Best practice & recommendations for the safe carriage of electric vehicles (EVs)

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1. Introduction

In light of the urgent need to decarbonize all modes of transport, the number of new energy vehicles has been on the rise. The European Automobile Manufacturers Association (ACEA) has collected passenger car registration data in the EU per fuel type which show a significant growth of alternative fuel vehicles (AFVs) registered over the past years (Figure 1). Electric vehicles (EVs) are projected to match the sales of internal combustion engine (ICE) vehicles by 2030, and to surpass them by 2040.[1]

Several misconceptions regarding battery electric vehicle fires circulate publicly and lead to uncertainty. Fires in battery electric vehicles are not more dangerous than fires in conventional vehicles and are currently not more frequent[2]. However, dealing with the specific characteristics of fires in battery electric vehicles must be addressed and trained for accordingly.

This paper will focus on risks and risk mitigation options associated with the carriage of electric vehicles (EVs) on two different ship types, i.e. Pure Car and Truck Carriers (PCTCs) and roro/ropax vessels. Hybrid cars and other alternative fuel vehicles are not considered since the largest share of new energy vehicles are EVs. The proportion of other AFVs in the global car fleet is currently limited and unlikely to grow significantly in the near future.

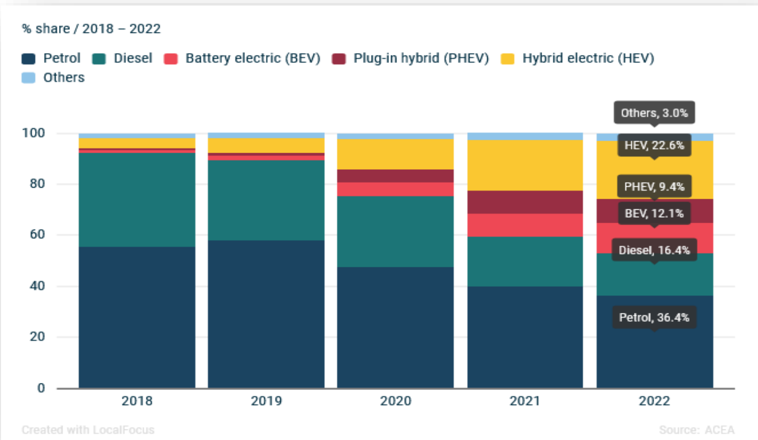


Fig. 1: New cars in the EU by fuel

[1] Electric Car Future Prediction, Siemens Digital Industries Software, White Paper
[2] EU Lashfire project: https://lashfire.eu/media/2022/09/2022-08_Facts_and_Myths.pdf

2. EVs: Technical information

In this section the set-up of the battery packs built into EVs is described to provide a better technical understanding. This section also considers some of the concerns raised in relation to EVs.

Technical information

Battery electric vehicles are usually fitted with a lithium-ion traction battery which is encapsulated and shielded by the vehicle's body.[3] The battery pack consists of various battery modules which in turn are comprised of several battery cells. The chemical process which produces electricity that can be used for propulsion of the EV takes place within the battery packs. The battery system is usually placed in the vehicle floor or undercarriage where it is protected from damage by an anti-crash frame.

Electric vehicles have extensive safety systems that will automatically shut down the power and isolate the battery pack when a collision or a short circuit is detected. An important safety feature of EV battery packs are in-built battery management systems (BMS). The BMS monitors and controls the battery and is a crucial factor in ensuring EV safety. It safeguards both the user and the battery by ensuring that the cell operates within its safe operating parameters. It monitors the state of a cell as represented by parameters such as:

- Voltage - indicates a cell’s total voltage, the battery’s combined voltage, maximum and minimum cell voltages.
- Temperature - displays the average cell temperature, coolant intake and output temperatures, and the overall battery temperature.
- The state of charge of the cell to show the battery’s charge level.
- The cell’s state of health - shows the remaining battery capacity as a percentage of the original capacity.
- The cell’s state of power - shows the amount of power available for a certain duration given the current usage, temperature, and other factors.
- The cell’s state of safety - determined by overseeing all parameters and determining if using the cell poses any danger. [4]

Technical validation and safety tests are adapted to the respective manufacturers’ design of the battery packs and are usually inherent in the production processes.

