S	https://www.nationthailand.com/blogs/tech/40004207	The car gave an alarm that the charging where interrupted before the fire started
2021	Tesla	https://www.republicworld.com/world-news/us-news/tesla-model-s-in-us-catches-fire-while-charging-overnight-in-a-garage.html	A California couple has said that their Tesla Model S caught fire while charging in their garage overnight, spread to a second Tesla vehicle before engulfing their house in flames.
2022		https://www.surfsantamonica.com/ssm_site/the_lookout/news/News-2022/April-2022/04_04_2022_EVs_Catch_Fire_in_Parking_Structure_Crash.html	In California, two electric vehicles caught fire when they crashed inside a Downtown parking garage
2022	100 cars involved	https://bikekharido.in/news/100-vehicles-catch-fire-in-delhis-electric-vehicle-charging-station/	a massive fire broke out in Delhi's Jamia Nagar electric vehicle parking station. The authorities are yet to conclude the reason for the fire. However, it could have happened because of a short circuit.
2022	Jaguar I pace	https://www.zeebiz.com/automobile/news-jaguar-i-pace-electric-car-catches-fire-while-charging-in-florida-192708	Jaguar I-Pace battery caught on fire without any crash after simply sitting charging in a garage.
2022	Tesla X and Y	https://carbuzz.com/news/watch-two-teslas-catch-fire-beside-a-garage-full-of-ammo	Two cars burned in a garage; the cause is not known
2018	Hybrid electric	6	PHEV alarmed for electrical fault, soon after the car started to burn during drive
2018	Hybrid electric	6	Fire in engine, car was parked
2018	Hybrid electric	6	Fire in parked vehicle, reason for fire is unknown, the fire spread to another vehicle (ICEV)
2018	Hybrid electric + 3 ICEVs	6	Four vehicles on fire, unknown cause and unknown vehicle that started the fire
2018	Hybrid electric	6	Driver started vehicle and flames erupted from the engine compartment

2018	Electric	6	Fire in carport, charger or cable was the origin of fire
2018	Hybrid electric	6	Fire in a hybrid electric vehicle on a car park, unknown reason for fire
2018	Hybrid electric	6	Fire in a hybrid electric vehicle on a car park, unknown reason for fire
2019	Hybrid electric	6	Fire during charging, the fire started in the wall socket
2019	Hybrid electric	6	Fire during drive
2019	Hybrid electric	6	Fire in a hybrid electric vehicle on a car park, unknown reason for fire
2019		6	Fire in coupe which spread to the carport, no damages on the battery
2019	Electric	6	Fire during drive, started in front seat
2019	Hybrid electric	6	Short circuit due to jump start cables which short circuited and ignited the luggage compartment
2020	Hybrid electric	6	Fire in engine compartment during drive
2020	Hybrid electric	6	Front of vehicle affected, parked vehicle, fire cause unknown
2020	Electric	6	Unknown cause, vehicle parked
2020	Hybrid electric	6	parked vehicle, charging, unknown cause of fire
2020	Hybrid electric + 5 other vehciles	6	fire in multi-car port, 6 vehicles on fire, one was hybrid electric, unknown cause of fire
2020	Hybrid electric	6	Race car, vaulted, batteries most likely not affected
2020	Gas vehicle and electric vehicle	6	Fire in garage, gas bottles were stored in the garage as well as one biogas vehicle and one electric vehicle, fire cause unknown'
2020	VW transporter	6	Parked vehicle, Unknown cause of fire, batteries most likely not affected
2020	Hybrid electric	6	Fire in engine compartment, parked vehicle, not charging fire cause unknown
2020	Hybrid electric	6	Parked in garage, charging vehicle, fire localized to the vehicle but cause unknown
2020	Hybrid electric	6	Daisy chain connection started the fire, fire did not spread to vehicle
2020	Electric	6	Parked vehicle, battery not affected, unknown cause of fire
2020	electric + 2 other vehicles	6	Unknown cause of fire, ICEVs completely burnet out, fire had started to spread to the electric vehicle, battery affected by fire

