



# STARRS STUDY TECHNICAL AND REGULATORY REVIEW

**SAFE TRANSPORT OF ALTERNATIVE FUEL  
VEHICLES ON RO-RO SHIPS (STARRS)  
STUDY**

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### Authors:

Eric De Carvalho (BV), Vladislav Sidorenkov-Duprez (BV), Anna Karlsson (RISE), Magnus Arvidson (RISE), Johan Anderson (RISE), Maria Quant (RISE).

### EMSA Review Panel:

Lanfranco Benedetti (EMSA), Mónica Ramalho (EMSA).

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## Document History

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## Abstract

This report is developed as a part of the European Maritime Safety Agency (EMSA) “Safe Transport of AFVs on Ro-Ro Ships” (STARRS) study. The main nature of the work is to provide scientific and technical knowledge on fire safety of Alternative Fuel Vehicles (AFVs) onboard of ships by carrying out a review of the state-of-the art, complemented by an experimental and numerical campaign. The final outcome of the study shall be to provide recommendations for further industry guidance and input to the development of International Maritime Organization (IMO) relevant instruments.

This report is the result of the first part of the study. First, it provides an overview of the regulatory landscape governing the safe transportation of AFVs, including a review of regulations, rules and guidelines across both maritime and non-maritime domains. Then, the state-of-the-art of experimental findings on fire safety of AFVs in ro-ro spaces, as well as prior research on numerical modelling and simulations, were reviewed and summarized. Finally, conclusions from the review are presented, including a summary of the scientific and technical knowledge identified in the form of a mapping. The results of the reviews will serve as technical justification for the development of recommendations in the upcoming parts of the STARRS study.

## Executive summary

The transport industry is responsible for one fifth of the world's greenhouse gas emissions. The European countries are working towards a fossil-independent vehicle fleet by 2030. This goal aligns with the EU's ambitious targets to increase the share of renewable energy in the road transport sector. According to the new regulations, "RED III" adopted in 2023, at least 29% of the final energy consumption in the transport sector must come from renewable sources by 2030 (NOW GmbH, 2025). Alternative fuel vehicles (AFVs) such as electric vehicles (EVs), hydrogen fuel cell vehicles (FCVs), and biofuel-powered vehicles, produce significantly less greenhouse gas emissions compared to traditional fossil fuel vehicles, which is a key to achieve a fossil-independent vehicle fleet.

As the number of AFVs grows, there is a growing need of understanding and tackling the challenges of safe transport of the vehicles, where ro-ro ships are an important component. These ships are designed to carry vehicles and cargo which can be rolled on and rolled off. This design, however, creates large cargo spaces onboard, which can provide ample oxygen for a fire to sustain and spread, as there is no fire partition vertically.

A fire in a ro-ro cargo space is an extremely challenging situation. Each vehicle type, with its unique condition - new, used, or damaged - presents distinct safety hazards for the ship. Addressing these challenges is essential to ensure the safe and efficient transport of vehicles. AFVs are relatively new and imply other hazards than regular vehicles; society is still learning how to handle them safely, supporting the broader goal of transitioning to a fossil-independent vehicle fleet.

Numerous research projects and technical studies have been conducted to enhance the understanding of fires on ro-ro ships. In FIRESAFE (2016), ro-ro ship fire safety was addressed by quantifying different fire protection measures for ro-ro spaces, with a clear focus on fire initiated by electrical failure and malfunction of the drencher system. In the EU project LASH FIRE, areas from fire prevention to containment of fire were covered in a formal safety assessment format to investigate cost effective risk control measures. With nationally-funded projects such as ALBERO (Germany), ELBAS (Denmark) and BREND 2.0 (Sweden) and COFFEE (Sweden), the knowledge has further increased.

Recent fire accidents at sea, such as the fires on the Fremantle Highway and Morning Midas have further raised concerns regarding safe transportation of vehicles. In particular AFVs has received the attention of the industry as well as regulatory authorities. In response, several shipping companies have implemented proactive measures to ensure the safety of passengers and crew. These measures include to go above and beyond the required fire safety standards, by adding fire-fighting equipment (e.g. fire blanket and thermal imaging camera), upgrading fire-fighters' outfits, offering specialized fire-fighting training, and a doubling of the carbon dioxide quantity on board vehicle carriers. In some cases, transportation of EVs has even been completely banned to ensure safety before knowledge is updated. Together with the ongoing discussions in the International Maritime Organization (IMO) Sub-Committees on Carriage of Cargoes and Containers (CCC) and Ship Systems and Equipment (SSE), this indicates the need for increased understanding of the fire behaviour of AFVs.

In order to reply to that need and fill the knowledge gaps, the European Maritime Safety Agency (EMSA) have awarded the "Safe Transport of AFVs on Ro-Ro Ships" (STARRS) study to RISE Research Institutes of Sweden (RISE) and Bureau Veritas Marine & Offshore (BV). The main nature of the work is experimental, complemented with numerical modelling of fire behaviours respect to the carriage of AFVs. The final outcome of the study shall be to provide recommendations for further industry guidance and input to the development of relevant IMO instruments. This report is the result of the first part of the study.

## What we did

A review of regulations, rules and guidelines across both maritime and non-maritime domains was conducted. For that purpose, 30 documents related to maritime domain and more than 40 related to road tunnels, car parks or multimodal transportation were reviewed. The main provisions or recommendations related the safe transportation of AFVs were extracted, organized per safety area and summarized.

A review of the state-of-the-art scientific and technical results of AFV experiments, as well as numerical modelling and simulations, was conducted. For that purpose, more than 80 documents were reviewed. The review highlights the main conclusions relevant to the safe transportation of AFVs in ro-ro spaces.

Lastly, in order to prepare the next stages of the STARRS study and to feed the on-going discussion at IMO, a summary of the scientific and technical knowledge identified in the study was provided in the form of a mapping.

## What we found

### *Regulatory review*

In general, the reviewed documents tend to agree that a combination of heat and smoke fixed detection systems coupled with a water-based fire-extinguishing system are a reliable solution to detect, cool down and prevent the fire spread in case of lithium-ion batteries thermal runaway events. However, for vehicle carriers which are generally not equipped with water-based fire-extinguishing systems or, for container carriers, where the accessibility to the batteries inside a container is complicated, alternative solutions are proposed such as increasing the capacity of the fixed gas-based fire-extinguishing system.

From the guidelines issued by the industry community and insurances, the prevention and mitigation of fire risks is also coming from operational constraints such as the verification of the battery conditions during the loading stage or crew training. These points are difficult to verify and therefore difficult to encompass in the regulatory framework.

Based on this regulatory study, some knowledge gaps are surfacing leading to the need of scientific and technical studies, experiments and modelling on specific items such as the efficiency of foam-based fire-extinguishing systems.

Lastly, from the review of the land-based documents, it was found that most of the measures for the safe transportation / use of AFVs on land are common with maritime. However, some interesting measures solely in land-based can be highlighted and further investigated for adoption in maritime.

### *Technical and scientific review*

#### ■ Fire and gas detection

Research on early detection of causes triggered an EV fire, such as thermal runaway, is on-going. This research addresses technologies, such as gas detection, video fire detection, battery management system (BMS) monitoring or temperature-based detection methods. The on-going projects will also address the performance of existing fire detection system in ro-ro spaces, i.e. spot-type smoke and heat detectors, and will compare them with the aforementioned technologies.

#### ■ Fixed fire-extinguishing systems

The existing research tends to agree that the existing provisions in ro-ro spaces for fixed water-based existing systems should be sufficient. However, as the capacity of the batteries increases, it may be worth to verify their performance on larger types of battery electric vehicles.

The research related to the performance of fixed foam and gas (CO<sub>2</sub>) fire-extinguishing systems involving battery electric vehicles are scarcer. Several projects on that systems are on-going. Recent projects on the performance of outside air foam system are encouraging but performance under actual marine conditions still need to be further investigated. A survey documented that CO<sub>2</sub> was used in eleven of the 22 fires on ro-ro vehicle carriers occurring from 2013 to 2023. In five of these verified incidents, the fire was suppressed or extinguished. For the cases when

fire was not extinguished, a long delay time combined with the fact that the space was not sufficiently sealed may explain the poor performance. None of the eleven fires involved battery electric vehicles.

- Manual fire-fighting equipment, tools and procedures

Existing and new fire-fighting equipment were tested in different projects as regards as EV fires. Based on results from field tests, existing equipment (e.g. fire hose nozzle) and new equipment such as portable water curtain were found to be complementary tactical options. However, the crew members need to be well trained and prepared to handle them. Research on other new equipment such as fire blankets, brine-based fire-fighting system and battery pack flooding devices progress well. Their safe deployment in ro-ro spaces still need to be further investigated. From the review, manual fire-fighting in the space of origin of the fire was not found to be the best option in case of EV fire, even impractical in vehicle carriers, and to be rather used in complement of fixed fire-extinguishing system, e.g. for boundary cooling or for re-ignition purpose. Some projects have developed guidelines for fire-fighting procedures and even training programmes. Those materials can be useful to ship operators in order to develop their company procedures.

- Explosion risk and mitigation

Research exists on explosion risk and mitigation in Battery Energy Storage System enclosures, but no research was identified related to ro-ro space. This is clearly identified as a knowledge gap.

- Numerical modelling and simulations

Several numerical models enable the assessment of AFV hazards in ro-ro spaces. Simpler tools can be used for quick and preliminary assessment but are generally limited to open air configurations with limited effects of geometry. For more detailed assessment, in particular in enclosed spaces such as closed ro-ro spaces, CFD tools shall be used. However, such tools require specific resources and competences. In complement to experimental data, numerical simulations were found to be necessary to understand and assess the hazards on domain such as fire and smoke spread, effect of the ventilation or tenability conditions.

### Way forward

The results will serve as technical justification for the development of recommendations in the upcoming parts of the STARRS study.

The STARRS study have the following plan ahead:

- Experimental campaign on:
  - (1) high expansion foam (effectiveness), focusing on inside air foam systems, and
  - (2) early detection of fire root causes (e.g. thermal runaway), complemented with numerical simulations;
- Maritime stakeholders' consultation in order to address the findings from the technical review and experimental campaign, and the development of recommendations; and
- Development of recommendations related to the safe transportation of AFVs for further industry guidance and input to the development of relevant IMO instruments.

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## List of abbreviations

ACEA	European Automobile Manufacturers Association
ACH	Air Change per Hour
ADR	Agreement concerning the international carriage of Dangerous goods by Road
AEGL	Acute Exposure Guideline Level
AFV	Alternative Fuel Vehicle
AI	Artificial Intelligence
ARC	Accelerating Rate Calorimetry
ATEX	Atmosphere Explosive
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BLEVE	Boiling Liquid Expanding Vapour Explosion
BMS	Battery Management System
BV	Bureau Veritas
CCC	IMO Sub-Committee on Carriage of Cargoes and Containers
CCTV	Closed-Circuit Television
CFD	Computational Fluid Dynamics
CG	Correspondence Group
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
CTU	Cargo Transport Unit
DBI	Danish Institute of Fire and Security Technology
DG	Dangerous Good
EMSA	European Maritime Safety Agency
ERG	Emergency Response Guide
EU	European Union
EV	Electric Vehicle
EVS	Electrical Vehicle Safety
FCV	Fuel Cell Vehicle
FDS	Fire Dynamics Simulator
FE	Finite Element
FEC	Fractional Effective Concentration
FED	Fractional Effective Dose
FPRF	NFPA's Fire Protection Research Foundation (USA)
FSRI	UL's Fire Safety Research Institute (USA)
FSS	International Code for Fire Safety Systems

FTP	International Code for Application of Fire Test Procedures
FV	Finite Volume
GIS	Geographic Information System
GISIS	Global Integrated Shipping Information System
GUI	Graphical User Interface
H <sub>2</sub>	Dihydrogen
H <sub>2</sub> O	Water
HC	Hydrocarbon
HCl	Hydrogen chloride
HCN	Hydrogen cyanide
HEV	Hybrid Electric Vehicle
HF	Hydrogen fluoride
HRR	Heat Release Rate
HTW	IMO Sub-Committee on Human element, Training and Watchkeeping
IACS	International Association of Classification Societies
IATA	International Air Transport Association
ICEV	Internal Combustion Engine Vehicle
IDLH	Immediately Dangerous to Life or Health
IMDG	International Maritime Dangerous Goods Code
IMO	International Maritime Organization
INERIS	French National Institute for Industrial Environment and Risks
IP	Ingress Protection
IR	InfraRed
ISM	International Safety Management Code
ISO	International Organization for Standardization
ITF	International Transport Forum
IUMI	International Union of Marine Insurance
KYC	Know Your Customer
LFL	Lowest Flammability Limit
LFP	Lithium iron phosphate (LiFePO <sub>4</sub> )
Li-ion	Lithium ion
LIDAR	Light detection and ranging
LiPF <sub>6</sub>	Lithium hexafluorophosphate
LMO	Lithium-ion Manganese Oxide
LNB	Leak-Not-Burst
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSA	Life-Saving Appliances

MC	Multi-Component
MCI	Marine Casualties and Incidents
MED	Marine Equipment Directive (EU)
MES	Marine Evacuation System
mLNB	micro-Leak-Not-Burst
MSB	Swedish Civil Contingencies Agency
NaCl	Sodium chloride (salt)
NEV	New Energy Vehicle
NFPA	National Fire Protection Association (USA)
NIPV	Netherlands Institute for Public Safety
NIST	National Institute of Standards and Technology (USA)
NMC	Lithium nickel manganese cobalt
NO	Nitric oxide
NRC	National Research Council of Canada
OEM	Original Equipment Manufacturer
PAH	Polycyclic Aromatic Hydrocarbon
PCC	Pure Car Carrier
PCTC	Pure Car and Truck Carrier
PFAS	Per- and polyfluoroalkyl substances
PHEV	Plug-in Hybrid Electric Vehicle
PRD	Pressure Relief Device
QRA	Quantitative Risk Assessment
RISE	Research Institutes of Sweden
Ro-Ro	Roll-on/Roll-off
SO <sub>2</sub>	Sulfur dioxide
SoC	State of Charge
SOLAS	International Convention for the Safety of Life at Sea
SP	Special Provision
SSE	IMO Sub-Committee on Ship Systems and Equipment
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
TP	Thermal Propagation
TPRD	Thermal Pressure Relief Device
TR	Thermal Runaway
TRL	Technology Readiness Level
UDM	Unified Dispersion Model
UECC	United European Car Carriers
UHF	Ultra High Frequency
UHP	Ultra High Pressure

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UL	Underwriters Laboratories
UN	United Nations
VFD	Video Fire Detection
VOC	Volatile Organic Compound
WG	Working Group

## List of definitions

Fixed fire-extinguishing system	IMO terminology defining fixed fire protection systems whose purpose is to suppress and swiftly extinguish a fire in the space of origin. One may remark that fire extinguishment (i.e. complete suppression of a fire until there are no burning combustibles) for lithium-ion battery fire may be challenging, even unfeasible in various circumstances (e.g. battery pack protected by casing). And so, the terminology “extinguishing” may be argued not appropriate. For the case of lithium-ion batteries, the fixed fire-extinguishing systems may be used to prevent the fire spread or for boundary cooling. However, in this study, we will stick to the IMO terminology
Ro-ro passenger ship (or RO-PAX)	means a passenger ship with ro-ro spaces or special category spaces (SOLAS Chapter II-2 Reg. 3.42)
Ro-ro cargo ship (or RO-RO)	ro-ro ship which are neither a ro-ro passenger ship nor vehicle carrier
Thermal Propagation	the sequential occurrence of thermal runaway within a battery system triggered by thermal runaway of a cell in that battery system
Thermal Runaway	uncontrolled intensive increase in the temperature of a cell driven by exothermic reaction (IEC 62619:2022)
Vehicle carrier (or PCC, PCTC)	means a cargo ship which only carries cargo in ro-ro spaces or vehicle spaces, and which is designed for the carriage of unoccupied motor vehicles without cargo, as cargo (SOLAS Chapter II-2 Reg. 3.56)

In addition, a general description of the different types of alternative fuel vehicles is provided in Appendix A.

# 1. Introduction

The transport industry is responsible for one fifth of the world's greenhouse gas emissions. The European countries are working towards a fossil-independent vehicle fleet by 2030. This goal aligns with the EU's ambitious targets to increase the share of renewable energy in the road transport sector. According to the new regulations, "RED III" adopted in 2023, at least 29% of the final energy consumption in the transport sector must come from renewable sources by 2030 (NOW GmbH, 2025). Alternative fuel vehicles (AFVs) such as electric vehicles (EVs), hydrogen fuel cell vehicles (FCVs), and biofuel-powered vehicles, produce significantly less greenhouse gas emissions compared to traditional fossil fuel vehicles, which is a key to achieve a fossil-independent vehicle fleet.

As the number of AFVs grows, there is a growing need of understanding and tackling the challenges of safe transport of the vehicles, where ro-ro ships are an important component. These ships are designed to carry vehicles and cargo which can be rolled on and rolled off. This design, however, creates large cargo spaces onboard, which can provide ample oxygen for a fire to sustain and spread, as there is no fire partition vertically.

A fire in a ro-ro cargo space is an extremely challenging situation. Each vehicle type, with its unique condition - new, used, or damaged - presents distinct safety hazards for the ship. Addressing these challenges is essential to ensure the safe and efficient transport of vehicles. AFVs are relatively new and imply other hazards than regular vehicles; society is still learning how to handle them safely, supporting the broader goal of transitioning to a fossil-independent vehicle fleet.

Numerous research projects and technical studies have been conducted to enhance the understanding of fires on ro-ro ships. In FIRESAFE (2016), ro-ro ship fire safety was addressed by quantifying different fire protection measures for ro-ro spaces, with a clear focus on fire initiated by electrical failure and malfunction of the drencher system. In the EU project LASH FIRE, areas from fire prevention to containment of fire were covered in a formal safety assessment format to investigate cost effective risk control measures. With nationally-funded projects such as ALBERO (Germany), ELBAS (Denmark), BREND 2.0 (Sweden) and COFFEE (Sweden), the knowledge has further increased.

Recent fire accidents at sea, such as the fires on the Fremantle Highway and Morning Midas have further raised concerns regarding safe transportation of vehicles. In particular AFVs has received the attention of the industry as well as regulatory authorities. In response, several shipping companies have implemented proactive measures to ensure the safety of passengers and crew. These measures include to go above and beyond the required fire safety standards, by adding fire-fighting equipment (e.g. fire blanket and thermal imaging camera), upgrading fire-fighters' outfits, offering specialized fire-fighting training, and a doubling of the carbon dioxide quantity on board vehicle carriers. In some cases, transportation of EVs has even been completely banned to ensure safety before knowledge is updated. Together with the ongoing discussions in the International Maritime Organization (IMO) Sub-Committees on Carriage of Cargoes and Containers (CCC) and Ship Systems and Equipment (SSE), this indicates the need for increased understanding of the fire behaviour of AFVs.

In order to reply to that need and fill the knowledge gaps, the European Maritime Safety Agency (EMSA) have awarded the "Safe Transport of AFVs on Ro-Ro Ships" (STARRS) study to RISE Research Institutes of Sweden (RISE) and Bureau Veritas Marine & Offshore (BV). The main nature of the work is experimental, complemented with numerical modelling of fire behaviours respect to the carriage of AFVs. The final outcome of the study shall be to provide recommendations for further industry guidance and input to the development of relevant IMO instruments.

The study will mainly focus on EVs, i.e. Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), and lithium-ion batteries technology. Liquefied Petroleum Gas (LPG) vehicles, Compressed Natural Gas (CNG) vehicles and Fuel Cell Vehicles (FCVs) will also be addressed when relevant. It will focus on ro-ro ships (ro-ro passenger ships, vehicle carriers and general ro-ro cargo ships) and ro-ro spaces, but AFVs transported in Cargo Transport Units (CTUs) (i.e. transported inside a multimodal freight container or by a road freight vehicle) will be addressed when relevant.

This report is the result of the first part of the study. It will provide a regulatory review, and a scientific and technical review associated to the safe transportation of AFVs. The Chapter 2 will plot the scene by reminding to the readers the global trend, fire hazards and challenges associated to the use and transportation of AFVs. Then, in Chapter 3, a review of the maritime and land-based regulations, rules and best practices governing the safe transportation of

AFVs will be provided. A review of the state of the art of scientific and technical experimental tests and their results will be provided in Chapter 4, as well as available numerical modelling of AFV fires in Chapter 5. Lastly, in Chapter 6, summary and conclusions of the two reviews will be provided.

## 2. Background, alternative fuel vehicles hazards and lessons learned

This chapter provides an overview of the use, hazards and challenges of the alternative fuel vehicles (AFVs).

### 2.1 Background

This section aims at providing useful insights and figures related to proportion of alternative fuel vehicles on European roads, their types and fire incidents. The purpose of this section is to plot the scene and not to provide exhaustive nor complete statistics. The justification about the types of AFVs, which will be further covered by the STARRS study, is also provided in this section.

#### 2.1.1 Type of power source

According to the European Automobile Manufacturers Association (ACEA, 2025), 22.3% of new passenger cars registered in the EU in 2023 were electrically-chargeable vehicles, while hybrids accounted for 25.8% and other types (including Liquefied Petroleum Gas (LPG) and E85) accounted for 3.0% (Figure 1). Based on Figure 1 and Figure 2, alternative power sources other than electric represent a negligible share for both new and in-use passenger cars, compared to electric. For buses, the share of natural gas vehicles is more significant and comparable to that of electric. For trucks, the share of AFVs (all type) is currently negligible compared to Internal Combustion Engine Vehicle (ICEVs).

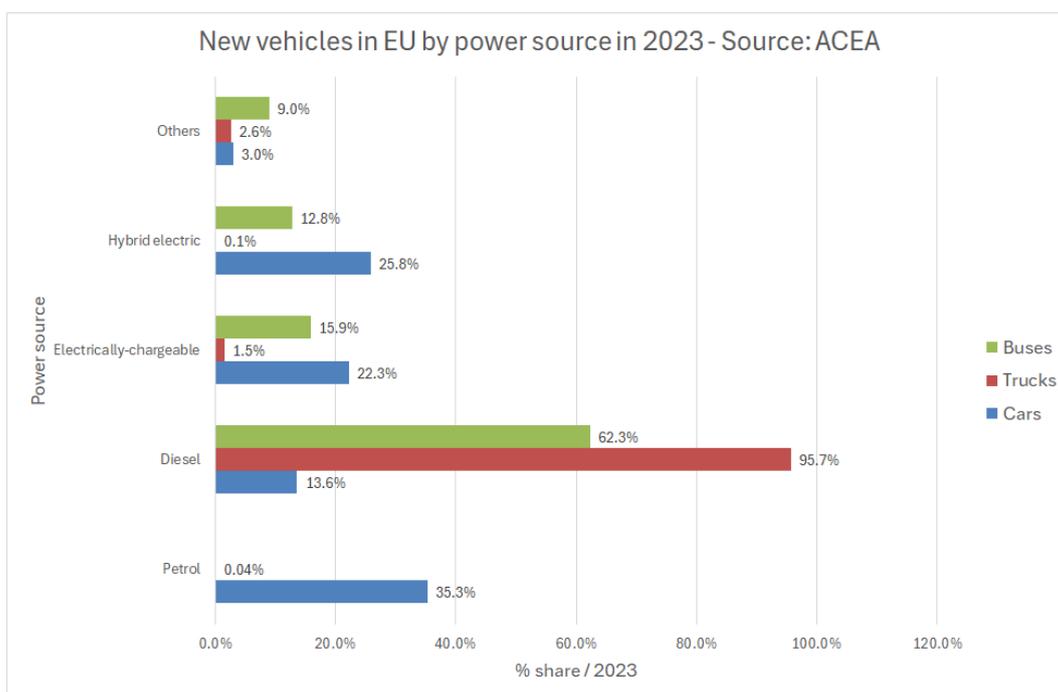


Figure 1. New registered vehicles in EU by power source in 2023 (ACEA, 2025).

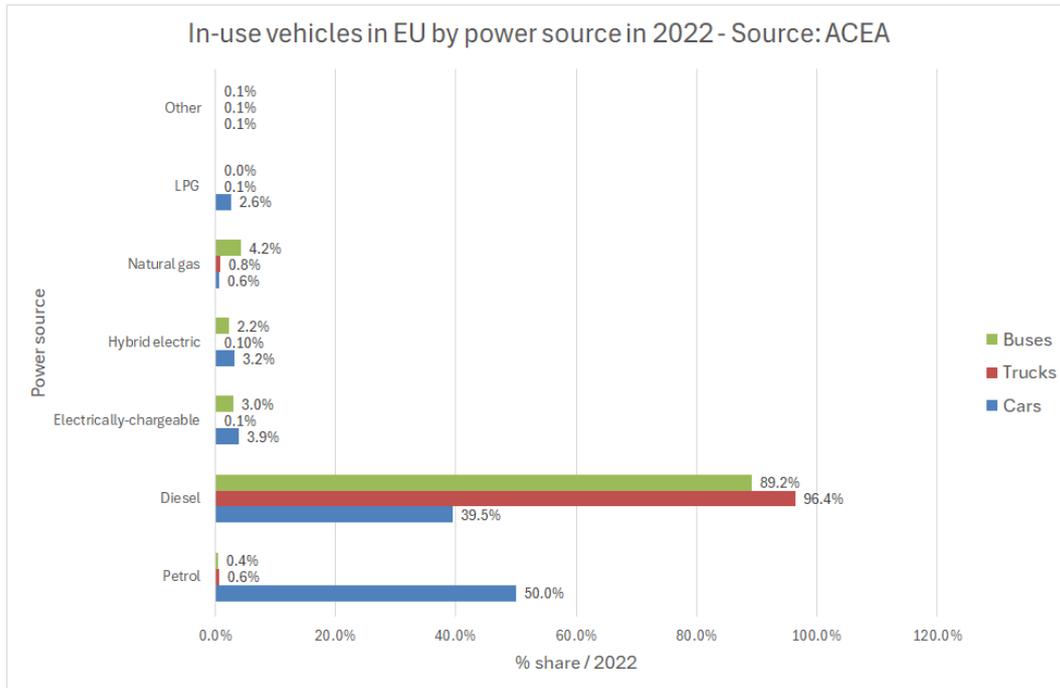


Figure 2. In-use vehicles by power source in 2022 (ACEA, 2025).

More recent statistics are provided by the European Alternative Fuels Observatory (EC, 2025), see Table 1. The trend stated in previous paragraph is confirmed for passenger cars and buses. For trucks, AFVs are dominated by Battery Electric Vehicle (BEVs) and Compressed Natural Gas (CNG) vehicles. For cars and trucks, the share of Liquefied Petroleum Gas (LPG) vehicles is non negligible.

Table 1. Breakdown of the European alternative vehicles fleet (EC, 2025)

	New EU AFVs in 2024			EU AFVs in use in Q1 2025		
	Cars	Trucks	Buses	Cars	Trucks	Buses
BEV	57%	47%	68%	31%	24%	44%
(P)HEV	30%	< 1%	1%	21%	< 1%	2%
H <sub>2</sub>	< 0.1%	1%	1%	< 0.1%	< 1%	1%
LPG	12%	< 0.1%	-	42%	14%	2%
CNG	< 1%	42%	30%	6%	46%	51%
LNG	-	10%	< 1%	< 0.1%	15%	< 1%

Recently, the International Union of Marine Insurance (IUMI) in its position paper (IUMI, 2025) with data from Clarkson Research provides the figure of around 20 million vehicles shipped by maritime transport since 2020. The estimation in 2023 of the shares of vehicles per type of power source is: 60% petrol, 11% diesel, 13% fully electric, 11% hybrid (non-PHEV) and 5% hybrid (PHEV).

Exploring fires in AFV on land, the Netherlands Institute for Public Safety (NIPV, 2025) reported that between 2021 and 2024, only a small percentage of AFV fires involved CNG vehicles (up to 6%), and even fewer involved Fuel Cell Vehicle (FCVs) or LNG vehicles (up to 2%), see Table 2.

Table 2. Number of fires broken down by power source of the AFVs (NIPV, 2025)

	2021	2022	2023	2024
BEV	58	74	91	114
(P)HEV	19	45	66	125
CNG	4	8	6	1
FCV	1	2	0	0
LNG	1	2	0	1
<b>Total</b>	<b>83</b>	<b>131</b>	<b>163</b>	<b>241</b>

**Conclusion:** Based on the statistics presented above, the STARRS study will mainly focus on EVs (BEVs, HEVs and PHEVs). LPG, CNG vehicles and FCVs will be addressed, but other types of AFVs will not be addressed. For EVs, the study will address the lithium-ion battery technology, as this technology dominates the current EVs market (IEA, 2024).

### 2.1.2 EV fire causes

When analysing the EV fires occurred in the Netherlands from 2021 to 2024 (NIPV, 2025), the NIPV found that approximately 1/3 of the EV fire (in average over the 4 years), the power battery was involved in the fire. In about 50% of the EV battery fires, the cause is unknown, then the main identified causes are collision or debris damaging the battery pack, battery or charging point fault, water ingress or submersion and external fire. The same trend was also identified by <https://www.evfiresafe.com/> (EV FireSafe, 2025) and from fire statistics based on rescue service reports in Sweden reported by (Willstrand, 2025). EV Fire Safe compiles passenger EV traction battery fires on land from 2020 to 30<sup>th</sup> June 2024. About charging, the statistics from NIPV and EV Fire Safe report figures between 20% and 40% of EV battery fires occurred when EV connected to a charging point.

### 2.1.3 New vehicles vs. used vehicles for sea transportation

For statistics related to importation and exportation of new and used vehicles, Norway is used as representative case and statistics are provided by the International Transport Forum (ITF, 2023). Unfortunately, the figures are not broken down per type of transportation (air/land/sea). However, exploring Norway’s case can serve as an indicator for the future trend in European countries, with the exception of countries where vehicles are produced locally. Assuming no exportation of new vehicles from Norway (i.e. no vehicles produces in Norway for exportation), Table 3 estimates that about 84% of vehicles transported to or from Norway are new and that 16% are used. Among those, EVs have the highest share.

Table 3. Vehicle imports and exports by energy carrier in Norway in 2022 (ITF, 2023)

		Share %
<b>New</b>		83.6%
	ICE-Gasoline	0.9%
	ICE-Diesel	3.6%
	HEV	6.3%
	BEV+PHEV	72.8%
<b>Used</b>		16.4%
	ICE-Gasoline	4.3%
	ICE-Diesel	4.4%
	HEV	0.1%
	BEV+PHEV	7.6%

When observing recent fire incidents on board ro-ro ships in the ongoing work at IMO and the “Detailed analysis of incident investigation reports” (CCC 10/6/2, Report from the Correspondence Group (CG), Annex (IMO CG, 2024)), it was found that a total number of 41 fire cases occurred on ro-ro passenger, general ro-ro cargo and vehicle carrier vessel types (based on available data on IMO GISIS MCI). Categorization based on type of vehicle that caused fire showed that in-use vehicles (a "used vehicle" that is accompanied by an operator) had contributed to 29% of the fires, used vehicles to 27% of the cases and 7% had been contributed by new vehicles, see Table 4.

Table 4. Categorization of past fires in ro-ro spaces based on type of vehicle that caused fire (IMO CG, 2024)

Type	Number of cases
New vehicle	3
Used vehicle	11
In-use vehicle	12
Reefer unit on vehicles	5
Unknown vehicle	5
Other (non-vehicle fires)	5
<b>Total</b>	<b>41</b>

## 2.2 Hazards related to AFVs

This section provides useful insights related to specific hazards and challenges associated with AFVs.

### 2.2.1 General

Hazards from conventional vehicle fires are heat, smoke, and toxic gases. Another hazard is small explosions and projectiles related to for example tires, shock absorbers and airbags. AFVs share many of these conventional hazards, but each energy carrier also adds its particular risks. The number of fires starting in AFVs (relative new fleet in comparison to the fleet of conventional vehicles) compared to conventional vehicle fires is currently lower, normalized for the number of vehicles in the fleet but consequences can be more severe or problematic if the energy carrier is affected by the fire (Gehandler, et al., 2022). Non-stoppable thermal runaway in a large traction battery as well as pressure vessel explosion or jet flames from gas fuelled vehicles (such as CNG or H<sub>2</sub>) are examples of such events.

Many studies, such as (Gehandler, Karlsson, & Vylund, 2017; Vylund, et al., 2019; EMSA, 2025; Gehandler & Lönnermark, 2024), have already exhaustively listed and analysed new hazards related to AFVs. For more detailed information, the reader is referred to them. The main hazards are summarized below:

#### Electric Vehicles

- Thermal runaway:
  - Gas release (flammable and toxic)
  - Fire: jet flame, difficult to stop/extinguish
  - Gas explosion
  - Reignition
- Stranded energy

#### LPG Vehicles

- Gas release (flammable)
- Fire: jet flame from pressure relief device (PRD)
- Gas explosion
- Boiling liquid expanding vapour explosion (BLEVE) of fuel tank: explosion (vapour phase expansion, explosive boiling and rapid combustion), fireball, projection of fragments of fuel tank

#### Compressed Natural Gas Vehicles / Fuel Cell Vehicles

- Gas release (flammable)
- Fire: jet flame from TPRD (the gas may instead be released in microjets through composite material in leak-not-burst (LNB) tanks)
- Gas explosion
- Rupture of fuel tank (for tanks that are not LNB and have a SoC above 50%): explosion (gas expansion and possible combustion), fireball, projection of fragments of fuel tank

Despite the fact that CNG and FCV share almost the same hazards, they do not share the same level of severity. Gaseous hydrogen is more flammable, reactive and easily ignitable than gaseous natural gas. Flames of hydrogen are hotter but less radiative than flames of natural gas. The hydrogen jet flame can be invisible (note: the diffusive flame of hydrogen is visible). Some recent research tends to show that the regions of highest erosive forces and highest heat fluxes coincide for a jet flame of hydrogen, which is not the case for a jet flame of natural gas and is of importance for impinging jets (Bradley, 2025). Hydrogen is generally stored at higher pressure in fuel tank than natural gas, which results in a larger fireball and more severe pressure vessel explosion (Venetsanos, Baraldi, Adams, Heggem, & Wilkening, 2008).

### 2.2.2 EVs transported in vehicle carriers

New challenges associated to the safe transportation of alternative fuel vehicles on board ro-ro ships were identified and analysed by various sources (e.g. (IUMI, 2025), MSC 96/INF.3, IMO SSE, ALBERO, BREND or

ELBAS project). The authors of STARRS study did the same exercise, but restricting the exercise to vehicle carriers only. The main hazards and challenges related to safe transportation of EVs in vehicle carriers are presented in Figure 3. This list is based on a preliminary analysis and may not be exhaustive. Standard hazards and challenges related to ICEV fires are shown in black whereas new ones related to EVs are shown in blue.

Transportation of EVs introduces new challenges in detection and fire-fighting. The challenges are to detect the abnormal state of an EV or the phenomenon of thermal runaway sufficiently early and to control, even stop the thermal runaway and its associated consequences. It raises the question of the performance of the existing onboard fixed detection and fire-extinguishing systems, the implementation of new systems, and how pre-loading checks and controls can be improved.

Safe transportation of EVs also brings the broader challenges related to manual fire-fighting to the forefront, e.g. operations, gear, equipment and training, including the post-fire-fighting activities and coordination with external emergency responders.

Lastly, to the knowledge of the authors, there are still some unknowns related to the escalation of the consequences of a thermal runaway (fire, explosion). For example, does an EV fire result in a quicker fire spread vehicle to vehicle than a ICEV fire? Are jet flame or explosion caused by thermal runaway a threat to ro-ro spaces decks or bulkheads? What is the explosion risk?

