REPORT

This study was performed by RISE Research Institutes of Sweden on behalf of Volvo Trucks.

Contact person	Date	Reference	Page
	2023-09-27	1195564	1 (21)

Division Safety and Transport
+46 10 516 62 44
jonna.hynynen@ri.se

Electric Trucks – Fire Safety Aspects

Contents

Abstract

This study was performed by RISE Research Institutes of Sweden on behalf of Volvo Trucks. RISE Research Institutes of Sweden was requested to conduct a study regarding the differences between fires in conventional internal combustion engine (ICE) trucks and electric trucks. A set of guiding questions (see section *Aim*) were given by Volvo Trucks and in this report these questions have been answered. The questions have been answered by performing literature searches and through previous knowledge of RISE. However, for some questions, due to scarcity of data on electric truck fires, knowledge regarding electric passenger cars has been used. In addition, contact has been made with fire and rescue services around the world (Australia, UK, USA, Sweden and Finland) to collect their views on management of fires in electric vehicles (EVs).

The main conclusions are:

- Data on electric truck fires are scarce due to the low number of vehicles as well as the low number of fire incidents. Available data show that battery electric passenger vehicle fires are less common than ICE vehicle fires, but that the risks are different. The main differences are that battery fires tends to be harder to extinguish than fires in ICE vehicles and that there is a risk of accumulation of flammable gases, especially in enclosed spaces, upon thermal runaway.
- Lithium iron phosphate (LFP) type cells, in comparison with nickel-based type cells (such as lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminium oxide (NCA)), have a higher thermal runaway onset temperature, a slower temperature increase rate, a lower maximum temperature as well as a lower gas production in total amount. However, the specific total gas production (L Ah^{-1}) can sometimes be higher for LFP-type cells and depends on the state of charge and on the amount of electrolyte in the cell. However, the safety of a battery pack in a vehicle is determined by several factors such as preventive measures aimed at reducing the occurrence of fires (safe design). For example, by early detection and pro-active mitigation using the battery management system and thermal management system and by limiting the thermal propagation in the battery pack, reducing the extent of damage.
- Fires in enclosed spaces, such as in underground parking garages and tunnels, generally imply a higher risk for firefighters due to the trapped smoke, decreased visibility and longer access routes than in open structures. Risk reduction measures for battery fires should focus on early detection of harmful events, reducing thermal propagation in the battery pack and on limiting the extent of fire spread. The severity of the consequences of vehicle fires (no matter if is an EV or an ICEV) in enclosed spaces could be reduced using suppression systems, such as a water sprinkler system, to hinder fire spread between vehicles.

Key words: Electric truck, fire safety, vehicle fire, electrical safety, enclosed space

Aim

The following questions, specified by Volvo trucks, were to be answered in this report:

1. How common are fires in electric vehicles and trucks?
   In the event of a collision/accident in which the traction battery is damaged, how common is it for a fire to develop?
2. In which situations do most EV fires occur?
3. What is the frequency of electricity-related incidents in connection with charging of EVs or during fires in EVs?
4. What is the difference between fires in conventional ICE vehicles compared to EVs?, and will the cell chemistry (LFP or nickel-based chemistries) affect the fire risks?
5. In the event of a fire in sensitive infrastructure, such as road tunnels, mines, underground garages or indoor loading docks (e.g., Nordstan), how are the risks affected by the fact that it is an EV that burns versus an ICE vehicle?
6. What types of risk reduction measures could be used (or are already used) to reduce the risks in the event of a fire in an EV in sensitive infrastructure?
7. How do the rescue services view operations against fires in electric vehicles?

Most questions have been answered by previous knowledge of RISE, additionally, literature searches have also been performed to collect data. Literature used in the report are referenced in section *References*.

List of Abbreviations

AC	Air Conditioner
AFV	Alternatively Fuelled Vehicle
Ah	Ampere Hour
AVD	Aqueous Vermiculite Dispersion
BEST	Battery Extinguishing System Technology
BRE	Building Research Establishment
CCTV	Closed-Circuit Television
CNG	Compressed Natural Gas
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EV	Electric Vehicle
HGV	Heavy Goods Vehicle
HRR	Heat Release Rate
HVO	Hydrogenated Vegetable Oil
ICE	Internal Combustion Engine
IEC	The International Electrotechnical Commission
IFV	Instituut Fysieke Veiligheid
ISO	The International Organisation for Standardisation
kWh	Kilowatt-Hour
L	Litre
LFL	Lower Flammability Limit
LFP	Lithium Iron Phosphate
LNG	Liquefied Natural Gas
LVD	Low Voltage Directive
MSB	The Swedish Civil Contingency Agency
MW	Megawatt
NCA	Lithium Nickel Cobalt Aluminium Oxide
NFPA	The National Fire Protection Association
NIPV	Nederlands Instituut Publieke Veiligheid
NMC	Lithium Nickel Manganese Cobalt Oxide
PFAS	Per- and Polyfluoroalkyl Substances
PHEV	Plug-in Hybrid Electric Vehicle
QR	Quick Response
SAE	The Society of Automotive Engineers
SoC	State-of-Charge
SOP	Standard Operating Procedure
THR	Total Heat Release
UL	Underwriters Laboratories

1. Fire statistics – Electric Vehicles and Electric Heavy Goods Vehicles

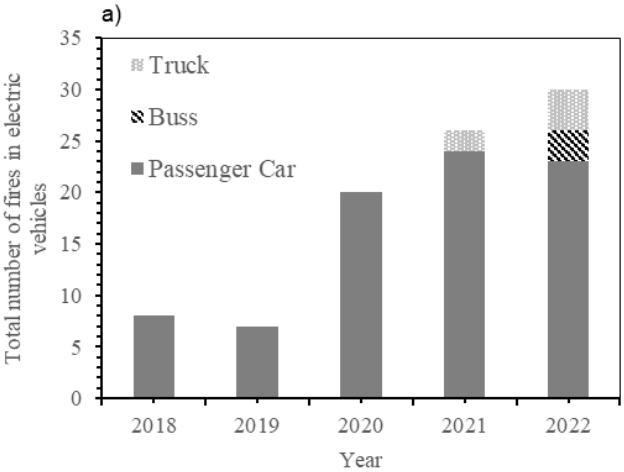
The website EVfiresafe.com reports a steady increase in the number of electric vehicle (EV) fires since 2010, following an increase in the size of the EV fleet [1]. However, data from Sweden for the years 2018 – 2022, see Figure 1a, indicate that even if the number of fire incidences is increased, fires in EVs are less frequent than fires in internal combustion engine (ICE) vehicles by a factor 10 – 20 [2]. Likewise, the Norwegian directorate for civil protection reports that fires in EVs are 8 times less likely than fires in ICE vehicles [3].

A similar analysis was performed by the Nederlands Instituut Publieke Veiligheid (NIPV) and presented in the NIPV annual report 2022 [4]. This report includes the analysis of 306 alternatively fuelled vehicle (AFV) accidents[1], including a total of 375 vehicles. The total number of fires reported was 179 (one fire in a land drilling rig, excluded from figure 1b). The fire incident frequencies for different vehicles are summarised in Figure 1b. In more than 50% of the incidents involving passenger vehicles, the traction battery was not involved in the fire.