2020	hybrid electric + 2 other vehicles	6	Unknown cause of fire, 2 vehicles (including the hybrid) was completely burnet out when the FRS arrived
2020	hybrid electric + ICEV	6	two cars on fire at a parking lot, fire started in petrol car and spread to the front of the hybrid, battery not affected, unknown cause of fire
2020	hybrid electric	6	Gas development from battery, unknown cause of smoke, unknown location of vehicle (drive/parked)
2020	Home built electric vehicle	6	Charging, started with explosion, followed by jet flames
2020	2 electric vehicles	6	Parked, unknown cause of fire
2020	electric vehicle	6	parked, unknown cause of fire
2020	Hybrid electric + 2 other vehicles	6	Unknown cause of fire, fire started in the hybrid vehicle
2021	Hybrid electric	6	Tow truck operator saw sparks from vehicle, car had been on fire the day before
2021	electric vehicle	6	Charging outdoors, no more details,
2021	electric vehicle	6	Fire upon driving, fire started in trunk where there were batteries, unknown type of vehicle, homebuilt?
2021	electric vehilce	6	Parked vehicle, unknown if charging or not
2021	electric + ICEV	6	Crash incident, electric car on fire, ICEV no fire, person in electric vehicle was able to rescue him/her-self whilst the driver of the ICEV died
2021	hybrid electric	6	Charging in carport, TR in battery which lead to full fire
2021	hybrid electric	6	Short circuit 12 V battery, traction battery not affected, vehicle was likely charging
2021	electric	6	Parking garage, charging
2021	older ICEV converted to electric	6	Car was charging

2021	electric	6	Car was charging
2021	Hybrid electric	6	Driving, smoke from battery then fire
2021	Hybrid electric	6	Parked, Fire in passenger compartment, battery most likely not affected
2021	Hybrid electric	6	Smoke development engine compartment, unknown if driven or parked, unknown if battery was affected
2021	4 electric vehicles	6	Parked and charging outdoors, unknown cause of fire
2021	Hybrid electric	6	Fire during drive, battery affected by fire, unknown cause
2021	2 electric and 2 other vehicles	6	parked vehicles, unknown cause, batteries not affected
2021	electric	6	Fire in vehicle at service, car had been in accident earlier during the day, re-ignition
2021	Hybrid electric	6	Crash incident
2021	3 electric + 1 gas vehicle	6	Unknown cause, unknown charging state, batteries affected by the fire
2021	electric vehicle	6	Fire started in passenger compartment; vehicle was charging
2021	Hybrid electric	6	Unknown cause and state
2021	Hybrid electric	6	Vehicle charging, 12 V battery involved - smoke development from 12 V battery
2021	Hybrid electric + a number of other vehicles	6	Fire in carport, unknown cause and origin of fire

Appendix B. HAZID Workshops

Four different HAZID session with different themes were carried out, with different undesired events identified, as listed in Table B1 below.

Table B1. Unwanted events identified for the different themes investigated

Arson	**Crash of EVs in tunnels**	**EV fires in enclosed car parks, when the origin of fire is external/ outside the vehicle. Vehicle is parked or parked and charging.**	**EV fires in enclosed car parks, when the origin of fire is the vehicle. Vehicle is ~~parked~~ or parked and charging.**
Arson in parked EVs in multiple carports	Explosion due to crash of EV in tunnel	Fire in an electrical socket/ adjacent electrical installation	Fire during charging
Arson in parked EVs in open above ground garages	Crash followed by toxic release of gases.	Fire in adjacent smaller 2-3-wheeler light electric vehicles	Explosion in EV while it is parked and charging
Arson in parked EVs in closed underground garages	Crash followed by fire without explosion in unidirectional and bidirectional tunnels.	Fire due to spill of flammable liquid	Release of gases from the battery of an EV without immediate ignition
	Fire in EV during active drive inside a tunnel.	Fire in adjacent storage room (rubber tyre storage/ garbage)	Arcing between EV and charging plug
	Crash of single or multiple EVs into tunnel walls.		Flooding of the charging station

Throughout the HAZID sessions, different events were qualitatively rated with regards to likelihood and severity of consequence. The scales of likelihood and consequence that were used for the estimations are presented in Table B2 and in Table B3, respectively.