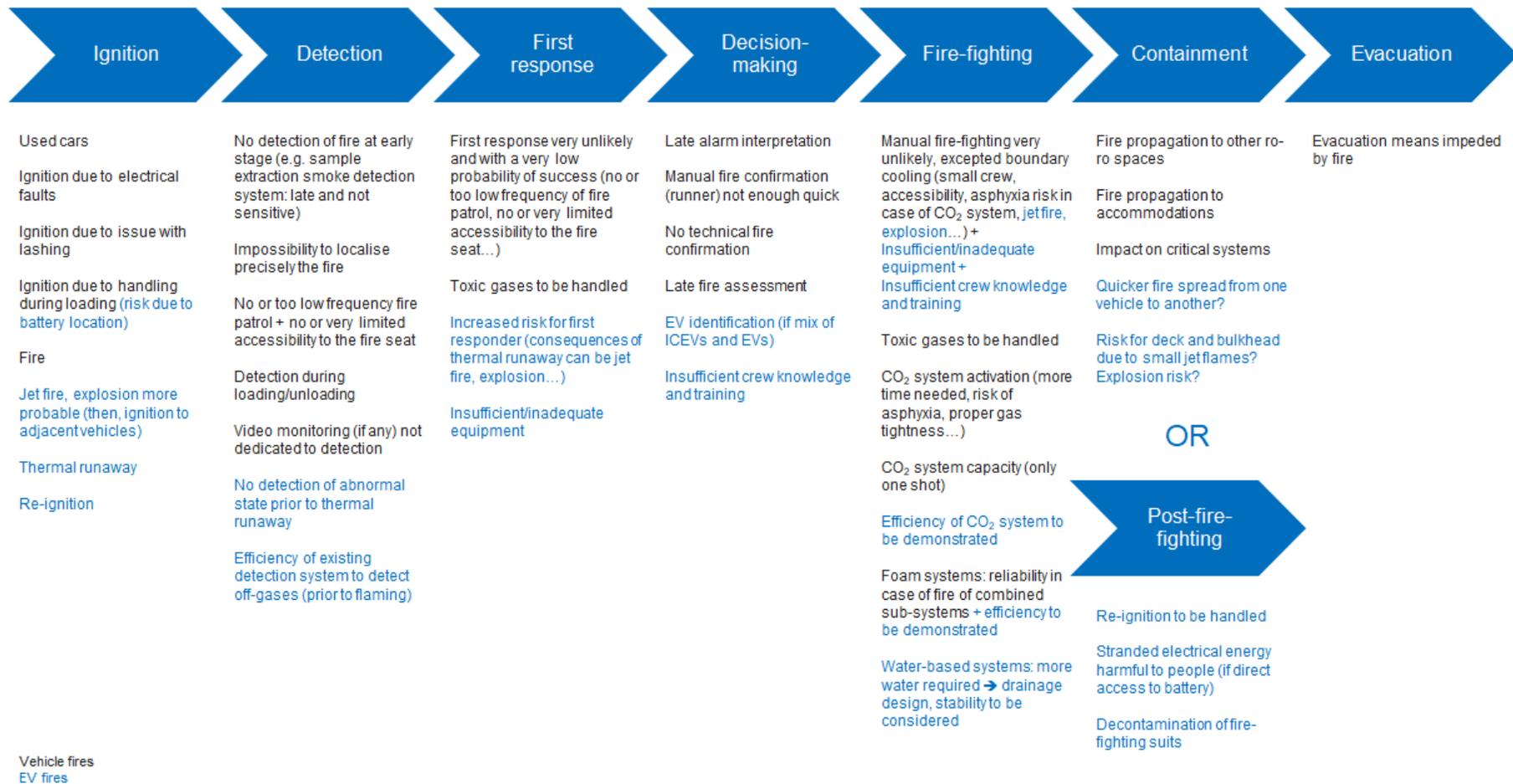


Figure 3. Pre-identification of hazards and challenges related to safe transportation of EVs in vehicle carriers.

## 2.3 Lessons learned and recommendations

Analysis of past marine casualties is crucial to prevent the reoccurrence of accident and enhance the maritime safety. In this study, past accidents involving EV fire in ro-ro spaces were collected through different sources of information:

- S&P Global Market Intelligence Casualty Database (time period = 2010-2024);
- Lloyds List Intelligence Seasearcher;
- IMO GISIS MCI;
- Maritime accident investigation reports; and
- Maritime news websites.

A time period from 01/01/2010 to 30/06/2025 was used. For the other search criteria (e.g. fleet definition, casualty categorized as fire/explosion, ignition occurring in ro-ro space), the same used in the LASH FIRE project were used (Gadel , De Carvalho, & Lewandowski , 2021).

### 2.3.1 Ro-ro passenger ships

Only one accident involving electric vehicles was found: Pearl of Scandinavia, 17 November 2010 (DMAIB, 2011). The origin of the fire was found to be a conventional internal combustion engine car, converted into an electric car. The fire broke out while the electric vehicle was charging using the car owner charging cable. The ship was at sea. The cause of the fire is unknown. The fire was extinguished by the fixed water-based fire-extinguishing system of the ro-ro space and subsequently by ship's fire-fighter teams assisted by land-based fire-fighter teams.

Lessons learned and recommendations from this accident was not considered to be useful for this study because of the date of the accident. More generally, the recent amendments to SOLAS II-2 Reg. 20 related to new and existing ro-ro passenger ships add new requirements in ro-ro spaces. Consequently, the lesson learned from past accidents, which have occurred on ships which may be not equipped with the safety systems required by the new amendments, may become irrelevant for new and existing ro-ro passenger ships compliant with the new amendments.

### 2.3.2 Ro-ro cargo ships

Only one accident involving electric vehicles was found: Delphine 16 April 2025. The origin and cause of the fire is still unknown. According to a press interview, the ship operator is discounting battery electric vehicle as origin of the fire. However, it is reported that the fire broke out on a deck where a mix of conventional cars and electric cars were stowed. The ship was at port. The fire was brought under control by the fixed carbon dioxide fire-extinguishing of the ro-ro space with assistance of fire-fighting tugboats. The fire was finally extinguished the day after. To the date of the study, no accident investigation report and so no lessons learned or recommendations were made available.

### 2.3.3 Vehicle carriers and container-ro-on/ro-off ships

Three to five accidents involving or suspected to involve electric vehicles were found:

- (2019 PCTC – The fire origin and cause are unknown. Electric vehicles were transported.)
- (2023 PCTC – The fire origin and cause are unknown. Electric vehicles were transported.)
- Felicity Ace, 16 February 2022 (PMA, 2023) – According to the crew, the fire started from an electric vehicle. The ship was transporting 3965 vehicles, including 574 electric vehicles.
- Fremantle Highway, 25 July 2023 (PMA, 2025) – The fire origin was most probably an electric vehicle. The fire started from an area of electric vehicles.
- Morning Midas, 3 June 2025 – The fire origin and cause are still unknown. The marine casualty is still under investigation. But the fire was reported to origin from a deck carrying electric vehicles. Therefore, even if the origin of the fire was not an electric vehicle, the electric vehicles would have contributed to the fire.

In addition to the above marine casualties, it was considered useful for the study to collect the various lessons learned and recommendations from recent accident investigation reports. As to the knowledge of the authors few marine casualties involved electric vehicles, it was decided to extent to any accident investigation reports of fire

casualties occurring in ro-ro spaces of vehicle carriers or container-ro-on/ro-off ships. Consequently, eleven accident investigation reports (Table 5) were reviewed, the lessons learned and recommendations were extracted and classed.

Note: for readers interested in more details related to fire incidents occurring in ro-ro spaces of vehicle carriers or container-ro-on/ro-off ships, it is recommended to read the work of Lighthouse (Lundh, Malmberg, Martinson, & Mattsson Larsson, 2024) or in the RISE project denoted COFFEE (Arvidson & Karlsson, 2024).

Table 5. List of reviewed marine accident investigation reports

Ship Name	IMO No.	Ship Type	Casualty Date	Author	Ref.
Golden Fan	8511263	Vehicle Carrier	22/06/2013	Panama Maritime Authority	(PMA, 2014)
Courage	8919922	Vehicle Carrier	02/06/2015	National Transportation Safety Board	(NTSB, 2017)
Silver Sky	8519722	Vehicle Carrier	19/10/2016	Panama Maritime Authority	(PMA, 2018)
Honor	9126297	Vehicle Carrier	24/02/2017	National Transportation Safety Board	(NTSB, 2017)
Mignon	9189251	Vehicle Carrier	04/04/2018	Swedish Accident Investigation Authority	(SHK, 2023)
Auto Banner	8608066	Vehicle Carrier	21/05/2018	Panama Maritime Authority	(PMA, 2019)
Grande America	9130937	Con-Ro	10/03/2019	Directorate General for Rail and Maritime Investigations	(DiGIFeMa, 2023)
Höegh Xiamen	9431848	Vehicle Carrier	04/06/2020	National Transportation Safety Board	(NTSB, 2021)
Felicity Ace	9293911	Vehicle Carrier	16/02/2022	Panama Maritime Authority	(PMA, 2023)
Grande Costa d'Avorio	9465382	Con-Ro	05/07/2023	National Transportation Safety Board	(NTSB, 2025)
Fremantle Highway	9667344	Vehicle Carrier	25/07/2023	Panama Maritime Authority	(PMA, 2025)

The recommendations from the marine investigations, which can be useful for future guidelines for vehicle carriers and container-ro-on/ro-off ships, are summarized below:

**Stability**

- Stability of the ship should be considered in case of use of large amount of water for fire-fighting.

**Ignition prevention**

- A more exhaustive and systematic survey and inspection of used vehicles should be conducted during pre-loading and loading (e.g. though mandatory checklist).
- The loading and positioning of EVs should be supervised by a dedicated crew member.
- The windows of the vehicles should be kept closed during loading.
- The stowage plan should indicate the exact position of AFVs and their type.
- The EVs should be well identified and, as far as practicable, segregated from other types of vehicles.

- A visual check of stowed vehicles should be conducted prior closing the watertight doors.

**Detection and alarm**

- The deactivation time of the fixed fire detection and alarm system during loading and unloading should be minimized.
- Video monitoring with video analytics for flame or heat detection should be mandatory in ro-ro spaces.
- Fire patrol should be mandatory in ro-ro spaces.
- The fire patrol should be equipped with thermal camera.

**Fire-fighting**

- Fixed foam fire-extinguishing system:
  - Potential failure of fans should be considered and averted in case of fire.
  - The vents should be able to be remotely controlled and open from a safe location.
- Fixed carbon dioxide fire-extinguishing system:
  - All ro-ro decks should be covered by CO<sub>2</sub> nozzles to allow direct release of CO<sub>2</sub> on the fire.
  - The gas tight doors should be able to be remotely controlled and closed from a safe location.
- Locating the fire hoses and nozzles, and the portable fire extinguishers in the stairways, outside the ro-ro spaces, should be evaluated.
- The onboard fire-fighting team should be equipped with:
  - Full-face respiratory mask;
  - Gloves rated for high-voltage use; and
  - Portable gas detector.
- Fire hydrants and firewater supply facilities should be available at every pier where a ship berth alongside.

**Containment**

- Means to prevent rapid fire spread should be considered.
- A fire blanket should be able to be used as a preventive measure (it will not prevent thermal runaway but may prevent fire spread to adjacent vehicles).

**Evacuation**

- The Life-Saving Appliances (LSAs) should be protected from smoke and heat or located at a safe location, in order to enable their safe lowering to the sea.
- Means of evacuation should be provided on the highest open deck.

**Operations and training**

- Crew members should be better prepared and trained to emergency situation related to EV fire. It should be reflected in the Safety Management System.
- Procedures, frequent drill exercises and trainings specific to EVs, in particular for fire patrol, manual fire confirmation and localization, and fire-fighting, should be developed and implemented.
- The cooperation with port authorities and ashore fire-fighters should be enhanced, e.g.:
  - The contact information for emergency response responsible of each port along the ship route should be available to bridge teams and crew members should know how to use it.
  - The ashore fire-fighters should be better prepared and trained to ship arrangements, ship fire safety systems and onboard emergency response.
  - Joint fire emergency exercise should be organized between crew members, port personnel and ashore fire-fighting services.

The regulatory review in Chapter 3 shows that some of these recommendations are being applied by National Maritime Authorities or class societies. IMO consensus is however yet to be found.

### 3. Regulatory review

This chapter provides an overview of the regulatory landscape governing the safe transportation of AFVs, including background at IMO, a review of regulations, rules and guidelines across both maritime and non-maritime domains.

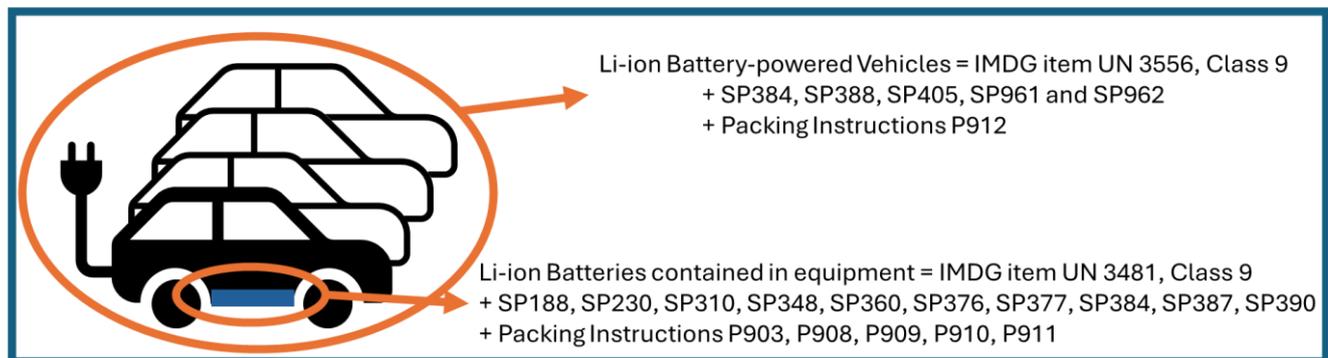
#### 3.1 IMO background

The purpose of this section is to plot the scene before commencing in the review of regulations, rules and guidelines related to safe transportation of AFVs. This section provides the general IMO framework related to the safe transportation of (all type of) vehicles by sea and summarize the current discussion and initiatives related to AFVs in the different IMO Sub-Committees.

This section does not detail all the requirements associated to the safe transportation of vehicles by sea. For that, the readers may refer to the LASH FIRE deliverable D5.6 (Radolovic, et al., 2022), which provides a quite comprehensive description of the IMO regulations related to ro-ro spaces up to 2020. For more recent developments of the IMO instruments, the readers will find interesting summaries in the LASH FIRE deliverable D4.8 (De Carvalho, Vicard, Karlsson, Steinlein, & Bilen, 2023) or in the Lighthouse study report (Lundh, Malmberg, Martinson, & Mattsson Larsson, 2024).

##### 3.1.1 Design, construction and equipment

In terms of international transportation, the safe transportation of vehicles is regulated by two main IMO instruments: SOLAS Convention Chapter II-2 and associated Code(s) and Circular(s), and IMDG Code (see Figure 4 for EVs).



- Carried in containers = IMDG Package Instructions P912 and SP384, SP388, SP405, SP961 and SP962 + SOLAS II-2 Reg 19 + MSC/Circ.608
- Carried in RO-RO Spaces = Only need to follow IMDG Package Instructions P912 and SP388 and SP977 + SOLAS II-1 Reg 14, II-2 Reg 19 and II-2 Reg 20

Figure 4. Main IMO instruments regulated the safe transportation of EVs.

In 2024 (IMO, 2024; IMO, 2024), Regulation 20 of SOLAS Convention Chapter II-2 has been amended by the IMO, providing new requirements mainly for ro-ro passenger ships. The new requirements include:

- For new ro-ro passenger ships – constructed on or after 1 January 2026:
  - Combined smoke and heat detectors in closed and open ro-ro and special category spaces and enhanced fire alarm interface. Linear heat detectors accepted as an alternative to point heat detectors;
  - Fixed fire detection system on weather decks intended for the carriage of vehicles;
  - Video monitoring in closed and open ro-ro and special category spaces;
  - Specification of structural fire protection of decks within ro-ro spaces when the drencher system cannot cover both levels;
  - Arrangement of openings in ro-ro and special category spaces;
  - Arrangement of weather deck intended for the carriage of vehicles;
  - Fixed water-based fire-extinguishing on weather decks based on monitor(s); and

- Suitable signage and marking aligned with drencher zones/fire detection and fire alarm sections/video monitoring in closed and open ro-ro spaces.
- For existing ro-ro passenger ships – constructed before 1 January 2026, including those constructed before 1 July 2012, not later than first survey on or after 1 January 2028:
  - Combined smoke and heat detectors in closed and open ro-ro and special category spaces;
  - Video monitoring in closed and open ro-ro and special category spaces; and
  - Fixed water-based fire-extinguishing on weather decks based on monitor(s).

The requirements of Regulation 20 and the new amendments were developed with hazards related to ICEVs in mind, prior to the growth of the AFV fleet. Despite that fact, the new amendments may benefit to safe transportation of AFVs on ro-ro passenger ships. Some of the new provisions were evaluated and demonstrated to mitigate EV fires in recent research projects (e.g. LASH FIRE project (LASH FIRE, 2025)).

In 2014 (IMO, 2014), new requirements for vehicle carriers carrying motor vehicles with compressed hydrogen or natural gas in their tanks for their own propulsion as cargo were adopted, as SOLAS Chapter II-2 Regulation 20-1.

More recently, IMO Members States have raised the concern of safe transportation of AFVs (called “new energy vehicles (NEV)” by IMO), especially BEVs, in ro-ro spaces (including vehicle spaces and special category spaces). In 2023, an output 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” was created and assigned to the Sub-Committee on Ship Systems and Equipment (SSE). In February 2025, and after agreed on a road map in 2024, the 11<sup>th</sup> session of the SSE Sub-Committee (SSE 11) has worked on a draft action plan, consisting of:

1. Review of scientific reports, studies, new technologies and casualty reports;
2. Identification of hazards related to new energy vehicles compared to ICEVs;
3. Consideration of a goal-based approach;
4. Identification of gaps in existing regulations and consideration of the way forward; and
5. Identification of placeholders for possible future amendments.

Between SSE 11 (February 2025) and SSE 12 (March 2026), a correspondence group has been established in order to further develop the above action plan, to consider further documents and to identify hazards related to new energy vehicles, including BEVs, and risk control options. The target completion year of the output is set to 2027 but it will likely be extended.

When AFVs are carried in a ro-ro space, this is mainly SOLAS Chapter II-2 Regulation 20 that applies. However, IMDG Code provides additional transport provisions, among other that there should be “no signs of leakage from the battery, engine, fuel cell, compressed gas cylinder or accumulator, or fuel tank when applicable” (SP961).

The safe transportation of vehicles in spaces other than ro-ro spaces, such as containers on container ships, is mainly regulated by SOLAS Chapter II-2 and IMDG Code. SSE is currently working to amend SOLAS Chapter II-2 and FSS Code concerning detection and control of fire in cargo holds and on the cargo deck of container ships. The target completion year of the amendments is 2028. Despite the fact that those amendments are developed with hazards related to any cargo transported by container ships in mind, they may benefit to the safe transportation of AFVs in container on container ships. Lastly, the Sub-Committee on Carriage of Cargoes and Containers (CCC) is currently working to amend transport provisions for vehicles in the IMDG Code. Among other, the delegations are discussing about further criteria to define unsafe vehicles to exclude such vehicles from transport via a new special provision (SP980) (not applicable to vehicles driven by passengers on board ro-ro passenger ships). They are also considering new criteria for transporting EVs. One item of discussion is whether to impose a criterion on the state of charge (SoC), but, at the date of this report, no consensus was found about imposing a SoC limit.

### 3.1.2 Operations

In terms of onboard operations and procedures, the IMO instruments are less detailed and “prescriptive” than technical and engineering measures. SOLAS Chapter II-2 Regulations 14 to 16, and Chapter III Regulations 19, 30, 35 to 37 provide general operational requirements in broad terms, while the International Safety Management (ISM) Code provides an international standard for the safe management and operation of ships. It is to be noted that IMO requirements regarding onboard procedures and actions to adopt in case of fire emergency remain on the

general, functional requirement level. The detail of the actions to be actually taken is reckoned to be case-specific and ship-specific, and is therefore left to specific onboard procedures, safety management system, and crew members experience and analysis of the situation. The operational requirements from IMO instruments do not specifically address hazards from AFVs.

### 3.1.3 Training

In terms of training and certification of seafarers, this is the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), supported by the STCW Code, which is applicable. In particular, the Chapter VI provides mandatory minimum standard of competence in fire prevention and fire-fighting, and in advanced fire-fighting. In addition to STCW Convention and Code, the IMO Model Courses assist instructors in developing training programmes for seafarers as per STCW. In particular, Model Course 1.20 addresses the fire prevention and fire-fighting training, while Model Course 2.03 covers the advanced fire-fighting training, including operations during onboard fire emergency. The STCW and the IMO Model Courses do not specifically address hazards from AFVs. However, in 2025, the Sub-Committee Human Element, Training and Watchkeeping (HTW) agreed on a draft generic interim guidelines on training for seafarers on ships using alternative fuels and new technologies (STCW.7/Circ.25) and to develop fuel/technology-specific guidelines, such as hydrogen fuelled ships or battery powered ships, for seafarer training (IMO WG, 2025). Those future guidelines on hydrogen and battery may ease the development of training requirements or standard of competence for safe transportation of AFVs. In parallel of that work, the HTW has started a comprehensive review of STCW. A list of gaps has been established and “training requirements of fire-fighting for seafarers on ro-ro passenger ships carrying new energy vehicles” was identified as a gap.

## 3.2 Review of maritime regulations, rules and guidelines

This section focuses on regulations, rules and guidelines governing the safe transportation of AFVs by sea.

### 3.2.1 Methodology

The analysis of the current regulatory landscape on the safe transportation of AFVs on board ships, especially BEVs, has been done through the lens of the main hazards and challenges related to fire propagation and fire-fighting, represented in Figure 3.

This section is focusing on the similarities and differences of a selection of documents related to the maritime industry.

The studied documents could be split in three types and are listed in Table 6:

- Mandatory international or national regulations: (Sweden, 2018), (USCG, 2020), (Australia, 2023), (UK, 2023), (Cyprus, 2024), (France, 2025), (ROK, 2024b), (EMSA, 2025);
- Class requirements: mandatory for ships registered to these class societies: (ABS, 2022), (BV, 2025a), (BV, 2025b), (BV, 2025c), (BV, 2023), (CCS, 2022), (PRS, 2022), (ClassNK, 2023), (DNV, 2024a), (DNV, 2024b), (KR, 2021); and
- Non-mandatory guidelines, standards or good practices: (Shanghai MSA, 2023), (CINS, 2023), (IUMI, 2023), (Steamship Mutual, 2023), (UECC, 2023), (Gard, 2023), (ICS, 2024), (ICS, 2025), (MTF, 2025), (ALBERO, 2021).

Whereas the two first types focus on the ship design, the different studied guidelines enlarge the safety concepts to operational and human-centred elements such as procedures or training. Although not directly mandatory, guidelines and good practices were included in the regulatory study as they may become mandatory if called upon by international or national regulations.

The transportation of AFVs on board ships can be made via several type of ships: ro-ro passenger ships (RO-PAX), ro-ro cargo ships (RO-RO), vehicle carriers such as Pure Car and Truck Carriers (PCTC/PCC) or container ships. The application scope of the studied documents may encompass all or only one of the ship types as defined in Table 6. This will also be indicated in the relevant paragraphs of this section to account for differences in the safety concepts.

Table 6. List of reviewed documents in the maritime regulatory study

Source	Scope	Type	Details
SSE 11/INF.6, 2024 submitted by the Republic of Korea - "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"	RO-PAX	Guidelines	Informative paper submitted by the Republic of Korea to IMO.
ABS Rules for Steel Ship - Pt 5C, Ch 10, sec 4, [7] - Ro-Ro Cargo Spaces Intended to Carry Electric Vehicles - 2022	RO-RO	Class Rules	Set of requirements for the assignment of the class notation <b>EFP-C(EV)</b> .
BV Rules for Steel Ships - NR467 Pt F, Ch 13, sec 4 – EVFP-1 - 2025	PCTC/PCC	Class Rules	Set of requirements for the assignment of the class notation <b>EVFP-1</b> .
BV Rules for Steel Ships - NR467 Pt F, Ch 13, sec 4 – EVFP-2 - 2025	PCTC/PCC	Class Rules	Additional requirements for the assignment of the class notation <b>EVFP-2</b> (extensive set of mitigation measures).
BV Rules for Steel Ships - NR467 Pt F, Ch 13, sec 4 – EVFP-3 - 2025	PCTC/PCC	Class Rules	Additional requirements for the assignment of the class notation <b>EVFP-3</b> (advanced technologies for the safety of EV onboard ships).
BV Rules for Steel Ships - NR467 Pt F, Ch 12, sec 9 – EVOC - 2023	RO-RO	Class Rules	Set of requirements for the assignment of the class notation <b>EVOC</b> (EV Onboard Charging).
CCS Rules for Steel Ships - Technical Guidelines for the safety of Ro-Ro Carriage of New Energy Vehicles - 2022	PCTC/PCC & RO-PAX	Class Rules	Set of requirements for the assignment of the class notation <b>NEV Carriage (X)</b> .
PRS - 39/I - Guidelines for the Safe Carriage of AFVs on RO-RO ships and Onboard Charging of EV – 2022	PCTC/PCC & RO-PAX	Class Guidelines	Based on (EMSA, 2022) Therefore, it was not included in the comparative study.
ClassNK - Guidelines for the Safe Transportation of Electric Vehicles - 2023	PCTC/PCC	Class Rules	Set of requirements for the assignment of the Class notations <b>AFVC(XX)(EV)</b> . XX can be replaced by FD, PS, PFS, FF, EFF, for enhancing Detection, Prevention of Secondary fire, Prevention of Fire Spread, fire-fighting or enhanced Fire-Fighting.
DNV - Pt 6, Ch 5, sec 4, [6] – Additional fire protection in cargo area in car carriers intended for carriage of electric vehicles – 2024	PCTC/PCC	Class Rules	Set of requirements for the assignment of the Class notation <b>F(EV)</b> .
DNV - Pt 6, Ch 5, sec 4, [6] – Enhanced additional fire protection in cargo area in car carriers intended for carriage of electric vehicles – 2024	PCTC/PCC	Class Rules	Set of requirements for the assignment of the Class notation <b>F(EV-E)</b> in addition to <b>F(EV)</b> .

Source	Scope	Type	Details
KR (Part 8, Annex 8-9) – Special Requirements of Fire Protection and Fire Extinction for Cargo Ships - 2021	PCTC/PCC & RO-RO	Class Rules	Set of requirements for the assignment of the class notation <b>AFP-C(EV)</b> .
SWEDEN – TSG 2018-3106 - Charging Electric Vehicles onboard Swedish ROPAX Vessels - 2018	RO-PAX	National Recommendations	
USCG – Marine Safety Alert 06-20 – Recognizing Fire Hazards & Proper Cargo Stowage on RO-RO Vessels - 2020	RO-RO	National Recommendations	Mostly insists on additional crew inspection of the cargo.
AUSTRALIA – Marine Notice 07/2023 - Guidance for the safe carriage of battery powered vehicles on ships - 2023	PCTC/PCC & RO-RO & RO-PAX	National Recommendations	
UK – MCA MGN 635 (M) Amd 1 – Electric Vehicles onboard passenger roll-on/roll-off (RO-RO) ferries - 2023	RO-PAX	National Recommendations	
CYPRUS – Circular No 16/2024 – Additional measures for the safe carriage of alternative fuel vehicles (AFVs) in ro-ro spaces of cargo and passenger ships departing from Greek ports	RO-RO & RO-PAX	National Regulation	Circular issued taking into account IMO MSC.1/Circ.1615, (EMSA, 2022) and (UK, 2023) without additional requirements. Therefore, it was not included in the comparative study.
GREECE - Circular No 2070.0/28541/2024 - Additional measures during the transport of vehicles using alternative fuels (AFVs) on Ro-Ro/Passenger and Ro-Ro/Cargo ships	RO-RO & RO-PAX	National Regulation	Circular issued taking into account IMO MSC.1/Circ.1615, (EMSA, 2022) and (UK, 2023) without few requirements.
FRANCE - Recommandations pour le transport de véhicules électriques et hybrides à bord des navires - 2025	RO-RO & RO-PAX	National Recommendations	Document issued after rounds of discussion with ship operators, fire-fighters and class society.
REPUBLIC OF KOREA – SSE 11/INF.6 Annex 2 – Guidelines for Fire Prevention and Response During Maritime Transport of Electric Vehicles	RO-PAX	National Recommendations	
EMSA – Guidance for the safe carriage of Alternative Fuel Vehicles (AFV) in RO-RO spaces of cargo and passenger ships, ed 1.2 - 2025	PCTC/PCC & RO-RO & RO-PAX	International Guidelines	

Source	Scope	Type	Details
SHANGHAI MSA – Guidelines for maritime transportation of Lithium battery hazardous goods at Shanghai port - 2023	PCTC/PCC & RO-RO & RO-PAX	Local Guidelines	
CINS – C-SAR NO 101.1 – Lithium-Ion batteries in containers guidelines - 2023	CONTAINER SHIPS	Industry Guidelines	
IUMI – Best practice & recommendations for the safe carriage of electric vehicles (EVs) - 2023	PCTC/PCC & RO-RO & RO-PAX	Industry Guidelines	
STEAMSHIP MUTUAL – Carriage of Electric vehicles in Containers - 2023	CONTAINER SHIPS	Industry Guidelines	
UECC – Electric Vehicles Carriage v2 – 2023	PCTC/PCC	Industry Guidelines	
GARD – Lithium-ion battery fires - Industry Guidance - 2023	PCTC/PCC & RO-RO	Industry Guidelines	Reference to (UK, 2023), (EMSA, 2022), (ABS, 2022) and (CINS, 2023) documents without additional items. Therefore, it was not included in the comparative study.
ICS – Common Guidance on the Presentation and Loading of Vehicles - 2024	PCTC/PCC & RO-RO	Industry Guidelines	
ICS – Fire Response- High Level Guidelines – 2025	PCTC/PCC & RO-RO & RO-PAX	Industry Guidelines	Reference to (EMSA, 2025) with a few additional items.
MTF – Safe Carriage of Electric Vehicles – 2025	PCTC/PCC	Industry Guidelines	
ALBERO – Catalogue of measures and recommendations for the transport of alternatively powered vehicles on board of RORO-ferries and for the provision of charging options for electric vehicles during the crossing	RO-RO & RO-PAX	Research project Guidelines	

As a starting point, the study focused on two reference documents: "EMSA Guidance for the safe carriage of alternative fuel vehicles (AFV) in ro-ro spaces of cargo and passengers ships" (EMSA, 2025) and SSE 11/INF.6 (submitted by the Republic of Korea) "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" (ROK, 2024a). These two documents were chosen (1) due to their scope, encompassing the whole subject of safety of EV transportation on ships and (2) due to their reach. Indeed (EMSA, 2025) is cited by several other papers and is known across the maritime industry, whereas (ROK, 2024a) has been submitted to the IMO SSE Sub-Committee and has therefore an extended worldwide reach. The solutions to control, detect or mitigate the risks and hazards of transportation of AFVs on board ships are put forward and either strengthened or completed by the other documents listed in Table 6.

In the current study, documents (PRS, 2022), (USCG, 2020), (Cyprus, 2024), (ROK, 2024b) and (Gard, 2023) will generally not be mentioned in the rest of the chapter as they did not include any particular deviations from (ROK, 2024a), (EMSA, 2025) and other documents as mentioned.

### 3.2.2 Ignition prevention or mitigation

In this section, we aggregate the requirements or guidelines related to safety items which may prevent or delay ignition of AFVs themselves or equipment on board the ship.

#### 3.2.2.1 Risk analysis

Several documents mention the necessity to perform a risk analysis, but with diverging scopes. BV (BV, 2023) recommends performing it when EVs charging stations are foreseen onboard. The reference documents (EMSA, 2025) and (ROK, 2024a) request that the risk analysis shall assess the hazards associated with installation, operation and maintenance of equipment related to the carriage of AFVs, including the loss of containment of fuels, electrical hazards, operational hazards in normal and in emergency situations. (France, 2025) is also suggesting a risk analysis to be carried out for the safety evaluation of the vehicle charging areas.

From the documents issued by the industry, looking into an operational point of view, both (CINS, 2023) and (Steamship Mutual, 2023) focusing on container ships suggest applying the “Know Your Customer” (KYC) guidelines to verify the risks associated with the customers. This may include factory audits or due diligence prior accepting the consignment to verify that the clients have the necessary knowledge and experience to ensure that the EVs are in a safe condition for transport.

The studied documents show that the risk of AFVs is relevant for transportation on ships. Even if current texts are already requesting prescriptive requirements, the need for a formal risk analysis is pinpointed as the different technologies or battery chemistries may have various risks and reactions to fire-extinguishing systems and procedures. Hence leading to requirements on ventilation, smoke extraction, fire containment philosophy and the protection of electrical equipment.

Interestingly, as the current study mostly focuses on EV, it also encompasses CNG and H<sub>2</sub> vehicles. Indeed, the risk related to battery thermal runaway is, among other, the production of off-gases (mostly H<sub>2</sub> and CO), their entrapment and their flammability/explosion potential.

#### 3.2.2.2 Protection of electric equipment

Risks related to electric equipment are addressed in 3.3.6.2 Explosion protection. However, the additional risks associated with the carriage and operation of AFVs may impact the electric equipment onboard. (BV, 2023) requests an extensive set of requirements when stations for the charging of EVs are installed onboard which are summarized below whereas (France, 2025) only requests for fire-resistant cabling:

- a) The charging cables are to be included in the ship’s equipment and operated by its crew.
- b) Enough electrical power for simultaneous operation of all charging stations is to be available.
- c) The charging stations are to:
  - o be built in order not to cause electromagnetic disturbances;
  - o have a degree of protection of IP 55 when installed in closed spaces or IP 56 when installed in open areas;
  - o be equipped with isolating switch or breaker; and
  - o have standardized cables, connectors and socket-outlets.
- d) The ship’s electrical system is to be equipped with isolating transformers and residual current device. In addition, means for detection and protection for earth faults, overloads and short-circuit faults are to be arranged. Finally, means are to be provided to avoid failures due to overload or short-circuits.
- e) Automatic disconnection of the charging stations upon activation of two fire detectors.

In addition, from the industry perspective (Steamship Mutual, 2023) suggests more generally to improve vessel design over and above minimum statutory requirements to improve vessels capability to monitor, detect, mitigate and address any potential EV associated hazard.

### 3.2.2.3 Vehicle identification

The reference documents (ROK, 2024a) and (EMSA, 2025) suggest identification and designation of loading positions for EVs. (EMSA, 2025) also requests that the vehicles fuels are identified during booking for ro-ro passenger ships (RO-PAX) or in the stowage plan for vehicle carriers (PCC/PCTC).

As this is related to operations, there are no additional requirements from classification societies. Some Maritime Authorities are following the above guidelines: (Australia, 2023), (UK, 2023), (Greece, 2024) and (France, 2025), specially focusing on the labelling of EVs.

Vehicle identification seems also to be important for the industry as stated in (UECC, 2023), (ICS, 2024) and (ALBERO, 2021). In addition to identifying the vehicle fuel, it may be necessary to identify vehicles with low-ground clearance (i.e. (UECC, 2023) and (ICS, 2024)) which is more common for EVs. (ALBERO, 2021) suggests the use of a dedicated software to visualize the position of AFVs onboard.

### 3.2.2.4 Condition of carriage (incl. new, used, damaged)

The reference documents (ROK, 2024a) and (EMSA, 2025) are both focusing on the importance of limiting the State of Charge (SoC) of EVs when loaded onboard. However, (ROK, 2024a) requires a limit at 50% and (EMSA, 2025) suggests a SoC between 20% and 50%. Besides, (ROK, 2024a) requires the development of an Electric Vehicle Fire Prevention and Response Plan whereas (EMSA, 2025) suggests the transport of damaged or defective batteries removed from vehicles and transported in accordance with SP376 of Chapter 3.3 of the IMDG code. In all cases, (EMSA, 2025) insists on the avoidance of repair work in the cargo area where EVs are stored. Finally, the EVs shall comply with the IMDG code (item UN3171).