[3] Test of the efficacy of a fixed water-based extinguishing system in relation to a lithium-ion battery fire in a vehicle, MSC 107/INF.5 (Interferry), March 2023
[4] Battery Management System in Electric Vehicles, Cient (March 2022)

State of charge (SoC)

State of charge (SoC) is an electrical cell or battery's charge level compared to the total capacity of the cell or battery. Batteries at high SOCs have been shown to experience more violent reactions during thermal runaway. Testing has indicated that high SoC cells produce higher heat release rates, maximum temperatures, and concentrations of flammable and toxic gases during thermal runway events. However, while the SoC does affect the growth and peak heat release, it does not affect the total heat release.

Thermal runaway

Despite this inherently safe design thermal runaway may occur if a cell is abused, e.g. by heat, mechanical damage or overcharge. Thermal runaway can also occur as a consequence of a cell or battery manufacturing error.

When thermal runaway occurs, the cell is undergoing an unstable chemical reaction that is difficult to bring under control. At some point, the separator structure collapses and the electrodes touch, causing an internal short circuit and masses of heat, bringing the cell to ever higher temperatures and generating toxic and flammable gases. Cell heating will continue until the rise in temperature exceeds the heat that can be dissipated to the cell's construction. This released heat will then increase and start to affect other nearby battery cells. When the generation of heat becomes self-sustaining - the heat releases energy and the energy in turn releases more heat - the overheating propagates from cell to cell and the battery is in thermal runaway.

The high safety standards integrated into EV traction batteries, including solid casings and the BMS, make the likelihood of damage to an EV battery pack and thermal runaway extremely low. However, in view of the low possibility for thermal runaway the significance of the BMS as incorporated into EVs is particularly relevant. These safety systems prevent the battery cells from over and under charging, and thus prevent thermal runaway. It is important to note that BMS are not incorporated into smaller capacity and less sophisticated vehicles such as electric bikes or scooters.

Probability of fire in EVs

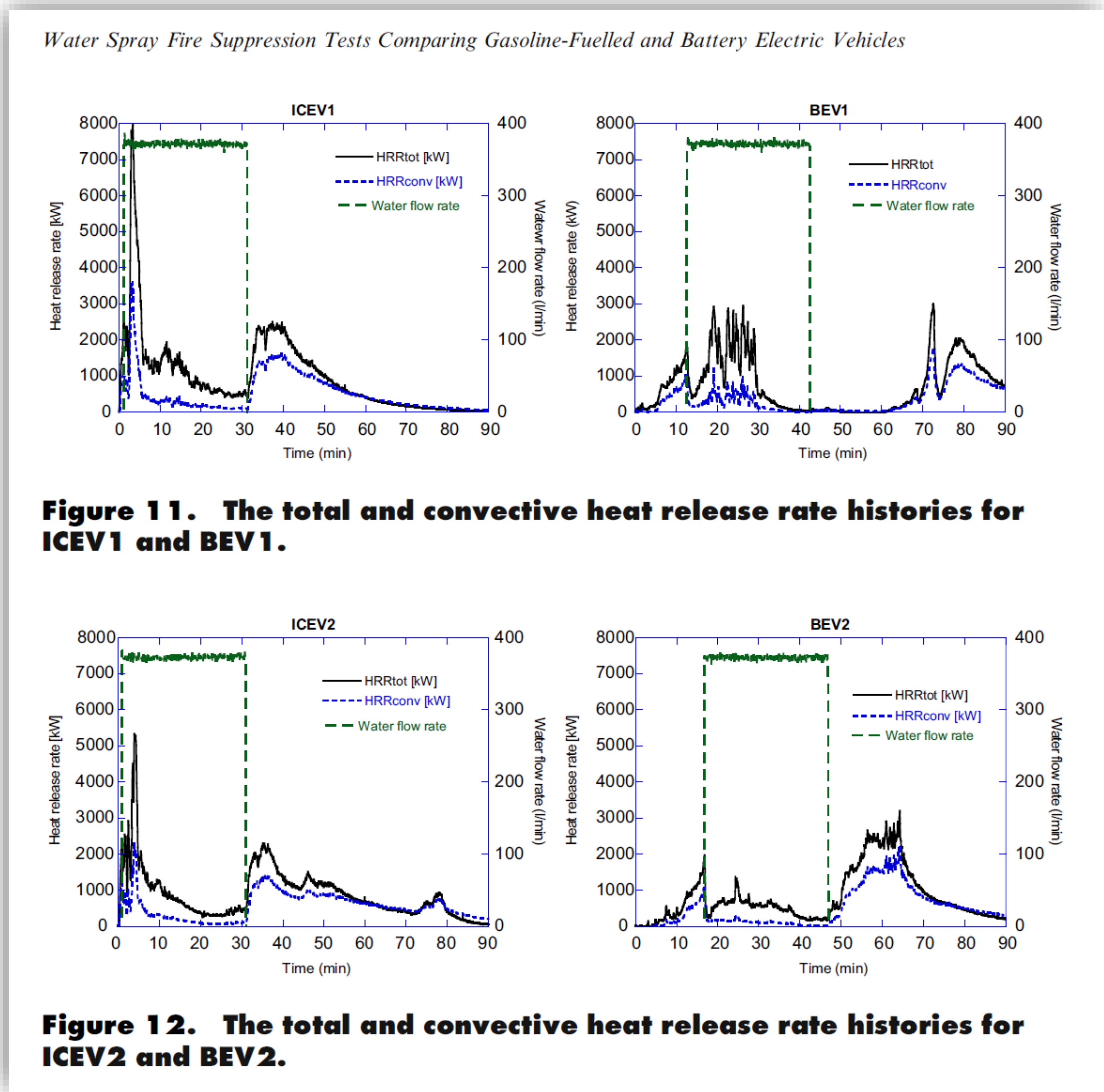
It is often said that EVs burn more often than internal combustion engine vehicles (ICEVs). However, as statistics continue to be gathered, they currently estimate that, in general, there are fewer fires from EVs compared with fires from conventional vehicles when driven over the same distance. Current statistics from Sweden[5] indicate that the probability of an EV fire is lower than that of a fire in an ICEV relative to the total number of vehicles.