In NIPVs annual report from 2021 [5], there is only one instance reported, out of 168 AFVs, 95% being battery electric or plug-in hybrid electric vehicles (PHEVs), in which the battery pack initiated the fire (passenger vehicle).

In data regarding fire incidents with electric busses and trucks reported by the Swedish Civil Contingency Agency (MSB) in 2023 [2] the fire incident frequencies for electric trucks and busses are 4 and 19 times lower, respectively, compared to trucks and busses with other fuels. However, the relative frequency of fire is higher for heavier vehicles compared to passenger vehicles as seen in figure 1b. However, this could be affected by the low number of vehicles in the fleet for the heavier electric vehicles (Figure 1b), which makes it hard to draw any statistical conclusions. In comparison, tunnel fire data from 12 countries presented by PIARC indicate that fires in ICE heavy goods vehicles (HGVs) are 1 to 4 times more common than in smaller types of vehicles (passenger vehicles, vans etc.) [6].

a)



b)

Source	Vehicle	Nr of vehicles in fleet	Nr of fires	Relative frequency of fires
Sweden EV/PHEVs	Passenger cars	610 716	23	4×10^{-5}
	Buss	1 062	3	3×10^{-3}
	Trucks	13 969	4	3×10^{-4}
Netherlands AFV*	Passenger cars	515 838	135	3×10^{-4}
	Light commercial vehicles (≤ 3.5 ton)	1 505	31	2×10^{-2}
	Buss	13 835	6	4×10^{-4}
	Truck >3.5 ton	390	6	2×10^{-2}

* 95% of the vehicles included in the statistics from Netherlands were EVs or PHEVs

Figure 1. a) Total number of EV fires in Sweden [2]. b) Total number of vehicles, number of fires and relative frequency of fires, data for Sweden obtained from [2] and for AFV fires in the Netherlands, three of the busses are battery electric whilst the trucks reported are gas-powered[2], data from [4,5].

[1] Accident – The criteria for determining whether a vehicle was or was not involved in an accident are: the vehicle caused the incident, and/or the vehicle sustained damage [5].

[2] Compressed natural gas (CNG) and liquefied natural gas (LNG)

To summarise, the reported data indicate that the fire incident frequencies for passenger EVs are generally 8 – 20 times lower for EVs than for ICE vehicles. However, the statistical data are limited and since the age of a vehicle may increases the risk of fire [7], comparing the risk of fires between the younger fleet of EVs with the entire fleet of ICEVs may be misleading.

The frequency of fire is reported to be higher (see Figure 1b) for HGVs compared to smaller vehicles across all sources, for vehicles of all types of propulsion. However, the number of electric HGVs included in the data is low. Finally, very little data regarding the frequency of fire in the traction battery, following a crash, involving EVs were found, data from the NIPV report the incidence of one fire out of a mean of 178 crashes in the last couple of years (2021 and 2022) [4,5].

2. When and why do fires in electric passenger vehicles occur?

In a publication from RISE [8], data from 101 EV fire incidents where compiled, see Figure 2. Most of the reported fires occurred when the vehicles were parked (47%) or parked and charging (21.3%). The Albero project [9] reported a similar trend where 66 out of the 113 (58%) identified EV and PHEV fire incidents had occurred when the vehicles were parked or parked and charging. Moreover, a summary of data for 252 electric passenger vehicle fires, made by EVfiresafe.com [1], reports that 55% of the vehicles were parked (35 vehicles were connected to a charging station and 5 caught fire (flaming fire) within one hour of charging). Of the vehicles charging, three fires were due to improper charging equipment (extension cord, improper cable, building electrical fault), 16 were due to cell faults, such as manufacturing defects, and 16 origins were stated as unknown.

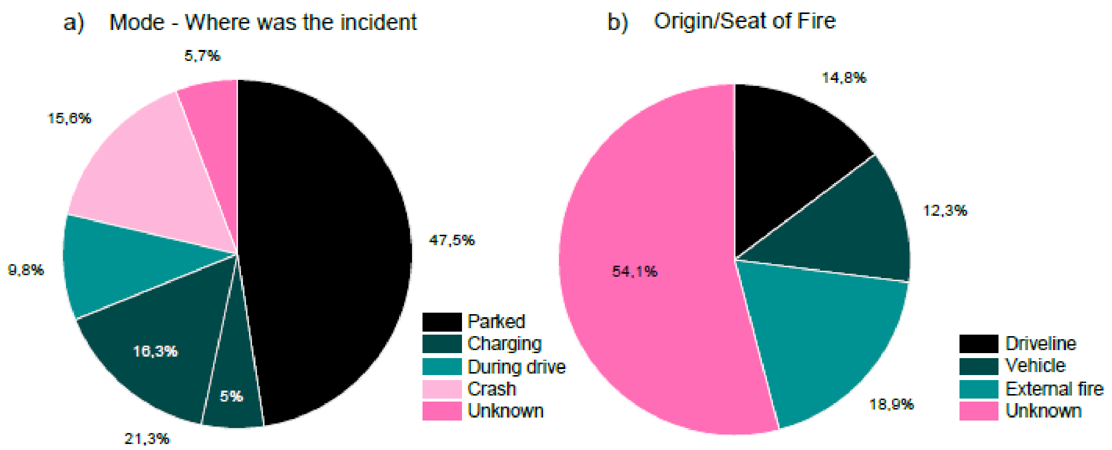


Figure 2. Incidents and origin/seat of fire involving passenger EVs published in [8]. In a) dark green colour indicates charging, where 5% are from non-adequate equipment used for charging.

NIPV reported that out of 78 parked AFV (passenger vehicles, 71 vehicles with a battery pack) fires, 43 were not at a charger, 33 vehicles were charging and two were unknown. The battery was involved in the fire for 16 (~ 50 %) of the fire cases when the vehicle was charging [4].

In total, the battery pack was involved in the fire in 51% of the AFV fires. Out of these 36 vehicles, the cause for one incident was attributed to overheating during towing; one incident due to technical defect while charging and two instances were due to failure in the battery pack. The remaining 32 incidents were either attributed to unknown causes of fire (23 cases), arson (4 cases) or technical failures elsewhere in the vehicle after which the battery got involved in the fire (5 cases).

In figure 2b, 14.8% of the fire origins were attributed to the driveline (i.e., the battery pack), the reasons for these fires varied and some of the reasons were due to: improper assembly of bolted joints inside of the battery pack; crash damage causing short circuits and electric arcs; flooding with salt water; road debris penetrating the battery pack; vehicle hitting a tow hitch causing damage to the battery pack and high speed collisions etc [8].

However, for electric passenger vehicles there is a large uncertainty in the root causes of these fires (figure 2b, pink – unknown). Additionally, the data presented above might suggest that the frequency of fire in EVs increases for parked or parked and charging vehicles. However, as mentioned in the RISE Report *Electric vehicle fire safety in enclosed spaces* [8], the amount of time the vehicle is driven versus parked is unknown and may give another view of the probabilities.

In work by the National Fire Protection Association (NFPA) [10], data for 267 600 ICE highway[3] vehicle fires (2003 – 2007) were analysed (71% passenger vehicles and 9% trucks). The causal factors were "mechanical failure or malfunction" 49%, "electrical failure or malfunction" 23%, "intentional" 8%, "collision or overturn" 3% and "exposure to other fire" 5%. The area of fire origin was reported to the: engine area, running gear or wheel area 64%, passenger compartment 14%, cargo or trunk 4%, fuel tank or fuel line 2% and other origins were reported for the remaining 16%.