Some classification societies, (CCS, 2022), requests a limit of SoC at 50%. (BV, 2025a) requires only the SoC limit of the EVs to be included in the ship's operation manual, and (DNV, 2024b) requires the availability onboard of a plan for the stowage of EVs and for fire-fighting in case of fire involving them.

For Maritime Authorities, (Australia, 2023) and (France, 2025) require an inspection of vehicles before and after loading and (France, 2025) requires that before loading, the passengers should be aware of the risks and be informed about the optimum SoC (30-40%). On the other hand, (Greece, 2024) limits the SoC at 40%. (France, 2025) also requires that the batteries of damaged EVs are to be transported separately and in compliance with IMDG code and with proper labelling.

From the industry side, the maximum SoC of EVs at the time of loading is also a key safety consideration, though recommended limits vary 30-40 % for (CINS, 2023), 20-50% for (Steamship Mutual, 2023) and (UECC, 2023) or the OEM's-defined safest SoC for thermal runaway as referenced by (ICS, 2024). A pre-loading inspection is also a requisite for checking that there are no sign of damage (i.e. (CINS, 2023), (IUMI, 2023), (Steamship Mutual, 2023) and (ICS, 2024)) or other signs of leakages or short circuits (Shanghai MSA, 2023). For documents related to the transport of EVs in containers, the ambient temperature inside the container is to be monitored (CINS, 2023) and when possible, the transport of the EVs is to be done in specialized containers equipped with monitoring and fire suppression systems (Steamship Mutual, 2023). Regarding the status of the batteries, (UECC, 2023) advises that EVs should not be loaded onboard until at least 24 hours have passed since any battery rework, and that hybrid vehicles should have their electric mode disengaged prior to loading.. (ICS, 2024) requests that no unsafe or damaged EVs are to be loaded onboard. (CINS, 2023) suggests that no other type of dangerous goods (defined in the IMDG code) is packed in the same container as lithium-ion batteries.

In conclusion, it can be noticed that most of the documents refer to a limit of the EV SoC in the low-mid range for safe transportation on board ships, but there is no consensus on the limit itself. In addition, several documents mention that the carriage of defective, damaged or unchecked batteries increase the risk level, consequently requesting for inspections and segregation of damaged batteries.

### 3.2.2.5 Loading, stowage, unloading

The designation of loading positions for EVs is requested by the reference document (ROK, 2024a) and similarly but more detailed by (EMSA, 2025). EMSA suggest considering (1) EVs low-ground clearance in the ship's design (e.g. ramp angles), (2) EVs weight (+25% compared to ICEV) for ship's stability and (3) direct access for patrols around EVs.

From classification societies, (ABS, 2022), (BV, 2025a), (CCS, 2022) and (DNV, 2024b) require a designated area onboard for EVs. In addition, (BV, 2023) requires a defined dedicated area for charging of EVs. More specifically, (CCS, 2022) states that the loading area is to consider (1) potential high-temperature climate and appropriate measures for EVs cooling on the weather deck and (2) that on ro-ro passenger ships (RO-PAX), the AFVs are not to be adjacent to fuel or flammable liquid tanks which (BV, 2025a) requests also for vehicle carriers (PCTC/PCC). For vehicle carriers (PCTC/PCC), (DNV, 2024a) requests that crew access to the weather deck must allow a clear view of the cargo, while loading in open ro-ro space is not permitted.

For Maritime Authorities, (Australia, 2023) requests on ro-ro ships that the EVs are stored in a dedicated area onboard, where possible on weather deck, away from dangerous goods and with adequate separation between vehicles for fire-fighter access. Whereas (UK, 2023) requests the EVs to be stored away from dangerous goods, under drenchers or on weather decks, at the discretion of the operator. Finally, for ro-ro passenger ships (RO-PAX), (France, 2025) suggests that the stowage of EVs is away from fuel tanks and flammable liquids, with engine trunk unlocked if possible and for vehicle carriers (PCTC/PCC) in a dedicated area and with a good accessibility for fire patrols.

On the industry's side, the positioning of containers containing EVs are defined in (CINS, 2023) and (Steamship Mutual, 2023) as follows: away from source of heat, away from accommodation, away from other Dangerous Goods (DG) cargo, accessible to fire-fighting equipment and avoiding block stowage (adjacent containers containing lithium-ion batteries). (UECC, 2023) suggests that the vehicles are to be self-propelled on vehicle carriers (PCTC/PCC) but towing can be accepted if all wheels are raised off the ground and that there is no fault on the battery. Finally, (ICS, 2024) suggests a monitoring of the EVs temperature during loading and (ALBERO, 2021) suggests stowage of AFVs above the waterline.

In conclusion, the studied documents mostly agree that the EVs are to be stored in a dedicated area, with easy access for patrols and fire-fighting but the preferred location (on weather deck or enclosed space) is not commonly shared. There is a compromise between ease of detection, ease of access or accessibility of fire-fighting equipment. The type of ship is also a parameter taken into account in the documents.

### 3.2.2.6 Charging of EVs onboard

In the reference documents, for ro-ro passenger ships (RO-PAX), charging of EVs onboard is generally prohibited (i.e. (ROK, 2024a) and (EMSA, 2025)) except if a risk assessment is conducted (example in (ALBERO, 2021)). For vehicle carriers (PCTC/PCC), the charging onboard should be done by stevedores (EMSA, 2025).

In the studied documents, only one classification society is allowing charging of EVs during sea voyage for ro-ro passenger ships (RO-PAX) (i.e. (BV, 2023)), with a defined set of requirements regarding electrical equipment, charging locations and monitoring. Other class societies such as (CCS, 2022) and (KR, 2021) define some requirements allowing the charging during unloading such as monitoring of power supply, battery SoC limitation and a protection against fire of the charging area.

National Maritime Authorities generally accept onboard charging of EVs (i.e. (Sweden, 2018), (Australia, 2023), (UK, 2023), (France, 2025)) upon design requirements on charging stations (i.e. (Sweden, 2018), (Australia, 2023), (UK, 2023), (France, 2025)), location of the charging area (i.e. (Sweden, 2018), (UK, 2023), (France, 2025)), ventilation (i.e. (UK, 2023), (France, 2025)) as well as vehicle status (SoC, battery temperature, make & model) (i.e. (UK, 2023), (France, 2025)). More specifically, (France, 2025) is requesting a risk analysis and recommends a confirmation that the equipment is certified and operation is covered by insurances. Interestingly, (France, 2025) also requests that the charging onboard should be done from a decarbonized source for ro-ro passenger ships (RO-PAX) and with dedicated Closed-Circuit Television (CCTV) monitoring and fixed fire-extinguishing system. An exception is (Greece, 2024) which does not encourage the charging of EV on board.

From the industry's side, it is generally accepted that EVs should not be charged on board vehicle carriers (PCTC/PCC) (i.e. (IUMI, 2023) and (UECC, 2023)). It is acknowledge in the industry that charging can be permitted on board ro-ro passenger ships (RO-PAX) with a risk assessment and implementation of risk control measures (IUMI, 2023) or with suitable charging stations, suitable power available, IP 55 or IP 56 protection level and an ATEX zone definitions (ALBERO, 2021).

In conclusion, for vehicle carriers (PCTC/PCC), the current status is a ban on charging stations, whereas for ro-ro passenger ships (RO-PAX), a risk assessment, suitable equipment and proper monitoring can allow EV-charging onboard.

### 3.2.2.7 Ventilation

In general, (ROK, 2024a), (ClassNK, 2023), (Australia, 2023), (France, 2025), (Shanghai MSA, 2023), (MTF, 2025) and (ALBERO, 2021) request that the ventilation prevents the accumulation of flammable gases in enclosed spaces or disperse smoke.

More specifically, (i.e. (BV, 2023), (CCS, 2022) and (DNV, 2024a) have more detailed requirements: 10 air change per hour (BV, 2023) provided by fans operable from outside the EV stowage space with dampers operable from outside as well (i.e. (BV, 2023), (CCS, 2022), (DNV, 2024a)). (CCS, 2022) also preconizes exhaust fans of a non-sparking type and wire mesh guards for air inlets and outlets.

### 3.2.2.8 Smoke extraction

Smoke extraction systems could be grouped with the ventilation (i.e. (CCS, 2022) (MTF, 2025)) but is seen more efficient with dedicated ducts (BV, 2025c) and dedicated fans at 6 air changes per hour with automatic shutdown when temperature reaches 280-300°C in the duct (i.e. (BV, 2025c), (CCS, 2022)). Additional automatic startup of the fans at 40% LEL of H<sub>2</sub> and 50ppm for CO is requested by (BV, 2025c).

## 3.2.3 Detection

In this section, we aggregate the requirements or guidelines related to safety items which may detect the onset of a thermal runaway or smoke/heat coming from an AFV fire.

### 3.2.3.1 Fixed fire detection and fire alarm

Appropriate detectors are requested in the reference documents (ROK, 2024a) and (EMSA, 2025).

Regulatory documents (from classification societies and Maritime Authorities) generally request combined smoke and heat or flame detectors (i.e. (BV, 2025a), (BV, 2023), (CCS, 2022), (DNV, 2024a), (DNV, 2024b), (KR, 2021), (Australia, 2023), (France, 2025)). (BV, 2025b) and (France, 2025) request for vehicle carriers (PCTC/PCC) that the detection system allows individual identification of detectors and call points, similar to (CCS, 2022) but for ro-ro passenger ships (RO-PAX).

From the industry, documents refer to innovative fire detection (CINS, 2023), shortening the time between fire detection and confirmation as much as possible (IUMI, 2023). For instance, with detection through the EV Battery Management System (BMS) (with car lights flashing or horn ringing) (MTF, 2025).

### 3.2.3.2 Video monitoring

80% of the studied documents require or suggest the use of video monitoring as a detection means. (ABS, 2022), (BV, 2025a), (BV, 2023), (DNV, 2024b) and (KR, 2021) precise that the display is to be located on the navigation bridge or in the fire control stations. The video monitoring system requirements vary and can be in colour (i.e. (DNV, 2024b), (KR, 2021)) or with infrared capability (i.e. (CCS, 2022), (Australia, 2023), (UK, 2023), (CINS, 2023)) or with AI-based flame recognition software (i.e. (BV, 2025b), (IUMI, 2023) and (MTF, 2025)).

### 3.2.3.3 Fire patrol

Fire patrolling in AFVs storage area is mentioned in 75% of the documents, enhanced with dedicated portable detection devices. Classification societies and Maritime Authorities request thermal imaging cameras (i.e. (ABS, 2022), (BV, 2025a), (BV, 2023), (CCS, 2022), (KR, 2021), (Australia, 2023), (UK, 2023), (France, 2025)) or portable gas (H<sub>2</sub> or CO) detectors (i.e. (BV, 2025b), (CCS, 2022), (EMSA, 2025)).

From the industry, in addition to portable thermal imaging cameras (i.e. (Shanghai MSA, 2023), (IUMI, 2023), (MTF, 2025)), dedicated protective equipment and self-breathing apparatus are suggested (Shanghai MSA, 2023) for the fire patrols.

### 3.2.3.4 Gas detection

Fixed flammable gas detection is requested by the reference document (ROK, 2024a) as well as some classification societies (i.e. (BV, 2025b), (ClassNK, 2023)), some Maritime Authorities (i.e. (Australia, 2023), (UK, 2023), (Greece, 2024)) and mostly by the industry (i.e. (Shanghai MSA, 2023), (IUMI, 2023), (Steamship Mutual, 2023), (MTF, 2025), (ALBERO, 2021)). Portable gas detectors are considered by (i.e. (Australia, 2023) and (EMSA, 2025)).

### 3.2.3.5 Thermal runaway detection

Analysis of the documents show that thermal runaway detection may be done via fixed heat detection system (3.2.3.1) or via portable thermal imaging cameras (3.2.3.3). However, (Shanghai MSA, 2023) also states that a spray of water can be used to detect thermal runaway via water evaporation.

## 3.2.4 Fire-fighting

In this section, we aggregate the requirements or guidelines related to fire-fighting AFVs fires.

### 3.2.4.1 Fixed fire-extinguishing systems

The studied regulatory documents have separate requirements per ship types and per protected area: weather deck or enclosed spaces.

#### A) Ro-ro passenger ships (RO-PAX):

##### a. Enclosed spaces:

In enclosed spaces, (ROK, 2024a), (EMSA, 2025), (Australia, 2023), (UK, 2023) and (Cyprus, 2024) request for a fixed water-based fire-extinguishing system or a drencher system corroborated by classification societies (i.e. (ABS, 2022) and (BV, 2023)).

##### b. Weather deck:

On the weather deck, (BV, 2023) requests fixed water monitors for charging stations on weather deck whereas (CCS, 2022), (KR, 2021), (UK, 2023) and (France, 2025) request water monitors covering the AFVs storage area.

#### B) Vehicle carriers (PCTC/PCC):

For vehicle carriers (PCTC/PCC), usually fitted with a fixed gas fire-extinguishing system, (BV, 2025b), (BV, 2025c) and (ClassNK, 2023) request nonetheless the installation of a fixed water-based fire-extinguishing system, whereas (DNV, 2024a) and (KR, 2021) only request a connection between the fire main line to the gas fire-extinguishing system piping as a redundancy.

To increase the effectiveness of the fixed gas fire-extinguishing system, (CCS, 2022) requests that AFVs stowage spaces are to be capable of being sealed from the outside and with an increase of the required extinguishing agent to allow two releases. In addition, (CCS, 2022) requests an international shore connection piece on the gas fire-extinguishing system and (BV, 2025a) requests an increase in the fire main capacity.

Interestingly, (BV, 2025c) and (DNV, 2024b) request a connection of the fixed water-based fire-extinguishing system to a freshwater tank. This connection allows the regular testing of the fixed water-based system without the risk of salt-induced corrosion in the pipes.

Industry sources generally promote water-based systems (i.e. (Shanghai MSA, 2023), (CINS, 2023)) or for boundary cooling (MTF, 2025). (IUMI, 2023) provides operational guidelines for each type of installed fire-fighting system, suggesting doubling the CO<sub>2</sub> capacity for gas-type fire-extinguishing systems and in any case releasing the fixed fire-extinguishing system before manual fire-fighting.

### 3.2.4.2 Manual fire-fighting equipment (incl. personnel protection)

Requirements and guidelines focus on two points related to manual fire-fighting equipment: portable fire-fighting equipment and personnel protective equipment.

#### a) Portable fire-fighting equipment:

(BV, 2025a), (CCS, 2022), (DNV, 2024a), (DNV, 2024b), (Greece, 2024) and (UK, 2023) request the installation of additional standard foam or powder fire extinguishers at each entrance of the EV storage areas onboard.

In order to enhance the ship's capability of fire-fighting, including boundary cooling in areas with low accessibility,, some innovative equipment is introduced, connected to the fire main, such as upward water spray lance, from a fixed or portable system (i.e. (ROK, 2024a), (BV, 2025c), (ClassNK, 2023), (UK, 2023), (MTF, 2025)) or portable water curtain nozzles (i.e. (BV, 2025a), (ALBERO, 2021)) or water mist lance (i.e. (KR, 2021), (MTF, 2025)).

In addition, (i.e. (ROK, 2024a), (BV, 2025b), (ClassNK, 2023), (KR, 2021), (Greece, 2024), (UK, 2023), (Shanghai MSA, 2023), (MTF, 2025) and (ALBERO, 2021)) suggest the provision of one (or several) fire blanket(s) and (i.e. (Shanghai MSA, 2023) and (MTF, 2025)) defines the use of the fire blanket to cover the surrounding cargo to avoid spread of fire. (BV, 2025b) cites the standard EN1869:2019 for fire blankets.

For the special case of EVs charging station, (BV, 2023) requests water fog applicators and the provision of a fire blanket close to the charging stations.

#### b) Personnel protective equipment:

Appropriate fire-fighting protective gear is requested (ROK, 2024a) such as additional sets of fire-fighter outfits (i.e. (ABS, 2022), (BV, 2025a), (CCS, 2022), (KR, 2021), (Australia, 2023), (Greece, 2024), (France, 2025), (MTF, 2025)), breathing apparatus (i.e. (DNV, 2024a) and (MTF, 2025)) and portable Ultra High Frequency (UHF) radios, which are MED approved (DNV, 2024a). Fire-fighter outfit type is defined as EN469:2020 level 2 (i.e. (BV, 2025a), (UK, 2023), (EMSA, 2025)). In addition (BV, 2025b), (UK, 2023) and (EMSA, 2025) request a decontamination area for fire-fighter outfits as toxic gases are emitted by the batteries during thermal runaway. Finally, a defibrillator is requested by (Australia, 2023).

### 3.2.4.3 Operations, procedures

As operations and procedures are very dependent on the shipowner, type of ship and standard practices, the focus points of the documents encompass a wide range of topics. An example of generic emergency operational guidance is provided in Annex I of EMSA Guidance on AFVs (mostly applicable to ro-ro passenger and cargo ships (RO-PAX and RO-RO)).

(ROK, 2024a) and (Shanghai MSA, 2023) focus on the development of Electric Vehicle Fire Prevention and Response Plans. In contrast, (BV, 2025a), (CCS, 2022), (France, 2025) and (MTF, 2025) primarily emphasize on the drainage arrangements to prevent the build-up of free surfaces. Additionally, (France, 2025) suggests continuous cooling to avoid re-ignition and the segregation of EV with leaking electrolyte.

It is also deemed necessary to develop and update policies, procedures, and checklists to cover any new fire-fighting measures (Steamship Mutual, 2023), as well as update existing procedures to cover EV charging stations during fire patrol routes (EMSA, 2025). Overall, the IMO emergency Schedules for IMDG Class 9 DG should be followed (CINS, 2023). Additionally, a recommended maximum delay of 15 minutes for activating the fixed fire-extinguishing system is suggested (ICS, 2024).

### 3.2.4.4 Training and drills

Proper training related to AFV fires and EV thermal runaway is emphasized in many documents for the crew members (i.e. (ROK, 2024a), (Australia, 2023), (Greece, 2024), (France, 2025), (EMSA, 2025), (MTF, 2025) and (ALBERO, 2021)), passengers and stevedores (France, 2025), and shore-based fire-fighters. However, such training is generally not addressed in the documents of classification societies, as operational procedures and training typically fall outside their regulation scope. These are to be included in Ship Safety Management procedures (i.e. (ROK, 2024a), (MTF, 2025)), fire-fighting procedures (France, 2025) and reinforced by onboard

drills using a scenario involving an AFV (i.e. (Australia, 2023), (EMSA, 2025), (ICS, 2025), (MTF, 2025) and (ALBERO, 2021)). In addition, several documents suggest that basic emergency response guidelines should be posted on the passenger seat of every vehicle (i.e. (UECC, 2023), (ICS, 2024), (ALBERO, 2021)).

#### 3.2.4.5 Fire-fighting at shore

During loading/unloading of vehicles, with open ramps and doors, the fixed fire-extinguishing system may not function as intended. Therefore, (ROK, 2024a) suggests the use of portable water immersion tanks for EVs and (ICS, 2025) suggests that a detailed port response plan should be developed, including drills that include fire response in ports.

### 3.2.5 Containment

In this section, we aggregate the requirements or guidelines related the containment of fire in ro-ro spaces and more generally ships carrying AFVs.

#### 3.2.5.1 Structural fire protection / Safety distance

The structural fire protection in the storage area for EVs has been addressed in the studied documents. For vehicle carriers (PCTC/PCC), an optional set of extensive and advanced requirements are proposed, (BV, 2025c) requests A-60 class division around the EV storage area, except when close to a void or a tank with non-flammable liquid, where A-0 is sufficient, similarly to (CCS, 2022) for vehicle carriers (PCTC/PCC) and ro-ro passenger ships (RO-PAX). Maritime Authorities (France, 2025) and (MTF, 2025) also request the fire division to be A-60 around the EV storage area. In addition, (MTF, 2025) suggests that fire tests on insulating material follow the Hydrocarbon (HC) curve instead of the ISO 834 curve. This deviates from the procedures outlined in the IMO Fire Test Procedures (FTP) Code, which primarily relies on the ISO curve for evaluating fire performance of materials used on board ships.

#### 3.2.5.2 Explosion protection

In order to avoid explosion of accumulated flammable gases, the EV storage area is regarded as a hazardous area zone 2 (BV, 2025a). Electrical equipment is therefore required to be suitable for use in hazardous areas (BV, 2023) or more specifically have an ATEX class IIC and T2 (BV, 2025a). More generally, electrical equipment is required to be explosion-proof (i.e. (CCS, 2022), (ClassNK, 2023), (France, 2025), (MTF, 2025)), especially in the ventilation ducts. This to avoid fire or explosion outside of the EV storage area.

Interestingly, the carried vehicles do not generally have an explosion-proof protection and therefore could be the ignition points of secondary fires.

### 3.2.6 Evacuation

(ROK, 2024a) suggests that designated passengers are to assist in guiding passenger evacuation and response for EV fires. Whereas (MTF, 2025) suggests to protect the evacuation means by additional fire insulation around the escape routes, water spray for lifeboats and liferafts stowage position, water spray curtain for escape routes and, if possible, water spray also at the installation of MES.

### 3.2.7 Testing

The AFV-specific systems installed onboard are to undergo testing during the commissioning stage. Testing requirements on these systems such as fire-fighting system, video monitoring system, gas detection system and smoke extraction system are mostly specified in the scope of classification societies (i.e. (BV, 2025a), (BV, 2025b), (BV, 2025c)).

## 3.3 Review of regulations, rules and guidelines other than maritime

This section focuses on regulations, rules and guidelines governing the safe transportation of AFVs via other transports than ships, and the safe use of AFVs on land.

### 3.3.1 Methodology

Fire safety regulations related to AFVs in use in road tunnels or in car parks may be of interest and provide useful additional knowledge to the maritime industry. For that reason, a selection of reference documents were reviewed: 17 documents addressing EVs, 8 addressing LPG, CNG vehicles and FCVs, and 5 documents not specific to AFVs (see Appendix B for the full list of reviewed documents).

Review of multimodal transportation was also conducted with a special focus on AFVs. A selection of 11 reference documents was reviewed.

The next sections provide the results of the review.

### 3.3.2 Ignition prevention or mitigation

In this section, we aggregate the requirements or guidelines related to safety items which may prevent or delay ignition of AFVs.

#### 3.3.2.1 Vehicle identification

##### All type of AFVs

The identification of the type of AFVs is essential in an emergency situation (NFPA, 2026). Label markings which could be used to identify the type of vehicles can be required by the local regulations (e.g. in Australia (SA, 2025)). There are some international initiatives to standardize the labelling (e.g. (ISO, 2018), (UECC, 2023)). Waiting for a worldwide mandatory implementation, the identification is mainly based on distinctive signs taught in emergency response guidelines, and the emergency responders shall be trained to recognize those signs.

#### 3.3.2.2 EV charging stations in car parks

Several reviewed documents require means to shut down the electrical supply of a charging unit in case of emergency. Most require manual isolation switch. The City of London adds automatic shutdown on fire alarm or activation of sprinklers and requires charging maximum up to 80% (City of London Corporation, 2019).

Some reviewed documents limit the maximum number of charging points per charging station. Charging stations shall be located near naturally ventilated areas or close to final mechanical discharge routes (for enclosed car parks), and far from the escape routes. Charging stations (including charging cables) shall be protected from vehicle impact and other mechanical damage or placed at a location preventing such hazards. The charging cable should be type-approved. Means to ease of returning the cable to its rest position is recommended by (ARUP, 2023).

#### 3.3.2.3 Ventilation

##### All type of vehicles:

For road tunnels and enclosed car parks, requirements for ventilation with the purpose of ignition prevention were not found so common. The ventilation is rather used in emergency situation for the purpose of smoke and gas control. The NFPA 88A requires a minimum of 300 l/min per m<sup>2</sup> of floor area during hours of normal operation in enclosed car parks (NFPA, 2023). This requirement addresses all type of vehicles.

##### EVs:

The guidelines by Fire Forum recommends garage box equipped with a charging station to be mechanically ventilated and provides specifications for ventilation openings (Fire Forum, 2023).

### 3.3.3 Detection

In this section, we aggregate the requirements or guidelines related to safety items which may detect the onset of a thermal runaway or smoke/heat coming from an AFV fire.

### 3.3.3.1 Fixed fire detection and fire alarm systems

#### All type of vehicles:

For enclosed car parks, fixed fire detection system is required given certain conditions on car park configuration in most of the reviewed documents, whereas for road tunnels it is a strict requirement. Fire alarm and means to raise the alarm are required for both enclosed car parks and road tunnels. For road tunnels, the NFPA 502 requires two independent means of identifying and locating the fire (NFPA, 2026). It provides performance criteria for the automatic fire detection system such as identification of the location of the fire within 15 m and detection of a tunnel fire incident of 5 MW or less within 90 second. The detection system shall be zoned to correspond to ventilation and fixed fire-fighting zones. NFPA also provides example of technologies: linear heat detection, video-based detection, flame detection, infrared heat detection, obscuration detection.

#### EVs:

For EVs parked in enclosed car parks, there is a consensus that fixed fire detection is required but not on the type of technology. The Fire Protection Association RC59 recommends suitable automatic detection (FPA, 2023). The Fire and Rescue New South Wales (Australia) recommends smoke or heat detectors (ARUP, 2023). The City of London recommends the use of multi-sensor type detectors without specifying the technology (City of London Corporation, 2019). ARUP T0194 recommends the use of thermal cameras, in complement of smoke or heat detectors, while admitting that further research is needed regarding its practicalities for EV (ARUP, 2023). An industrial company managing a fleet of EVs for its industrial sites has installed CO detectors at ventilation openings (Roosendans & Dutertre, 2023).

A review of BESS guidelines conducted by (Æbelø, Funk, Livkiss, Gallas-Hulin, & Sauca, 2025) has also concluded that there is no consensus on the technology of detectors. Most of the selected guidelines reviewed by Æbelø, *et al.* (2025) suggests use of smoke detectors, completed by CO detectors.

### 3.3.3.2 Video monitoring

#### All type of vehicles:

Enclosed car parks and road tunnels are equipped with CCTV, mainly for surveillance purpose. Good practices in Australia and New Zealand for road tunnels are to train road tunnels operators to video monitoring and to use automatic video incident detection (Ernst, Bergeson, Harelson, Williams, & Bilson, 2018).

#### EVs:

In addition to CCTV, the City of London recommends linking the security CCTV to an addressable fire alarm (City of London Corporation, 2019).

### 3.3.3.3 Fire patrol

No real requirement or recommendations for fire patrol was found in the land-based reference documents.

### 3.3.3.4 Gas detection

#### LPG, CNG vehicles and FCVs:

For LPG, CNG vehicles and FCVs, detection of flammable gases (such as activation upon lower flammability limits) is recommended for indoor spaces (NFPA, 2008). A major fuel retailer is equipping its fuel stations with acoustic detectors in order to detect high pressure leaks (Do, 2025). Acoustic detection is also used in road tunnel to detect traffic issues (e.g. road accidents) (AKUT, 2025). According to EMSA HSAFE study (Johnsrud, Skaret-Thoresen, Hammer, & Leisner, 2024), the use of acoustic detectors is uncertain and not proven in maritime environment due to the potential for ultrasonic noise interference.

### 3.3.3.5 Thermal runaway detection

No requirement or recommendations for thermal runaway detection or link between the BMS of an EV and the car park or road tunnel alarm system was found.

## 3.3.4 First response

In this section, we aggregate the requirements or guidelines related to first response.

### 3.3.4.1 First response equipment

#### EVs:

Charging stations installed in enclosed car parks shall be equipped with portable fire extinguishers of appropriate type. The recommended extinguishing medium varies from one guide to another (e.g. water, carbon dioxide or dry powder). Some guidelines also recommend the use of fire blanket, while questioning its safe deployment. In June 2025, the International Association of Fire Fighters (IAFF) issued a safety alert where they recommend fire service members not to deploy fire blanket for suppression efforts when responding to an EV fire involving the battery, until industry standards are developed to certify the use of fire blankets and demonstrate their safe deployment or upon validation that the use is effective and safe through full-scale research (IAFF, 2025).

### 3.3.4.2 Operations, procedures

#### EVs:

The City of London recommends developing clear instructions and procedure to follow on discovering electric vehicle or charging unit fire (City of London Corporation, 2019).

### 3.3.4.3 Training and certification

#### EVs:

Slovakian guidelines ATN010 stress the importance of emergency training including the use of portable fire extinguishers and power supply isolation of charging stations (EC, 2025).

## 3.3.5 Fire-fighting

In this section, we aggregate the requirements or guidelines related to fire-fighting of AFV fires.

### 3.3.5.1 Fixed fire-extinguishing systems

#### All type of vehicles:

For enclosed car park fire and road tunnels, water-based fire-fighting system is required given certain conditions on car park configuration in most of the reviewed documents. The water-based fire-fighting system shall be automatic and it is often specified that either sprinkler or water mist systems can be used. The application rate is found in same range of the ones required by the IMO Guidelines MSC.1/Circ.1430 (IMO, 2023).

#### EVs:

The City of London clearly states that the purpose of the automatic sprinkler system is to limit the fire spread and not to extinguish an EV battery fire (City of London Corporation, 2019). It also specifies a maximum space between the sprinkler heads of 2000 mm, and between the head and the highest vehicle of 500 mm. The sprinkler shall come into operation at 57°C. For lorry and truck, the guidelines refer to maritime regulations for ro-ro spaces.

### 3.3.5.2 Manual fire-fighting equipment (incl. personnel protection)

#### All type of vehicles:

For road tunnels and depending on their length, the NFPA 502 requires emergency ventilation in order to remove and control the smoke and heated gases resulting from a fire, and to assist evacuation or rescue operations (NFPA, 2026). It is recommended to tunnel operators to implement a ventilation strategy, which consists of selecting sequence of fan operation.

#### EVs:

Larger amount of water is required to control an EV fire. Therefore, recommendations on fire water supply and apparatus are provided (e.g. fire main of 1500 l/min for 60 minutes (ARUP, 2023), 2 hours of water (City of London Corporation, 2019), fire hose of 500 l/min, diam. 45 (SDIS86, 2020)).

Additional equipment may be recommended as replacement of conventional fire hose, such as ultra high pressure (UHP) fire-fighting system or battery pack water flooding device (Hessels T. , 2024), or as complement of conventional fire hose, such as portable water curtain (NFA, 2023; Hessels T. , 2024). In the first case, conventional fire hose will be used to protect the UHP or battery pack water flooding device operator. The use of thermal camera is advised in order to assist the fire-fighting operations; operational ventilation is recommended too (e.g. based on engineering calculations but anticipated to be at least 14 ACH (City of London Corporation, 2019)).

In addition to standard personal protective equipment (PPE) and self-contained breathing apparatus (SCBA), high-voltage gloves and footwear, and static dissipative equipment are specified for rescue operations.

#### LPG, CNG vehicles and FCVs:

Land-based fire and rescue services recommend the same water supply that for EV fire (SDIS86, 2020). Portable flammable gas detectors or explosimeters, as well as thermal camera for hydrogen fires, are advised in order to assist the fire-fighting operations.

### 3.3.5.3 Operations, procedures

#### All type of vehicles:

In land-based situations, vehicle fires are handled by well trained and equipped (professional, in several countries) fire-fighters with predefined fire-fighting strategies and procedures. Rescue of passengers stuck in vehicle is an important aspect of the operations and is addressed by emergency guidelines (NFPA, 2015; SDIS86, 2020).

#### EVs:

The land-based fire-fighting strategies related to EV fires evolve a lot as the research progress. When the EV fire involved the battery pack and there is no need to protect people or buildings, a defensive attack is advised. It consists of securing the area around the vehicle and preventing fire spread, letting the EV burn. On the other hand, if there is a need to rescue someone or to protect buildings, an offensive attack should be applied. It consists of two teams of fire-fighters, a first team to cool the energy storage and a second to extinguish the fire. They approach the vehicle in fire with an angle of 45° (3/4 front) wearing SCBA (Vylund, et al., 2019; SDIS86, 2020). A safety perimeter of 50 m is set. Alternatively, NIPV has developed more specific strategies (Hessels T. , 2024):

- When battery pack is involved and the vehicle is easily accessible, fire access in battery pack or submerging the EV should be privileged; or
- When battery pack is involved and the vehicle is poorly accessible, fire access in battery pack or battery flooding device should be privileged.

In a land-based context, additional post-fire-fighting operations are also recommended in order to prevent re-ignition and to handle any contamination:

- The EV involved in the accident shall not be stored less than 50 feet (ab. 15 m) from buildings or other vehicles (NFPA, 2015); or

- Create a physical barrier around the EV (NTSB, 2020); or
- The EV should be placed in a portable water container. For that purpose, it is recommended to design the infrastructure to enable access of such device. The portable water container is then used for safe transportation of the damaged EV (ARUP, 2023);
- PPE should be cleaned and decontaminated (SDIS86, 2020); and
- Fire water should be managed (ARUP, 2023).

The Swedish Civil Contingencies Agency (MSB) have published guidance that aims to advance the fire services' knowledge and understanding of lithium-ion batteries, electric vehicles and other lithium-ion battery-powered applications (MSB, 2024). The guidance is based on the current state of knowledge in the field in 2023. The guidance concerns the cause, handling and response methodology of lithium-ion batteries involved in fires. It is underlined that the proposed methods should be seen as possible methods. Development is taking place rapidly in the field and new ways of dealing with fires and accidents are being developed on a regular basis. In cases where laws, rules, regulations, the manufacturer's or the manufacturer's own organization's instructions impose higher or other requirements, these take precedence. With the help of routines, training, technical solutions and the right level of protective equipment, accidents can be prevented and the consequences reduced if an accident should nevertheless occur. The guide presents general facts about lithium-ion batteries and explains the cause and origin of thermal runaway, as well as how it spreads from battery cell to battery cell, i.e. thermal propagation. Additionally, it provides suggestions for response methodology in the event of a fire. In recent years, knowledge about hydrogen fluoride (HF) and its impact on rescue service personnel has increased, with positive consequences. Thanks to the new knowledge, the risk of battery gas toxicity is assessed to be lower than previously assessed and is considered being at the same level as other fire smoke. Thereby, the rescue services can handle burning lithium-ion batteries in the same way as other fires in terms of toxicity. The risk that is least known, and perhaps most serious at the moment, is that lithium-ion batteries in thermal runaway can produce flammable gases that can be explosive. This means that any volume where gases can accumulate must be considered as having a risk of explosion. At the time of the guidelines (2023), there is no knowledge about the relationship between the size of battery cells and the size of room volumes that is hazardous in view of explosions. It is a challenge, which the guidance explains together with rough guidelines on how rescue service personnel should consider this, before and during an operation. Another hazard area that is relevant and where a lot of investigative work is being done right now is the re-ignition of burnt or damaged electric vehicles. This guidance describes it on an overall level, as it is an important and sought-after area. Cooperation between emergency services, towing companies, garages and vehicle manufacturers is needed to ensure that vehicles known to have a risk of fire re-ignition are transported safely and efficiently and then placed wisely to reduce the risk of fire hazards. The guidance develops the knowledge of how to deal with fires in lithium-ion batteries in order for a response to take place safely.

#### LPG, CNG vehicles and FCVs:

According to the reference documents, it is nearly impossible to extinguish a high-pressure jet fire using water jets. Moreover, it may prevent the TRPD from correctly opening. Therefore, for CNG vehicles and FCVs, it is recommended to adopt a defensive attack and let the gas flow through the PRD or TPRD. When the gas flow is stopped and the fuel tank is empty, the remaining fire can be extinguished using standard techniques. For LPG vehicles and due to the risk of BLEVE, it is recommended to adopt an offensive attack, while avoiding spraying water on the PRD.

#### 3.3.5.4 Training and drills

Several guidelines emphasize the importance of training as regards as AFVs fire. Even though some initiatives already exist, the same guidelines (e.g. (EC, 2025)) conclude that enhanced and comprehensive training programs shall be developed.