Fire intensity

EV fires have often been claimed to be more intense than ICEV fires. In this regard, heat release rates (HRR) from full-scale fire tests performed in recent years with modern vehicles,

[5] "Electric Vehicle Fire Safety in Enclosed Spaces", Hynynen, Quant, Pramanik, Olofsson, Zhen Li, Arvidson, Andersson, March 2023

including both ICEVs and EVs were reviewed. The data compiled showed a minor difference in the total energy released during the fire (total heat release) between ICEVs and EVs.[6] In this context it is important to emphasize that the SoC affects the growth and peak heat release, but it does not increase the total heat released as indicated in the following graph:



Graph: "Water Spray Fire Suppression Tests Comparing Gasoline-Fuelled and Battery Electric Vehicles" published in Fire Technology, August 2023[7]

Despite the potential for thermal runaway, studies by the Danish Institute of Fire and Security Technology and NFPA have determined that EV fires, once established, are largely fuelled by the car body and interior parts made from plastic materials and that the fire load is similar

[6] EU Lashfire project: https://lashfire.eu/media/2022/09/2022-08_Facts_and_Myths.pdf
[7] Water Spray Fire Suppression Tests Comparing Gasoline-Fuelled and Battery Electric Vehicles, Fire Technology, August 2023: https://link.springer.com/article/10.1007/s10694-023-01473-w

to that of internal combustion engine (ICE) vehicles.[8] Generally, approx. 20% of the fire load, regardless of its propulsion method, is from the energy source and approx. 80% is from plastics and the interior of the vehicle. While the latter is largely comparable for all vehicles, the lower share related to the propulsion technology has fairly limited impact on how to fight the fire, i.e. pool fires from petrol vs re-ignition in EVs.

Fire fighting

It is often stated that EV fires are impossible to extinguish. A thermal runaway in a Lithium-Ion battery is indeed difficult to extinguish unless the firefighting agents are injected directly into the battery to enable efficient cooling. If a fire breaks out in an EV (and in an ICEV also), activities in support of early detection and verification/confirmation, early fire suppression and boundary cooling are critical actions to stop the spread of the fire to the battery and to adjacent vehicles.