2.1 Fires in electric trucks and busses in Sweden

Looking closer at the fire incidents in electric buses (3 incidents) and electric trucks (6 incidents) reported by MSB [2]. The following descriptions were given for each of the incidents:

1. Electric truck driven at a test rig started to emit smoke, traction battery not affected.
2. Electric truck (test vehicle) was driven on an electric road and smoke started to emerge from the battery unit (traction battery affected).
3. Fire in a light electric truck in a lithium-ion battery mounted underneath the driver's seat (not the traction battery).
4. Fire in a truck (electric combined with HVO), unknown cause of fire, unknown if the traction battery was affected.
5. Battery fire in a modified light electric truck (carrying an extra battery), unknown cause of fire.
6. Fire in a small electric truck during charging, charging current was disconnected which reduced the fire and smoke. Unknown if the battery was affected.
7. Fire in an electric hybrid bus during travel, the cause of the fire was a compressor (for the AC) malfunction.
8. Fire in an electric bus during travel, an electric converter on the roof of the bus had caught fire, the battery was not affected by the fire.
9. Battery fire inside a workshop (electric bus). The cause of the fire was that a part of a battery (weight of 40 kg) was dropped on a larger battery system which caused mechanical damage that resulted in thermal runaway.

Looking at these nine incidents, excluding the modified vehicles and the incident which was caused by human error (i.e., incident nine), it shows that the traction battery was only validated to have been affected in one of these cases (case two).

[3] Highway vehicle fire: "A fire involving a vehicle intended for highway use, including passenger road vehicles and trucks or freight road vehicles. The term "highway" is used to describe the vehicle, not the place the fire occurred." [10]

To summaries, fires in electric passenger vehicles seem to initiate whilst the vehicle is parked. However, the statistics are limited, and it would be good to relate the fire occurrence for the mode “parked” with the time that the vehicle is driven versus the time it is parked. Fire statistics on electric trucks are too limited to draw further conclusions.

3. Electrical safety upon charging

No incidents of electric shock upon charging were found in the study for this work. However, it is important to note that charging should be performed using adequate equipment according to the manufacturer’s specifications. As faulty or damaged charging equipment could increase the risk of fire.

Upon a workshop together with representatives from several Swedish fire and rescue services, two anecdotal cases of electric shock were given. Note that no investigation or incident report has been retrieved regarding these incidents. Additionally, the mentioned shock incidents were effects of accidents (not related to charging), so the existing safety systems may have been damaged.

The first case involved a collided vehicle where the contactors had been damaged and the safety features had failed, which resulted in an electric shock for one of the firefighters. 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 an electric shock occurred, and the tow truck operator had to be taken to the hospital. During the workshop, concerns regarding new vehicle manufacturers and their safety systems were expressed. Additionally, the need to be able to earth/ground the vehicle was expressed.

The national fire protection association (NFPA) performed several suppression tests of EVs, where they measured the voltage and current for the chassis as well as for the nozzle of a fire hose. The test results showed that the chassis and nozzle currents were negligible. The voltage levels at the chassis reached ~ 0.4 V. The conclusions drawn were that no adverse electrical conditions were noted upon manual suppression of EVs [11].

3.1 What protection measures exist to avoid electric shock in vehicles?

Charging stations need to fulfil the EU Directive 2014/35/EU, the so-called Low Voltage Directive (LVD) [12]. The LVD requires that the charging station is safe against electric shock and fire. In the LVD, it is up to the producer to certify that the product meets these requirements.

For the overall safety of vehicles there are several organisations that work with standardisation. For example, the International Organization for Standardisation (ISO) [13] is a global organisation that develops standards in collaboration with numerous countries. ISO 26262 focuses on the safety of vehicles, including EVs. Some ISO standards apply specifically to electrical safety, such as ISO 17409, *Electrically propelled road vehicles — Conductive power transfer — Safety requirements*, which was developed to minimise shock hazards within high-voltage testing. Additionally, the International Electrotechnical Commission (IEC) [14] is an organisation that develops standards related to anything electrical or electronic, such as IEC 61851, a standard that addresses electromagnetic compatibility (EMC) and electromagnetic interference (EMI) testing.

Another organisation setting standards is the Society of Automotive Engineers (SAE) [15]. One example is the SAE J2990/2_202011 “*Hybrid and Electric Vehicle Safety Systems Information Report*.” This report provides an overview of a typical high voltage electric vehicle and the safety systems employed to protect the high voltage systems. Since dealing with high-voltages can be hazardous, it is key to have labels on manual switches that disconnect and de-energize the high-voltage system. The SAE recommended guideline: J2990_201907, "*Hybrid and EV First and Second Responder Recommended Practice*", addresses the hazards of EV-related accidents. Upon a crash, the high-voltage system needs to be automatically deactivated within a certain amount of time so that the first responders can perform a safe rescue operation.

SAE, ISO and IEC standards are often considered as "recommended guidelines" but are not legally required. In the International Classification for Standards (ICS) 43.120 [16], standards related to "*Electric road vehicles engineering*" can be found.

4. EV and ICEV fires – What's the difference?

In the previous RISE project *Electric Vehicle Fire Safety in Enclosed Spaces* [8], literature values of the peak heat release rate (HRR) and total heat release (THR) were collected to compare similarities and differences between fires in passenger ICE vehicles and EVs, see Figure 3.[4] The collected data show that there are no significant differences between ICE vehicles and EVs regarding the peak HRR (maximum intensity of the fire) or the THR (total energy combusted). However, the time to peak HRR is generally shorter for ICE passenger vehicles, due to the large amount of energy released upon rupture of a fuel tank and release of petrol/diesel but will vary depending on the fire initiation (i.e., where the fire starts) and the amount of fuel in the tank. A petrol tank is designed to withstand an external fire for two minutes and the burn time of the fuel can be considered as quick, depending on the amount of fuel released.

In a former RISE project where large-scale vehicle fire tests were performed, the burn time for ~ 40 l of petrol was < 5 min. Thermal runaway propagation through the battery pack was slower, having a burn time of ~ 20 min for a ~ 50 kWh battery pack [17]. The burn time will vary depending on the size of the battery pack and on the number of cells experiencing thermal runaway. Additionally, the burn time may vary depending on the design of the battery pack, including how the cells are arranged and the design of the thermal management system, determining how fast the thermal propagation is through the battery pack. For a 50 kWh battery pack the THR was 0.8 GJ [18]; for larger battery systems such as the ones used in trucks (as example the Volvo FH Electric, 180 – 540 kWh [19] or Tesla Semi, 850 kWh), the THR would be higher. However, the available amount of fuel in a tank for an ICE truck will also be considerably higher than for a passenger vehicle.

The total chemical energy available in a vehicle (which determines the HRR and THR) will depend and vary with the vehicle type and size, and on the materials used in the vehicle. For example, the trend towards heavier vehicles and use of more plastic in vehicle production [8,20] has increased the chemical energy. This is also visible in Figure 3b if comparing the peak HRR and THR for ICE vehicles where (1) represents vehicles manufactured before year 2000[5], and (2) represents vehicles manufactured after year 2000. These data indicate that the largest contribution to the fire energy comes from the vehicle and not the petrol/diesel/battery.