#### 3.3.6 Containment

In this section, we aggregate the requirements or guidelines related the containment of fire in the space of fire origin.

### 3.3.6.1 Structural fire protection / Safety distance

#### All type of vehicles:

For enclosed car parks, fire-resistance is fundamental. The regulations require the structural walls, floors and ceilings to be at least 1 to 2 hours fire-rated (depending on the regulations and the car park configuration). The fire-rating might be allowed to be decreased if the car parks is equipped with automatic fire-fighting systems. The Swedish regulations mention the standardized cellulosic time-temperature curve (ISO-834) for structure of car parks, whereas, for road tunnels, more severe time-temperature curves are recommended (e.g. hydrocarbon or Rijkswaterstaat (Hynynen, et al., 2023)).

#### EVs:

For enclosed car parks, a segregation is generally applied to charging station: either through a safety distance to car park structural walls (e.g. 8 m (CGEDD, 2022)), a minimum space for the charging bay (e.g. space of minimum 900-1200 mm (City of London Corporation, 2019), at least 3.5 m width (EC, 2025)), or through a fire-resistant physical barrier (e.g. with 1 hour fire-rating (FPA, 2023)). A major fuel retailer limits the number of EVs to four per charging bay (in open air) (Do, 2025).

#### LPG, CNG vehicles and FCVs:

Depending on local (city) regulations, restrictions to park LPG, CNG vehicles and FCVs in underground structures can be applied (Gehandler, Karlsson, & Vylund, 2017). For refuelling stations (almost always located in open air), safety distance or fire-resistant physical barrier is recommended. A major fuel retailer applies 2-10 m for CNG vehicles and 5-9 for FCVs as safety distance depending on the target (Do, 2025).

### 3.3.6.2 Explosion protection

#### EVs:

In its review of BESS guidelines, Æbelø, et al. (2025) concludes that: “*Ventilation is suggested as the main explosion mitigation measure. However, most reviewed guidelines do not provide specific recommendations on the situation when ventilation should be installed*” (Æbelø, Funk, Livkiss, Gallas-Hulin, & Sauca, 2025).

#### LPG, CNG vehicles and FCVs:

Somes sources (Gehandler, Karlsson, & Vylund, 2017; Brauner, et al., 2022) raise the question of consequences of flammable gas cloud explosion in large volume (not mentioned in the sources but it is the case for ro-ro spaces) versus smaller volumes (e.g. garage or battery room), which were more subjected to research work, but also the action of fire-fighting medium (water spray, mist, foam) on the consequences of an explosion.

### 3.3.7 Evacuation

#### EVs:

Despite the fact that charging stations shall be located far from escape routes, it is recommended to verify that the ventilation design for enclosed car parks will not jeopardize the protection of escape routes (City of London Corporation, 2019).

### 3.3.8 Multimodal transportation

On road, the transportation of dangerous goods is regulated by different regulations such as the UN Recommendations on the transport of dangerous goods (UN, 2023) or the Agreement concerning the international carriage of dangerous goods by road (ADR treaty) (UNECE, 2025). Those texts provide a classification of dangerous goods, provisions concerning their safe transportation (labelling, packaging, etc.), as well as provisions concerning transport equipment and operations.

## EVs:

In its 2023 edition, the UN Recommendations on the transport of dangerous goods changes the provisions for the transport of battery powered vehicles, creating three new UN numbers in order to address the different battery technologies (previously, only UN 3171 *Battery-powered vehicle* exists):

- 3556 *Vehicle, lithium ion battery powered*
- 3557 *Vehicle, lithium metal battery powered*
- 3558 *Vehicle, sodium ion battery powered*

Special Provision (SP) 388 defines vehicles battery powered such as cars, motorcycles, scooters, trucks, bicycles, self-balancing vehicles, powered by batteries transported with the batteries installed. Therefore, those UN numbers do not only cover cars, trucks, motorcycles, etc. but also (smaller) e-mobility devices. ADR treaty also uses those three new numbers and provides this special provision.

The installed lithium-ion batteries are classified Category 9 *Miscellaneous dangerous substances and articles*. Among other requirements, the batteries shall be of type that has successfully passed each test of the Manual of tests and criteria, Part III, Sub-Section 38.3 (UN, 2023). That series of standardized tests does not include any fire test but includes a thermal test, T.2, which consists of extreme and rapid temperature changes (to +72°C during at least 6 hours and to -40°C during at least 6 hours).

According to UN Recommendations on the transport of dangerous goods edition 2023, “where a lithium battery installed in a vehicle in a vehicle is damaged or defective, the vehicle shall be transported as defined by the competent authority.” ADR treaty edition 2025 requires the vehicle to “be carried in accordance with the conditions defined in special condition 667 (c)”. Among other, if the damage of the defect has a significant impact on the safety of the battery, then the battery shall be removed and carried according SP376.

HEVs or PHEVs shall be assigned to UN number 3166 according to UN Recommendations on the transport of dangerous goods and ADR treaty.

In terms of transport road vehicles, ADR treaty edition 2025 now allows EVs to be approved for ADR transport in category FL (*vehicles intended for the carriage of flammable gases and liquids*) and AL (*vehicles intended for the carriage of dangerous goods other than flammable gases and liquids, and explosive substances*), providing new provisions. The objective of the new provisions is to mitigate hazards from the electric drive to the dangerous goods that are being carried. In particular, according to the new provisions 9.2.4.4 related to electric power train:

- The electric power train shall comply with UN Regulation No. 100 (UNECE, 2022);
- The EV shall give external signals, in addition to the warning signal inside the passenger compartment required by UN Regulation No. 100 in case of internal short circuit leading to a cell thermal runaway. The warning signal inside the EV shall be triggered 5 minutes before the presence of a hazardous situation in the passenger cabin;
- Measures against thermal propagation shall be taken; and
- The vehicle charging inlet shall be provided with thermal sensors which can limit or shut off the current according to ISO 17409:2020.

UN regulations No. 100 includes a fire-resistance test, required when the battery pack is mounted such that the lowest surface of the casing is less than 1.5 m above the ground. The purpose of the fire-resistance test is to verify the resistance of the battery pack against a fire due to, for example, a fuel spill. The objective is to provide sufficient time to the driver and passenger(s) to escape the EV. Depending on either the test is vehicle-based or component-based, the tested device shall be 1) exposed to 60 seconds pre-heating then 70 seconds direct heating then 60 seconds indirect heating or direct heating, by a gasoline pool fire, or 2) exposed to about 2 minutes and 30 seconds direct heating by a LPG burner fire. To be noted that the 2025 edition of the Chinese standard GB38031-2025 *Electric vehicles traction battery safety standards* provides require different fire-resistant performance. But this standard was not reviewed by the authors.

For transport by air, the IATA issued a Battery guidance document (IATA, 2025). Among other, IATA recommends that lithium-ion batteries, including batteries used for powering vehicles, have their state of charge (SoC) not exceeding 30% of their rated capacity or an indicated capacity not exceeding 25%. From 1 January 2026, this recommendation will become a mandatory requirement for vehicles powered by batteries with a Watt-hour rating exceeding 100 Wh, unless otherwise approved by the relevant authorities. The guidance states that: “it has been

demonstrated that reducing the state of charge in a lithium-ion cell or battery, reduces the potential for a lithium-ion cell to go into thermal runaway.” The indicated battery capacity is defined as “the indicated remaining usable battery capacity that the user sees via a display gauge or indicator lights.” The indicated battery capacity is seen by IATA guidance as “easier for shippers to identify and determine” than SoC. And “25% is not directly equivalent to a 30% SoC but is practical approach that delivers an equivalent safety mitigation.” The shipper does not need to include an additional document or statement to certify the SoC level. However, the shipper must make a legal statement that all the applicable air transport requirements have been meet.

Lastly, it is interesting to note that the transport by air of defective or damaged batteries (that have the potential to lead to hazardous situation) is forbidden.

#### LPG, CNG vehicles and FCVs:

LPG, CNG vehicles and FCVs shall be assigned to UN number 3166 according to UN Recommendations on the transport of dangerous goods and ADR treaty.

ADR treaty allows LPG and CNG vehicles and now FCVs with its 2025 edition to be approved for ADR transport in category FL and AL.

In particular, LPG vehicles shall comply with UN Regulation No. 67 whereas CNG vehicles shall comply with UN Regulation No. 110.

According to the new provisions 9.2.4.5 related to hydrogen fuel cell vehicles, FCVs shall comply with UN Regulation No. 134 (UNECE, 2022) and, if using liquid hydrogen, the UN Global technical regulation No. 13 (UNECE, 2023) applies.

UN regulations No. 134 includes a fire test. The purpose of the fire test is to verify the resistance of compressed hydrogen storage tank and the effectiveness of the venting through the TPRD(s). The storage tank is firstly exposed to a localized fire (600°C) for 10 minutes then to an engulfing fire (800°C) through LPG burner(s) until the pressure inside the tank decreases below 10 bar. UN Global technical regulation No. 13 includes a fire test for liquid hydrogen storage system. It consists of a fire burning underneath the tank and over the entire footprint of the tank. The fire shall reach at least 590°C. The test lasts until either the storage pressure decreases to or below the starting pressure or the PRD has opened for a second time.

## 4. Review of existing experimental testing principles and results

### 4.1 Introduction

There are several ongoing and completed initiatives to explore and evaluate fire safety on ships in the event of AFV fire onboard. This chapter provides a review of the state-of-the-art scientific and technical results of AFV experiments. As much as possible, the review covers different types of AFV. However, the main interest concerns EV fires and this is also where the most work has been conducted and disseminated. The review summarizes the tests and highlights the main conclusions relevant to the safe transportation of AFVs in ro-ro spaces. The results will serve as technical justification for the development of recommendations in the upcoming parts of the STARRS study.

### 4.2 Test standards

Transporting AFVs does not oblige any special requirements if they meet the IMDG Code and the special provision SP 961. For battery electric vehicles and its battery, a variety of safety testing standards are applied throughout the battery development and certification process to ensure reliability, performance, and fire safety. These standards help validate how batteries respond to mechanical stress, thermal events, and electrical faults. Ola Willstrand (Willstrand, 2025) introduces international safety test standards for lithium-ion batteries, below are the ones relevant for battery electric vehicles:

**UN 38.3** is a globally required standard for shipping of lithium-ion batteries, focusing on abuse testing to prevent hazardous events. However, UN 38.3 is not required when shipping battery electric vehicles on ro-ro ships, provided the conditions of Special Provision (SP) 961 under the IMDG Code are met.

**UN GTR 20 (2018)** on Electrical Vehicle Safety (EVS) has a functional requirement that the occupants in the vehicle shall not be exposed to any unsafe environment caused by thermal runaway in a single battery cell. Further, the occupants must be warned five minutes before a hazardous situation. One method to fulfil the five-minute-criterion is to conduct a thermal propagation (TP) test, which is to trigger an internal short circuit in a single cell, and relate the result to the European Council for Automotive R&D (EUCAR) hazard levels. The thermal propagation test procedure in GTR 20 is not yet universally adopted but other TP procedures are work in progress.

**ISO 6469-1**, **UNECE R100**, **SAE J2464**, and China's **GB 38031** are other vehicle-related standards with varying approaches to thermal propagation testing. Notably, starting July 2026, China will require that thermal runaway in a single cell must not result in fire within two hours, instead of the five-minute criterion.

For gas fuelled vehicles the following international safety test standards are relevant:

**UN ECE GTR 13**, Amendment 1, and **UN ECE R134**, Revision 1, Amendment 3, which is a transposed version of GTR 13 contain requirements for hydrogen vehicles. Requirements for CNG vehicles are found in **UN ECE R110**, and for LPG vehicles in **UN ECE R115** (retrofit systems) and **UN ECE R67** (OEM systems).

Gambone (2007) offers an overview for how safety of compressed gas tanks in road vehicles (initially CNG, methane) have evolved (Molkov, 2023). A solution advocated by Molkov (2023) to deal with fire exposed tanks is to use "explosion free in fire self-venting (TPRD-less) composite tanks" (Molkov, Kashkarov, Makarov, Fletcher, & Rattigan, 2023; Molkov, Kashkarov, & Makarov, 2024), also called micro-leak-not-burst (mLNB), tanks. Both LPG and LH<sub>2</sub> vehicles are equipped with a pressure relief valve (PRV) designed to release any overpressure. CNG and compressed hydrogen vehicles are protected by thermally activated pressure relief devices (TPRDs). Initially, compressed gas vehicles, especially those using CNG, lacked effective pressure relief systems, which led to several safety incidents. Over time, TPRDs were introduced to prevent catastrophic tank ruptures during fire exposure. These devices are designed to activate at a specific temperature, releasing the gas to reduce internal pressure and avoid structural failure of the tank. Early TPRDs were not always reliable, particularly in localized fire scenarios where the fire might not reach the TPRD, allowing the tank to weaken and potentially rupture. This led to the development of more robust testing standards and performance-based regulations, such as UN ECE GTR13 and R134, which now require that the entire compressed hydrogen storage system be tested under both localized and engulfing fire conditions.

Recent innovations have explored alternatives to traditional TPRDs, such as the micro-leak-not-burst (mLNB) concept. This approach allows hydrogen to escape through microscopic leaks in the tank material during fire exposure, avoiding the need for a dedicated TPRD and significantly reducing the risk of explosion or long jet flames. While promising, mLNB systems are not yet widely accepted in regulations.

## 4.3 Test results on characteristics of AFVs fires / explosions

### 4.3.1 Introduction

Toxic gases are released in all types of fires, but certain materials and products pose a greater concern due to their potential for hazardous emissions.

In a passenger vehicle, the materials include plastics found in, for example, seats, interior panels, fuel tanks, electrical cables, and rubber components such as tires. These are supplemented by flammable liquids like engine oil, transmission fluid, petrol or diesel and for AFVs a battery pack or a gas tank. Over the decades, the composition of vehicles has evolved significantly. When fire safety standards for vehicles were first introduced in the 1950s, plastics were scarcely used, and vehicles were predominantly made of metal (Emilsson, Dahllöf, & Ljunggren Söderman, 2019). Plastics can produce a wide range of toxic combustion byproducts. These include, for example, carbon monoxide (CO), organic irritants, and carcinogenic organic compounds. Additionally, some plastics may release corrosive and harmful gases such as hydrogen chloride (HCl) and hydrogen fluoride (HF) during combustion.

Battery thermal runaway in EVs also produces a wide range of gases, including carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), hydrogen (H<sub>2</sub>), volatile organic compounds (VOCs), and hydrocarbons (HCs). Some events occur almost instantaneously, while others begin with a slow release of the previously mentioned gases minutes before the cell enters thermal runaway. The explosion hazards associated with lithium-ion batteries is still under investigation, especially in large compartments such as ro-ro spaces onboard.

This section summarizes findings from various projects and scientific articles focused on fire characteristics in AFVs, with particular attention to gas emissions, substances found in extinguishing water, and explosion hazards with EVs.

### 4.3.2 The E-TOX project (2020)

Willstrand, *et al.* (2020) conducted the E-TOX project with partners from insurance industry, Swedish rescue services and the Swedish Civil Contingencies Agency as well as the local scrap yard. The aim was to provide a basis for risk assessment in case of fires in EVs. The project reviewed literature and conducted large-scale vehicle fire tests (see section 4.5.5), battery fire tests and numerical simulations. The literature review summarizes previous studies on e.g. gas composition by different battery chemistries and different SoCs. E-TOX found that the test results from both vehicle and battery fire experiments align well with previously published data in the literature, confirming consistency in terms of heat release and gas emissions. The reader is referred to the RISE Report 2020:90 for the full reading, tables and graphs (Willstrand, Bisschop, Blomqvist, Temple, & Anderson, 2020).

EVs with lithium-ion batteries release toxic gases during fire primarily from combustion of the electrolyte. At the time of E-TOX, the electrolyte of lithium-ion batteries contained lithium hexafluorophosphate (LiPF<sub>6</sub>) and can also include other fluorine containing compounds. Decomposition of the conductive salt will result in production of HF. The project also introduces the topic of metal residues and suggests that the specific metal compounds formed during fires in EVs could be further investigated.

The E-TOX study concluded that there are several acute toxic gases present from a vehicle fire, regardless of the type of vehicle burning (BEV or ICEV), e.g. CO, HF, HCl and SO<sub>2</sub>. The result was based on total amounts of different substances compared to health exposure limit values such as immediately dangerous to life or health (IDLH) values and acute exposure guideline levels (AEG-2). E-TOX also highlights that soot particles in fires are a concern due to their long-term health effects, small particles can end up in pulmonary (lung) system and be deposited in the bronchi.

In 2023, a follow up project of E-TOX, also called E-TOX 2, resulted in a scientific article by Hynynen, *et al.* on toxic gases and a technical RISE Report 2023:22 on extinguishing water (see section 4.3.4). Additional to the E-TOX

vehicle fire tests, three new vehicle fire tests were performed and analysed at RISE facilities. The authors (Hynynen, Willstrand, Blomqvist, & Andersson, 2023) conclude that HF, along with certain battery metals such as nickel, cobalt, lithium, and manganese (depending on the cell chemistry) represents the most significant difference in combustion gas composition between EVs and ICEVs. They also emphasize that accurate quantification of HF requires further investigation into the origin of fluoride ions in the sampling process. Given the variability in vehicle types, battery chemistries, and fire scenarios, the composition and concentration of gaseous emissions are subject to considerable variation.

#### 4.3.3 Fire exposed CNG and H<sub>2</sub> tanks reported in BREND 2.0 project (2021)

Fire exposed gas tanks from gas fuelled vehicles were studied in the BREND 2.0 project. Jet flame can be a consequence in case of fire exposure to a gas tank of a gas fuelled vehicle and “controlled” release of gas from the pressure relief device. The gas tank can also explode if the pressure relief device does not release.

Jet flames occurred in the fire test reported in the BREND 2.0 project (Gehandler & Lönnermark, 2024). The test involved fire exposure of three types of compressed gas containers used in passenger cars: two steel CNG tanks, three composite CNG tanks, and two composite hydrogen tanks. Each tank was equipped with a valve and a thermally activated pressure relief device (TPRD) at one end.

The longest jet flame was 10 m horizontally, and smaller jet flames were observed in different directions after the TPRD was released. The project stated that jet flames from compressed gas tanks last for about one minute and the power is declining as the pressure inside the gas tank decreases. If feasible and safe to do so, the recommendation from the project is that a jet flame should burn out (Gehandler, et al., 2022).

#### 4.3.4 Investigation of extinguishing water and combustion gases from vehicle fires (2023)

As a follow up on E-TOX project, a study (also called E-TOX 2) investigating extinguishing water (‘run-off water’) from three vehicle fires and one battery pack fire were conducted and reported in RISE Report 2023:22 (Hynynen, Willstrand, Blomqvist, & Quant, 2023).

The aim was to address the potential environmental impact of electric vehicle fires analysing the run-off water for both organic and inorganic compounds. An ecotoxicity assessment, including analysis of PFAS, was also performed. The tested vehicles included on reference test of a BEV where the battery pack had been removed, one BEV and one ICEV of the same model. A water spray system that homogenously discharged water was used to be able to analyse the run-off water.

The results showed higher concentrations of lithium and fluoride in the run-off water from the BEV and the battery pack than from the ICEV. In the ICEV test, lead was detected at significantly higher concentrations than in the BEV test, both in the combustion gases and in the run-off water. Additionally, polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) were found in greater amounts in the ICEV compared to the BEV. PFAS was found in both tests, and flushing the inside of the battery pack led to an increased concentration of PFAS found. The authors highlighted that more studies are needed to understand the origin of the PFAS.

#### 4.3.5 Jilin University, Fire boundaries of lithium-ion cell eruption gases caused by thermal runaway (2021)

The authors of the paper *Fire boundaries of lithium-ion cell eruption gases caused by thermal runaway* (Li, et al., 2021) studied eruption gases from 29 thermal runaway tests in inert atmosphere. The analysis aimed to study fire boundaries of four types of battery cells with varying SoC. The boundaries are, according to the article, corresponding to ignition concentration of O<sub>2</sub> in the gas-air mixture, ignition of eruption gas-mixture concentration (meaning the lower flammability limit) and the thermal ignition point. The results of this paper can provide guidance for the battery cell selection, battery pack design, and safety battery design.

The work summarizes other work published in 2014-2020. Li, et al. explain that during thermal runaway in lithium-ion cells, gases build up inside the cell (Li, et al., 2021). When the internal pressure reaches a critical level, the safety valve opens or the pouch cell casing cracks at its weakest point. This leads to a sudden release of gases, referred to by the authors as cell eruption gases. The summarized work identifies the following components in the cell eruption gases in inert atmosphere: hydrogen (H<sub>2</sub>), oxygen (O<sub>2</sub>), nitrogen (N<sub>2</sub>), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), ethyne (C<sub>2</sub>H<sub>2</sub>), ethylene (C<sub>2</sub>H<sub>4</sub>), ethane (C<sub>2</sub>H<sub>6</sub>), and other hydrocarbons, diethyl

carbonate (DEC), methyl ethyl carbonate (EMC), dimethyl carbonate (DMC), hydrogen chloride (HCl), ethylene carbonate (EC) and hydrogen fluoride (HF).

#### 4.3.6 SH2IFT-2 project – gaseous hydrogen jet fire experiments (2025)

The SH2IFT-2 project has the main objective to develop new knowledge on critical aspects of hydrogen safety. The project conducted gaseous hydrogen (GH<sub>2</sub>) jet fire experiments to evaluate the resistance of passive fire protection against the direct impingement of a jet fire. RISE Fire Research in Norway conducted the jet fire experiments using a high-pressure GH<sub>2</sub> jet fire test setup using a steel tank (500 L) containing 23 kg hydrogen at 896 bar. Two scenarios were part of the experiments: (A) a release at a constant pressure of 250 bar through a 1-mm nozzle, positioned 0.5 m from the target. The pressure was allowed to drop at the end of the experiment. (B) a blowdown release from a tank initially at 895 bar, with a leak pressure of 855 bar. This release used a 2-mm nozzle placed 1 m from the target.

The following was measured: The release pressure and gas flow rate, total and radiative heat fluxes, surface and gas temperatures, and flame size. Result showed that the 250-bar GH<sub>2</sub> jet fires generated mostly invisible flames. The flames were 1.3 m vertically and up to 1.5 m horizontally. The highest temperature recorded was 1367°C. The 855-bar jet fires generated visible flames initially but also invisible flames that reached 8 m horizontally and 5 m vertically. The highest recorded temperature was again 1367°C, which is the highest measurable temperature using K-type thermocouples. It was therefore suggested that both scenarios reached higher temperatures than what was measured. More results, discussion and conclusions are found in the report (Zeinali & Westbye Jacobsen, 2025).

Regarding the passive fire protection that was tested in the 250-bar scenario; one of them showed failure (a critical temperature rise of 405°C) between 14.5 min and 20 min and the other one between 4 min to 9.5 min. Jet flames and their consequences for steel structure was not investigated in this study.

#### 4.3.7 The BESAFE project (2025)

The BESAFE project was a collaboration between DBI - The Danish Institute of Fire and Security Technology, RESC Rednings- & Sikkerhedscenter, HBR Hovedstadens Beredskab, Stena Recycling A/S, SEM-SAFE Fire Safety A/S (formerly known as Danfoss Fire Safety), and Lund University (Drustrup, Funk, Hansen-Bruhn, Livkiss, & Sauca, 2025).

This study was designed to better understand the behaviour of lithium-ion battery fires, by investigating gas emissions, battery surface temperatures, mass loss and burning behaviour. The project also studied the explosive atmosphere and the effect of water mist on explosions. Test specimens were prismatic NMC battery cells and three modules, 2.07 kWh/module, 12 cells/module. The test compartment was a tailored 12 m<sup>3</sup> mobile battery testing facility.

Cell level tests were conducted for evaluation of gas emissions during failure event without ignition. Module level tests were conducted to evaluate gas emissions from thermal runaway and explosions were intentionally triggered. In two of the module tests, water was discharged to observe the effect of water on the triggered explosions. More details are reported in [BESAFE-short paper.pdf](#). Figure 5 shows the test set up.

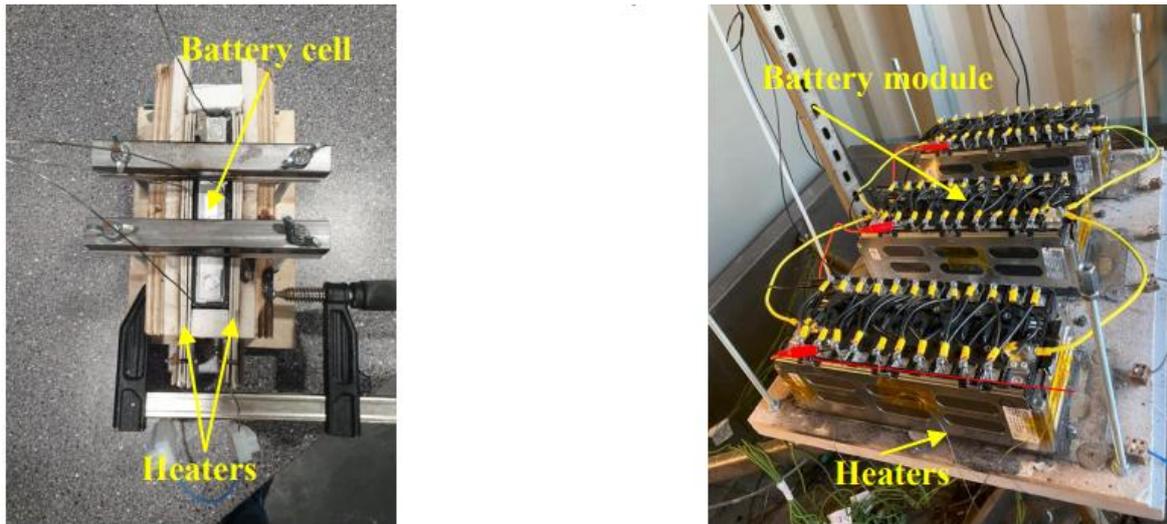


Figure 5. Instrumented cell (left) and module (right) during the BESAFE tests (Drustrup, Funk, Hansen-Bruhn, Livkiss, & Sauca, 2025).

Two distinct venting events were observed during heat-induced failure, the first was triggered by gas pressure breaking the safety valve, accompanied by sound, material ejection, and release of gases, e.g. CO, CH<sub>4</sub>, and C<sub>2</sub>H<sub>4</sub>. The second venting occurred during full cell failure, marked by voltage drop and rapid temperature rise.

Explosions occurred in three out of four module-level tests, strong enough to open pressure relief hatches in the test compartment. Water mist that was applied in two tests at different flow rates (36 and 51 l/min). Its effectiveness in reducing explosion hazards remains inconclusive and requires further study.

#### 4.3.8 The COMBAT project (2025)

Quant, *et al.* (2025) recently published a report from the pre-study “Compartment Explosions Induced by Batteries” (COMBAT) including a theoretical investigation of the explosion hazards associated with accumulated gases from lithium-ion batteries in compartments (Quant, *et al.*, 2025). The focus was on manganese-cobalt-oxide (NMC) and lithium-iron-phosphate (LFP) batteries, which dominate today’s market. The system design, SoC, cell format, cell aging and cell chemistry are battery parameters that affect the composition, volume and production rate of the vent gases. Thus, these parameters will influence the explosion risk. In addition, the test method or the thermal runaway trigger method also have an impact on the outcome (Willstrand, Pushp, Andersson, & Brandell, 2023). A summary of battery parameters that affect the explosion hazards are presented in Table 7 and more details are available in the COMBAT project report (Quant, *et al.*, 2025).

Table 7. Summary of battery parameters that affect the battery vent gas and thereby the explosion risk

Affected	Cell chemistry	Cell Format/capacity*	State of charge	Thermal runaway Trigger method**	Cell aging***
Total gas production (l/kWh)	Yes	Yes	Yes	No	Yes
Gas production rate (l/s)	Yes	Yes	Yes	Yes	-
Gas composition	Yes	-	Yes	No	-

\*) Cell format and cell size are partially connected.

\*\*) Overcharge conditions can increase the total gas production.

\*\*\*) Different ageing mechanisms have different impacts on safety.

-) Additional studies are needed to draw conclusions.

Regarding the cell chemistry, LFP cells are often considered safer than NMC cells due to the generally higher thermal stability. However, the battery vent gases from LFP cells generally contain more hydrogen and hydrocarbons than NMC vent gases, resulting in a lower lowest flammability limit (LFL) that in turn can increase the explosions risks (Bugryniec, et al., 2024). However, this is only valid if the gases are not ignited immediately or during the release. Some studies claim that an increased LFL might pose a larger hazard since more gas may be accumulated before ignition (Baird, Archibald, Marr, & Ezekoye, 2020). Since many other parameters will influence the battery vent gases, it is complicated to analyze explosion hazards based on cell chemistries. Also, with the rapid development of new battery technologies like sodium-ion and solid-state batteries, it is essential to stay updated on safety aspects regarding other technologies than lithium-ion batteries.

Explosion mitigation strategies through mechanical ventilation aims to maintain flammable gas concentrations below the lower flammability limit (LFL). For explosions related to accumulation of battery vent gases, the effectiveness will vary for different thermal runaway scenarios. It is improbable that a ventilation system would be capable of managing a worst-case scenario in which all cells within a system undergo thermal runaway simultaneously. In a DNV study, the required ventilations rates for batteries in different sizes of confined spaces were analyzed. For a battery system of 4000 Ah, the average total gas production will be around 8000 L (8 m<sup>3</sup>) which would require a ventilation system that can handle over 100 air changes per hour (Gully, Helgesen, Skogtvedt, & Kostopoulos, 2019). To put these numbers in the context of EVs, a battery pack of 80 kWh can produce 48 000 L (48 m<sup>3</sup>) of gas if all cells enter thermal runaway without ignition.

Deflagration panels, designed according to NFPA standards, can help prevent structural failure and minimize injury by venting overpressure during explosions. However, generally large areas are required to handle worst case scenarios (Peng, et al., 2023). Deflagration panels and mechanical ventilation serve different purposes and are advantageous for different types of thermal runaway events.

The risk of explosion can be influenced by the type of fire suppression system in use. In the COMBAT study (Quant, et al., 2025), various fire suppression systems were evaluated regarding their effectiveness in preventing explosions. Inert gas fire suppression agents can, to varying degrees depending on the specific agent, reduce the intensity of explosions and temporarily lower the risk of ignition. However, both inert gas and aerosol-based systems lack long-term cooling capabilities, which may increase the likelihood of re-ignition or delayed ignition of accumulated gases.

Water mist systems generally offer better long-term cooling and, when properly designed, they can mitigate the severity of gas explosions (Cao, Zhou, Wang, Fan, & Wang, 2022; Li, Bi, Zhou, & Gao, 2022). Nevertheless, several studies suggest that poorly designed water mist systems may intensify explosions involving hydrogen and methane. Whether this effect also applies to battery vent gases remains uncertain, as there is currently a lack of research addressing this specific issue (Quant, et al., 2025).

## 4.4 Early detection of fire root causes: Fire and gas detection

### 4.4.1 Introduction

This section presents results from experiments investigating fire and gas detection in AFV fires, with a focus on early identification of root causes such as thermal runaway in batteries. The relevance of this topic is underscored by ongoing discussions within the IMO SSE, including interest in video-based fire detection, battery management system (BMS) monitoring, and temperature-based detection methods. These developments, highlighted in submissions to SSE, reflect a growing cross-industry focus on improving early detection capabilities for thermal events in alternative fuel systems.

### 4.4.2 Fire detection tests described in SSE 7/INF.11 (2020)

Two comparative fire tests were designed to verify the response of a smoke and a heat spot-type detector installed at the same position or at different positions.

In the first fire detection test, the battery cells vented for more than one minute, which caused the whole battery pack to explode. In this test, the smoke detector detected the fire prior the heat detector. In the second test, the battery cells vented, and the battery pack exploded almost simultaneously. Therefore, the smoke detector and heat detector responded simultaneously.

A lithium-ion battery vehicle mock-up was used in the tests that are described in section 4.10.2.

#### 4.4.3 Fire detection tests in the ELBAS project (2022)

The fire detection tests conducted in the ELBAS project are described in section 4.6.3. The tests included optical smoke and hydrogen fluoride (HF) detectors of two types: Aspiration type gas detectors positioned at the ceiling, directly above the battery electric vehicle, and HF spot-type detectors, placed behind the battery electric vehicle at ground level.

#### 4.4.4 Evaluation of Detection Principles and Challenges in Early Detection of Thermal Runaway in Batteries in LASH FIRE project (2023)

The LASH FIRE project conducted 14 detection tests by using two types of smoke and heat detectors (spot-type detectors), a carbon monoxide detector (spot-type detector), a lower explosion limit detector (spot-type detector), thermal imaging, video analytics and light detection and ranging (LIDAR). The aim was to evaluate different techniques of detection and their capability to detect the early stage of a thermal runaway in a battery cell. The supplier and model of each detector/technique is specified in the report together with the results are documented in the LASH FIRE report IR09.15 - report *Evaluation of Detection Principles and Challenges in Early Detection of Thermal Runaway in Batteries* (Dahlbom , Sanfridson, & Sjöblom , 2023).

The detectors were tested in various positions relative to the battery cell and comparative tests using wood sticks were conducted to assess their ability to detect more conventional fire sources. One part of the test was set up inside a 20-ft container without ventilation (Figure 6), and one was in the large fire test hall with approximately 14 air changes per hours. In some of the test the battery cell was shielded, to make the conditions more challenging for the detectors. Ten of the tests were performed with 53 Ah battery cell, with around 50 % SoC and the rest with the wood sticks.

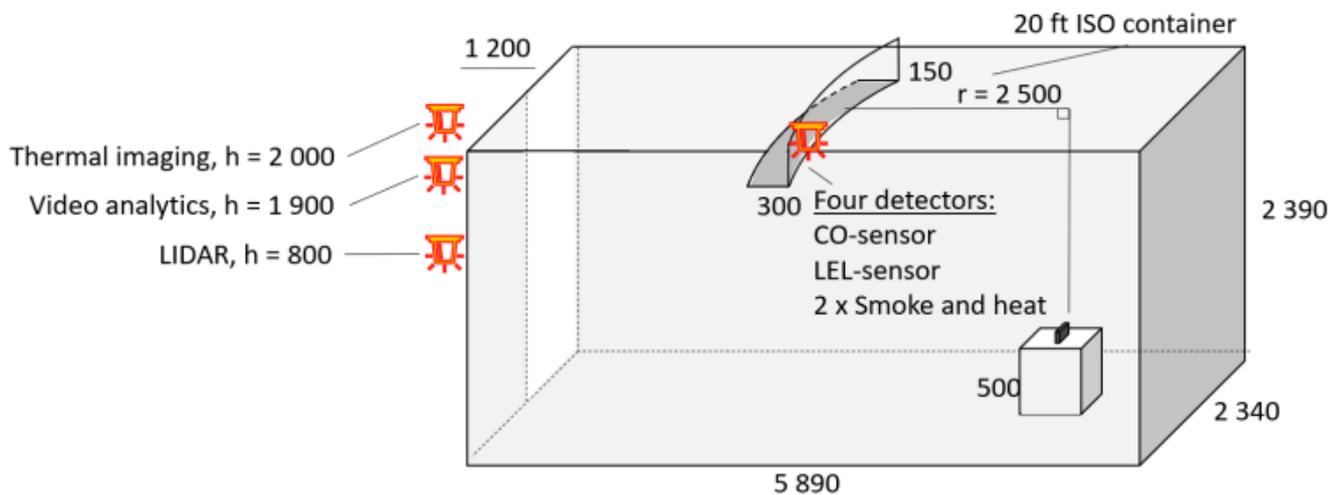


Figure 6. Test set up in the free-standing battery cell inside a 20-ft ISO container, illustration of the different detectors' locations (Dahlbom , Sanfridson, & Sjöblom , 2023).