Table B2. Likelihood scale used to rate different events during the HAZID sessions

Likelihood Scale	Score	Description
Highly unlikely	1	Almost impossible this will happen
Unlikely	2	Unlikely
Somewhat likely/ Medium	3	Possible
Likely	4	Likely
Highly likely	5	Almost certain this will happen

Table B2. Scales used to rate the likelihood for fire spread as well as the severity of consequences during the HAZID sessions

Interpretation of Likelihood and Consequence (1-5 scale)					
Likelihood	1	2	3	4	5
	The fire is highly unlikely to spread.	The fire is unlikely to spread.	The fire is somewhat likely to spread.	The fire is likely to spread.	The fire will almost certainly spread.
Severity of Consequence	1	2	3	4	5
Severity of Consequence Severity of Consequence (Fire spread)	No effect	Minor effect	Moderate effect	Major effect	Hazardous effect
	Fire does not spread at all	Fire spreads to up to 1 vehicle	Fire spreads to up to 5 vehicles	Fire spreads to more than 5 vehicles	Fire spreads to more than 10 vehicles
Severity of Consequence (Damage to infrastructure/ property)	No damage to infrastructure	Damage to surface of infrastructure	Damage to loadbearing structure but no collapse	Partial collapse	Complete collapse
Severity of Consequence (Availability of tunnel and/or car park)	Unavailable for less than 1 day	Unavailable between 1 day and 1 week	Unavailable between more than 1 week and 1 month	Unavailable between more than 1 month and 1 year	Unavailable for more than 1 year. (E.g.: refurbishing of 1 km of tunnel lining needed).
Severity of Consequence (Environmental impact) [E.g.: waste water collection from car parks after fire; smoke].	No real damage	Short-term damage with small geographic spread.	Reversible long-term damage with small geographic spread. OR Short-term damage with large geographic spread.	Permanent (Non reversible) damage with small geographic spread. OR Long-term (Reversible) damage with large geographic spread.	Permanent (Non reversible) damage with large geographic spread.

The results from the four HAZID sessions are documented in tables B4-B7.

Table B4. Results from HAZID Theme 1: Arson

Unwanted event	**Current safety measures already existing (preventive and mitigating)**	**Likelihood**	**Risk Factors**	**Differences between EV and ICEV**	**Mechanism of failure**	**Consequence**	**Potential safety measures (preventive and mitigating)**
What do we NOT want to happen?	**FFFS Fixed firefighting systems installed/ technical aspects for e.g. type of sprinklers, type of ventilation etc. Tactical aspects for e.g. related to manual firefighting and first response etc.**	**Description**	**Factors affecting Likelihood of the Unwanted Event and/or Severity of Consequence of the Unwanted Event.**		**Mechanism of failure = How does the fire spread?**		**Fixed systems installed/ technical aspects for e.g. type of sprinklers, type of ventilation etc. Tactical aspects for e.g. related to manual firefighting and first response etc.**
Parked; Carport multiple.	No FFFS: no ventilation, detection or sprinkler system. Requirement for safety distance for adjacent buildings exists today.	Somewhat likely if there is anything nearby, provided the arsonist is able to get the fire started.	It depends on whether there are any cars nearby. Open or closed windows in vehicle. How early or late the fire is detected. This depends on if it is in a remote area and time of the day, Place of ignition source. The size of the car. Etc.	No difference	Jet flames, radiation, liquid pool, smoke layer, other flammable material, ceiling height.		detectors, sprinklers, shorter arrival times for the rescue services
		Probably rather high provided there are vehicles nearby, we should check numbers in literature on how long time it takes to spread		Longer burning time of the EV influence the risk of spread. The potential jet flames from the battery, does this pose a larger spread risk. Liquid pools from ICEV is a comparable factor. Jet flames usually not that long (m). The E-tox2 tests showed rather short jet flames for the vehicle but longer for the battery itself. The jet flames are not long lasting in time.			Manual firefighting; Portable fire extinguisher
Parked; Open above ground car park		Building material, (normally concrete); Influenced by wind condition; Ceiling height, direction of vehicles					Detection, sprinkler, other FFFS.