[4] Due to the limited data on HRR and THR for trucks, passenger vehicles have been used to illustrate the differences between EV and ICE vehicle fires.
[5] Less plastic was used, and vehicles were generally smaller in size.

In work by Instituut Fysieke Veiligheid (IFV) [21], the fire load of passenger vehicles was compared with the fire load of ICE trucks, see Table 1. A bus or truck would have a 5 – 10 times higher fire load than a passenger vehicle, depending on the cargo, and will therefore pose more adverse consequences and risk in case of a fire. Additionally, lithium-ion batteries pose the risk of directional flames and venting of flammable gases (upon thermal runaway) which could pose a risk for gas explosions[6], see further section 4.1.

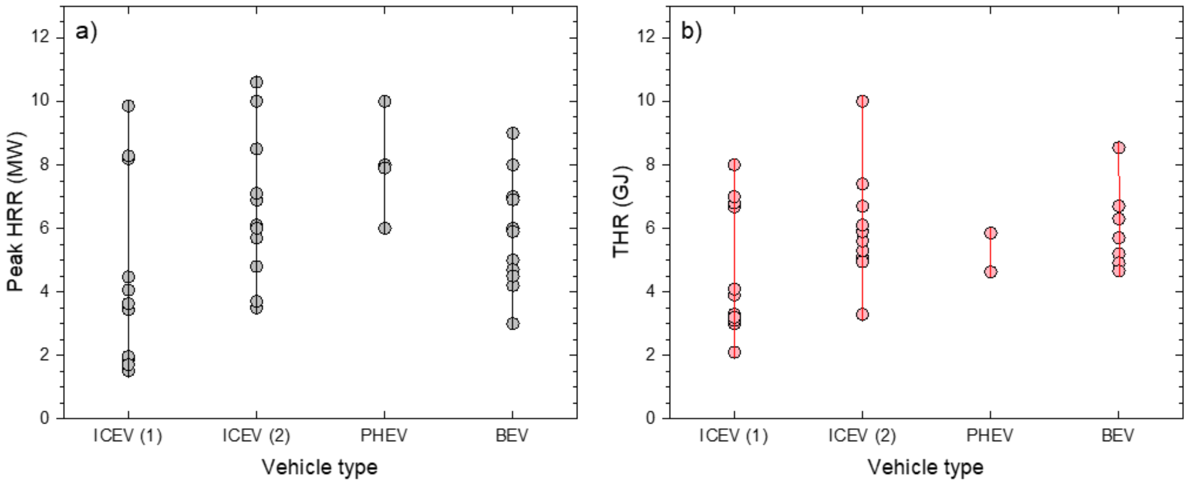


Figure 3. a) Peak HRR and b) THR for ICEVs, PHEVs and battery electric vehicles (BEVs). ICEV (1) represents vehicles manufactured before year 2000 and ICEV (2) vehicles manufactured after year 2000. Figure taken from reference [8].

Table 1. Vehicle fire loads, data from [21]

Vehicle type	Fire load (MW)	Time to peak HRR (min)
Passenger vehicle	5 – 10	10
Multiple passenger vehicles	10 – 20	20
Delivery van	15 – 30	10
Bus	45 – 60	15
Truck, including load	50 – 150	15
Truck with flammable liquid	200 +	unknown

4.1 Gas explosions and directional flames

Upon thermal runaway, lithium-ion battery cells release flammable gases, such as hydrocarbons and hydrogen gas. The percentage of hydrogen in the vented gas varies from a few percent up to 30% [22–24]. Hydrogen has a broad flammability range[7] (4 – 74 % in air) [25] and a great laminar flame speed which will pose an explosion risk. Furthermore, the risk of having a gas explosion will be affected by the ventilation conditions as well as the release scenario. If the flammable gases are accumulated and reach the lower flammability limit

[6] Deflagration mechanism
[7] In comparison to LFL and upper flammability level (UFL) of diesel and petrol 0.6 to 7.5 and 1.4 to 7.6 %, respectively. https://doi.org/10.1051/matecconf/2018249030

(LFL), or if there would be a delayed ignition of the accumulated gases, it could potentially result in a gas explosion.

Several explosion incidents related to battery energy storage systems have been reported, for example in [26]. Furthermore, the EV FireSafe website reports that for all the EV fires they have investigated, 5% resulted in an explosion. In 72% of these cases, the explosion occurred in an enclosed space [1]. Indicating that enclosed spaces, such as parking garages, tunnels and ship cargo spaces could be more vulnerable towards these events than if they occur out in the open. Additionally, for fires in all types of vehicles, tire or damper explosions may occur due to the increased temperatures and pressure, care should be taken in approaching a vehicle on fire.

The concentration of gaseous compounds and the total amount gas released will depend on factors such as the chemistry of the battery cell, state-of-charge (SoC), and size/number of cells experiencing thermal runaway [22,24,27]. As trucks generally have larger battery packs (i.e., an increased capacity) than passenger vehicles, the risk and magnitude of the consequence in the event of a gas explosion, could be more severe. Early detection of faults that could lead to a thermal runaway, as well as to limit the thermal propagation in the battery pack could be used to reduce the risks of accumulating large concentrations of flammable gas and its consequences.

Through testing, for example by using the test standard UL 9540A, the concentration of different gases and the total amount of gas released upon thermal runaway can be examined. Data obtained from such a test enables the design of adequate safety measures to minimize the risk of explosion events. For example, thermal management (such as cooling, insulation or phase change materials) could delay or inhibit further thermal propagation in the battery pack, resulting in a slower or lower total amount of gas released, which would lower the risk of an explosion.

More commonly, the gases released are immediately ignited due to open flames or other hot surfaces/ejected particles, resulting in a flaming fire. For battery pack/module/cell tests, these flaming fires usually involve long directional flames. These directional flames (or jet flames) could possibly impose a risk for faster fire spread, however studies regarding the effect of jet flames from lithium-ion batteries on the fire spread are currently lacking.

4.2 Difficulties in extinguishing of battery fires

There have been numerous reports from firefighters on the difficulties in extinguishing lithium-ion battery fires. There are two main reasons why fires in passenger EVs are more difficult to extinguish than fires in ICE vehicles. Firstly, the battery cells are generally well protected (placed between the wheelbase, as well as having a rigid protective structure), which makes cooling from the outside more difficult. For electric tucks the placement of the battery pack might differ compared to passenger EVs. However, no experience or reports on the suppression of electric truck fires were found for this report. Secondly, the reactions upon thermal runaway are exothermic chemical reactions, leading to accelerating chain reactions producing even more heat.

The difficulties in extinguishing an EV fire could potentially increase the risk that the fire spreads and also prolong the rescue operation. Due to the difficulties in extinguishing battery fires, numerous new strategies/suppression systems for lithium-ion battery fires have seen the market in recent years. Some examples are the Rosenbauer Battery Extinguishing System Technology (BEST), vehicle fire blankets, EV submerging containers and different water additives (F500, AVD etc.). However, the efficiency, overall impact (environmental, economic etc.) and not least the usability of these systems still need to be validated. Additionally, to our knowledge none of these methods have been validated against electric trucks.