A particularity of EVs is the risk of re-ignition which tends to be higher for a longer period than for ICEVs. Precautionary measures to avoid re-ignition of the traction battery must therefore be taken for an extended period after a fire has been extinguished.

Toxic gases

Another aspect is related to gases from EV fires which are perceived as being extremely toxic. Hydrofluoric gases which are highly poisonous are indeed emitted from Lithium-Ion battery fires. In this context it is however important to consider that combustion gases from all types of vehicle fires are highly toxic and can cause incapacitation. Carbon monoxide and hydrogen cyanide are common causes of death when smoke has been inhaled in a fire accident. Staying out of the smoke plume and wearing adequate personal protective equipment when dealing with burning or burnt vehicles is crucially important for all fires regardless of the energy source of the vehicle.[9]

3. Differences between PCTCs and RoRo/RoPax

Pure car and truck carriers (PCTCs) and roro/ropax vessels have significant differences in their design, hence many safety measures, risk control options and incident responses are different on these ship types. This section will look at the key differences.

- Roll-on/roll-off (roro) and ropax vessels

The roll-on/roll-off (roro) ship was defined in the November 1995 amendments to Chapter II-1 of the International Convention for the Safety of Life at Sea (SOLAS), 1974 as “a passenger ship with ro-ro cargo spaces or special category spaces”. They are designed to carry wheeled cargo such as cars, motorcycles, trucks or buses which are driven on and off the ship on their own wheels. Roro and ropax vessels have either built-in or

[8] “Fire safety in garage systems, storage of lithium-ion batteries and batteries for photovoltaic systems in buildings”, DBI (Danish Fire and Safety Institute) and TI (Danish Technological Institute), 2022 and “Modern vehicle hazards in parking structures and vehicle carriers”, NFPA Research Foundation, 2020
[9] EU Lashfire project: https://lashfire.eu/media/2022/09/2022-08_Facts_and_Myths.pdf

shore-based ramps or ferry slips that allow the vehicles to roll on and off the vessel when in port.

Roro spaces are categorized as either open, closed or weather decks. An open roro space is generally a space with more than 10% openings in the hull sides. A roro space is defined as a closed space if it is not an open or a weather deck. The large openings in semi-open and open decks on roro passenger vessels make firefighting challenging due to the air flow. A fire on an open deck could grow significantly while fires in spaces with smaller openings are restricted by the available oxygen.

A challenge specific to ropax vessels is the cargo they carry. EVs such as cars, buses and excavators are often used and may have hidden damages. It is a difficult to visually check at the terminals which units are safe to carry and which ones may not be safe.

A particularity of ropax vessels is the growing interest by passengers to have the possibility to charge EVs on board. In this context it is important to note that charging stations and cables have to be approved by classification societies and that the charging cables are to be connected by the vessel's crew. EMSA has published guidelines on the carriage of alternative fuel vehicles in roro spaces[10]. These include a section on how charging on board may take place safely.

— Pure car and truck carriers (PCTCs)

Pure car and truck carriers (PCTCs) are purpose-built vessels for the transportation of different types of rolling cargo, e.g. new and used passenger cars and trucks, heavy construction equipment, and other heavy loads.

PCTCs are usually configured with 10-13 decks for the loading of different vehicle types. The height between the decks can be adjusted depending on the types of vehicles being transported. The height of the vehicle decks is extremely low to reduce the loss of cargo space. Adjustable decks further optimize the cargo space. The vehicles are loaded with very little space between them. This impedes quick access to specific cars.

A particular challenge associated with PCTCs are alongside fires because the CO2 extinguishing systems cannot be used. When both the internal doors and the stern/side ramps are open during the loading process the CO2 cannot be contained within the vessel. Foam based extinguishing systems are less effective due to the uneven airflow which distracts even spread of the foam. Due to their construction the ramps cannot be closed quickly. External firefighting teams are not familiar with the design of vessels and are not trained to fight fires in such environments.