		parked, placement of the vehicles, multiple floors.					
Parked; Closed underground car park						Jet fans, might produce high velocities and thus spread the fire	Sprinkler, (jet fan could perhaps be used as a safety measure also), detection, not so large fire cells, larger parking slots
Parked and charging; Closed underground car park			No impact on fire development unless the EV is fully charged	Yes			Improve education and awareness

Table B5. Results from HAZID Theme 2: Collision of EVs in tunnels

Unwanted event	Factors affecting the unwanted event	Current safety measures already existing (preventive and mitigating)	Factors affecting the Likelihood of occurrence	Differences between EV and ICEV fires	Consequences	Potential safety measures (preventive and mitigating)	Post HAZID comments
What do we NOT want to happen?	**Fire size, fire spread, fire development, gases released etc. E.g.: Explosion from crash = Unwanted event. Factors affecting explosion from crash = Amount of gas released, ventilation circumstances, type of vehicle in the crash etc.**	**Fixed systems installed/ technical aspects for e.g. type of sprinklers, type of ventilation etc. Tactical measures**	**Description**	**Compare between gas release; How prone are EVs vs ICEVs to fire from crash? how prone are EVs vs ICEVs to fires from active drive?**	**Description**		

Chain of events: Crash followed by explosion. Explosion caused by flammable gases from battery in EV.	Amount of ventilation, type of tunnel (unidirectional or bidirectional), length of tunnel. Tunnels in Sweden more than 1000 m and with more than 4000 vehicles per 24 hours are required to have mechanical ventilation. Tunnels in USA: no such requirement for mechanical ventilation / emergency ventilation for tunnels less than 1000 m.	Portable extinguishers, drainage to prevent fire from liquids, telephones, escape routes, accessibility for fire fighters, lightning. Fixed firefighting systems - not requirements but advice on what to evaluate if these are installed. "If a fixed system is installed then what should the evaluation parameters for that fixed system be?"	High SOC high probability of immediate ignition and thus no explosion. Lower SOC means less H2.		Damage to structure	Fire and gas detection system, CCTVs, Fire suppression. Any changes in first responders? Mechanical ventilation system (emergency ventilation) also for shorter tunnels	More than the fire spread in the explosion, focus on the severity of damage to structure. Personal safety.
Chain of events: Crash followed by toxic release of gases.				No difference between ICEV and EV			Toxic gas are generally more severe for humans than for the building construction.
Chain of events: Fire followed by crash BUT no explosion.	Severity of crash						Inputs from MSB and leading vehicle manufacturer: Most crashes in vehicles may not lead to fire. This is valid even in frontal crashes with ICEV (hot surfaces and flammable liquids. Most accidents are lower speed accidents.
Crash in unidirectional tunnel	Probably a less severe crash as all vehicles are driving in the same direction	probably difference in cities and rural tunnels. CCTV in cities and then it is possible to notice the crash. AI for identifying traffic flow. Surveillance for tunnels longer than 3000m, CCTV and automatic detection of incidents/accidents. Differences between cities if the rescue services direct the traffic or not. IN Gothenburg it is the traffic surveillance that do this.		No difference in likelihood for crash if there would be the same number of vehicles (EV and ICEV)		Systems for identifying traffic flow rate. A stop is detected fast. Currently surveillance for tunnels longer than 3000m, CCTV and automatic detection of incidents/accidents, an option also for shorter tunnels?	
Crash in bidirectional tunnel	Can be more severe in frontal crash						Possibility of explosion is high.