In an enclosed space, where there is an increased risk of fire spread and where the environment in case of fire is harsh (see section 5), boundary cooling to limit structural damages and reduce the fire spread should be prioritised (if it is safe to perform). Note that fires that start in (or even involve) the traction battery are rare (see further section 1 and 2). Fires that do not involve the traction battery can be treated similarly to a conventional vehicle fire.

4.3 How will the risks differ depending on the chemistry in the battery cell?

LFP-type cells, in comparison with nickel-based type cells (such as NMC and NCA), have a higher thermal runaway onset temperature, slower temperature increase rate, lower maximum temperature as well as a lower gas production in total amount [28]. However, the specific total gas production (L Ah^{-1}) can sometimes be higher for LFP-type cells and depends on the state of charge and on the amount of electrolyte in the cell [24].
The higher specific gas production can be attributed to the typically more power optimised LFP cells, leading to cells larger in size compared to a NMC cell of the same capacity. The larger cell size means that there would be more available electrolyte and active material in these cells.

Additionally, the gas production will affect the peak HRR and THR, which are also influenced by the test methodology. Since LFP-type cells generally have a lower energy density, compared to nickel-based cells, the normalised THR can be higher (i.e., per kWh in battery capacity) [29].

The slower temperature increase rate and lower maximum temperature for LFP-type cells results in a lower probability of thermal runaway propagation and typically also a lower peak HRR [30]. The THR is primarily correlated to the total chemical energy available, which may vary between different types of cells e.g., power optimised cells versus energy optimised cells. Additionally, due to the lower maximum temperature, LFP-type cells are typically less prone to self-ignite in contrast to cells that contain a high nickel content. For cells with a high nickel content, many ejected hot particles are commonly noticed upon thermal runaway, which can ignite the released gases far away from the cell itself.

Whether a flammable gas release without early self-ignition is a lower or higher risk will depend on the application and fire scenario. A non-ignited flammable gas cloud may result in more severe consequences compared to a flaming fire, as the risk for gas explosion increases. Additionally, the highest normalised concentrations of hydrogen fluoride (normalised to electric energy) are found for LFP-type cells [31].

4.4 Fire effluents from vehicle fires

4.4.1 Gas emissions

Gas emissions from vehicle fires contain a variety of toxic gases such as carbon monoxide, hydrogen cyanide, hydrogen halides, volatile organic compounds, polycyclic aromatic hydrocarbons and inorganics (metal particles) [18,32].

Comparison of emissions from EV and ICE vehicle 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 ICE vehicles [18]. Additionally, in a previous RISE project, *Fire in new energy carriers on deck, BREND 2.0,* computer simulations were performed to study the fractional effective dose of asphyxiants and the fractional effective concentration of irritants. These were modelled in an enclosed space, and it was found that the danger of the combustion gases posed no practical difference between EV and ICE vehicle fires [33,34]. It is important to bear in mind that all vehicle fires, regardless of the energy carrier, pose danger to human health due to the toxic emissions formed.

4.4.2. Extinguishing water

In the RISE led project "*Investigation of fire extinguishing water from vehicle fires, ETOX-2*" [17,35], fire extinguishing water from both ICE vehicle and EV fires were analysed. All analysed extinguishing water was highly toxic towards the tested aquatic species (bacteria, green algae and crustacean). The extinguishing water collected from the ICE vehicle fire test was somewhat more toxic than the water collected from the EV fire test. However, per- and polyfluoroalkyl substances (PFAS) were found in higher concentrations in the extinguishing water collected from the battery pack fire. Studies on the existing PFAS substances in lithium-ion batteries and lithium-ion battery fires are currently very limited and further tests will be performed at RISE during 2023 to validate these initial findings.

Similar results, regarding the toxicity of the extinguishing water, were found in a Swiss study [36]. Additionally, the de-contamination of infrastructure after lithium-ion battery fires was also investigated. The conclusions were that current fire de-contamination procedures used for ICE vehicle fires were also suitable for EV fires.

To summaries, the difference between fires in ICEV and EV is that fires EVs tend to be harder to extinguish than fires in ICEVs. Additionally, the potential of thermal runaway in the battery pack could result in the accumulation of flammable gases, such as hydrogen, carbon monoxide and other hydrocarbon gases, which in a worst-case scenario could lead to an explosion/deflagration.

5. Fires in enclosed spaces

There are currently discussions regarding the dimensioning of fire protection measures for enclosed spaces, and if these are sufficient for today's vehicles. The increased use of plastic components in modern vehicles [20], which has increased the fire load, is one of the factors for these worries. In the past 20 years, plastic components have been used to replace steel and other metallic compounds. Additionally, vehicles today are generally larger, primarily in width but also since SUVs have become popular, which also increases the risk of fire spread as the parking slots have not been increased in width. Vehicles are hence parked closer to each other, and in a study by Terlouw, it was concluded that in 42% of car park fires the fire spread from the initial vehicle to an adjacent vehicle [37].

The major difference when attending to a fire in an enclosed space compared to an open structure is the environment for the fire and rescue services. The environment becomes difficult to orient due to the trapped smoke. Additionally, the generally longer access routes in enclosed spaces will also increase the risk for firefighters. Intense fires with high temperatures may result in structural damages (such as concrete spalling) and can potentially impose a great danger to firefighters.

Since ventilation, both natural and mechanical, plays an important role in fire scenarios, it is critical to be aware of the risks and opportunities with ventilation, i.e., when to use it as a firefighting tactic and when it might lead to a secondary side effect causing a greater risk (as ventilation may increase fire spread by supplying oxygen to the fire).

Tunnels are another example of an enclosed space. However, in tunnels vehicles will be actively moving and are not parked as in garages. In the work by Bai et al. [38] it was concluded that long tunnels experience a greater number of fire accidents and that accidents were more likely to occur at the tunnel entrance/exit (within 200 m from portals). In general, the most common cause of fires in tunnels is attributed to vehicle defects[8]. This is supported by statistics from Austria [39], where 90% of tunnel fires were appointed to vehicle defects and 10% due to collisions. The same trend is seen in Chinese data, reported by Bai et al. [38], in which 85 out of the 156 (54%) tunnel fires studied were due to spontaneous combustion of vehicles, originating mainly in the engine or tires. The fires resulting from collisions were more frequent in the Chinese data, where 36% of the fires were caused by collision.

Several sources report that the risk of fire increases with the number of HGVs[9] travelling in tunnels [6,40]. The rate of fires caused by vehicle defects was 3 – 6 times (Australian and French data) and 1.5 – 2 times (Norwegian data) higher for HGVs than for passenger vehicles [3,6,41]. As reported by Casey [40], 45% of the HGV fires (17% of all tunnel fires) in Australia were initiated in the cargo of the vehicle and 40% of the fires were due to mechanical or engine bay origin. Only 3% of the tunnel fires in Australia were due to collisions.

As a general conclusion, data from several reports suggest, even if the figures vary, that collisions are attributed to a relatively small portion of the fires (10 – 36%). From tunnel fire data, covering different types of vehicle types, the rate of fires can instead much more often be attributed to vehicle defects (poor maintenance), especially for ICE HGVs.