[10] Guidance on the carriage of AFVs in RO-RO spaces, EMSA, May 2022: https://emsa.europa.eu/publications/reports/item/4729-guidance-on-the-carriage-of-afvs-in-ro-ro-spaces.html

4. Recommendations and best practice

Loading process and loading condition of cars

In light of the safety systems incorporated into EVs, new cars present a lower risk as compared to used vehicles. There are currently no documented cases of factory-new electric vehicles causing a fire on board. In contrast, used cars may have had accidents causing mechanical damages which may negatively impact the intactness of the battery pack.

- ➔ Roros & PCTCs: A clear policy on the cargo which is accepted/rejected for roro spaces should be in place. Vehicles should be screened, and used/second-hand vehicles in particular should be carefully checked before being allowed on board. If there is suspicion that the battery of an EV is damaged or defective they should only be allowed if their battery is removed and if they are free from leakages. IMDG Special Provisions 961 and 962 address requirements for vehicles which are being carried on board a transport vessel.

Charging on board

- ➔ Roros: Charging on board ro-ro passenger ships can be permitted if the ship operator conducts a comprehensive risk assessment and approves and implements appropriate risk control measures. Research indicates that charging an EV on board is the safer option as inbuilt safety mechanisms are activated during charging. As mentioned above, information regarding safe charging on board is available in the EMSA Guidance on the carriage of AFVs in RO-RO spaces.

- ➔ PCTCs: PCTCs are not fitted with charging stations.

Detection & confirmation/verification

- ➔ Roros & PCTCs: Detection and verification/confirmation of a fire is key to enable successful firefighting operations. These two steps should not be considered as separate but as one step. Time between detection and confirmation/verification must be reduced to the shortest possible time. The installation of technologies which enhance early detection are therefore supported for these vessel types. Options include gas detection systems, thermal imaging cameras, and AI powered systems.

Firefighting

- ➔ Roros: The EU's LASHFIRE project has shown that drencher systems are effective to fight fires on board roro and ropax vessels. Full scale tests show that a drencher system has the same impact on the fire regardless of the source of the fire being an ICEV or an EV. Drencher systems are thus effective to manage and control EV fires.

This is reflected in the revised requirements developed by the IMO's Sub-Committee on Ship Systems and Equipment (SSE). The amendments to SOLAS and the Fire Safety Systems (FSS) Code will mainly apply to new passenger ships and include, inter alia, requirements for a fixed fire detection and fire alarm system to be provided for the area on the weather deck intended for the carriage of vehicles; an effective video monitoring system; and a fixed water-based fire-extinguishing system based on monitor(s) to be installed in order to cover weather decks intended for the carriage of vehicles.

- ➔ PCTCs: CO2 extinguishing systems if applied quickly after the detection and verification/confirmation of a fire have worked successfully to fight fires on board PCTCs. To further improve the usefulness, the CO2 capacity should be doubled on board PCTCs. Research projects are ongoing to methodically assess and evaluate the effectiveness of the CO2 extinguishing systems.

- ➔ PCTCs: Research indicates that while high-expansion foam fire extinguishing systems were unable to stop thermal runaway (like any other fixed systems), it hindered the ignition of flammable gas, including gaseous electrolyte from the batteries. The system effectively prevented heat transmission from a vehicle on fire as long as it was submerged in the foam. This suggests the potential effectiveness of high-expansion foam fire extinguishing systems.[11]

- ➔ PCTCs: Early detection, confirmation/verification and a short response time are crucial to fight a fire successfully. The fixed firefighting systems should be applied first rather than manual firefighting by the crew.

Overarching approach

- ➔ PCTCs and RoRos: Different design, resources, equipment and circumstances have to be considered for each vessel. Individual risk assessments and tactics are essential to ensure an effective response in case of a fire on board.

The IMO's Sub-Committee on Ship Systems and Equipment (SSE) will start work on the "Evaluation of adequacy of fire protection, detection and extinction arrangements in vehicle, special category and ro-ro spaces in order to reduce the fire risk of ships carrying new energy vehicles" beginning in March 2024. The regulatory process will be an opportunity to improve safety requirements making them fit for the new reality of large numbers of alternative fuel vehicles being carried on board vessels.

[11] SSE 9/INF.4 "Experimental test on lithium-ion-battery-powered vehicle fires with outside air high-expansion foam fire-extinguishing system" submitted by Japan

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