Single collision (into tunnel wall)							Most common of the different crashes in general but we do not know specifically for tunnels.
Multiple collision (collision between vehicles)	Both frontal crash or side to side crash; Depends on the amount of traffic in tunnel, rear end crashes are the most common (75%).						Fire spread to more vehicles or cloud explosion risks is relatively high.
Jet flame							Assumes that the battery pack is involved, which may not always be the case. Such jet flame lengths are short.
Explosion of vehicle itself							Compare with explosions in the EV, difference is the delay of explosion
Fire involving several vehicles	If there is a queue, size of fire, amount of traffic						Depends on whether heavy good vehicles are involved.
Fire in one vehicle	it is quite common with these fires but when one considers that the vehicle should be in a tunnel the likelihood decreases.	Surveillance, emergency parking places	engine compartment, wheel, brakes, hot surfaces, flammable liquids	Difficult to tell. Brakes are different, not sure how it will affect the likelihood. Engine compartment is different	Not so large if the vehicle is able to drive out of the tunnel	Early detection, getting the vehicle out of the tunnel, sprinkler not so useful while the vehicle is moving, ventilation	The fire consequence can be huge if there is a queue with trucks.
Fire spread to other vehicles	if the vehicle stops or not, driving to the outside is better but will people do that. Not if it is in the compartment	Surveillance, emergency parking places					Fire spread is not likely if the vehicle can be kept driving out of the tunnel.
Fire spread to other vehicles	Depends on how many vehicles nearby	Sprinklers are installed in some cases as this allows less fire ventilation openings, larger distances to evacuation routes, etc. (per Swedish building regulations)	Less space so maybe more likely to spread, also the cars are parked not moving, ceiling height is less which increases the likelihood of spread				Usually, it is only a few cars that are involved in the fire. Uncertain if it is due to ventilation control or perhaps sprinklers. Semi-enclosed above ground gives much more intense fires. UK: multistorey fires above ground are much more common (but might be due to more parking garages above ground).

Gas release (toxic)			Maybe less ventilation in car park than tunnel				Simulations done in BREND and ETOX using data on from free burning vehicle. The source terms should still be OK considering how enclosed the vehicle is itself.
Explosion			Higher SOC results in more gas			Structural safety to be considered, currently Katarina garage in Stockholm is designed	How is the load-bearing structures designed in parking garages? Seems it is only escape routes that are designed for explosion. Designed only against load and fire. Explosion is only considered if you have a storage of explosives.

Table B6. Results of HAZID Theme 3: EV fires in enclosed car parks, when the origin of fire is external/ outside the vehicle. Vehicle is parked or parked and charging.

Unwanted event	Factors affecting the unwanted event	Current safety measures already existing (preventive and mitigating)	Factors affecting the likelihood	Differences between EV and ICEV fires	Consequence	Potential safety measures (preventive and mitigating)	Post HAZID comments
	Fire size, fire spread, fire development, gases released etc. E.g.: Explosion from crash = Unwanted event. Factors affecting explosion from crash = Amount of gas released, ventilation circumstances, type of vehicle in the crash etc.	**Fixed systems installed/ technical aspects for e.g. type of sprinklers, type of ventilation etc.** **Tactical measures**					