The results presented are hence based on tests conducted at the cell level, serving as an initial observation of fire-related events and a screening of detection technologies. It is important to note that early signs such as the first venting may not be observable from outside a battery or battery pack. In the performed tests, a small amount of smoke was typically visible 2–4 min before the first venting occurred, which in turn preceded thermal runaway by approximately 10–15 min.

The results suggest that detection is relatively possible in small, confined spaces, but poses greater challenges in large, open environments. When the gas is sufficiently cooled, it tends to sink and spread along the floor or deck rather than rising toward the ceiling or deckhead. This behaviour presents a challenge for conventional smoke detectors, which are typically installed at the ceiling and may not effectively detect such low-lying emissions.

#### 4.4.5 Early warning of thermal runaway for larger-format lithium iron-phosphate battery by coupling internal pressure and temperature (2025)

Cheng, *et al.* state that “*Understanding the gas production mechanism during thermal runaway is crucial for safety protection and early warning*” (Cheng, *et al.*, 2025).

The study by Cheng, *et al.* (2025) examine how changes in internal pressure and temperature within a battery cell can help reveal how thermal runaway starts and develops. A main conclusion was that “*internal pressure is a significant characteristic of TR*” and the results include an early warning scheme based on the internal pressure and temperature. The battery included in the testing was 52 Ah LFP batteries.

#### 4.4.6 The EDOT project (2024-2026)

Early detection of thermal runaway is currently being investigated in the ongoing project *Early Detection of Thermal Runaway (EDOT)*. EDOT is a partnership between Underwriters Laboratories (UL) and RISE Research Institutes of Sweden. The project has the aim to identify battery parameters influencing gas composition during different thermal runaway scenarios and to determine the most effective detection methods.

A literature study and experiments are underway in EDOT, and results are planned to be published during 2026. Factors such as initiation methods, cell chemistry, and state of charge impact the gas composition and production rates, making it essential to evaluate detection strategies across various conditions. The EDOT project also aim to assess methods for real-time monitoring of flammable gas concentrations during a thermal runaway event, offering critical information to responders who might otherwise face the risk of failing to detect an explosive atmosphere caused by battery vent gases.

The project includes tests at three different scales:

1. Evaluation of gas sensors using artificial thermal runaway gas compositions in small-scale lab environment.
2. Detection tests in cell-level, incorporating various technologies, sensor placements, initiation methods, state of charge and cell chemistries.
3. Large-scale battery electric vehicle tests to evaluate the best-performing detection technologies from the cell-level tests in a larger scale.

#### 4.4.7 The ALBERO project (2020)

The ALBERO-project focused on transport of AFV on ro-ro ferries. One part of the project aimed to develop efficient early detection methods. Based on the review of the existing detection technologies and on the gas emission and battery temperature results from thermal runaway tests, an efficient gas detection method was developed. Proper sensors were selected and tested mainly in laboratory at cell-scale. Sensitivity of sensors to marine environment (e.g. salt, water) was tested and normal gas background level was measured in ro-ro space (GTE, 2020). H<sub>2</sub> was identified as a suitable gas to track. Lab tests of an air intake system for H<sub>2</sub> were also conducted. Finally, a concept of combined gas sensor for H<sub>2</sub> with ventilator for aspiration and IR sensors at dedicated parking positions for EVs / charging stations was developed and demonstrated (Figure 7) (GTE, 2020).

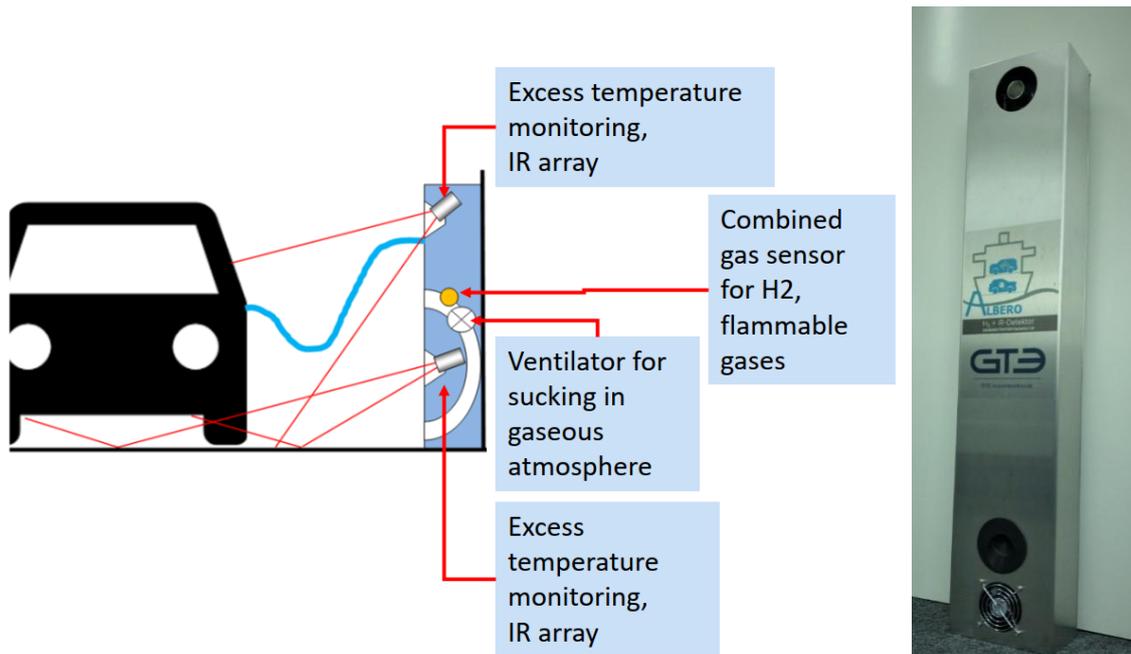


Figure 7. ALBERO early detection of thermal runaway concept: combined sensor system H<sub>2</sub>-gas sensor and IR-Sensor. Left: principle of concept. Right: photo of demonstrator (GTE, 2020).

#### 4.4.8 Video fire detection proposal in SSE 11/16/1

SSE 11/16/1 (ROK, 2024), submitted by the Republic of Korea and IUMI is a proposal for application of Video Fire Detection (VFD) system for vehicle and ro-ro space of cargo ships carrying new energy vehicles. The background is a BEV fire in an underground parking lot in Incheon, Korea, in August 2024 and a video that was processed using VFD.

When a fire accident video sourced from news media was processed using a Video Fire Detection system, smoke was detected within approximately one second. The authors suggest that VFD technology would be effective in vehicle and ro-ro spaces on board ships, due to the similarities in vehicle arrangement and ventilation conditions with underground parking facilities. The submission also explains a video of a fire in a typical living room, where VFD detected smoke “immediately”. Moreover, it is mentioned that VFD, as an AI-based system, enables continuous 24/7 monitoring, which could significantly reduce the surveillance workload for crew members. No reference literature was provided in the submission, which limits the ability to validate the detection system based on the tests described in the paper.

#### 4.4.9 Video fire detection in LASH FIRE project (2023)

A video fire detection system was installed in a closed ro-ro space, and a fog machine was used to accomplish smoke detection tests in the LASH FIRE project. The set-up was an empty closed ro-ro space with mechanical ventilation turned off. VDS detected the smoke in both the tests, depending on the distance 27 m respectively 72 m from the VDS, it took from 30 s to 114 s for the system to detect the fog. The test was not specifically aimed to test AFV fire, rather general ro-ro space fire detection.

The VDS was installed onboard for long-term evaluation. The overall rating from the time onboard was deemed useful with the motivation that a closed ro-ro space has stable light conditions and that few cameras can cover large distances.

Full evaluation of fire detection solutions and recommendations are found in LASH FIRE D09.2 Developed ro-ro spaces fire detection solutions and recommendations (Zeinali, et al., 2023).

#### 4.4.10 Using battery management system (BMS) to provide early warning of anomalies

In the LASH FIRE report IR09.15 (Dahlbom, Sanfridson, & Sjöblom, 2023), it was proposed to further explore if communication with the battery management system (BMS) could be a suitable method to early detect thermal

runaway. Other reports (Rahmani, et al., 2025; Anttila, 2024; ClassNK, 2023) also highlight an interest in exploring the potential for communication between an EV BMS and ships. Such integration, they mean, could provide more detailed information on battery malfunctions compared to current onboard monitoring systems, enabling earlier detection of thermal runaway and thereby enhancing safety during the transport of EVs on vessels.

In China submission SSE 10/INF.8 and SSE 11/INF.7 (China, 2023; China, 2024), two early safety warning systems are introduced: (1) vehicle-ship safety information monitoring system and (2) battery pack temperature monitoring system. The first system is based on safety data sharing from vehicle BMS to ship or detection of alarm(s) triggered by the BMS of the EV (e.g. audible or visual alarm) by appropriate sensors located in the ro-ro spaces. The authors suggest that research is expected to be able to detect signs of thermal runaway in the battery and sound the alarm at least one hour before an event occurs, giving the ship ample and valuable time for follow-up response. Two main difficulties are listed: (1) Vehicle companies concern about privacy protection of data. (2) To keep the vehicle energized to ensure the operation of the BMS system. The second system (not related to BMS) is based on detecting temperature abnormalities via a sensor placed on the battery outer packaging. The authors state it is “cost-effective, convenient and highly applicable, suitable for both new and used vehicles”. The systems have been implemented and demonstrated on board six general-purpose ships in order to validate signal stability and effectiveness. The results reported that the software functionality and hardware configuration and installation was ensuring signal stability and effectiveness.

One part of the STARRS study is to explore if and how BMS connectivity with ship can provide early warning of anomalies in the battery pack of a vehicle. In the first step, a brief state-of-the-art assessment on BMS data access and availability will be documented and thereafter a workshop with stakeholders will be held.

## 4.5 Free-burn fire tests using battery electric vehicles

### 4.5.1 Introduction

The fire growth rate, the peak heat release and the total heat release from fires involving battery electric vehicles is the starting point to understand the fire hazard of these types of vehicles. This section summarizes the outcome from some projects.

### 4.5.2 Free-burn fire tests at INERIS (2012)

Lecocq, *et al.* (Lecocq, Bertana, Truchot, & Marlair, 2012) at the French National Institute for Industrial Environment and Risks (INERIS) have conducted free-burn comparison fire tests using internal combustion engine vehicles (ICEV) and battery electric vehicles (BEV) from two French car manufacturers. In total, four tests were conducted. The battery pack of the vehicle from manufacturer 1 had an energy capacity of 16.5 kWh and the battery pack of the vehicle from manufacturer 2 an energy capacity of 23.5 kWh. It is noted that these energy capacities represented modern vehicles at the time of the tests. The fuel tanks of the internal combustion engine vehicles were filled with diesel fuel. All fires were initiated inside the passenger compartment of the vehicles, with the side windows fully open. The fire development was similar for all vehicles in that the fire spread inside the passenger compartment before propagating to the rear and then to the front of the vehicle. No explosion or projectiles related to fire involvement of the battery pack was observed. The peak heat release rates were: 4.2 MW (BEV1) and 4.8 MW (ICEV1) as well as 4.7 MW (BEV2) and 6.1 MW (ICEV2). Peaks corresponding to fire involvement of the battery pack appeared about 35 min after fire ignition. Based on the data, it was not possible to determine the specific contribution of the battery fire to the overall heat release rate and there is no information in the reference whether the diesel fuel tanks of the ICEVs were involved in the fire or not.

### 4.5.3 Free-burn fire tests by Watanabe, *et al.* (2012)

Watanabe, *et al.* (Watanabe, et al., 2012) have conducted large-scale tests comparing the severity of a fire in a battery electric vehicle (Nissan Leaf, 24 kWh battery pack) with a gasoline-powered vehicle (Honda Fit, filled with 10 L of gasoline). The gasoline-powered Honda Fit vehicle was significantly smaller than the Nissan Leaf, however, the latter contained less combustible material. Fire ignition was achieved with a small fuel pan filled positioned at the left-hand side rear end of the vehicle. The heat flux from the vehicle fires was measured at different positions. The lithium-ion battery pack of the Nissan Leaf released gas 40 min after the test started, which coincides with the peak heat release and with the peak heat fluxes towards the side of 61 kW/m<sup>2</sup>. Fire in and near the right rear tire at about 22 min generated a peak heat flux of 51 kW/m<sup>2</sup>. The upper and lower parts of the battery pack are made of steel. No explosions occurred during the test, nor did the battery pack burst. For the Honda Fit, the gasoline tank

did not burst or leak fuel during the test, likely it evaporated through the fuel filling pipe. The maximum heat flux was 40 kW/m<sup>2</sup>. The Nissan Leaf fire generated a peak heat release rate of 6.3 MW and a total heat release of 6.4 GJ, whilst the peak heat release rate of the Honda Fit fire was 2.1 MW and a total heat release of 4.3 GJ. It is noted that the vehicles represented modern vehicles at the time of the tests and that both vehicles were relatively small.

#### 4.5.4 Free-burn fire tests by the National Research Council of Canada (2016)

The National Research Council of Canada (NRC) have conducted free-burn fire tests comparing a total of seven vehicles of different types (Lam, MacNeil, Kroeker, Lougheed, & Lalime, 2016). The tests included three battery electric vehicles (BEV), two plug-in hybrid electric vehicles (PHEV) and two internal combustion engine vehicles (ICEV), refer to Table 8. During fire testing, the vehicle was positioned above a propane sand burner sized 2.4 m by 1.2 m that generated 2 MW and a flame temperature of about 800°C. The intent of using the burner was to simulate a fuel spill fire under the vehicle. The clearance between the burner and undercarriage of the vehicle was about 200 mm. All side windows and doors of the vehicle under test were kept fully closed and all parts were original. The weight of each vehicle was measured before and after the test.

The following vehicles were tested:

- Vehicles A. These vehicles were from the same manufacturer. The ICEV was not identical with the BEV and was slightly smaller;
- Vehicles B. The ICEV and BEV were of the same model, but with different propulsion systems. The BEV models of Vehicles A and B contained similar battery energy storage capacities, but Vehicle B contained two separate battery packs at different locations instead of a single pack, as in Vehicle A; and
- Vehicles C and D. These vehicles were PHEVs from different manufacturers, with Vehicle C having a smaller battery than Vehicle D. The fuel tanks (where applicable) were completely filled during testing.

Correspondence with the authors of the paper have revealed that the 'small' lithium-ion battery pack (LIB) relates to an energy capacity of <10 kWh, the 'medium' battery pack to an energy capacity of <20 kWh and the 'large' battery pack to an energy capacity in excess of 20 kWh. Note: The battery pack capacities are generally smaller than typically used in present-day (2025) passenger vehicles.

Table 8. The types of vehicles and the test results from the free-burn fire tests conducted at the National Research Council of Canada. The data is shown without the contribution of the propane gas burner (Lam, *et al.*, 2016)

Type	Vehicle (model year)	Mass (kg)	Energy stored	Peak HRR (MW)	Time to peak (min)	Total heat release (GJ)
BEV	Vehicle A (2014)	1448	'Large' LIB, 100% SoC	6.0	7.0	-
	Vehicle A (2013)	1475	'Large' LIB, 85% SoC	5.9	5.8	4.9
	Vehicle B (2013)	1659	'Large' LIB, 100% SoC	6.9	10.2	4.7
PHEV	Vehicle C (2013)	1466	'Small' LIB, 85% SoC and full tank of gasoline	6.0	7.5	4.6
	Vehicle D (2013)	1711	Medium' LIB, 100% SoC and full tank of gasoline	7.9	8.3	5.9
ICEV	Vehicle A (2015)	1096	Full tank of gasoline	7.1	6	3.3
	Vehicle B (2013)	1344	Full tank of gasoline	10.8	8	5.0

It was observed that the peak heat release rate and heat flux values were higher for the ICEVs for the cases when the fuel tank burst compared to when the battery pack of a BEV became involved in the fire. Burning of the battery pack did not seem to result in any significant peak in heat release rate or heat flux. Vehicle type D was the only vehicle that had a metal fuel tank. The flames from the fire damaged the heat flux gauge facing the rear of the vehicle, just after 7 min. This event was most likely caused by the release of the fuel. After the gasoline burned off, the heat release rate and heat flux remained relatively constant until shortly after 10 min, when they started to decrease gradually until the end of the test. Higher state of charge (SoC) resulted in faster involvement of the battery.

The peak heat release rates for the internal combustion engine vehicle models were higher than those for their battery electric vehicle counterparts and the times of the peak heat release rates occurred similar to or earlier than those for the battery electric vehicles. Given that the peak heat release rate for the internal combustion engine vehicles corresponded to the burning of gasoline, it seems that a vehicle with a full fuel tank produces a greater hazard in terms of heat release rate than does a vehicle with a battery pack.

#### 4.5.5 Free-burn fire tests in the E-TOX project (2020)

In the E-TOX project (Willstrand, Bisschop, Blomqvist, Temple, & Anderson, 2020) conducted at RISE, three large-scale free-burn fire tests were conducted, involving one conventional internal combustion engine vehicle (ICEV) and two battery electric vehicles (BEV). The ICEV and one of the BEVs were of the same vehicle model from the same manufacturer which allows a good comparison of the influence on the fire by the powertrains. The vehicle denoted ICEV A was a full-size van (model year 2011), and the fire was initiated by a diesel spill fire in a small (0.25 m<sup>2</sup>) fire tray fire located directly underneath the fuel tank. The total amount of diesel (44 L) used in the test corresponded to 80 % of the full tank capacity and the fuel was split between the fuel tank and the fire tray. The BEVs were charged to approximately 80% of the available energy capacity and a propane gas burner positioned underneath the battery pack, with a defined output of 30 kW, was used to ignite the vehicles. The vehicle denoted BEV A was a full-size van (model year 2019) and had battery capacity of 40 kWh, the vehicle denoted BEV B was

a small family car (model year 2016) with a battery capacity of 24 kWh. The total heat release rate from three free-burn fire tests are shown in Figure 8.

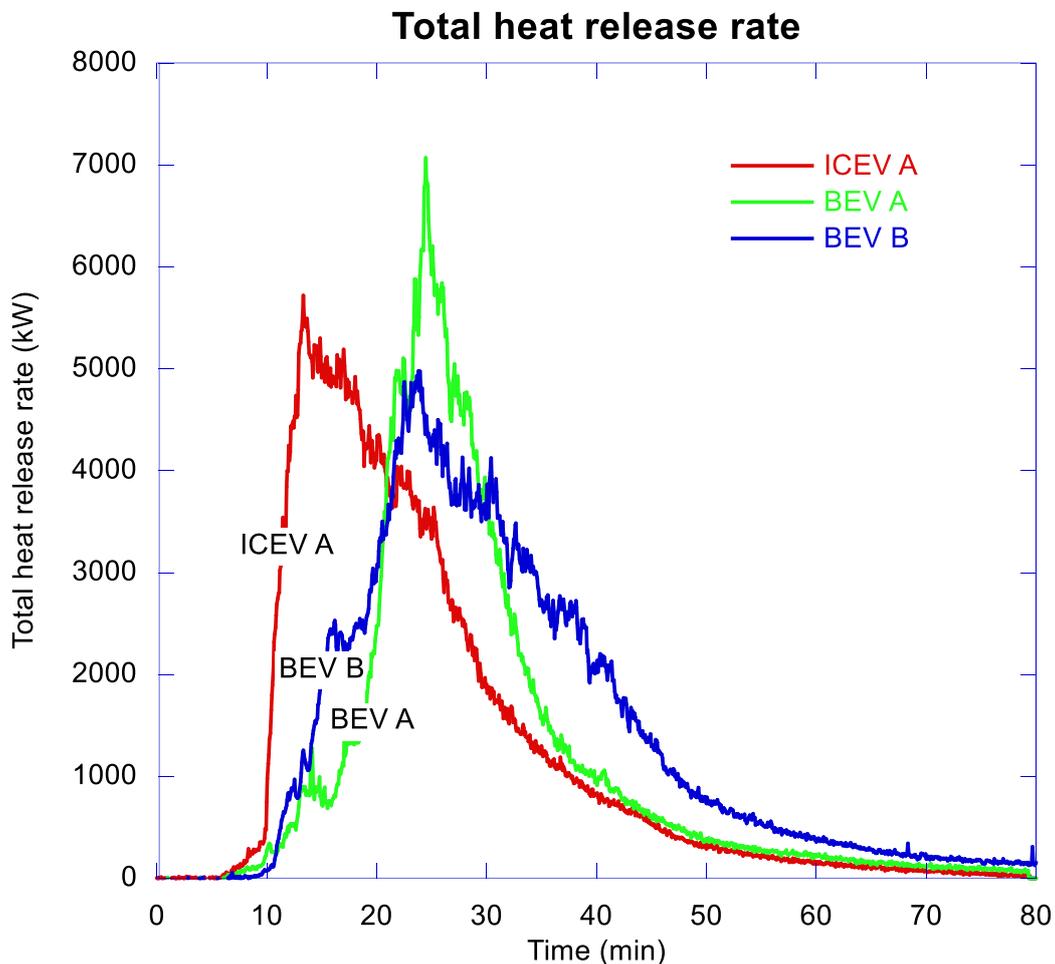


Figure 8. The total heat release rate from three free-burn fire tests in the E-TOX project, involving one conventional internal combustion engine vehicle (ICEV) and two battery electric vehicles (BEV). ICEV A and BEV A were of the same vehicle model from the same manufacturer which allows a good comparison of the influence on the fire by the powertrains (Willstrand, *et al.*, 2020).

The heat release rate from the fire was measured by oxygen consumption calorimetry. As the fuel tank ruptured for ICEV A test there was a much more rapid fire development compared to the fires in the BEVs. The subsequent diesel pool fire burned out before the fire, that involved the engine bay and passenger compartment, reached its maximum. Therefore, a higher peak heat release rate was achieved for BEV A (as noted, the BEV was similar to ICEV 1) where the battery ventilation and the fire involvement of the combustibles of the vehicle occurred at approximately the same time. It was noted that diesel pool fire probably had been larger if the outflow on the ground had not been limited by the fire tray.

ICEV A provided a total heat release of 5.9 GJ, BEV A provided a total heat release of 5.2 GJ and BEV B provided a total heat release of 6.7 GJ.

#### 4.5.6 Free-burn and automatic fire sprinkler tests by the Fire Protection Research Foundation (2025)

RISE Fire Research AS in Norway and RISE Research Institutes of Sweden have undertaken a project for the Fire Protection Research Foundation. The objective of the project was to validate the sprinkler protection criteria in NFPA 13, Standard for the Installation of Sprinkler Systems. Part of the results of the project have been presented (Arsava, *et al.*, 2025), including the results from a free-burn test of a modern passenger car. The fire was initiated using an oxy-acetylene burner positioned under the battery pack. The peak heat release rate was approximately 7.5 MW and occurred after about 60 min. From post-test photos that was presented, it was observed that large

parts of the vehicle body were consumed in the fire, such as the front hood, all four door panels, the hatch for the trunk and the wheel wells. These parts were made from aluminium. Steel is used in other parts of the vehicle's body structure and remained intact. The vehicle had a glass roof structure that also was consumed in the fire.

The automatic fire sprinkler tests included two internal combustion engine vehicles (gasoline-fuelled) and one battery electric vehicle. Automatic sprinklers with two different K-factors (orifice opening sizes) were used in the tests, K80 and K160 sprinklers. The maximum temperature around each vehicle was around 40 °C. The reference concludes that further studies are required to study the impact of water density and sprinkler configuration in parking garage fires with battery electric vehicles.

## 4.6 Manual fire-fighting equipment testing

### 4.6.1 Introduction

Manual intervention of fire in a ro-ro space is hazardous for fire-fighters due to radiant heat and thick, toxic smoke beneath low overheads, generating intense heat and degrading visibility. Vehicles are closely stowed which leave only narrow passageways, so advancing with fire hoses to the seat of the fire is difficult. Therefore, fire-fighting teams cannot rely on generic gear or tactics. Thermal imaging cameras become indispensable for locating fires and tactically, a coordinated approach balances limited offensive attacks to knock down flames in vehicles with defensive cooling of adjacent cars to prevent fire spread. In summary, the confined geometry, compounded by modern vehicle fuel technologies, demands tailored equipment, specialized tools, and hybrid tactics that marry cautious perimeter defence with precise targeted attacks.

Three types of manual fire-fighting devices have been reviewed:

- Handheld fire hose systems;
- Portable water curtain systems; and
- Devices that inject water directly into a battery pack.

### 4.6.2 Testing of fire hose and water curtain nozzles in the BREND project (2019)

Vylund, *et al.* (Vylund, Mindykowski, & Palmkvist, 2019) at RISE conducted fire tests and practical usability evaluations as parts of the Swedish research project BREND to evaluate fire-fighting methods for fire involving alternative fuel vehicles (AFV) in a ro-ro space. The fire tests were performed with a steel sheet mock-up simulating a passenger vehicle. The fire was established with a propane gas test rig, providing a 4 MW fire. Steel sheet barriers were positioned parallel with the vehicle mock-up at a 0.6 m horizontal distance (Figure 9). The steel sheets were 4.0 m in height to mimic a cargo trailer and had spot-welded thermocouples to measure the surface temperature. Water or foam (one test) was applied between the mock-up and the steel barrier to the left and the temperature reduction was measured. The results are presented as a temperature reduction coefficient achieved by different systems. A high surface temperature reduction coefficient indicates that the system has a high capacity to reduce heat exposure and prevent fire spread to an adjacent vehicle. However, the fire tests did not take in consideration how the system can be applied during a real fire-fighting operation in ro-ro spaces. Therefore, a field test (outdoor) was conducted to evaluate the practical usability and different tactical options of the tested systems (Figure 11).

The systems used during the tests were identified in a workshop together with ship personnel, authorities and onshore fire and rescue services, and thereafter during interviews with system suppliers. The selected systems were divided in two groups: Handheld systems and water curtain systems. The main difference between these system types is that the fire-fighter needs to handle the first system during the entire operation, whereas water curtain systems only require presence of fire-fighters to position the system. A total of ten systems were studied. For the handheld system tests, the operator was standing at an 8 m distance from the vehicle mock-up, except in two tests, where the distance was reduced to 3 m. This reduced distance was necessary as the operator could not reach with the jet all the way to the mock-up. A supporting construction was built so that the nozzle could be positioned at the same height and same distance from the vehicle. The operator placed the nozzle in the supporting construction and directed the water spray between the vehicle mock-up and the closest steel barrier with a duration of 4 min. The different water curtain systems were positioned between the vehicle, and the steel barrier prior ignition of the propane gas burner and water application was started when the temperature on the steel barrier had stabilized.



Figure 9. The position of the vehicle mock-up and the steel barriers in relation to the fire-fighting operator in the fire tests by Vylund, et al. (2019).



Figure 10. Two fire tests by Vylund, *et al.* (2019) with a water curtain system consisting of a fire hose fitted with exchangeable nozzles. The hose automatically stabilizes when it is pressurized with water and creates water jets that can reach up to 15 m in height. The upper pair of photos shows a flow rate of 210 l/min and the lower pair of photos a flow rate of 310 l/min.

The report concludes that handheld systems and water curtain systems are two tactical options, and one cannot replace the other. Handheld systems are needed for fire-fighters to be able to position the water curtain, but when operating the curtain nozzle, no personnel is required. The water curtain nozzle therefore enables personnel to perform other tasks while it is active.

All handheld systems, except a so called “fog nail”, a high-pressure system discharging 22 l/min and the foam-based system, reduced the heat exposure in half or more. With the foam-based system, the fire-fighter needed to

be close to the vehicle to be able to reach the fire. The short throw length and small water flow rate made it difficult to reach the fire from a safe distance. A safe distance for fire-fighters requires a long throw length, which depends on the pressure, flow rate and type of nozzle and hose. The water spray pattern of two of the tested systems could be adjusted during the fire-fighting operation to adapt to the fire and accessibility conditions. The other tested systems were more difficult to adjust. Easiness is important to save time and to provide a fast response, but at the same time consideration to the water spray capacity is necessary. Furthermore, the reaction force from high-pressure or high-water flow systems can require more personnel and tires the operator faster. It is heavier and more difficult to handle large water flows rates but with the right tactics there is no need for very large water flow rates.

The blockage effect of the different water curtain systems was similar, but the reach of the water spray and how the systems can be applied in a ro-ro space were different. The hose and larger nozzle (800 l/min) will likely cover the full side of a cargo trailer whereas the smaller water curtain can cover one or two vehicles. However, smaller water curtain equipment is easier to handle and is therefore easier to position close to the fire. The larger nozzle will also release a large amount of water, which can be a problem on a ro-ro space.



Figure 11. Simulation of the environment inside a ro-ro space in a field test (outdoor) to evaluate the practical usability and different tactical options of the tested systems (Vylund, *et al.*, 2019).

In the practical evaluation, it was found that a semi-rigid hose with a small inner diameter is much easier to handle in most cases, but that advantage must be balanced against the desired capacity of pressure, water flow rate and throw length. A hose with a larger inner diameter will have greater stiffness which proved to be useful when trying to position water curtain nozzles. The tests showed that it is possible to position water curtain nozzles to prevent fire spread, but the hose must be further developed to be able to use in ro-ro spaces.

### 4.6.3 Fire-fighting, water mist and fire detection tests in the ELBAS project (2022)

The ELBAS project (*Electric Vehicle Fires at Sea: New Technologies and Methods for Suppression, Containment, and Extinguishing of Battery Car Fires Onboard Ships*) was conducted by DBI Fire and Security and finalized at the end of 2022 (Kleiman, *et al.*, 2022). The objective was to develop performance based holistic fire safety strategies for electric cars fires when transported on board ferries. Various fire detection and fire-fighting technologies were identified and tested using a set-up that resembled a ro-ro space, and fire simulations were performed using CFD modelling of actual ro-ro spaces. The technologies that were tested included portable water spray curtain and undercarriage cooling devices, a couple of battery penetration extinguishing systems, a large thermal fire blanket, a fixed water mist sprinkler system, gas detection, as well as combined fire-fighting methods. The overall conclusion was that all the fires in the tests could be extinguished safely. With correct fire-fighting technologies onboard, proper training of the crew and a well-coordinated cooperation with the emergency services on land, battery electric vehicles should not present an increased safety problem in ferry traffic.

The test set-up was constructed by combining two 40 ft. shipping containers side-by-side, providing a 12.2 m long by 7.13 m wide by 2.4 m high compartment, that was open at both ends. The vehicles were positioned inside the test compartment such that the conditions mimicked a realistic ro-ro space. The gaps among cars were set to

40 cm and 20 cm ( $\pm 5$  cm) from door to door and bumper to bumper, respectively. The centremost vehicle (no. 5) was a battery electric vehicle (Figure 12). Over the course of the tests, the following three electric car models were tested: Renault Fluence ZE (2012), Tesla Model 3 (2021) and Nissan Leaf (2011). The surrounding eight vehicles were conventional internal combustion engine vehicles, that were drained of all oils and other fluids and did not contain any fuel in their tanks due to environmental and safety reasons.

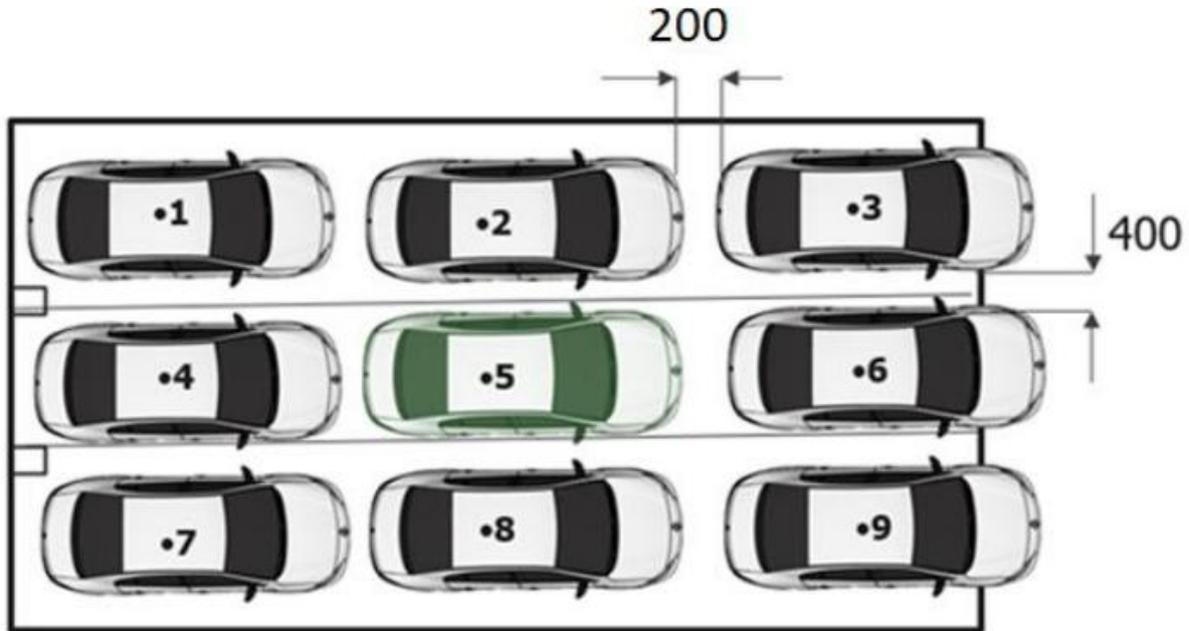


Figure 12. The general vehicle arrangement in the fire tests in the ELBAS project. The centremost vehicle (no. 5) was a battery electric vehicle. All dimensions in mm (ELBAS, 2022).

Some of the conclusions from the fire tests in WP3 are summarized below:

**Car fire blanket:** Two fire-fighters are required to pull the blanket over the car on fire. When used on a tightly stowed ro-ro space on a ferry, the two fire-fighters must go around and over the adjacent vehicles to reach the car on fire. With some initial training this was possible, and the blanket was relatively easy to use. This tactic also provided some additional protection to the fire-fighters deploying the blanket as they were shielded from the ignited car to some degree by the nearby cars. The use of a fire blanket requires space to be able to cover the burning vehicle correctly and a minimum of two persons in appropriate breathing apparatus are required. The applicability and efficiency depend on how close the vehicles are stowed. On a smaller ferry with fewer vehicles and crew, fire blankets could be a helpful tool as a supplement to the existing fire-fighting arrangement. Whereas in larger fires and/or tightly stowed ro-ro spaces which limits direct access to the fire, the use of fire blankets may not be as effective given limited accessibility.

**Direct water injection and portable water mist curtain and undercarriage cooling devices:** Both direct and indirect cooling methods were tested. The usability of larger devices proved to be challenging due to the limited space around vehicles. The smoke layer descends to eye levels, resulting in challenges regarding locating of the seat of the fire and manoeuvring and handling of the devices. These challenges were observed when hammering in an extinguishing lance into the battery pack and manoeuvring larger devices. Direct cooling of the battery pack was the most efficient way of cooling it below thermal runaway thresholds with a lower water consumption. Indirect cooling, with water mist or spray devices around the electric vehicle, contained the fire to the vehicle and prevented flame spread to adjacent vehicles. Independent of the methodology (direct or indirect cooling), the time to application is the key for success. The water consumption was considerably lower with direct cooling methods. The use of water for efficient direct cooling of the battery pack and containment of the fire with non-water-based techniques (as fire blankets) could limit the water consumption without generating ship stability issues. Both direct and indirect cooling methods have their pros and cons but combining both methods proved to be an efficient approach during the tests. Portable water spray or undercarriage cooling devices are the most efficient in use with an active smoke control system, as they can control the fire growth and spread while the excess smoke production can be extracted with a powerful ventilation system. Direct cooling devices is not capable of putting out the flames inside the passenger cabin and are the most applicable when only the battery fire is the concern. It is therefore

required that the flames outside the battery have been put out prior being used, to allow fire-fighters to attack the battery without the effects from external flames and smoke. The devices could also be used as a precautionary method to ensure that battery thermal runaway reactions have stopped. Given the complexities of use, direct cooling devices may be most appropriate for use by professional fire-fighters having proper training to deal with battery and battery electric vehicle fires. The tests using direct injection of water is described in more detail in section 4.6.5.4.