EVs (both for passenger vehicles and heavier vehicles) involved in fires in enclosed spaces are scarce and there is not enough data to draw any statistical conclusions.

To summaries, the major difference when attending a fire in an enclosed space compared to an open structure is the environment for the fire and rescue services. The enclosed space becomes difficult to orient due to the trapped smoke and increases the risk for firefighters. The potential risk for explosions in enclosed spaces due to accumulation of flammable gases is an additional risk related to EVs, described further in section 4.1.

6. Risk reduction measures for fires in enclosed spaces

6.1 Early detection and reduction of fire spread

Early detection of fire is key to reduce the severity of consequences. Early detection could be assisted by fire detection systems and by using CCTV.

As fires in EVs are more difficult to extinguish than fires in ICE vehicles (see section 4.2), preventive measures and early detection of the fire should be prioritised. Preventive measures are aimed at reducing the occurrence of fires (safe design), for example by early detection and pro-active mitigation using the battery management system and thermal management system or by limiting thermal propagation in the battery pack, reducing the extent of damage. 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 for detection, enabling a quicker response to the fire [8].

From a workshop with the Swedish fire and rescue services in November 2022, technical solutions that enable water injection into the battery pack were suggested as a risk reduction measure at the vehicle level. The technical viability of such systems was not further discussed. Additionally, the use of extinguishing lance or fog nails was discussed but dismissed since the

[8] Vehicle defects are more common in older vehicles and include for example faults in engine and brakes, often due to poor maintenance of the vehicle.
[9] Data collected for ICE HGVs

risk of electric shock was highlighted. The risk of electric shock upon using extinguishing lances or by flooding the battery pack should be communicated by the manufacturer (e.g., in the emergency response guide).

In case of a fire in an enclosed space, it is highly important to reduce the risk of fire spread. The probability of fire spread in an enclosed space is affected by three main factors: 1) the distance between parked vehicles/combustible material, 2) the materials used to manufacture the vehicle (available fire energy) and 3) the ceiling height of the enclosed space. To limit fire spread, combustible material near the vehicle/s should be avoided and an increased distance between parked vehicles or/and an increased ceiling height would be efficient means to reduce the risk of fire spread. Additionally, the installation of suppression systems has shown a good effect on reducing the fire spread (see further section 6.2).

6.2 Suppression systems

Requirements for sprinkler systems in enclosed spaces may vary and depend on factors such as the floor area (parking garages)/traffic flow (tunnels) and other functions of the building, and it can also be a subject for a risk analysis if the building is complex.

In a previous RISE study [8] it was concluded that a sprinkler system design in accordance with EN 12845:2015+A1:2019 for parking garages is adequate also for EVs (passenger vehicles). However, the effectiveness of a sprinkler system (in accordance with EN 12845:2015+A1:2019) towards a truck fire, having a higher fire load, was not investigated in this work.

The positive effects of using suppression systems were also reported by Casey [40].[10] The study investigated 16 Australian urban road tunnel fires and found that when 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) [42]. In contrast, some 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 sign for installation of water-based fire suppression systems in tunnels.

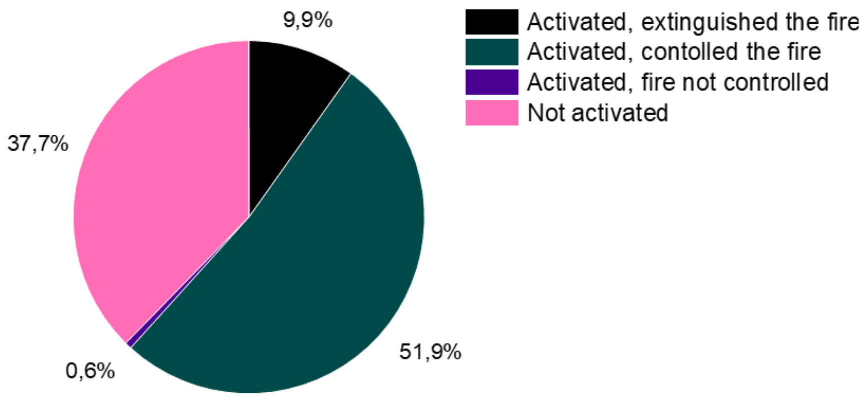


Figure 3. Parking garage fires in United Kingdom (1994 – 2005) where a sprinkler system was installed (activated or not during the fire) and the outcome of the fire. Figure re-printed from [8].

[10] Not EV specific study.

Similar positive effects were also found in work by the Building Research Establishment (BRE) in UK for sprinkler systems in parking garages [43].[8] A total of 3 096 parking garage fires in United Kingdom were studied and out of these fires ~ 1 600 (~ 51%) started in a vehicle. For the cases where an automatic sprinkler system was present and deployed, only in 0.6% of these fires the sprinkler system was not able to control the fire, see Figure 4. The failure of the system to control the fire could in some cases be linked to the late activation of the system. Indicating the importance of fast activation of the fixed fire suppression system. For the cases where the sprinkler system was not activated (figure 3, pink), the reasons for not activating the system could be for example that the fire was either too small for automatic activation or that the fire was extinguished manually by for example using a handheld fire extinguisher.

6.3 Requirements for mining vehicles and machines

Mines constitute a harsh, hazardous and isolated environment, so all vehicles and machines used in mines need to fulfil strict requirements (e.g., for tires, the hydraulic system, electric system, brakes); these come in many different standards and can be found in *SveMin's instructions for vehicles, machines and technical equipment* [44].

Petrol, ethanol or gaseous fuels are not permitted in mines (exemption are made for rescue vehicles) [45], whereas diesel drivelines are permitted. Furthermore, a suppression system according to SBF 127 (*Rules for fire protection of work vehicles*) may be required depending on the vehicle. The use of electric drivelines are currently being assessed for the use in mines in Sweden. However, SBF 127 does not regulate EVs and a similar document for EVs is currently not available. However, a “safe by design” approach should always be considered as it is the responsibility of the manufacturer (or representative) to ensure that these vehicles meet the requirements of the mandatory EU directives, at the time of commissioning and delivery. The manufacturer or retailer must systematically look for sources of risk, analyse the risks and assess the consequences and design to reduce these risks.

If machine functions are changed, for example through vehicle alterations, these changes or alterations may affect the original CE marking. For every alteration, the possible impact on the safety of the machine should be investigated and documented. The one who modifies or alters a machine is responsible for the machine's safety thereafter. This also applies if the change is carried out on behalf of the customer/machine owner [46].

In the GRAMKO handbook [46], preventive maintenance and daily supervision of vehicles and machinery are considered equally important as vehicle modifications (such as sprinkler systems installed in the engine compartment or modifications made to reduce wear and tear) [46]:

“During service and maintenance work, fire must be considered as a consequence and influence the ambition to keep, for example, hydraulic systems in top condition. Functional routines for cleaning in combination with training of operators, service and maintenance personnel is at least as powerful a preventative measure as modifications and sprinkler protection.”

7. Standard operating procedures for the fire and rescue service

For this report, contacts in Sweden, Finland, USA, UK and Australia, working at or with the emergency agencies, were asked to share their standard operating procedures (SOP) involving fires in EVs. According to the EV FireSafe project director, Emma Sutcliffe (email contact), no fire agency has published a SOP for an EV. A similar response was obtained from contacts in the UK, USA and Finland.