Fire in electrical socket; EV is parked and charging.	Quality of installation, how well the plug fits, damaged cables, dirty socket		Daisy chain is one cause that is seen in statistics and also using indoor cables outdoor.		Fire might spread to vehicle or other materials, but this depends to a large degree on distance, there are some accidents where this has happened but maybe not so often.	checking the cables and charging station, not allowing charging in normal wall socket. Not allowing charging by outlets for engine heaters. Covered sockets. Fire rounds. Raising awareness of the risk of fires in electrical installations.	Of the 100 fires 5 were caused by faulty installation. Fires in power stations in buildings and open spaces in Denmark, charging electric car: 7 cases in 2021, electrical panel, cables, socket. Statistic from China on AFV fires, 50% caused by smoking, carelessness, etc. 28% caused by electricity.
Fire in adjacent vehicle; EV is parked and charging.	Distance between vehicles, type of other vehicle (gas powered), size of fire. Attack on a fire nearby a charging vehicle could be delayed because of wanting to cut power before attack. Low ceiling in general increases the radiation and thus the fire spread but on the same token a small compartment limits the amount of air makes the fire self-extinguish.	In many cases sprinklers are installed	Distance		It is very rare that underground parking fires grow big, whether this is due to lack of oxygen or if there is sprinklers.	In general, make the fire compartment smaller has a positive effect on number of vehicles that can take part in the fire and amount of air available. But there is a risk of explosion when the compartment is opened. Control of where people park their cars, should not park next to another car. Parking assistance, distance between cars, Valet parking.	Potential Risk Reduction Measure: Large fire blankets. Not cost efficient to have installed all the time, better that the rescue service has them. Fire curtains especially in underground car parks. Inspired from EU's LASH FIRE Risk Control Options in closed roro space to mitigate fire risk. Divided (not solid), rollable fire curtains to enhance fire compartmentalization. Complemented by sprinklers. Fire robots. In the car park no one knows where the driveable areas are. Drones to identify where the fire is. The robots can be equipped with thermal imaging and other sensors like for flammable gases.
External fire not part of vehicle in e.g. garbage; EV is parked.	Amount and kind of material stored, complexity of building both in terms of entrance and other building factors and organisation	Should not be done according to regulations but still happens, fire rounds, fire alarms might not be required but still might be in place, sprinklers are required underground in USA but perhaps not in other countries. By installing sprinkler, one could allow longer distances to the escape doors and staircases.	Amount and kind of material stored, organisational factors	No difference		Proper housekeeping, awareness, detection	The fire that occurred spread smoke to the buildings connected to the garage: reference to the accident.

Fire in spill of flammable liquid; EV is parked.	Functioning drainage, slope of floor, distance between leakage and drainage. Surface roughness, dirt etc. Amount of spill; Need to unplug.	Drainage, slope of floor, R100 and R34 standards.	Surface roughness of floor	More probable from ICEVs. No difference when exposed.	Depending on size of pool the fire might ignite one or several vehicles.	Housekeeping, maintenance of drainage	Very rare.
Fire in adjacent vehicle spreading to vehicle; EV is parked.	Functioning drainage, slope of floor, distance between leakage and drainage. Surface roughness, dirt etc.		Distance between vehicles		Probably not so much difference, if charging		Higher than charged and parking since more cars are parked than charging, so more than possible; Severity of consequence depends on if the fire spreads.
Fire from flammable gas; EV is parked.	if other things are stored in car park or from gas powered vehicles						A flammable gas release may result in either a long jet flame that ignites everything along its path (fire spread) or a gas cloud explosion that poses a high risk to personnel. Low likelihood but severe consequence.
Fire in e-bikes, kick bikes, moped, vespas, motorcycles etc.; EV is parked.	if other things are stored in car park, distance between bike/moped etc. and vehicle	Bikes should probably not be in the same "room" as the vehicles	Distance between vehicles			Charging of these items should not be allowed in underground parking, arrange special lots for these items	Rather high likelihood if the EV is charging.
Fire in adjacent storage rooms like storage for tyres; EV is parked.	These types of storage are not so common in public garage, but more common in garages for apartment buildings					Awareness of fire risk, if this is used then proper compartmentalisation	Large amounts of fuels are probably available and thus flashover of that room is highly possible. The flames could extend from the room to car park. Therefore, fire spread to cars nearby and further spread are probable. There is a need to set a fire barrier between them.
Fire from gas powered vehicles; EV is parked.		In some communities in Sweden these are not allowed in public garages. In some countries gas-powered vehicles are not allowed in tunnels and/or underground car parks.					Due to restrictions, the likelihood could be low. But the consequence could be high due to the high probability of causing fire spread in car park that may damage the structure.

Table B7. Results of HAZID Theme 4: EV fires in enclosed car parks, when the origin of fire is the vehicle. Vehicle is parked or parked and charging.