**Fixed-installed water mist system:** Open low-pressure water mist nozzles were evenly installed at the ceiling of the test compartment. The system was manually activated 7.5 min after the first detector signal. The vehicle used in the test was not in good condition, a set of passenger seats was placed inside, and the roof was covered with a steel plate to avoid water droplets reaching the passenger compartment from above. As soon as the water mist system was activated, the temperature on the battery dropped as well as in the smoke layer above the vehicle and the surrounding vehicles. The temperature drop in the battery was most likely due to the bad condition of the vehicle allowing droplets to reach the battery pack which would otherwise be better shielded. Although a fixed-installed water mist system may not fully extinguish a battery electric vehicle fire it can limit the spread of the fire, such that the shipboard fire-fighters can approach and continue fire-fighting with traditional extinguishing methods, possibly combined with appropriate specialized tools.

**Fire detection:** Various fire detection and extinguishing technologies were identified and tested. Six optical smoke detectors were placed at the ceiling level directly above vehicles 1, 3, 4, 6, 7 and 9. Additionally, hydrogen fluoride (HF) detectors were positioned above the battery electric vehicle, near its hood in some selected tests. Two types of HF detection technologies were used in the tests: Aspiration type gas detectors positioned at the ceiling, directly above the battery electric vehicle, and HF spot-type detectors, placed behind the battery electric vehicle at ground level. The conventional smoke detectors installed at the ceiling responded shortly after the smoke was visible. The HF detectors also generated alarms but, based on the location of the detection system the times varied. The HF detectors placed inside the battery compartment gave the earliest detection as expected. The aspiration system installed above the battery electric vehicle at the ceiling triggered after a longer time. Nevertheless, the readings from the HF sensors showed the possibility of detection using selective HF detectors. Positioning of smoke/gas detectors should be done considering the ventilation and wind effects within the decks. Reduced detection times can be achieved by proper location of such detectors. The project also concluded that training on use of Closed-Circuit Television (CCTV) as a means for fire detection and verification of a fire could potentially improve the response time to the fire.

#### 4.6.4 Testing of water curtain nozzles in the LASH FIRE project (2023)

The LASH FIRE report D06.08 (Bleye, et al., 2023) describes a “boundary cooling” device developed to provide water cooling in addition to, or as an intermediate option between a fixed-installed drencher water spray system and manual application of water by fire hose nozzles. The device creates a vertical barrier of water sprays between passenger cars and a spray pattern directed towards the traction battery or the gas tank (located in the lower part of the vehicle). A first prototype was developed under the umbrella of the ALBERO project ([www.alberoprojekt.de](http://www.alberoprojekt.de)) and then several tests were carried out in the LASH FIRE project. After the testing (Figure 13), the LASH FIRE project developed different and updated versions of the prototype, reaching 4.0 version.



Figure 13. The “boundary cooling” device tested in the LASH FIRE project that creates a vertical barrier of water sprays between cars and a spray pattern directed to the traction battery or the gas tank located in the lower part of the vehicle (LASH FIRE, 2023).

## 4.6.5 Testing of equipment for water flooding of battery packs

### 4.6.5.1 Introduction

There are fire-fighting equipment and tools available to stop a thermal runaway in a battery pack. Part of the problem is, however, that the battery pack need to be penetrated before water, or any other agent can be injected into the pack. The mechanical protection steel plate that is installed on the underside of a battery electric vehicle serves as both a shield and a structural element, forming the lower shell of the battery enclosure and guarding against stones, road debris, curbs or even off-road obstacles. This plate forms part of a larger steel battery housing assembly. By preventing punctures and intrusion into the battery pack, it helps ensure the integrity of individual cells, contributes to bottom-impact crash energy management and aids in maintaining stable thermal and electromagnetic conditions around the modules. Manufacturers typically choose high-strength steels or specialized stainless alloys, balancing rigidity, weight and corrosion resistance in sheets roughly 2 mm to 6 mm thick. The housing must also protect passengers in the event of a fire (thyssenkrupp AG, 2025). In late 2013 Tesla began equipping the undercarriage with a dedicated armour shield fabricated from titanium to further protect the battery pack from puncture and abrasion under severe driving conditions (Tesla Motors Club, 2025).

### 4.6.5.2 Water flooding fire suppression tests by MSB (2023)

The Swedish Civil Contingencies Agency (MSB) have conducted fire tests to contribute with experimental experience of the methodology of flooding lithium-ion batteries with water in the event of a fire (MSB, 2023). The tests were limited to test objects that were composed of lithium-ion cells with a maximum nickel content of 60% in the cathode material. More nickel-rich and energy-dense electrode systems have higher reactivity and need to be investigated separately. Both prismatic cells and pouch cells were represented in the test objects, but not cylindrical cells. Potable water without any additives was used. The test method was designed based on the state of knowledge that was current at the time of the tests. New methods and guidelines are developed as battery technology develops, and new research findings emerge. The results of the report should therefore be seen as an example of how the method, and the tested tools can be applied to the type of objects included in the study.

Two commercial tools were used in the tests, a “cutting extinguisher” and an “extinguishing lance” (Figure 14). A cutting extinguisher initially cuts an opening in a wall or door with abrasive and water. When the material is pierced, only water is flowing, and the entire process is carried out in one and the same movement. With a lance extender, the operator can reach into a vehicle and apply the cutting extinguisher to a propagating battery from above. The cutting extinguisher is applied with the support of the three- or four-point support that is attached to the

end of the lance. In this case, the support prevents the nozzle from coming into contact with destroyed battery cells. The extinguishing lance is a tool specifically adapted to get water into a battery pack. It has a chamfer at the tip that allows only the part of the tip that sprays water to enter the battery without damaging more battery cells than necessary. The lance is powder-coated on the handle part with electrically insulating paint, and it is equipped with a handle that prevent that the person holding the lance will be hit by the sledgehammer used to force the lance into the battery pack. There is an extension to the handle to allow the user to stand at a longer distance, but it was not available at the time the actual tests. Note: The extinguishing lance was also tested in the ELBAS project and two different cutting extinguishers (denoted Ultra High Pressure (UHP) fire-extinguishing systems) were tested by the Netherlands Institute for Public Safety (NIPV), as described below.



Figure 14. The use of cutting extinguisher (left) and an extinguishing lance (right). The extinguishing lance is made of stainless steel, and the tip of the lance is forced into the battery pack using a sledgehammer (MSB, 2023).

One large-scale extinguishing test using a battery electric vehicle was carried out to demonstrate that the method of water flooding of battery packs can be applied at vehicle level under certain conditions. The test was designed to cover the entire course of the fire, from initiation of thermal runaway in a cell, propagation and a fully developed fire to confirmed fire extinguishing. The cutting extinguisher with abrasive and water was used, supported by a conventional fire hose nozzle to provide personal protection for the cutting extinguisher operator. The cutting extinguisher had an operating pressure of 300 bar, and a water flow rate of 58 l/min. Thermal runaway was initiated in a module of the battery pack. At the first sign of propagation, a 15 min countdown was started to mimic the emergency services' response time. The water mist spray from the cutting extinguisher was used to knock down the flames and to suppress the fire inside the passenger compartment. When it was possible to open the rear door, a thermal imaging camera was used to scan the interior of the vehicle and search for hot spots in the battery pack. Wind and control of gases using a PPV (Positive Pressure Ventilation) fan meant that one side of the vehicle was difficult to access due to thick smoke and flames. The cutting extinguisher was employed in the gimbal tunnel and lance extensions were used to facilitate access and avoid contact with the body of the vehicle. While the cutting extinguisher was in operation, an operator with a conventional fire hose nozzle provided personal protection for the cutting extinguisher operator. This primary task throughout the operation of this operator was to protect the cutting extinguisher operator from stick flames and flames. The test ended when the thermal imaging camera showed a stable temperature below 50°C. After the extinguishing operation was finalized, continuous monitoring of the temperature with a thermal camera continued for 15 min, to ensure that the thermal propagation stopped.

The tests showed that it is possible to interrupt thermal propagation in a lithium-ion battery module or pack through an offensive fire-extinguishing operation where the battery is flooded with water. Flooding of water of a lithium-ion battery can shorten the response time and reduce human and material resources. It was, however, difficult to determine the degree of propagation in a lithium-ion battery based on external observable factors such as temperature monitoring with thermal imaging cameras, smoke and noise. Cell chemistry, the degree of charge,

battery architecture and vehicle architecture are examples of system properties that affect how a thermal runaway and propagation develops during a thermal event in an electric vehicle.

When planning an operation, it is therefore important to consult the vehicle's Rescue Sheet and Emergency Response Guide (ERG) to assess the conditions for an active extinguishing operation. It was possible to access the battery with the tested tools. Thermal imaging cameras and rescue sheets can provide information that provides better conditions for success with an operation. The risk of stranded energy that can lead to fire re-ignition must always be considered when handling an electric vehicle and its traction battery after a thermal event.

#### 4.6.5.3 Ultra High Pressure (UHP) fire-extinguishing system tests (2024)

The Netherlands Institute for Public Safety (NIPV) have conducted research to determine whether an Ultra High Pressure (UHP) fire-extinguishing system can be safely used by the Dutch fire service to fight battery fires in electric vehicles (Hessels & Brans, 2024). The work consisted of a working visit, a literature review and interviews. Additionally, two fire suppression tests were conducted, in which the battery pack of an electric car was put into thermal runaway.

An UHP fire-extinguishing system is a portable device connected via a hose to a pump. It uses ultrahigh pressure water jets containing an abrasive to create an opening in the battery pack and thereafter it introduces water directly into it. The thermal runaway in the battery can thereby be stabilized on site. As previously mentioned, another designation of the type of device is “cutting extinguisher”.

Two fire suppression tests were conducted using new electric vehicles with 75 kWh battery packs. The aim was to put the battery pack into a state of thermal runaway, so that flames would occur that involved the entire vehicle. Thermal runaway was initiated by mechanically damaging the battery pack. The fire was then given 10 min to develop and spread to involve the entire vehicle. To mimic the situation after an electric vehicle fire is reported in the Netherlands, a fire unit was first organized to extinguish the vehicle fire. After this, a specialist fire service unit with access to a UHP fire-extinguishing system assisted, with the objective to stop thermal propagation and thus stabilize the battery pack. The tests involved units from two different fire departments, using two different (brands) systems. The battery pack was approached from its top, i.e. from the inside of the vehicle.



Figure 15. Localization and monitoring of hot spots and preparation for penetration (left) and steam formation (right) during the use of an UHP fire-extinguishing system in one of the two fire suppression tests (Hessels & Brans, 2024).

An active monitoring period of 45 min was used in both tests, and no fire re-ignition was observed during this time. Some smoke kept coming out of the battery in the first test, but it was recognized that this smoke did not originate from a battery cell in thermal runaway. It was likely that the smoke was caused by smouldering of insulation materials or cables. Based on this experience it was concluded that the injected water cannot reach all locations or openings in the battery pack. In an actual event, the situation may arise where repeated use of the system is considered not to be successful, and the vehicle needs to be immersed in water.

Based on the experiences in the project, the following four safety measures should be used for a safe deployment of the UHP fire-extinguishing system when tackling a battery fire in a battery electric vehicle:

- Use low-pressure jets (i.e. standard fire hoses with a combination fog nozzle) to suppress flares from the battery and to protect the UHP operator.

- Ventilate any accumulated flammable gases in the vehicle by breaking its windows with the UHP fire-extinguishing system from a distance or for example by using fans.
- Position fire-fighters away from (toxic) smoke. Use low-pressure jets to shield them from any flames if necessary.
- Use the long lance or extension of the UHP fire-extinguishing system.

Hot spots need to be located with a thermal imaging camera, thereafter the battery pack is penetrated at these locations and water is injected with the UHP fire-extinguishing system using a lance (Figure 15). Steam formation serves as an indicator that there is cooling of the battery cells (Figure 15). The leakage of water out of the battery pack, combined with the cessation of steam formation, indicates that the thermal runaway has stopped. A period of visual monitoring, supported by observations with a thermal imaging camera, is required to observe if the actions are effective or not. Fire-fighters who participated in the fire suppression tests were positive about deployment with the system and indicated that the method is relatively easy to implement.

In conclusion, the results of the fire suppression tests provided the NIPV with sufficient confidence to recommend the use of the UHP fire-extinguishing system by trained teams within the Dutch fire department. Detailed procedures on how to approach and handle a fire in the battery pack of electric vehicle have been published by NIPV (NIPV, not dated). The starting point for the recommendations is that the fire in the body work has already been extinguished. The fire situation should thereafter be approached in the following steps: 1) Recognize, 2) Explore, 3) Stabilize, 4) Fight and 5) Aftercare, refer to Figure 16.

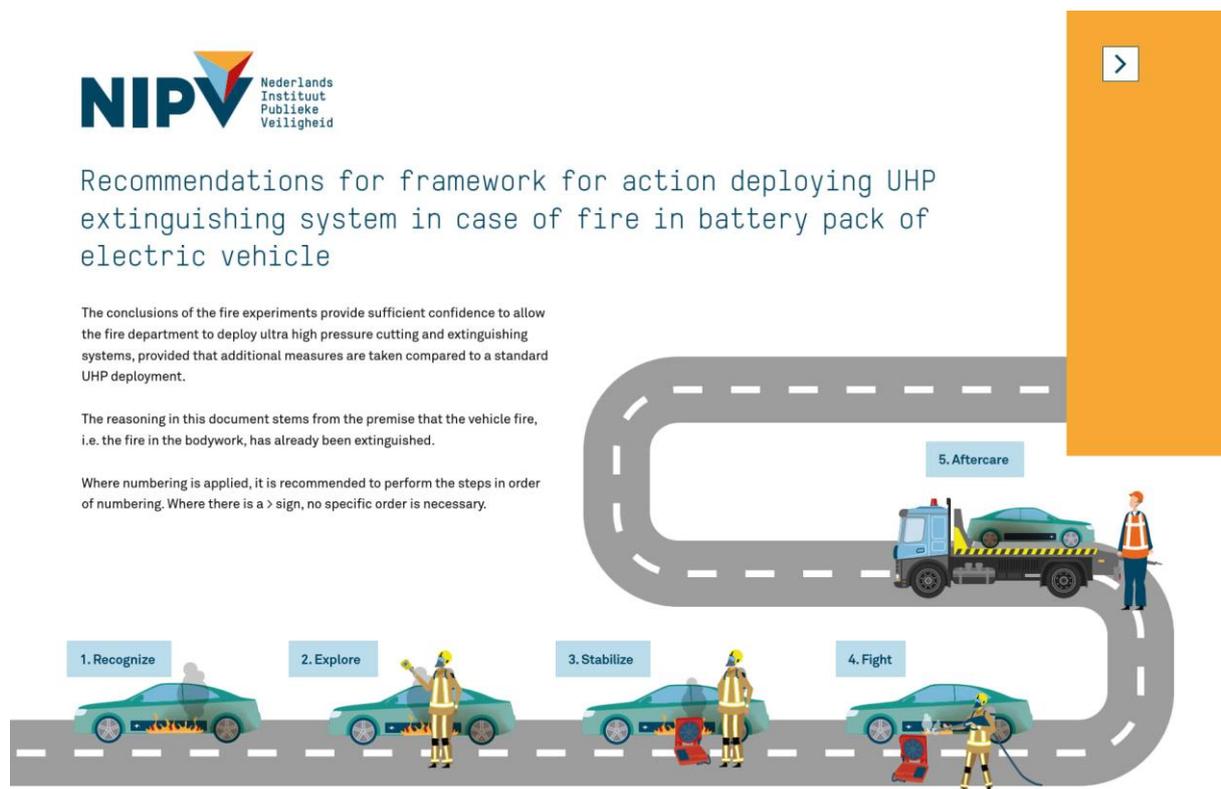


Figure 16. Detailed procedures on how to approach and handle a fire in the battery pack of electric vehicle published by the Netherlands Institute for Public Safety (NIPV, not dated).

#### 4.6.5.4 Testing of direct application of water in the ELBAS project (2022)

Refer to section 4.6.3 for details regarding the test set-up. The tests in the ELBAS project with direct injection of water included one test with an equipment that is a purpose-built solution for electric vehicle high-voltage lithium-ion battery pack fires. The equipment combines a self-contained compressed-air actuator with a precision piercing nail on a wheeled device (Figure 17). The equipment is connected to a standard fire hose supplying water.

Operation of the device requires two fire-fighters, one that position the wheeled piercing device under the vehicle and another one at the control unit to activate the device.



Figure 17. The wheeled device that is placed underneath the battery pack of an electric vehicle. The device is connected to a hose line and a self-contained compressed-air actuator with a precision piercing nail. Once the nail has penetrated the undercarriage into the battery pack, water begins flowing to cool the battery cells (ELBAS, 2022).

Once penetration occurs, water flows at approximately 30 l/min at 6.9 bars directly into the affected modules or cells. The equipment underwent one test in the ELBAS project, where the reach of the piercing lance was insufficient to fully pierce the battery pack of the battery electric vehicle. Therefore, the tires of the vehicle were deflated which allowed the battery pack to be pierced. The equipment failed to extinguish the fire as the battery compartment was being opened during the short-circuiting process. Further investigation after the test concluded that the device successfully pierced through the battery compartment, but due to the opened compartment the test was unsuccessful. The device relies on the injected water remaining in the battery pack absorbing heat from the battery.

The equipment is suitable for battery packs which are positioned on the underside of the vehicle. Identification of the specific battery pack which is on fire is vital for the effectiveness of the device. In vehicles where the battery modules are positioned at different parts of structure of the vehicle there could be an additional challenge. But if the equipment is effectively used on the battery pack on fire in due time, the device can cool the battery pack down with a lower water consumption than the extinguishing lance. The other concern raised in the ELBAS project with this method is that it can be costly, both in time and financial resources, it would require significant training for field applications, and there is a risk the fire hazard increases if an operator penetrates an uninvolved battery cell.

The extinguishing lance is designed to be used after the major fire in other parts of a vehicle has been extinguished and there are signs of thermal activities in the battery pack. The lance is electrically isolated and equipped with different extension tubes allowing adjustments depending on circumstances. A sledgehammer is used to penetrate the battery with the tip of the lance. This requires both skill and strength for operation under very extreme conditions. Once the lance is placed securely into the battery pack the water can be allowed to run until the battery has cooled down sufficiently. Two tests were conducted, one using sea water, the other using potable water. During the testing day, flaming combustion was not achieved in the battery pack and therefore, the conditions inside the structure were not as severe as in a fully developed fire.

The overall conclusion in the project was that cooling of the battery is advantageous and extremely efficient when controlling the battery fire and that a considerably lower amount of water is required as compared to other water based extinguishing systems used in the series of tests. However, the device is not capable of putting out the flames inside the passenger cabin and is the most applicable when only the battery fire is the concern. It is required

that the flames outside the battery have been put out prior to using the device. The intended use is primarily to cool down the battery after the fire has been extinguished. It is worth noting that the device was used further after some of the other tests as a precautionary method to ensure the battery thermal runaway reactions had stopped. Direct injection methods can be effective but need to be tested in a more realistic condition and if implemented, the equipment requires in-depth crew training.

#### 4.6.5.5 Testing of the Battery Briner system (2023)

Brine is a high-concentration solution of salt (NaCl) in water (H<sub>2</sub>O) and is used on board ships as a secondary fluid in large refrigeration installations as a coolant. The lowest freezing point obtainable for NaCl brine is -21.1°C at a concentration of 23.3% NaCl by weight. Brine needs an insulated tank that can circulate the fluid, to keep the right temperature (Figure 18).

A Battery Briner system has been fitted by Smyril Line on the 1 600 passenger ships *Norrøna* (built 2003). It utilizes super-cooled salt water at -19°C. The system is installed on the car deck of the ship, with normal fire hydrant connections for hoses. The system relies on a device with nozzles, which fire-fighters or crew can push into the burning car and flood the interior with super-cooled brine at a rate of 250 l/min. The vessel's system can deliver the brine for an hour. It is believed that the high conductivity of the salt and water solution also supports cooling of the battery and its environment, thereby reducing the risk of fire propagation. Smyril Line is also building the system into its methanol-powered newbuilding's. The fire-fighting tool has been developed by Faroese offshore vessel operator Skansi Offshore and Danish naval architects Knud E Hansen (TradeWinds, 2025).

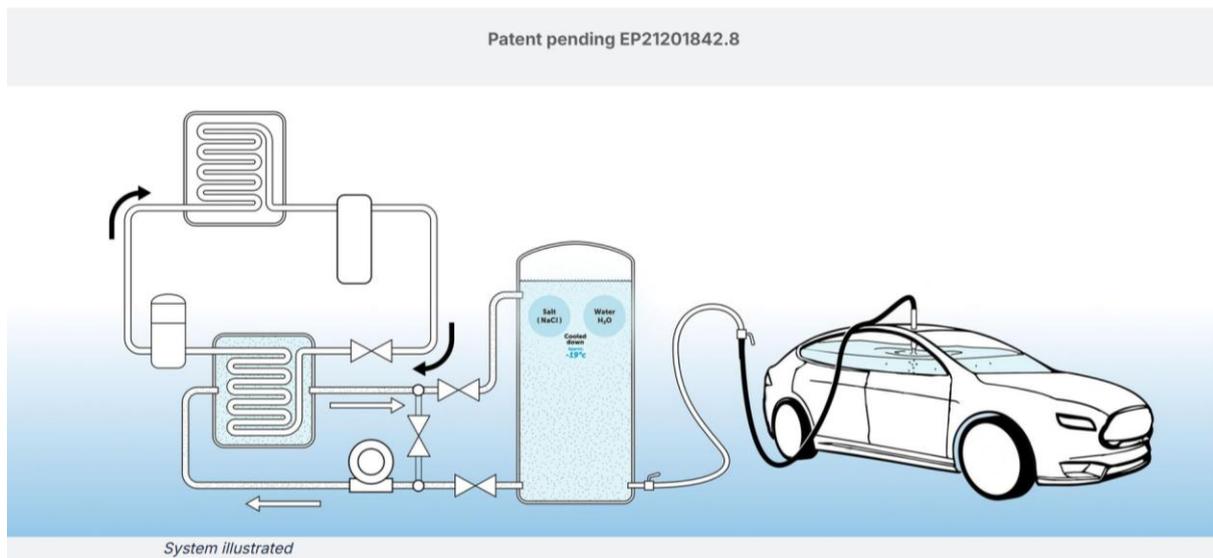


Figure 18. An illustration of the Battery Briner system (<https://www.batterybriner.com/our-process>).

In the event of a fire, one window of the vehicle is penetrated, and cold, saturated brine is delivered directly into the cabin using the device with nozzles. This discharge will not only suppress the fire inside the passenger cabin but allows the fluid to pool around the battery compartment. Fluid that enters the battery pack can cool the cells, limit oxygen exposure, suppress flammable materials, and even short-circuiting and depowering the battery.

In 2023, a large-scale free-burning test of an electric vehicle was conducted. DBI was assigned to document the test by local temperature measurements on the vehicle, inside and outside of the battery pack, by means of an infrared thermographic camera and to conduct test observations supplemented by photos and video recordings. However, DBI did not assess the extinguishing method and its effectiveness.

A Renault Zoe (model year 2018) was used in the test and the battery was charged to its full capacity. Testing was performed outdoors, at local premises in Faroe Islands. The fire was initiated inside the battery pack with a heating element introduced in-between battery modules. After about five minutes, there was visible smoke and after eight minutes, an alarm sounded. A water spray from nozzles, mimicking a drencher system installed above the vehicle, was initiated after 13 minutes. After 16 minutes the water spray application was stopped, and a minute thereafter the rear and one of the side windows were smashed by a fire-fighter. The application of Brine was started by

inserting the device with spray nozzles through the rear window after 18 minutes, followed by starting water spray application from the over-head nozzles after 20 minutes. After 30 minutes, flames were observed underneath the vehicle and fire-fighters returned to the scene to continue battling the fire, and an undercarriage water spray device was inserted under the vehicle after 44 minutes. After 52 minutes, no visible flames were observed, the Brine device was removed after 72 minutes, the application of water from the over-head nozzles were stopped after 75 minutes and after 78 minutes water discharge from the lateral sides of the vehicles started. The test was stopped after 98 minutes. The day after, the fire scene was examined. There were no signs of fire re-ignition, and the battery pack was completely flooded by water (Radulescu & Firkić, 2023).

4.6.5.6 Water injection through a hose pre-installed on the electric vehicle (2025)

Kang, *et al.* (Kang, Yu, & Lee, 2025) at the School of Mechanical Engineering in South Korea have conducted research that suggests a concept with cooling by water delivered directly into the battery case through a hose pre-installed on the electric vehicle. Model-scale experiments with lithium-ion batteries were conducted, and the results were analysed using a simplified heat transfer model. The findings show that water injection can suppress a battery electric fire in a passenger car within minutes using approximately 100 kg of water. Compared with conventional fire-fighting tools, the concept offers faster response, reduced water use, improved containment of harmful gases, compatibility with various vehicle designs, and enhanced fire-fighter safety.

The principle of a proposed water injection system consists of a primary discharge fire hose (from a fire truck or a water hydrant), a water injection socket on the body of the electric vehicle, a connecting fireproof hose to the battery case, and inlet and outlet valves installed on the case (Figure 19). Pressure-relief valves at the inlet and outlet of the case protects the battery from external moisture and dust during normal operation.

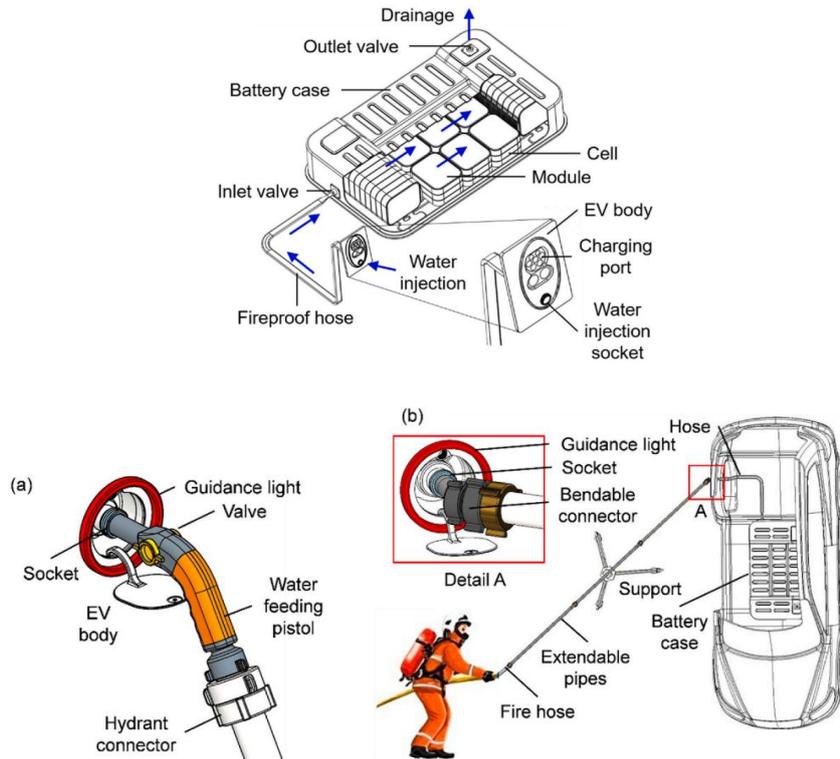


Figure 19. The principles of a permanent water-cooling connection to suppress a thermal runaway in the battery pack of an electric vehicle and the required equipment (Kang, *et al.*, 2025).

4.7 Testing of fire blankets

4.7.1 Introduction

Fire blankets are deployed over a burning electric vehicle to smother flames by cutting off the oxygen supply to both the exterior fire and the underlying battery pack. This tactic can rapidly eliminate visible flaming and provide a

control the fire growth rate. Fire blankets can also be used to cover a vehicle not on fire to protect it from being involved in fire. However, recent testing has raised concerns regarding accumulation of unburnt combustible vapours under the fire blanket cover, creating an explosion hazard. The results from some projects that have investigated the performance and tactics of using fire blankets are summarized here.

#### 4.7.2 Testing of fire blankets in the ELBAS project (2022)

Refer to section 4.6.3.

#### 4.7.3 Testing of fire blankets in the LASH FIRE project (2023)

LASH FIRE report D06.8 (Bleye, et al., 2023) describes that fire scenarios with battery electric vehicles in ro-ro cargo spaces were simulated to evaluate fire blanket effectiveness in smothering flames and slowing down thermal propagation. The performance was measured by the time to flame knock-down, surface heat flux reduction, and duration of smothering under varying vehicle configurations. Fire blankets may be an option in certain cases, however, there are challenges and limitations. To apply a fire blanket properly on a vehicle fire, the fire team need to act near the fire. Also, the fire blanket need to be placed accurately to reach the maximum expected performance. The short distances between vehicles in a ro-ro space is also a challenge due to reasons of access. Based on practical testing, the following benefits of fire blankets were listed:

- Good efficiency for general car fires, in particular for engine/passenger/hood compartment fires.
- Large sized, typically 6 m by 8 m fire blankets, allows safe approach with adjacent vehicles as heat/flame barriers, if these adjacent vehicles are not involved in fire.
- Contains energy bursts in case of fire re-ignition.
- Reduces the amount of smoke in the space and additional steam generation.
- Stabilizing psychological effect due to fire/car not visible.
- Short crew heat/smoke exposure time.
- Good option if water system supply is not operative.

The following shortcomings are listed:

- A fully parked scenario with great cargo variation can jeopardize the effective blanket deployment.
- Fire-fighters need to be close to the car to apply blanket, which is not possible with a fully developed fire, without previous suppression by water.
- Captures smoke underneath at time of application and may temporary direct it towards the fire-fighters.
- Require manual activities on all sides of fire scene, challenging tactical ventilation.
- Requires two fire-fighters for application plus, in a developed fire state, two protective hose operators if water shield is needed for application and return.
- Limitation with roof racks and high vans to deploy the blanket smoothly.

In the LASH FIRE report D06.9 (Ribeiro, Karimpour , Flachi, Bleye, & Gehandler, 2023), it is concluded that a fire blanket may be valuable for a general car fire, but it does not stop a thermal runaway or jet flames. The thermal runaway will proceed regardless of oxygen, but the consequences can be suppressed with the blanket. If the fire is in the engine compartment or if the traction battery is involved, cooling of the battery and the surrounding with water is required to prevent fire spread or apply a fire blanket as a defensive strategy that prevents fire spread.



Figure 20. The application of a large fire blanket by two fire-fighters, with protection by two fire-fighters using fire hoses (LASH FIRE, 2023).

The following tactics are suggested in the report: Place the fire blanket on the deck in a safe position in front of or behind the vehicle and unfold it. Organize a fire hose team for protection of the fire blanket team to allow for a safe approach. The weight of a fire blanket is 20 kg to 25 kg and requires fit, strong crew members for handling and application. Two fire-fighters should grab the blanket by the handles and pull it over the vehicle in a continuous movement, using adjacent vehicles as a safety barrier (Figure 20). It should then be ensured that the fire blanket is tight to the ground, by walking around the vehicle as close as safely possible. There is no need to remove the blanket, water mist lance or water-cooling device once they are in position. Leave the fire blanket in place and continue water supply until arrival at port and only discontinue on advice from shore-side fire department. One of the attributes with lithium-ion battery fires is the risk of re-ignition after the fire has apparently been extinguished. It is therefore important to monitor and cool an “extinguished” electric vehicle fire until it has safely returned to port. This should be done even if there is no evidence of a fire in the battery.

#### 4.7.4 Testing of fire blankets by the NFPA (2025)

Research by the NFPA’s Fire Protection Research Foundation (FPRF) and UL’s Fire Safety Research Institute (FSRI) has evaluated fire blankets for battery electric vehicle fires alongside standard hose streams (water only, water with injected agent) and under-vehicle nozzles (NFPA, 2025). These studies aim to determine each method’s effectiveness in suppressing fires and managing “stranded” energy in battery packs. The following drawbacks of using fire blankets have been raised when there is battery involvement:

- Continued thermal runaway in the battery pack releases flammable gases beneath the blanket. Although flames are suppressed, the chemical reactions inside the cells persist, generating combustible vapours that accumulate in the oxygen-depleted space under the cover.
- If air is re-introduced through blanket movement, venting, or lifting the trapped gas mixture can ignite or explode, endangering fire-fighters operating nearby. Experimental trials recorded instances where such events posed significant blast hazards during post-suppression overhaul activities.

It is stressed that deployment tactics and standard operating procedures must be revised to incorporate gas-monitoring and controlled venting strategies. Until comprehensive guidelines are established, first responders are advised to use blankets in battery electric vehicle fires with caution and consider alternative suppression methods when battery involvement is confirmed.

## 4.8 Fixed-installed drencher, automatic sprinkler and water mist system testing

### 4.8.1 Introduction

Vehicle spaces and ro-ro spaces not capable of being sealed and special category spaces shall be fitted with a fixed water-based fire-extinguishing system complying with the provisions of the Fire Safety Systems Code (FSS Code). Detailed design and installation guidelines for such systems are given in MSC.1/Circ.1430. These guidelines were published in 2012 and are intended to replace both the prescriptive requirements of Resolution A.123(V) (from 1967) for conventional water spray systems (often denoted 'drencher systems') and the performance-based requirements of MSC.1/Circ.1272 (from 2008) for automatic sprinkler and deluge systems.

Two different system options can be used according to MSC.1/Circ.1430:

- Prescriptive-based systems: These systems are designed and installed per sections 1, 2 and 3 in MSC.1/Circ.1430. In addition, prescriptive-based systems should comply with section 4 and be designed per the design tables 4-1 to 4-3 of MSC.1/Circ.1430; and
- Performance-based (or 'alternative') systems: These systems are designed and installed per sections 1, 2 and 3 in MSC.1/Circ.1430. In addition, performance-based systems should comply with section 5 and should be tested to the satisfaction of the Administration in accordance with the fire test procedures in the Appendix of MSC.1/Circ.1430. Note: Performance-based (or 'alternative') systems are typically water mist fire protection systems.

The first manual intervention in case of a fire onboard is manual fire confirmation, where a crew member is sent to locate and confirm a fire upon fire alarm. It is a common procedure for all ro-ro ships. For ro-ro passenger ships, the best practice is to activate the fixed the drencher system as quickly as possible upon fire confirmation, as these systems have been shown to effectively suppress the fire if they are activated at an early stage (Tosseviken, 2005; Siewers & Tosseviken, 2016).

### 4.8.2 Drencher system testing in the LASH FIRE project (2023)

A straightforward comparison of the fire suppression performance of a deluge water spray system ('drencher system') for fires involving gasoline-fuelled and battery electric vehicles in test conditions as equivalent as possible with actual conditions onboard was undertaken in the LASH FIRE project (Arvidson, Virkajärvi, Tuomisaari, Eggert, & Meedendorp, 2023). The results from the tests are also described in a submittal from Interferry to the Maritime Safety Committee (Interferry, 2023).

During testing (Figure 21), key parameters such as the heat release rate, the gas temperature above the vehicle and the surface temperature of target steel sheet screens at the sides of the tested vehicle were measured. The make and model of the vehicles are not provided, but all vehicles were considered representative of modern vehicles in the marketplace at the time of the tests. The vehicle denoted BEV1 (model year 2022) had a usable battery energy capacity of 77 kWh, and the vehicle denoted BEV2 (model year 2021) a usable capacity of 45 kWh. Both vehicles were charged to 90 % capacity. The vehicle denoted ICEV1 (model year 2022) had a fuel tank capacity of 58 L and the vehicle denoted ICEV2 (model year 2022) a capacity of 44 L. The fuel tanks were filled to 90 % capacity.



Figure 21. Drencher system tests at RISE comparison of the fire suppression performance of a deluge water spray system ('drencher system') for fires involving gasoline-fuelled and battery electric vehicles (LASH FIRE, 2023).