In Sweden, the fire and rescue services will in general have a similar approach to a fire in an EV versus an ICEV. A workshop conducted at RISE with several Swedish fire and rescue services in November 2022 [8] indicated that the following actions regarding EV fires should be prioritised to enable safe operations:

- *"How to handle damaged batteries after a fire and the potential risks of electric shock should be included in the emergency response guide. There should be a possibility to ground/isolate the vehicle to avoid electric shock."*
- *"How to extinguish a battery fire and how to / or not to approach a battery fire should preferentially be communicated from the manufacturer."*
- *"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 to fight fires in battery packs should be made clear by the manufacturer and stated in the emergency response guides."*

Conclusions

The data available today does not indicate that fires in passenger EVs are more likely than fires in ICE vehicles, rather the contrary by a factor of 8 – 10. However, the frequency of fire is reported to be higher for ICE HGVs compared to smaller vehicles. For fires in electric trucks, the existing data is scarce, and more data is needed to draw further conclusions. Recommendations on more detailed statistics are encouraged, especially regarding the origin of fires, as well as if the traction battery was involved or not in the fire.

Collected data from large-scale vehicle fire tests show that there are no significant differences between fires in ICE passenger vehicles and passenger EVs regarding the peak HRR, THR or the toxicity of fire effluents. The total chemical energy available in a vehicle will vary on the size and type of the vehicle (and depend largely on the materials used in the vehicle).

A bus or truck would generally have a 5 – 10 times higher fire load than a passenger vehicle, depending on the cargo, and will therefore pose a higher adverse consequences and risk in case of a fire. Furthermore, EV fires that experience thermal runaway in the battery pack usually have a prolonged fire scenario compared to ICE vehicles, due to the difficulties in extinguishing battery fires. The difficulties in extinguishing an EV fire and the potential of having a large volume of flammable gases accumulated poses an additional risk, especially in enclosed spaces.

Data and field experiences studied in this work indicated that catastrophic fire incidents often involved ICE HGVs, and that most of these fires were caused by vehicle defects (location of ignition most often involved the engine or tires/wheels) often related to poor maintenance of the vehicles. The rate of fires caused by vehicle defects was 3 – 6 times higher for ICE HGVs than for passenger vehicles.

Regarding the cell chemistry, LFP type cells, in comparison with nickel-based type cells (such as NMC or NCA), have a higher thermal runaway onset temperature, a slower temperature increase rate, a lower maximum temperature as well as a lower gas production in total amount. However, the specific total gas production (L Ah^{-1}) and hydrogen fluoride emissions from LFP-type cells can sometimes be higher than for nickel-based type cells. Additionally, ignition of gases is more commonly seen for nickel-based chemistries than for LFP. Whether a flammable gas release without early self-ignition is a lower or higher risk will depend on the application and fire scenario. A non-ignited flammable gas cloud may result in more severe consequences compared to a flaming fire, as the risk for a gas explosion increases (especially in enclosed spaces). The risk of gas explosions are higher in enclosed spaces and preventive measures should aim at reducing the occurrence of fires (safe design).

Lastly, early detection of faults and pro-active mitigation of thermal events using the battery management system, thermal management system and through “safe design” should be used to hinder or limit the thermal propagation in the battery pack, reducing the extent of damage.

References

[1] EVFireSafe.com, Passenger EV LIB fire incidents, (2023) 1–1. https://www.evfiresafe.com/_files/ugd/8b9ad1_ef09f84776fa49329b3b6d937b035a29.pdf (accessed June 15, 2023).

[2] U. Bergholm, MSB PM - Sammanställning av bränder i elfordon och eltransportmedel 2018-2022, Karlstad, 2023. https://www.msb.se/sv/publikationer/sammanstallning-av-brander-i-eltransportmedel-2018-2019/ (accessed June 15, 2023).

[3] C. Liu, L. Zhao, C. Lu, Exploration of the characteristics and trends of electric vehicle crashes: a case study in Norway, European Transport Research Review. 14 (2022) 6. https://doi.org/10.1186/s12544-022-00529-2.

[4] T. Hessels, V. Oosterveen, M. Huisman, C. Wissink, Incidenten met alternatief aangedreven voertuigen, Jaarrapportage 2022, 2023. https://nipv.nl/jaarrapportage-incidenten-alternatief-aangedreven-voertuigen-aavs-2022-gepubliceerd/ (accessed June 15, 2023).

[5] T. Hessels, V. Oosterveen, M. Huisman, F. van der Ploeg, B. Kuiper, P. van Dooren, Incidents involving alternative fuel vehicles - Annual report 2021, 2022. https://nipv.nl/wp-content/uploads/2022/05/20220412-NIPV-Annual-report-2021-Incidents-involving-alternative-fuel-vehicles.pdf (accessed June 15, 2023).

[6] PIARC, Experience with significant incidents in road tunnels, 2016.

[7] K. Szewczyński, A. Król, M. Król, Should We Expect a Disastrous Fire Accident in an Urban Road Tunnel? Literature Data Review and a Case Study for Selected Tunnels in Poland, Sustainability. 13 (2021). https://doi.org/10.3390/su13116172.

[8] J. Hynynen, M. Quant, R. Pramanik, A. Olofsson, Y.Z. Li, M. Arvidson, P. Andersson, Electric Vehicle Fire Safety in Enclosed Spaces, 2023.

[9] ALBERO project, (n.d.). https://alberoprojekt.de/#xl_xr_page_index-eng.

[10] M. Ahrens, U.S. vehicle fire trends and patterns, Quincy, MA, 2010.

[11] T.R. Long, A.F. Blum, T.J. Bress, B.R.T. Cotts, Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results, 2013. https://www.energy.gov/sites/prod/files/2014/02/f8/final_report_nfpa.pdf (accessed January 18, 2022).

[12] European Comission, Low Voltage Directive (LVD), (n.d.). https://single-market-economy.ec.europa.eu/single-market/european-standards/harmonised-standards/low-voltage-lvd_en (accessed June 15, 2023).

[13] ISO, International Organization for Standardization, (n.d.). https://www.iso.org/standards.html (accessed June 15, 2023).

[14] IEC, International Electrotechnical Commission, (n.d.). https://iec.ch/standards-development (accessed June 15, 2023).

[15] SAE, Society of Automotive Engineers, (n.d.). https://www.sae.org/standards (accessed June 15, 2023).

[16] ICS, International Classification for Standards, ICS 43.120 - Electric Road Vehicles Engineering. (n.d.). https://www.iso.org/ics/43.120/x/ (accessed June 15, 2023).

[17] J. Hynynen, O. Willstrand, P. Blomqvist, M. Quant, Investigation of extinguishing water and combustion gases from vehicle fires, 2023.

[18] J. Hynynen, O. Willstrand, P. Blomqvist, P. Andersson, Analysis of combustion gases from large-scale electric vehicle fire tests, Fire Saf J. 139 (2023) 103829. https://doi.org/https://doi.org/10.1016/j.firesaf.2023.103829.

[19] Volvo Trucks, Volvo FH Electric. From city to city in comfort, (n.d.). https://www.volvotrucks.com/en-en/trucks/trucks/volvo-fh/volvo-fh-electric.html (accessed June 15, 2023).