Unwanted event	Factors affecting the unwanted event	Current safety measures already existing (preventive and mitigating)	Factors affecting the Likelihood	Differences between EV and ICEV fires	Severity of Consequence	Potential safety measures (preventive and mitigating)	Post HAZID comments
What do we NOT want to happen?	**Fire size, fire spread, fire development, gases released etc.**	**Fixed systems installed/ technical aspects for e.g. type of sprinklers, type of ventilation etc.; Tactical measures**				**Fixed systems installed/ technical aspects for e.g. type of sprinklers, type of ventilation etc.; Tactical measures**	
Parked and charging; Fire in vehicle.	Not proper appliances, malfunction in charging station, using normal plug appliances	charging stations do have measures for preventing fires, tactics: unplug before intervention	not proper appliances, malfunction in charging station, use of normal plug appliances, Higher SOC will result in a more intense fire. Overcharge increases the likelihood a lot	ICEV cannot be charged, except the 12V	Rather severe if the fire spreads	more proper charging stations, not possible to use normal plugs, check of charging station after installation has it been done properly, more training and information. Better statistics would be useful but there is always a lack of fire statistics. A first step would be manufacturers to share statistics.	Data is not detailed enough to tell if the TR is more common during charging. Much of the data reported is fires starting in the electrical socket.
Parked and charging; Release of gases from the battery not immediately ignited	Not proper appliances, malfunction in charging station, using normal plug appliances	charging stations do have measures for preventing fires, tactics: unplug before intervention, gas detection				more proper charging stations, make it not possible to use normal plugs, check of charging station after installation has it been done properly, gas detection, improved detection around charging stations	
Parked and charging; Explosion	The strength of the "container" i.e. the cell, module, pack. Of the 100 cases 5 mentions explosion. One of the cases was a accumulating gas case. There were 2 cases that occurred while charging.	charging stations do have measures for preventing fires, tactics: unplug before intervention	Homebuilt, improper installation	A lot of things can explode related to a vehicle like tyres, gas dampers, etc. Not so much difference between.	Rather severe	Explosion is not a well-defined term, unclear definition, essentially anything that makes a sound. Simulations conducted in BREND. There are videos, but no data on how common.	Plenty of the parking slots in underground parking garages built today are equipped with chargers. In the future, it is not unlikely that all slots will have its own charger or electrical connection point. Severity of consequence will depend on the size of garage and what is next to the vehicle; Placement of charging stations, near entrance would allow easy access to disconnect and the rescue service do not need to go very far into the building.

Parked and charging; Arcing between vehicle and charging plug or overheat	Quality of connectors, too many fuses, overload					more proper charging stations, make it not possible to use normal plugs, check of charging station after installation has it been done properly, inspection of charging stations?	Refer to arcing: https://www.dubizzle.com/blog/cars/arcing-in-automobiles/
Parked and charging, Arcing in vehicle	Quality of connectors. We do not know to what extent this happens. Dust etc. Too many fuses, overload						
Parked and charging; Vehicle starts moving	Not sure if this can happen. We have not seen any fires as a result of this.	Is it possible to start/moving the vehicle while it is charging?				Is it possible to start/moving the vehicle while it is charging?	May not be fire but only damage
Parked and charging; Fire spread to other vehicles	Distance to other vehicles, size of fire	How is the charging station dimensioned geometrically, is it like a normal parking slot or not? Does a fire in one vehicle have an impact through the charging stations on the other vehicles? Perhaps extinguishing systems/sprinkler. Building recommendations not to place the charging so that the building does not burn down				distance to other vehicles? A fire blanket that is on the market but not so much used. In Sweden usually 20 cm wider parking spots for EVs.	Risk of severe damage to structure.
Parked and charging; Flooding of the space and the vehicles.	Storms, heavy rain, hurricanes, design of drainage in car park	Drainage				Place charging stations where the flooding is less likely, cleaning of vehicle after flooding. Inspection after flooding, tow away the vehicle after the flooding, measure on vehicle level. Flooding should be covered in the design.	There are several reported cases of EV fires after flooding. Inputs & claims: Tesla claims that their vehicle can float on the water and the pack completely sealed. Opel Mocha claims just that there is no extra risk if the vehicle is submerged
Parked and charging; Explosion of accumulated gas	Amount of gas released						Not so many reported. Most severe case from the perspectives of personnel safety.

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