Fire ignition was arranged such that the gasoline fuel or the battery pack was involved at the initial stage of the fire. It is concluded that fires in the two types of vehicles are different but have similarities. The overall conclusion from the tests was that a fire in an electric vehicle (passenger cars) does not seem to be more challenging for the water spray system design used in ro-ro cargo and special category spaces than a fire in a gasoline-fuelled vehicle of comparable size. It was also concluded that full fire extinguishment of vehicle fires is typically not possible with an over-head deluge water spray system. When the application of water is intentionally stopped, resources should be available to undertake manual fire-fighting efforts.

#### 4.8.3 Automatic sprinkler system testing in the LASH FIRE project (2022)

In the European Union funded LASH FIRE project, design and installation guidelines for automatic water-based fire sprinkler systems, supplementary to a fixed-installed carbon dioxide system, were developed for cargo spaces on ro-ro vehicle carriers (Arvidson, Virkajärvi, Tuomisaari, Eggert, & Meedendorp, 2022). The work was partly based on a comprehensive literature review that identified relevant standards and information applicable to the design of automatic fire sprinkler and deluge water spray systems. Large-scale fire tests (Figure 22) verified that the suggested system designs were able to provide control of realistic vehicle fires, including fires in passenger cars and a freight truck. However, none of the vehicles were battery electric vehicles.

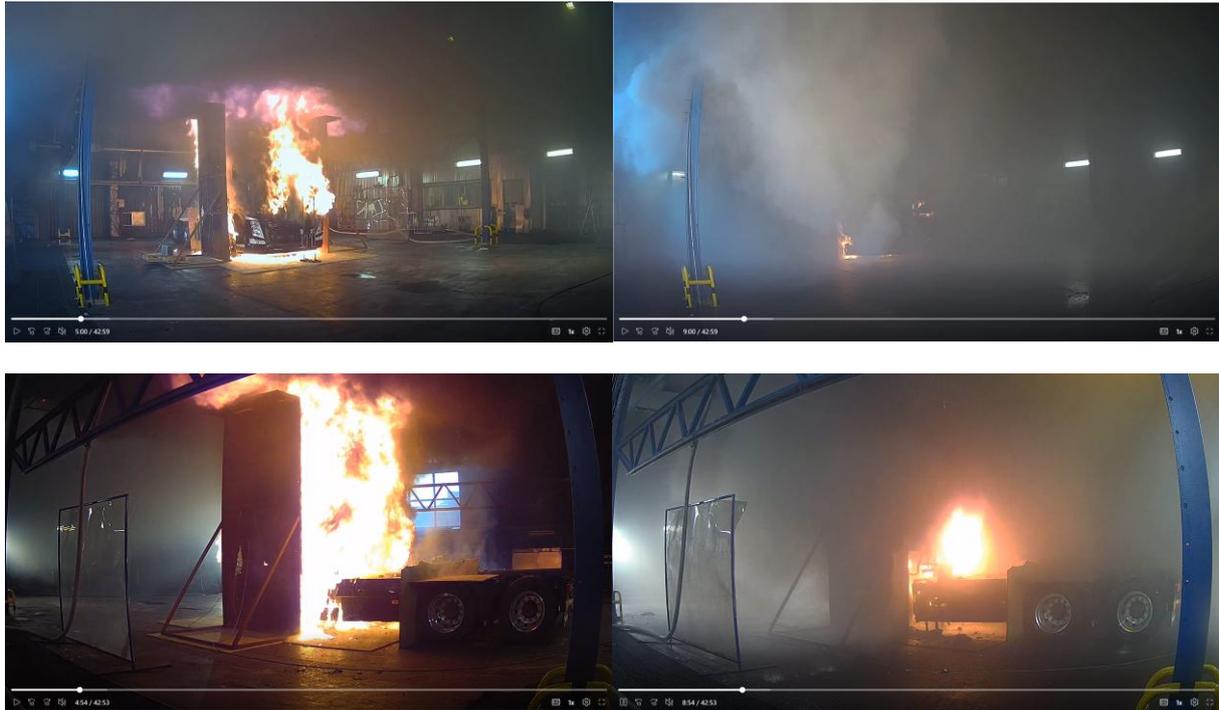


Figure 22. Fire suppression of a freight truck fire by automatic sprinklers installed at the ceiling, seen from two different observation positions. The first of the pair of photos shows the fire at the time when water was distributed from the sprinklers and the second of the pair of photos shows the fire four minutes thereafter (LASH FIRE, 2022).

An important design feature is that the system automatically activates at an early stage of a fire. With automatic sprinklers, only the sprinklers closest to a fire will activate by the heat which will limit the water flow rate. This would allow more time to fight the fire manually or to safely evacuate. If being kept under control by fire sprinklers, the carbon dioxide system can be discharged when the fire is controlled to one or a few vehicles, rather than when it has escalated. However, water from the sprinklers need to be drained from the decks to avoid ship stability issues.

#### 4.8.4 Floor-mounted water spray fire suppression system testing (2024)

EV FirePro is a floor-mounted, water-based fire suppression system (EV Fire Protection Pty., 2024). The system consists of a unit that is installed at the parking area of individual vehicles in for example a parking garage. The unit consists of 21 pcs of stainless-steel water spray nozzles that is either directed vertically (seven nozzles) or laterally (fourteen nozzles). The minimum flow rate of the system is 285 l/min at 1.6 bars, but the optimal flow rate is 480 l/min at 7.5 bars. Water supply is provided through a 1 1/2" pipe connection and the feed pipe is connected to a normally open solenoid or motorized ball type valve. Fire detection and activation is based on a signal from an integrated 68°C linear heat detection cable connected to a control panel. The cover plate of the system is sized 1990 mm by 1270 mm and extend about 30 mm above the finished floor. Parked vehicles are supposed to be positioned above the cover plate (Figure 23).

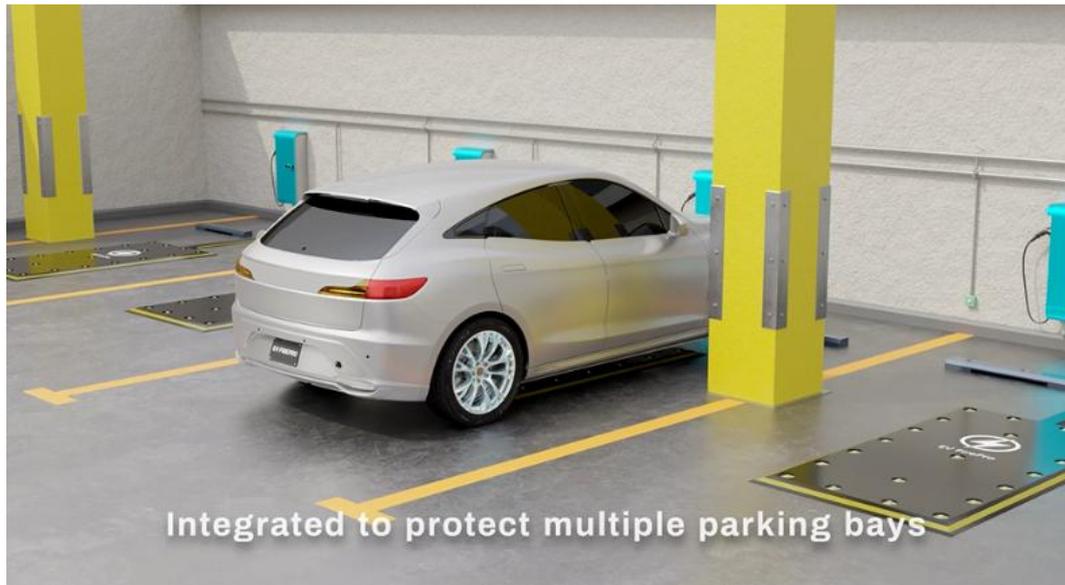


Figure 23. The EV FirePro is a floor-mounted, water-based fire suppression system (illustration from <https://evfirepro.com.au/>).

The system is designed to prevent fire spread to adjacent vehicles and structures, thereby providing a rapid, localized response that helps contain the situation before it escalates into a major fire. The system has undergone independent third-party certification by APPLUS+ Laboratories, validating performance against a battery electric vehicle thermal runaway scenario. The fire test involved a smaller sized electric vehicle having a lithium-ion battery (22 kWh) where the fire was started by nail penetration of the battery pack. Minimum system pressure and water flow rates (as described above) was used, and it was proven that no fire spread to adjacent vehicles occurred, that the gas temperatures around the vehicle was kept below 60°C, that the ceiling gas temperatures were below 250 °C and that the heat flux around the car was below 2.5 kW/m<sup>2</sup> (SpiderFire, 2025).

#### 4.8.5 Fixed-installed high-pressure water mist system testing (2023)

The submittal SSE 10/INF.10 from China to the Sub-Committee on Ship Systems and Equipment (China, 2023) describes a fire suppression test conducted using a fixed-installed high-pressure water mist system. A test area that was 12 m by 12 m by 2.5 m (H) was built inside a fire test hall having a floor area of 336 m<sup>2</sup> with an 8.2 m ceiling height. A passenger car mock-up as described in MSC.1/Circ.1430 was constructed (Figure 24). This mock-up consists of a vehicle body steel sheet structure. Target screens made from plywood panels were positioned at each side of the mock-up to mimic adjacent vehicles. A lithium-ion battery pack was in the middle and rear of the mock-up, placed on top of a heating plate. The battery pack was supported by a steel frame, so that the bottom of the battery pack (including the heating plate) was flush with the bottom plate of the mock-up. The battery pack was of the lithium nickel manganese cobalt oxides (NMC) type, had a total energy capacity 50 kWh and was charged to 95 % of its capacity. The battery cells were arranged inside a battery tray according to the 3P90S, having a size of 800 mm by 400 mm by 200 m (H).

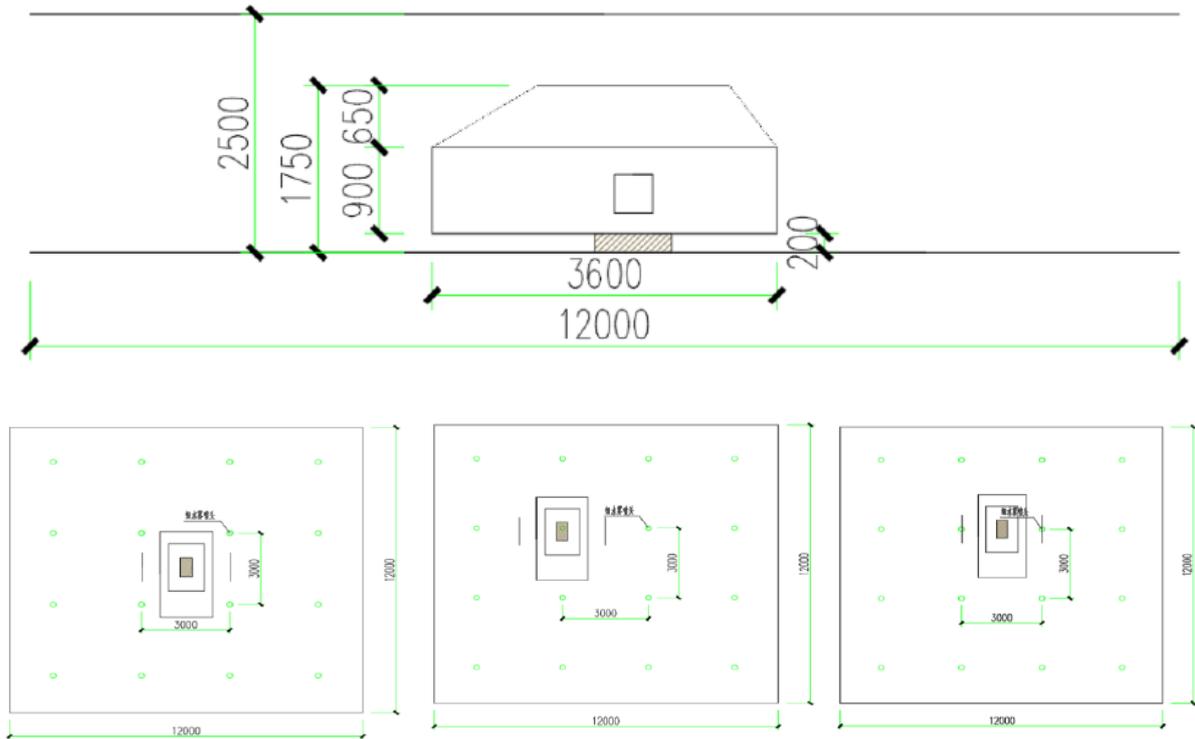


Figure 24. A side view of the passenger car mock-up with the position of the battery pack and the position of the mock-up in relation to the open high-pressure water mist nozzles at the ceiling (SSE 10/INF.10, China, 2023).

A total of sixteen open high-pressure water mist nozzles were located 200 mm below the ceiling of the test area (Figure 24). The rated working pressure of the nozzles was 10 MPa (100 bar), and the flow coefficient pf the nozzles was  $K=1.0 - 2.0$ . Note: The flow rate from each nozzle was thereby between 10 l/min and 20 l/min. The nozzles were spaced 3 m apart, and the spray angle of the nozzles was  $120^\circ$ . Three fire tests were conducted where the passenger car mock-up was positioned either between four water mist nozzles, directly below one nozzle or between two nozzles. The fire tests procedures were as follows: The battery pack was continuously heated until thermal runaway occurred. After open flames were observed the battery pack was allowed to burn for 2.5 min and the high-pressure water mist was [manually] activated and allowed to spray water for 10 min.

The temperature around the passenger car mock-up was at most  $270^\circ\text{C}$  before the high-pressure water mist system was activated, but the temperature was significantly reduced after activation. After about 1.5 min, the surrounding temperature was below  $50^\circ\text{C}$ . The maximum temperature at the bottom of the mock-up was  $243^\circ\text{C}$  but dropped to below  $50^\circ\text{C}$  after applying water mist for one minute and was reduced to ambient temperature three minutes later.

The overall conclusion from the three tests is that a high-pressure water mist fire suppression system could effectively suppress the fire in the passenger car mock-up. The average temperature measured by any thermocouple at the ceiling did not exceed  $350^\circ\text{C}$  within five minutes and target plywood panels to the side of the mock-up did not ignite. The test mock-up was allowed to stand for 24 h without re-ignition. Note: It does not seem that the battery pack was “built-in” and shielded from the application of water to the degree expected in an actual battery electric vehicle and the mock-up did not contain additional combustible materials as plastics, rubber, lubricants, flammable liquids, etc. associated with an actual vehicle. The overall fire severity is therefore probably less than anticipated in reality.

#### 4.8.6 Fixed-installed low-pressure water mist system testing in the ELBAS project (2022)

Refer to section 4.6.3.

## 4.9 Fixed-installed high-expansion foam system testing

### 4.9.1 Introduction

Paragraph 6.1.1 of SOLAS II-2, Regulation 20 - Protection of vehicle, special category and ro-ro spaces, requires that vehicle spaces and ro-ro spaces, which are not special category spaces and are capable of being sealed from a location outside of the cargo spaces, shall be fitted with either a fixed gas fire-extinguishing system, a fixed high-expansion foam fire-extinguishing system or a fixed water-based fire-extinguishing system for ro-ro spaces and special category spaces.

This section describes fire tests using fixed-installed high-expansion foam systems.

### 4.9.2 Fire suppression testing involving a single battery electric vehicle (2022)

The submittal SSE 9/INF.4 from Japan to the Sub-Committee on Ship Systems and Equipment (Japan, 2022) describes a fire suppression test conducted with an outside-air high-expansion foam system utilizing a single battery electric vehicle (passenger car). The vehicle had a lithium-ion battery pack with an energy capacity of 24 kWh. The vehicle was surrounded by walls of metal sheeting, that allowed air to pass through to the fire but not foam to escape (Figure 25). No ceiling was used. The fire was allowed to burn until the intensity was approximately constant. Thereafter, high-expansion foam having a nominal expansion ratio of 900:1 was discharged at a nominal filling rate of 1 m/min.



Figure 25. A fire suppression test using an outside-air high-expansion foam system utilizing a single battery electric vehicle. The vehicle was surrounded by walls of metal sheeting, that allowed air to pass through to the fire but not foam to escape (SSE 9/INF.4, Japan, 2022).

It was concluded that the fire was suppressed by the high-expansion foam, and although the foam could not stop the thermal runaway of the battery pack, it successfully prevented fire ignition of flammable gaseous electrolyte from the battery and suppressed the fire. Therefore, it is judged that high-expansion foam fire-extinguishing systems are effective in preventing propagation of heat from a vehicle on fire if the vehicle is submerged in the foam.

**4.9.3 Fire suppression testing varying the foam filling rates (2024)**

The submittal SSE 11/INF.5 from Japan to the Sub-Committee on Ship Systems and Equipment (Japan, 2024) describes fire suppression testing with an outside-air high-expansion foam system using a fire test source that simulates a fire in a vehicle. During the fire tests the nominal foam filling rates were varied. The test fire consisted of three rectangular fire trays, each measuring 1.2 m<sup>2</sup>, filled with heptane (Figure 26). The fire trays were positioned inside a mock-up mimicking the body of a passenger car. The mock-up was constructed using perforated steel sheets, which was permeable for air, to provide the desired heat release rate. However, the construction prevented foam from reaching the fire, apart from foam entering through the openings that modelled the window openings. The measured heat release rate with one, two and three fire trays was 2.7 MW, 4.5 MW and 6.3 MW, respectively.

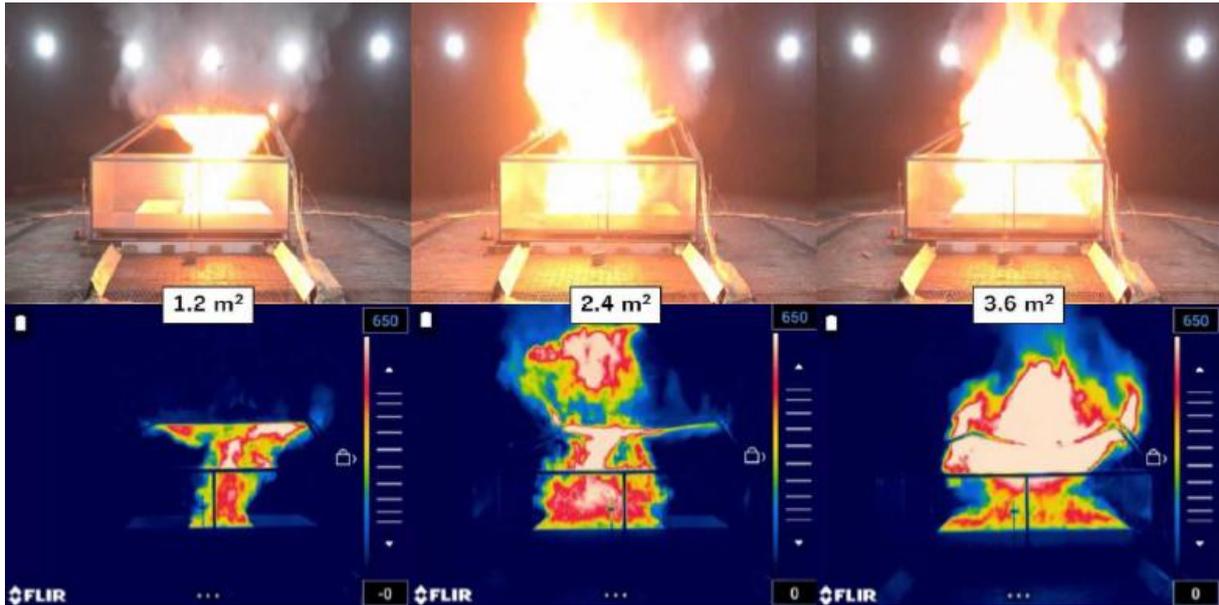


Figure 26. The arrangement of fire trays with heptane inside a positioned inside a mock-up mimicking the body of a passenger car, illustrated with actual photos and with thermal imaging photos (SSE 11/INF.5, Japan, 2024).

The discharge of foam was started 60 s after initiation of fire. When the layer of foam started to build at the front of the vehicle mock-up, air started to flow from the back and towards the front. The flames that had been straight up then changed direction and projected from the opening simulating the broken windshield. When the foam reached the height of the windshield opening, it was blown away by the flow of hot gases. It was not until the discharge rate was sufficiently high to overcome the heat-induced gas flow that the foam flowed into the inside of the mock-up and covered the fire trays, resulting in successful fire extinguishment. Fire suppression and fire extinguishment was not possible when the heat-induced gas flow was stronger than rate of foam discharge. Based on the fire tests, it was concluded that a filling rate of approximately 0.72 m/min for a foam having an expansion ratio of 900:1 is required to extinguish a 4 MW vehicle fire. This implies that an outside-air high-expansion foam system need to be designed for filling rate of at least 1 m/min to provide a certain safety margin.

**4.9.4 Fire suppression testing using multiple vehicles (2024)**

The submittal SSE 11/INF.5 from Japan (Japan, 2024) also describes fire suppression tests with an outside-air high-expansion foam system involving multiple vehicle fires (Figure 27). A “test fire platform” sized 12.2 m by 10.7 m width was built inside fire test hall with a 400 m<sup>2</sup> floor area. The platform was surrounded by walls of metal sheeting, that allowed air to pass through to the fire but not foam to escape. The objective of the fire suppression tests was to evaluate the effectiveness of high-expansion foam under conditions that simulated actual situations more closely. A single or multiple vehicle fires was simulated using mock-ups that had the same structure and fire tray arrangement as described above. Mock-up vehicles made of steel sheet plates surrounded the fire test sources and acted as obstacles for the spread-out of foam. The ceiling height of the platform was 2.5 m, and the depths of the girders and stiffeners of the deck were 600 mm and 200 mm, respectively.

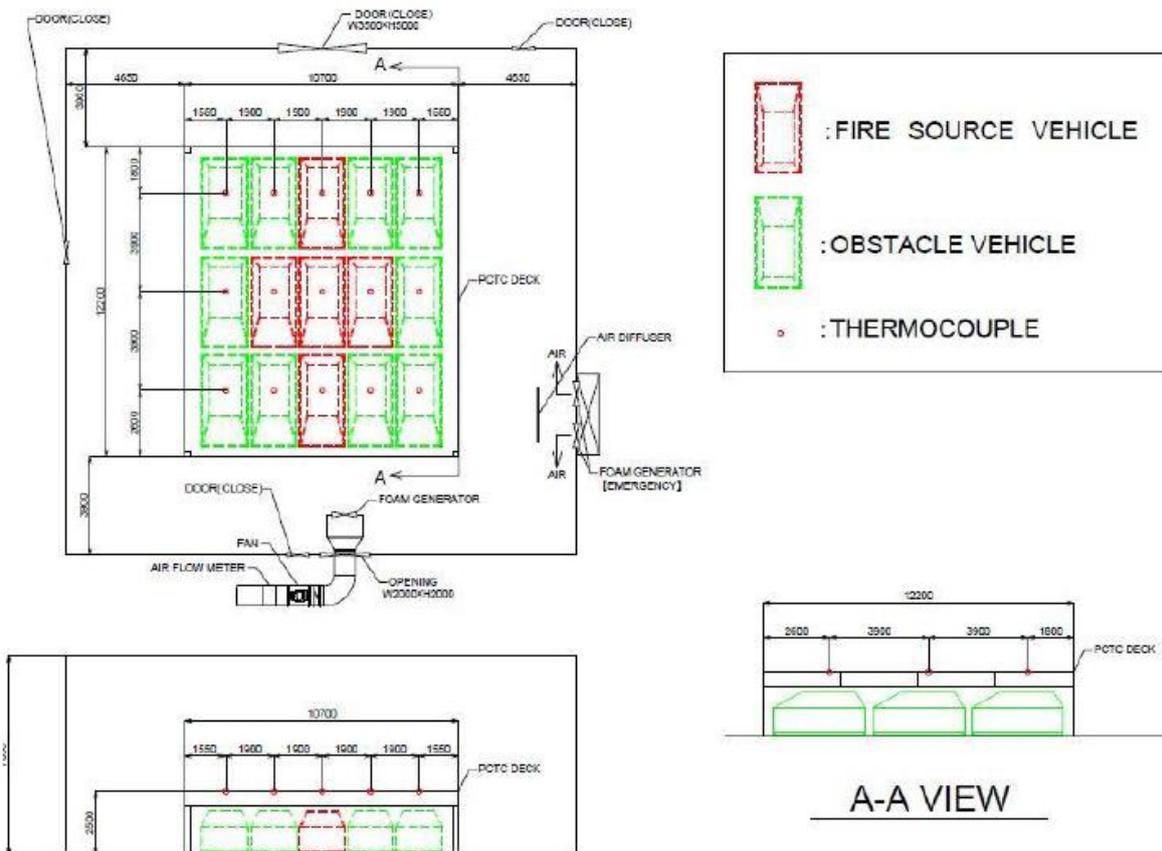


Figure 27. Fire suppression tests with an outside-air high-expansion foam system involving multiple vehicle fires. Mock-up vehicles made of steel sheet plates surrounded the fire test sources and acted as obstacles for the spread-out of foam (SSE 11/INF.5, Japan, 2024).

Two fire trays were used for each mock-up representing the fire test source, i.e. each vehicle provided a heat release rate of 4.5 MW. The fire test series included simultaneous fire in one, three or five simulated vehicles, respectively. The foam discharge rate was adjusted to the nominal filling rate of 1 m/min. The foam discharge was started after 60 s from the ignition of all fire trays (the last fire tray) in all tests and the time required for the suppression of the fire source was measured from the starting of foam discharge. The time to suppression corresponded to the time when the temperature measured by a thermocouple located immediately above the fire tray (100 mm below the deck) started decreasing. The results of the fire suppression tests indicate that an outside-air high-expansion foam system providing a nominal filling rate of 1 m/min can suppress fires in up to five vehicles. No delays in foam spreading speed or fire suppression time were observed during the tests. This suggests that systems with the same foam filling rate could potentially suppress fires involving even more vehicles.

## 4.10 Fixed-installed gas-extinguishing system testing and experience

### 4.10.1 Introduction

Paragraph 6.1.1 of SOLAS II-2, Regulation 20 - Protection of vehicle, special category and ro-ro spaces, requires that vehicle spaces and ro-ro spaces, which are not special category spaces and are capable of being sealed from a location outside of the cargo spaces, shall be fitted with either a fixed gas fire-extinguishing system, a fixed high-expansion foam fire-extinguishing system or a fixed water-based fire-extinguishing system for ro-ro spaces and special category spaces.

On vehicle carriers, the fixed fire-extinguishing system (carbon dioxide or high-expansion foam) needs to be activated until all crew members have been counted in, to make sure no person is left in the space. Moreover, all ro-ro spaces openings (e.g. ramp, ventilation ducts, etc.) shall be closed to ensure effectiveness of carbon dioxide system, whereas, for foam system, it is necessary to open specified ventilation ducts. The discharge time for the carbon dioxide system during a real fire event is typically around 30 minutes (Arvidson & Karlsson, 2024). For foam systems, Kashiwa tech, *et al.* conclude that *“The timing of foam discharge in the cargo space where a fire has*

*occurred has a dominant effect on whether fire extinguishing/suppression by high-expansion foam fire extinguishing systems is successful or not” (Ota, 2024).*

#### 4.10.2 Testing of carbon dioxide and other agents by China (2020)

A submittal (China, 2020) from China to the Sub-Committee on Ship Systems and Equipment at the International Maritime Organization includes a short report on a series of fire detection and fire suppression system tests for ships carrying lithium-ion battery electric vehicles. The actual testing was conducted inside a modified 20 ft. freight container. The container had several operable doors. When closed, the container simulates a closed space, and when open an open space was simulated. The inner side of the container was covered with thermal insulation material, and the top of the container had an air inlet, an outlet and a mechanical fan. The test series consists of two parts: Fire detection tests and fire-extinguishing tests. During the fire detection tests, two comparative tests were designed to verify the response of a smoke and a heat spot-type detector installed at the same position or at different positions. In the fire-extinguishing tests, the effectiveness of five fixed fire-extinguishing systems (carbon dioxide, heptafluoropropane, an aerosol fire-extinguishing system, a water mist system and a low-expansion foam system) was compared. Each type of system was tested at least four times in order to handle any random variations in the tests. Note: Heptafluoropropane is also known as HFC-227ea (ISO name), HFC-227 or FM-200.

A passenger car mock-up as described in MSC.1/Circ.1430 was constructed. This mock-up consists of a vehicle body steel sheet structure, and it was fitted with a battery pack that was in the middle and rear of the body and at the chassis position. Note: There is limited or no information in the report about the size, number of modules, number of battery cells, energy capacity, state of charge, etc. of the battery pack. From the illustration and photos in the report it seems that the battery pack was positioned on a framework of square steel tubes placed directly on the floor inside the mock-up. It does not seem that the battery pack was “built-in” and shielded from the application of the agents used in the tests to the extent expected in an actual battery electric vehicle.

During the fire-extinguishing tests in the closed container, the fire was initiated by overcharging the battery pack with the vents and mechanical fan in operation. After fire ignition, the fire was allowed to burn for about 2 min, the vents were closed, the mechanical fan was stopped, and the gas or aerosol fire-extinguishing system was discharged. The temperature change of the battery pack, the vehicle mock-up and the inside of the container was measured, and any fire re-ignition or explosion of the battery pack was visually observed. The fire tests in the open container were undertaken using the same procedure, but the container was open when the water mist or low-expansion foam fire-extinguishing system was discharged. Note: There is limited or no information in the report about the amount of agent used, discharge rates, operating pressures, positions of discharge nozzles, type of foam agent, the foam expansion ratio, etc.

The results of the fire-extinguishing tests are summarized below:

**Carbon dioxide system tests (closed container):** Four repetitive tests were conducted, two tests using NMC and two tests using LFP chemistry battery cells. In all four tests, the flame was extinguished immediately after the discharge, and a large amount of white smoke filled the container, resulting in poor visibility, and the temperature of the thermocouples decreased. However, after a period of time, the battery pack re-ignited and the fire could not be controlled in two of the NMC tests and one of the LFP tests. The battery pack in each test was observed during 24 h and had completely burnt out. In the other test using LFP chemistry, the battery pack did not re-ignite, and only the overcharged module was damaged.

**Heptafluoropropane system tests (closed container):** Four repetitive tests were conducted, three tests using NMC and one test using LFP chemistry battery cells. In all four tests, the flame was extinguished immediately after the discharge, and a large amount of white smoke filled the container, resulting in poor visibility, and the temperature of the thermocouples decreased. However, after a period of time, the battery pack re-ignited and the fire could not be controlled in three of the NMC tests. The battery pack in each test was observed during 24 h and had completely burnt out. In the test using LFP chemistry, the battery pack did not re-ignite, and only the overcharged module was damaged.

**Aerosol system tests (closed container):** Three repetitive tests were conducted, including two tests using NMC and one test using LFP chemistry battery cells. In three of the tests, the flame was extinguished immediately after the discharge, and a large amount of white filled the container, resulting in poor visibility, and the temperature of the thermocouples decreased. However, after a period of time, the battery pack re-ignited and the fire could not be controlled. The battery pack in each test was observed during 24 h and had completely burnt out.

**Water mist system tests (open container):** Five repetitive tests were conducted, including three tests using NMC and two tests using LFP chemistry battery cells. In all five tests, the flames were extinguished immediately after system discharge, and a large amount of white smoke filled the container, resulting in poor visibility. The temperature of the thermocouples decreased significantly. The battery pack did not re-ignite in any of the tests. The battery pack in each test was observed during 24 h and were basically damaged by water.

**Low-expansion foam system tests (open container):** Four repetitive tests were conducted, including two tests using NMC and two tests using LFP chemistry battery cells. The flames were not extinguished immediately in any of the four tests after the system discharge as the foam could not reach the battery pack. But the flames gradually diminished due to the cooling effect, followed by presence of a large amount of white smoke in the container. The temperature of thermocouples decreased overall. The battery pack did not re-ignite in any of the tests. The battery pack in each test was observed during 24 h and were basically damaged by water.

Based on the extinguishing experiments, the following conclusions were drawn:

- The water mist system was the most effective and its cooling effect was significantly better than the tested gas fire-extinguishing agents.
- The fire in NMC battery pack was more difficult to extinguish than the fire in the LFP pack. In the heptafluoropropane, carbon dioxide and aerosols system tests, the NMC battery packs re-ignited. The time interval from extinguishment of the flames to fire re-ignition was the shortest in the aerosol system tests.
- The use of a gas fire-extinguishing system alone in the space carrying lithium-ion battery electric vehicles is not effective. If used, there is a need to put forward strengthened requirements of gas tightness of the space, vehicle isolation, and response to fire re-ignition.
- The low-expansion foam system had a good cooling effect but did not provide rapid extinguishment of the flames. In addition, the foam increases the electric conductivity of the liquid agent, which may cause short circuits and electric sparks during the fire-extinguishing process. After a fire is extinguished, there are certain safety risks.

The overall practical conclusions in the report are as follows:

- A fixed fire detection system with smoke detectors or combined smoke and heat detectors is recommended in ro-ro spaces. In addition, it is also recommended to use a supplementary video monitoring system as means to achieve comprehensive detection in the space.
- A fixed water-based fire-extinguishing system, with similar extinguishing mechanisms as that used in the tests (a water mist system) is recommended. If using a gas fire-extinguishing system, the spaces shall be capable of being sealed, and the system is recommended to be designed to provide protection twice so as to deal with any battery re-ignition. Moreover, in the aspect of vehicle isolation, a fire separation water curtain system can be set up for the use of cooling and separation functions.

Note: A general remark regarding the tests is that the design of the passenger car mock-up does not simulate all aspects of an actual battery electric vehicle fire. It can also be remarked that the use of heptafluoropropane and other types of halogenated agents are questionable in large spaces as ro-ro spaces. Halogenated agents used in fixed systems require short discharge times, in the order of 10 s, which would be impossible for the large quantities required in ro-ro spaces. Another critical issue is that fluorochemical specialty gases are used in halogenated fire suppression agents which will likely be classified as per- and polyfluoroalkyl substances (PFAS). This could result in future legislation restrictions on their use (OUSD, 2023).

#### 4.10.3 Field experience with carbon dioxide systems composed in the COFFEE project (2024)

During 2024-2026, RISE is undertaking a project denoted *Carbon diOxide Fire Fighting Experimental Evaluation*, referred to as the COFFEE project. The overall objective of the project is to ensure a safe transportation of battery electric vehicles in ro-ro vehicle carriers. The performance of fixed-installed carbon dioxide systems during vehicle fires on ro-ro vehicle carriers was documented in the first part of the project (Arvidson & Karlsson, 2024). From 2013 to 2023, at least 22 severe fires started in the cargo space of ro-ro vehicle carriers. Eight fires started during loading operations (i.e. when the doors and ramps are open) and fourteen fires started while at sea. In eleven of the 22 fires, information verifies that a carbon dioxide system was used. In five of these verified incidents, the fire was suppressed or extinguished, in five of the incidents the fire was not suppressed nor extinguished, and in one case information about the performance is lacking. For the cases when fire was not extinguished, a long delay time

combined with the fact that the space was not sufficiently sealed may explain the poor performance. Electrical failure, including short circuits, is a commonly noted fire cause in used cars onboard. One of the 22 fires probably originated in a new production electric vehicle; no other fires in electric vehicles were documented. This fire occurred on board Felicity Ace in February 2022, and after the publication of the RISE report it was confirmed that the ship was protected by a high-expansion foam system. The ship capsized and sank in early March 2022 (PMA, 2023).

## 4.11 Test results on effectiveness and operability of fire-fighting procedures in ro-ro spaces

### 4.11.1 Operability and practicability of manual fire-fighting equipment and operations

Several projects have studied the operability and practicability of manual fire-fighting equipment and operations applied to AFV fires in ro-ro spaces.