[20] E. Emilsson, L. Dahllöf, M. Ljunggren Söderman, Plastics in passenger cars, Stockholm, 2019. https://www.ivl.se/download/18.14d7b12e16e3c5c36271082/1574935157259/C454.pdf (accessed May 5, 2022).

[21] N. Rosmuller, Guidelines for the officer-in-charge for fighting fires in road tunnels immediately following a report, 2020. https://nipv.nl/wp-content/uploads/2022/06/20200630-IFV-Guidelines-officer-in-charge-for-fighting-fires-in-road-tunnels.pdf (accessed June 15, 2023).

[22] A.R. Baird, E.J. Archibald, K.C. Marr, O.A. Ezekoye, Explosion hazards from lithium-ion battery vent gas, J Power Sources. 446 (2020) 227257. https://doi.org/https://doi.org/10.1016/j.jpowsour.2019.227257.

[23] Y.Z. Li, Study of fire and explosion hazards of alternative fuel vehicles in tunnels, Fire Saf J. 110 (2019) 102871. https://doi.org/https://doi.org/10.1016/j.firesaf.2019.102871.

[24] O. Willstrand, M. Pushp, P. Andersson, D. Brandell, Impact of different Li-ion cell test conditions on thermal runaway characteristics and gas release measurements, J Energy Storage. 68 (2023) 107785. https://doi.org/https://doi.org/10.1016/j.est.2023.107785.

[25] R. Rhodes, Explosive lessons in hydrogen safety, ASK Magazine. (n.d.). https://www.nasa.gov/pdf/513855main_ASK_41s_explosive.pdf (accessed June 15, 2023).

[26] R. Zalosh, P. Gandhi, A. Barowy, Lithium-ion energy storage battery explosion incidents, J Loss Prev Process Ind. 72 (2021) 104560. https://doi.org/https://doi.org/10.1016/j.jlp.2021.104560.

[27] A.W. Golubkov, S. Scheikl, R. Planteu, G. Voitic, H. Wiltsche, C. Stangl, G. Fauler, A. Thaler, V. Hacker, Thermal runaway of commercial 18650 Li-ion batteries with LFP and NCA cathodes – impact of state of charge and overcharge, RSC Adv. 5 (2015) 57171–57186. https://doi.org/10.1039/C5RA05897J.

[28] Y.-S. Duh, Y. Sun, X. Lin, J. Zheng, M. Wang, Y. Wang, X. Lin, X. Jiang, Z. Zheng, S. Zheng, G. Yu, Characterization on thermal runaway of commercial 18650 lithium-ion batteries used in electric vehicles: A review, J Energy Storage. 41 (2021) 102888. https://doi.org/https://doi.org/10.1016/j.est.2021.102888.

[29] T. Rappsilber, N. Yusfi, S. Krüger, S.-K. Hahn, T.-P. Fellinger, J. Krug von Nidda, R. Tschirschwitz, Meta-analysis of heat release and smoke gas emission during thermal runaway of lithium-ion batteries, J Energy Storage. 60 (2023) 106579. https://doi.org/https://doi.org/10.1016/j.est.2022.106579.

[30] B. Ditch, D. Zeng, Development of Sprinkler Protection Guidance for Lithium Ion Based Energy Storage Systems, Norwood, 2020. https://www.fmglobal.com/research-and-resources/research-and-testing/~/media/58F4DDFC28A146A59D5CEEC18EC4A6A8.ashx (accessed June 15, 2023).

[31] O. Willstrand, R. Bisschop, P. Blomqvist, A. Temple, J. Anderson, Toxic Gases from Fire in Electric Vehicles, 2020. http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-52000.

[32] A. Lönnermark, P. Blomqvist, Emissions from an automobile fire, Chemosphere. 62 (2006) 1043–1056. https://doi.org/10.1016/j.chemosphere.2005.05.002.

[33] J. Gehandler, A. Olofsson, J. Hynynen, A. Temple, A. Lönnermark, J. Andersson, J. Burgén, C. Huang, BREND 2.0 - Fighting fires in new energy carriers on deck 2.0, 2022. http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-59162.

[34] A. Temple, J. Anderson, BREND 2.0: Fire simulation technical report, 2022. http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-59161.

[35] M. Quant, O. Willstrand, T. Mallin, J. Hynynen, Ecotoxicity Evaluation of Fire-Extinguishing Water from Large-Scale Battery and Battery Electric Vehicle Fire Tests, Environ Sci Technol. (2023). https://doi.org/10.1021/acs.est.2c08581.

[36] M. Held, M. Tuchschmid, M. Zennegg, R. Figi, C. Schreiner, L.D. Mellert, U. Welte, M. Kompatscher, M. Hermann, L. Nachef, Thermal runaway and fire of electric vehicle lithium-ion battery and contamination of infrastructure facility, Renewable and Sustainable Energy Reviews. 165 (2022) 112474. https://doi.org/https://doi.org/10.1016/j.rser.2022.112474.

[37] K. Terlouw, The fire safety of car parks, TU Delft, 2019. http://resolver.tudelft.nl/uuid:eef3e542-c2f9-4e2a-ae21-eae8fff1732a (accessed October 24, 2022).

[38] J. Bai, H. Liao, Y. Xia, Study on Fire Accidents in Tunnels, IOP Conf Ser Mater Sci Eng. 741 (2020) 012095. https://doi.org/10.1088/1757-899X/741/1/012095.

[39] G. Rattei, A. Lents, B. Kohl, How frequent are fires in tunnels - Analysis from Austrian tunnel incident statistics, in: 7th International Conference Tunnel Safety and Ventilation 2014, Graz, 2014: p. 5.

[40] N. Casey, Fire incident data for Australian road tunnels, Fire Saf J. 111 (2020) 102909. https://doi.org/https://doi.org/10.1016/j.firesaf.2019.102909.

[41] PIARC, PIARC - Impact of new propulsion technologies on road tunnel operations and safety, case studies, 2022.

[42] Burnley Tunnel fire, 2007, Australian Institute for Disaster Resilience. (n.d.). https://knowledge.aidr.org.au/resources/transport-burnley-tunnel-fire-melbourne-2007/ (accessed December 5, 2022).

[43] BRE, Fire spread in car parks BD2552, London, 2010. https://webarchive.nationalarchives.gov.uk/ukgwa/20120919204054/http:/www.communities.gov.uk/documents/planningandbuilding/pdf/1795610.pdf (accessed May 5, 2022).

[44] SveMin, Maskinanvisning, 2019. https://wwwsveminse.cdn.triggerfish.cloud/uploads/2019/11/maskinanvisningarsvemin20190522.pdf (accessed June 15, 2023).

[45] Arbetsmiljöverket, AFS 2010:1, Arbetsmiljöverket, 2014. https://www.av.se/globalassets/filer/publikationer/foreskrifter/berg-och-gruvarbete-foreskrifter-afs2010_1.pdf (accessed June 15, 2023).

[46] SveMin, Brandskydd i gruv- och berganläggningar, 2016. https://www.svemin.se/?file_download&file=2210 (accessed June 15, 2023).

RISE Research Institutes of Sweden AB
Fire and safety - Fire Safe Transport

Performed by: Jonna Hynynen, Hanna Kumlin, Ola Willstrand   Examined by Franz Evegren