The BREND project (2018-2019) aimed to identify or develop practical and efficient methods and tactics to limit the consequences of AFV fires (LPG, CNG vehicles, FCVs, EVs, etc.) in ro-ro spaces (Vylund, Mindykowski, & Palmkvist, 2019; Vylund, et al., 2019). It focused on passenger vehicles transported in ro-ro spaces of ro-ro passenger ships. The project work was described in section 4.6.2. Based on that work, the BREND project developed a 6 pages guide related to AFV fire-fighting tactics and equipment for ro-ro spaces, including dedicated sections about preparedness (incl. training and fire drills), manual fire-fighting tactics and post-extinguishment (Appendix 1 of (Vylund, et al., 2019)). One year later, the BREND 2.0 project (2020-2022) investigated two major risks identified in BREND: the risk of toxic gases from EV fires and the risk of pressure vessel explosion from compressed gas vehicles (Gehandler, et al., 2022). As conclusion, the BREND 2.0 project provided updated recommendations, elaborated with a maritime stakeholder group, related to actions to be taken in case of initial fire-fighting, activation of fixed fire-extinguishing system, intervention of the fire team, post-extinguishment and training. A 2 pages guide was developed (Appendix A of (Gehandler, et al., 2022)).

The LASH FIRE project (2019-2023) aimed to develop and validate effective design and operative solutions addressing fire safety challenges on board ro-ro ships. LASH FIRE addressed manual operations, such as cargo screening, fire patrol, fire confirmation and location, first response and fire-fighting. The operative solutions were developed based on literature review, interviews and workshops with maritime stakeholders, onboard visits, and field or simulation tests. Among other, LASH FIRE developed several short guides for ship operators (LASH FIRE, 2025):

- Guidelines for quick manual screening of cargo fire hazards and fire patrols;
- Guidelines for effective first response;
- Guidelines for fire-fighting gear, equipment and tactics considering AFVs; and
- Guidelines for improving procedures and design for activation of fixed fire-extinguishing system (water-based or CO<sub>2</sub> systems) in ro-ro spaces.

The ELBAS project (2021-2022) aimed to develop fire safety strategies for EV fires on board ro-ro passenger ships (Kleiman, et al., 2022). Among other, the project conducted field tests simulating a fire situation in a closed ro-ro space and several manual fire-fighting equipment were tested (refer to section 4.6.3 and 4.6.5.4).

Kim & Jeon have studied cargo hold fire accidents on ro-ro ships and recommend providing additional information to crew members responsible for ventilation and sealing operations, emphasizing the importance of these actions from the initial fire-fighting stages. It is also crucial to ensure an effective training system for personnel responsible for the operation of fixed fire-extinguishing systems. Additionally, it is suggested that simplifying relevant diagrams will enhance comprehensibility for all crew members (Kim & Jeon, 2023).

In November 2024, a process simulation of a vehicle carrier fire was conducted in the Port of Emden, Germany (BMV, 2025). The onboard and port simulation not only involved the maritime stakeholders but also the port and land-based ones. The purpose of that simulation was to analyse the process from fire detection to the end of all actions taken. A fire was simulated on deck 9 thanks to a fog generator. The deck was populated with cars and all the ramps were initially closed excepted the one on main deck which was open. The fire emergency simulation was not specific to AFV.

Port of Trelleborg together with the Rescue Service and Stena Line also conducted a cooperation exercise on board the ro-ro passenger ship Mecklenburg-Vorpommern in the port (2023) and recently (2025) had another practise in port. The purpose of the exercise is to practice cooperation and response in the event of a fire on board a ship, a situation that requires close and effective cooperation between several authorities and organizations (FerrySafe23, 2023).

#### 4.11.2 Training and on-board safety drills

Lastly, several projects worked on the development of training or onboard safety drills specific to ro-ro spaces or to hazards of AFVs. All those initiatives received positive feedback from participants (i.e. seafarers) and have raised their awareness, readiness and confidence in case of emergency situation related to AFVs.

The ALBERO project (2018-2021) developed a web-based interactive training system, structured according to the different operations on board ro-ro passenger ships (ALBERO, 2021). The training module provides knowledge about how to identify the different types of AFVs, recommendations about how to safely load and locate the AFVs onboard or how to safely install charging points. It also includes instructions in case of emergency situations. The training materials cover different types of AFVs: EVs, LPG, CNG, LNG cars, FCVs and electric bikes.

The LASH FIRE project (2019-2023) developed and tested several training modules (Figure 28), such as:

- 2 days training module on first response and manual fire-fighting on AFVs; and
- 1 day training module on activation of fixed fire-extinguishing systems.

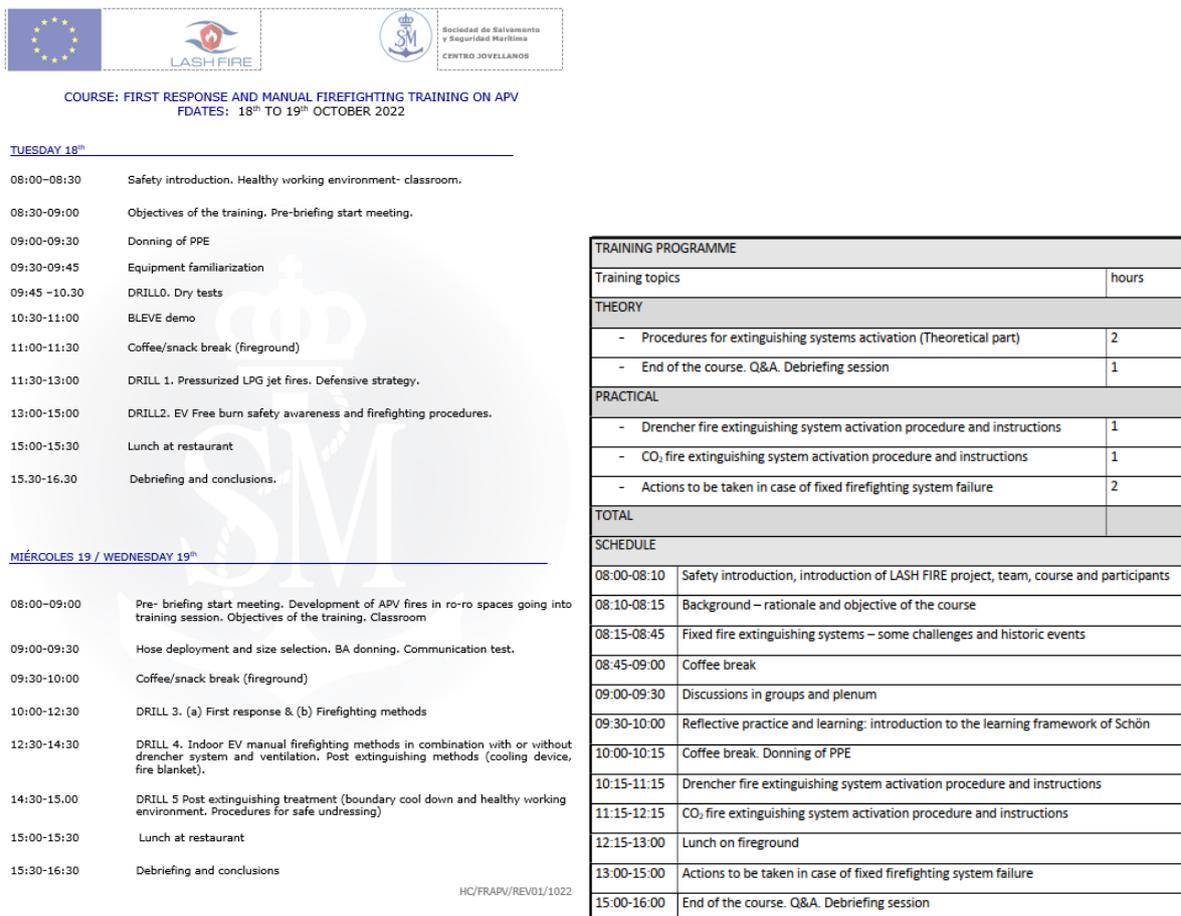


Figure 28. Training programmes developed and tested by LASH FIRE.

The ELBAS project (2021-2022) conducted a pilot fire training course, with focus on how to extinguish a modern vehicle fire on board a ro-ro passenger ship (Kleiman, et al., 2022).

To the knowledge of the authors, several land-based first responders training programmes on hazards of compressed gases infrastructures or mobility already exist. As example, the French School of Fire-Fighter Officers (ENSOSP) proposes a hydrogen risk training programme, including theory, virtual reality and simulation exercises (e.g. activation of the pressure relief device of a FCV) in real conditions (ENSOSP, 2025). For that programme, a dedicated training platform was built in order to train first responders and fire-fighters on hydrogen up to 700 bars or on liquid hydrogen.

In November 2025, NFPA should update their EV land-based training modules based on recent research findings and issue eight new micro learning modules related to hazard recognition, traditional fire attack, blanket system suppression, post-incident operations, etc. (NFPA, 2025)

## 5. Review of the available numerical physical-chemical-mathematical models and simulations

### 5.1 Introduction

With the growing adoption of electric vehicles and hydrogen-powered alternatives, the maritime sector faces new challenges in fire safety, particularly aboard ro-ro ships and in port environments. This chapter reviews prior research on battery fire modelling, emphasizing its relevance to marine transport and shipping operations. Key areas include heat transfer analysis, computational fluid dynamics (CFD), and toxic gas dispersion from battery fire events. CFD tools like Fire Dynamics Simulator (FDS) (McGrattan, et al., 2025) and others have been used to simulate gas spread within enclosed spaces such as ro-ro and vehicle spaces.

### 5.2 State-of-the-art modelling tools

The state-of-the-art in numerical modelling of battery thermal runaway, propagation, and associated hazards focuses on multi-physics simulation methods that integrate electrical, thermal, chemical, and fluid dynamic processes. According to (Huang, Temple, Ramachandra, Anderson, & Andersson, 2021), advanced tools such as GT-Suite, COMSOL Multiphysics, and ANSYS LS-DYNA are increasingly being used to simulate thermal runaway initiation and propagation at the cell, module, and pack level. These models use finite element (FE) or finite volume (FV) formulations to capture heat transfer and reaction kinetics, often supported by experimental validation (e.g. Accelerating Rate Calorimetry (ARC) tests). Simulations enable researchers to predict the conditions under which thermal runaway propagates, study short circuit effects, and evaluate tenability conditions through coupled CFD analyses of toxic gas dispersion (e.g. HCN, HF, CO).

While high-fidelity multi-physics coupling provides insight into detailed failure mechanisms, these models remain computationally intensive and require extensive calibration data. Simplified 1D/3D hybrid models, like those available in GT-Suite, offer faster simulation times but less accurate flow and dispersion predictions compared to full CFD tools such as FDS. The emerging research trend emphasizes integrating experimental data with numerical simulations to develop validated, predictive tools for battery safety design, propagation mitigation, and toxic gas risk assessment in both domestic and industrial applications. Below follows a short note on commonly used software to simulate gas dispersion and consequence modelling in fire safety.

The Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) software developed by National Institute of Standards and Technology (NIST) for modelling fire-driven fluid flow, heat transfer, and smoke movement. It solves the Navier–Stokes equations for low-speed, thermally driven flows, incorporating combustion chemistry, radiative heat transfer, and species transport. For toxic smoke dispersion, FDS tracks key gases such as CO, CO<sub>2</sub>, HF, HCl, HCN, SO<sub>2</sub>, and NO<sub>x</sub> using conservation equations for mass fractions of chemical species. The software outputs local gas concentrations, temperatures, and flow velocities, allowing assessment of tenability and occupant exposure via metrics like fractional effective dose (FED) and fractional effective concentration (FEC). Because it can simulate the complex interaction of heat, smoke, and ventilation in three-dimensional spaces, FDS is widely used to evaluate toxic gas spread and visibility conditions in enclosed environments such as tunnels, parking garages, and ship decks during fire scenarios.

EFFECTS (Gexcon, 2025) is a consequence modelling software developed by Gexcon for analyzing the dispersion, fire, and explosion effects of hazardous releases. It uses validated empirical and semi-empirical models to simulate the behaviour and spread of toxic, flammable, or explosive substances in the atmosphere (open air) following accidental releases. For toxic smoke or gas dispersion, EFFECTS computes concentration profiles, plume travel distances, and exposure levels over time, accounting for factors such as wind speed, atmospheric stability, release rate, and terrain. The software provides outputs like toxic dose contours, concentration versus time graphs, and hazard zones, enabling assessment of health risks and emergency response requirements. While it is less detailed than CFD tools like FDS in terms of fluid dynamics, EFFECTS is valued for its speed, ease of use, and validated dispersion models, making it suitable for safety assessments, Quantitative Risk Assessment (QRA), and regulatory reporting of toxic or flammable releases in industrial and pipeline transportation scenarios.

Phast (DNV, 2025) is a widely used consequence-modelling software for handling discharge, dispersion, fire, explosion, and toxic effects from loss-of-containment scenarios to the atmosphere (open air). It integrates empirical/semi-empirical “free-field” models with optional CFD add-ons for more complex geometries and flow

interactions. In toxic dispersion modelling, Phast uses a unified dispersion model (UDM) approach to compute concentrations of released toxic species over time and distance, taking into account atmospheric conditions (e.g. wind, stability) and release characteristics. It can also incorporate multi-component (MC) modelling (especially via its Multi-Component add-on) to more rigorously handle mixtures and phase equilibrium (vapour / liquid / rainout behaviour). Phast is used in consequence analysis across many industries (e.g. oil & gas, chemical, LNG) and is accepted by regulators in various jurisdictions for hazard modelling and siting. It includes features for generating visual outputs (2D/3D graphs, Geographic Information System (GIS) maps, tabular reports), supporting emergency planning, design, and land-based regulatory compliance.

Table 9 provides a summary of the comparison of the three main software. There are other notable software's such as for example FireFOAM/OpenFOAM, COMSOL Multiphysics not mentioned in this report since they not as prevalent in this area and not validated for these simulations.

Table 9. Comparison of FDS, Phast, and EFFECTS for Toxic Smoke and Gas Dispersion Modelling

Aspect	Fire Dynamics Simulator (FDS)	Phast <sup>1</sup>	EFFECTS
Developer / Type	NIST – CFD-based fire and smoke simulator	DNV – consequence analysis suite	Gexcon – consequence analysis suite
Primary Focus	Fire dynamics, heat transfer, and smoke/toxic gas movement in enclosed or complex spaces	Dispersion, fire, explosion, and toxic effects from loss-of-containment scenarios to the atmosphere (open air)	Dispersion, fire, explosion, and toxic effects of accidental releases to the atmosphere (open air)
Modelling Approach	Full CFD, solves Navier, Stokes equations for fluid flow and species transport	Unified Dispersion Model (UDM), semi-empirical or integral model, faster than CFD	Empirical / semi-empirical or integral dispersion and consequence models, faster than CFD
Spatial Detail	Very high (3D, transient flow, detailed geometry, obstructions, ventilation effects). Detailed 3D geometry (e.g. garages, tunnels, ship decks)	Moderate (simplified geometry; plume, pool, and jet models). Simplified geometry limited 3D handling	Moderate (simplified geometry; plume, pool, and jet models). Simplified geometry, limited 3D handling
Toxic Gas Modelling	Tracks multiple species (CO, CO <sub>2</sub> , HF, HCl, HCN, SO <sub>2</sub> , NOx) with full transport equations	Uses validated dispersion algorithms; concentration profiles and dose contours	Uses validated dispersion algorithms; concentration profiles and dose contours
Tenability Analysis	Includes FED, FEC, temperature, visibility, and radiation exposure	Includes concentration, radiation, toxic dose, thermal dose, probability of death	Includes concentration, radiation, toxic dose, thermal dose, probability of death
Fire and Heat Effects	Full combustion, radiation, flame spread, and thermal feedback	Simplified fire and explosion models	Simplified fire and explosion models
Computation Speed	Slow – requires long simulation times and fine mesh tuning	Fast – runs in minutes for most scenarios	Fast – runs in minutes for most scenarios
Ease of Use	Requires expert CFD knowledge and setup	User-friendly GUI, clear visual outputs, land-based regulatory acceptance	User-friendly GUI, clear visual outputs, land-based regulatory acceptance

Aspect	Fire Dynamics Simulator (FDS)	Phast <sup>1</sup>	EFFECTS
Output Types	3D visualization of smoke, gas, temperature, and velocity fields	2D hazard contours, concentration vs. time graphs	2D hazard contours, concentration vs. time graphs
Best Suited For	Detailed, physics-based smoke and toxicity studies in enclosed environments (e.g. tunnels, garages, ship decks)	Quick consequence assessment, land-based Safety Case, QRA	Quick consequence assessment, land-based Safety Case, QRA
Key Strength	High accuracy and physical realism	Fast, validated, recognized consequence modelling tool	Fast, validated, recognized consequence modelling tool
Key Limitation	Computationally heavy; requires detailed input and expertise	Some modelling limits compared to CFD; simplified assumptions for complex geometries	Some modelling limits compared to CFD; simplified assumptions for complex geometries

<sup>1</sup> Phast also includes a CFD add-on, which is not considered in the table.

### 5.3 EV off-gas modelling

The Fire Dynamics Simulator (FDS) modelling in (Willstrand, Bisschop, Blomqvist, Temple, & Anderson, 2020) investigated the spread of smoke and toxic gases from electric vehicle (EV) fires in a closed garage to assess tenability and fire-fighter safety. The simulations were based on a “worst-case” scenario derived from experimental Test 3 (Fig. 29 in Willstrand, *et al.*, 2020), which produced the highest heat release rate (HRR) and hydrogen fluoride (HF) output. Using a 3 m<sup>2</sup> fire area and a 0.1 m mesh resolution, the study simulated various ventilation and ignition conditions. Results showed that smoke spread rapidly through the space, with corners and recesses trapping higher concentrations of gases. Toxic species such as CO, HF, HCl, SO<sub>2</sub>, HCN, and NO were tracked, and their fractional effective doses (FED) and concentrations (FEC) indicated that conditions could quickly become untenable in poorly ventilated garages, see Figure 29. Opening the garage door or adding crossflow ventilation significantly reduced toxic gas concentrations at low levels but had limited effect at head height. A second car ignition worsened conditions for fire-fighters but had little early impact on egress for occupants. Overall, the FDS results demonstrated that while toxic gases, especially HF, pose health risks, adequate ventilation and early intervention substantially improve survivability and tenability within enclosed garages.

As an example of a car fire from the Willstrand, *et al.* (2020) report (Figure 30) gives the HRR used in the simulations together with the mesh resolution parameter  $D^*/\delta$  suitable for buoyant plumes, where a higher value gives a more robust result. It is recommended to use a value between 10 – 20, however larger values are better; this range is indicated with the green field in the Figure 30. Although, no real fire spread was studied in the project, simulations where several cars were on fire at the same time were studied yielding increased doses and concentrations. Note that the dose computed assumed that the person would stand the same physical position during the accident. To give a reasonable dose calculation the simulated concentrations have to be coupled with an evacuation model tracking the people in the concentration field, since it is dependent on a summation of concentrations and time.

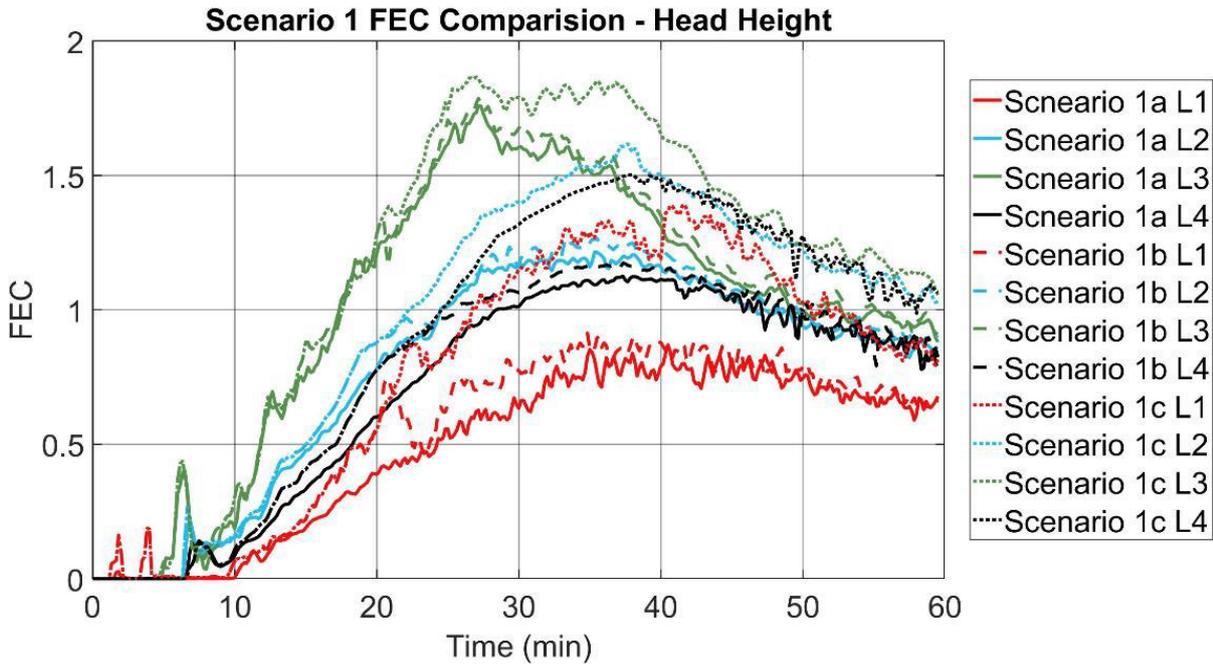


Figure 29. The local Fractional Effective Concentration (FEC) in Scenarios 1a and 1b (E-TOX, 2020).

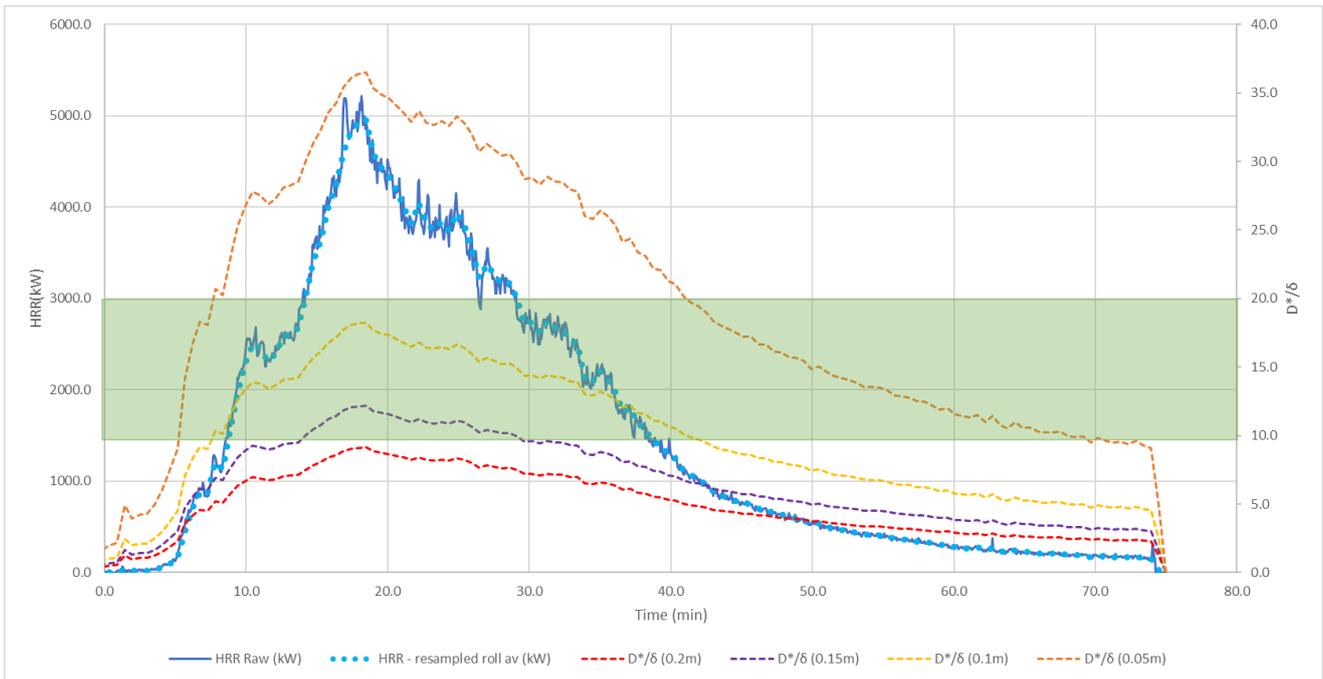


Figure 30. The heat release rate used in the E-TOX simulations with the mesh-resolution test parameter  $D^*/\delta$  for different resolutions.

The FDS simulation results in (Jang, Jeon, & Oh, 2025) assessed the dispersion of toxic gases, especially hydrogen fluoride (HF), from electric vehicle (EV) fires in underground parking garages. Using Fire Dynamics Simulator (FDS 6.9.1), the study modelled fires from 24, 53, and 99.8 kWh lithium-ion battery vehicles based on experimental data from RISE, (Willstrand, Bisschop, Blomqvist, Temple, & Anderson, 2020). Simulations examined multiple ignition locations and natural ventilation conditions. Results showed that HF concentrations in poorly ventilated zones reached up to 488 ppm, exceeding the AEGL-2 threshold (12 ppm) for over 53 minutes in the 99.8 kWh case. As battery capacity increased, both HF emission and total heat release rose, leading to greater toxic exposure and up to 47% shorter tenability times. The fractional effective dose (FED) and fractional effective concentration (FEC) analyses revealed that larger batteries and proximity to the ignition source sharply reduced evacuation times with occupants needing to escape within roughly 13–20 minutes to avoid incapacitation. The

study concluded that enhanced ventilation, early detection systems, and battery-specific fire suppression are vital for mitigating toxic gas hazards in enclosed EV parking structures.

The FDS simulations in (Temple & Anderson, 2022) were conducted as part of the BREND 2.0 project to assess the tenability and fire behaviour of electric vehicle (EV) fires in ro-ro (roll-on/roll-off) ship spaces. Using Fire Dynamics Simulator (FDS) with a 0.2 m mesh resolution, the study modelled several fire and ventilation scenarios: a multi-EV fire ignited by an external source (Scenario 1) and a single-EV fire from thermal runaway (Scenario 2), under enclosed, semi-open, and open deck conditions. Additional sensitivity cases examined diesel vehicle fires, drencher suppression, and the effect of heavy goods vehicles (HGVs) on smoke movement.

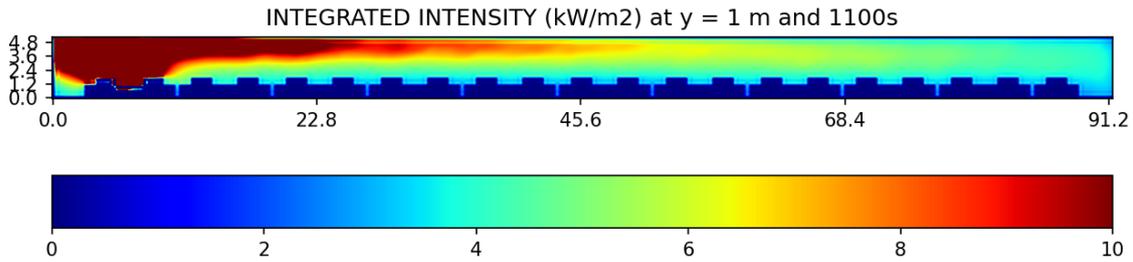


Figure 31. The integrated radiation intensity from the hot gases in Scenario 1a (closed ro-ro spaces) close to maximum intensity of the fire (BREND 2, 2022).

Results showed that low-ventilation cases led to rapid smoke layer descent, filling the ro-ro space volume and reducing visibility, while higher-ventilation scenarios maintained a clear air layer about 2 m above the deck. Temperature and radiation levels were strongly influenced by ventilation and fire size: enclosed spaces produced more uniform heating and higher radiation exposure, whereas open configurations localized the heat and smoke near the fire source, with most areas remaining below 50 °C and under 5 kW/m<sup>2</sup> radiation, see Figure 31. Toxic gases including CO, CO<sub>2</sub>, HCl, HCN, HF, and NO were monitored, enabling estimation of fractional effective doses (FED) and fractional effective concentrations (FEC) for evaluating tenability. Overall, the FDS results indicated that ventilation greatly affects smoke stratification and radiation intensity, and while closed ro-ro spaces pose severe tenability risks, improved airflow or suppression systems could mitigate conditions for both occupants and fire-fighting personnel.

First-principal models of gas release during a thermal runaway event were recently developed. To the knowledge of the authors, most of them are based on empirical models (i.e. from off-gas measurements during thermal runaway test of lithium-ion battery from cell to EV) and two commercial software propose such models (EFFECTS from Gexcon (Gexcon, 2025) and Phast Online from DNV (DNV, 2025)). Both models were developed for Battery Energy Storage System (BESS) and need the battery chemistry (e.g. NMC, LFP) and the battery energy capacity (J or kWh) as inputs. In return, the models estimate the production rate (kg/s) of off-gases, such as HF, CO, etc. Those production rates are then used as inputs for gas dispersion modelling in both software. The two models are based on the paper from (Bugryniec, et al., 2024).

## 5.4 EV fire modelling

The EV fire models support the development of design fires, fire suppression strategies, and ventilation systems for applications such as tunnels, parking garages, and ro-ro ship decks. As battery technology evolves and EV adoption increases, accurate fire modelling has become essential for assessing safety risks and informing regulatory and engineering standards.

Zhang, *et al.* (Zhang, et al., 2025) conducted a comparative study of full-scale battery electric vehicle (BEV) fires to evaluate their heat release, flame development, and hazard potential relative to internal combustion engine vehicles (ICEVs) and hydrogen fuel cell vehicles under both open and semi-enclosed conditions. The results showed that battery electric vehicle fires reached peak heat release rates of approximately 6.5 MW – 7.3 MW and total heat release values around 8.5 GJ – 9.0 GJ which is comparable to ICEV fires of similar size vehicles, indicating that overall fire severity was governed largely by the combustion of interior and body materials rather

than the battery pack alone. However, the battery system contributed localized high-intensity “jet-fire” behaviour, which accelerated flame spread and increased radiative heat flux to nearby combustibles. The study highlighted that the modelling of thermal runaway and its coupling with vehicle fire growth remains complex, and that the external ignition methods used in current tests may underrepresent internal battery-driven events. Zhang, *et al.* concluded that larger-capacity batteries, more realistic initiation modes, and standardized testing and modelling protocols are needed to accurately characterize BEV fire behaviour and to inform future design-fire parameters and safety regulations for electric vehicles.

A paper by (Hodges, Salvi, & Kapahi, 2024) presents a model to extrapolate currently available test data from vehicle fire tests to evaluate the fire hazard associated with larger passenger vehicles. Current public data (some which are described above) indicates peak heat release rates ranging from 5 MW to 10 MW. However, the vehicles tested in these studies are smaller with less energy capacity than vehicles currently (refers to 2024) on the market. The model was validated based on data from 20 large-scale vehicle tests and was then used to develop conservatively bounding fire scenarios for current market vehicles. The paper concludes that no significant difference was observed in the heat release rates between similarly sized internal combustion engine vehicles and battery electric vehicles, but the predicted heat release rates for both vehicle types significantly exceeded existing design guidance. Although the model may be shown to be excessively conservative in future testing, it indicates an alarming trend in the fire protection industry, where the hazard posed by single passenger vehicles may exceed existing design guidance. Table 10 shows the calculated fire hazard of representative vehicles on the market.

Table 10. Calculated fire hazard of representative vehicles on the market (reproduced from Hodges, *et al.*, 2024)

Class	BEV			ICEV		
	t <sub>max</sub> (min)	Q <sub>max</sub> (MW)	E <sub>tot</sub> (GJ)	t <sub>max</sub> (min)	Q <sub>max</sub> (MW)	E <sub>tot</sub> (GJ)
Compact car	10.6	8.5	9.8	10.5	8.3	8.4
Sports car	12.4	11.6	17.4	12.8	12.2	12.2
Large car	13.1	12.8	17.2	12.5	11.8	11.8
8 passenger van	14.1	15.0	19.0	14.6	16.1	16.3
Pickup truck	14.5	15.8	21.3	15.3	17.6	17.6
Large SUV	16.0	19.3	30.2	16.7	20.9	20.6

Mohd Tohir and Martín-Gómez (Mohd Tohir & Martín-Gómez , 2025) have conducted a comprehensive statistical analysis of heat release rate profiles of electric vehicles and internal combustion engine vehicles based on experimental data. The analysis included the peak heat release rate, the time to peak heat release rate, the total heat release and fire growth coefficients. Results show that electric vehicles, present distinct fire dynamics, often demonstrating higher peak heat release rates than internal combustion engine vehicles. The paper thereby concludes that there is a potential for greater fire intensity and fire growth rates in electric vehicles fires. A design fire model was constructed based on the analysis, offering fire protection engineers a probabilistic alternative to conventional deterministic approaches in performance-based design. The study observed a correlation between larger battery sizes and increased fire severity, although the authors claim that this should be interpreted cautiously given the limited dataset.

The paper reflects on the work by Hodges, *et al.* (2024) as described above. Their model uses vehicle parameters such as battery energy capacity, curb weight, and gas tank capacity to provide predictions of the heat release and total heat release of fires in vehicles. This makes their model suitable for assessing fire hazards in a range of vehicle types, especially larger, high-energy-capacity vehicles. In contrast, the current study’s probabilistic framework provides a flexible alternative, allowing fire protection engineers to simulate a range of potential scenarios that can be refined as more data becomes available. The paper concludes that future research efforts should focus on incorporating diverse experimental data to capture a wider spectrum of vehicle fire behaviours, particularly as new electric vehicles models and configurations are introduced.

Pitana, *et al.* (Pitana, Soewirjo, Siswantoro, & Nurwahyudy, 2025) used Fire Dynamics Simulator (FDS) to model electric vehicle (EV) fire behaviour aboard a ro-ro ferry, comparing two scenarios: one with EVs parked on a

standard deck and another within a dedicated containment space. The study found that conventional sprinklers were largely ineffective at suppressing lithium-ion battery fires, with deck temperatures exceeding 140 - 800°C and extensive smoke spread across multiple decks. In contrast, the containment configuration reduced smoke dispersion and helped stabilize temperatures below 70°C after 400 – 500 s, though complete fire extinguishment was still not achieved. The authors concluded that containment compartments, improved ventilation, and enhanced suppression systems (e.g. F-500 with water mist) significantly improve safety but that crew training, monitoring systems, and operational controls are equally vital. They emphasized the need for further experimental validation of extinguishing coefficients and design optimization for EV parking and fire-fighting systems aboard ro-ro ships.

Olona, *et al.* (Olona & Castejon, 2025) conducted controlled fire tests on two battery electric vehicles, a Nissan Leaf and a Smart EQ ForFour, to evaluate the effectiveness of fire blankets as an early-stage fire containment method. The results showed that fires initially developed as small jetting flames before spreading to the passenger compartment, where combustion intensified sharply. The fire blanket successfully contained the flames, reduced radiative heat transfer, and limited fire spread; however, it could not stop battery thermal runaway, which continued as an internal chemical reaction. Upon removing the blanket, re-ignition occurred quickly, emphasizing the need for careful handling and ventilation to disperse accumulated flammable gases. The study concluded that fire blankets are effective for initial containment and post-fire quarantine of EVs but should be complemented by cooling (e.g. water application) and proper ventilation to manage thermal runaway and toxic gas accumulation safely.

CFD simulations in the *Safe and Suitable Firefighting* (Burgén, Gehandler, Olofsson, Huang, & Temple, 2022) study modelled pressure vessel and tire explosion scenarios in ro-ro spaces using validated OpenFOAM setups pressure vessel explosion in a ro-ro space, sized 91.4 m × 22.3 m × 5 m. The results showed that a 42 L CNG tank rupture at 230 bar and a 122 L hydrogen tank at 700 bar generated overpressures capable of causing serious injury or fatality within 4 - 7 m, with negligible mitigation from adjacent vehicles acting as barriers. Pressure reflections from structural boundaries amplified local overpressure peaks, while a 10 bar tire burst remained below injury thresholds. Overall, the simulations demonstrated that pressure vessel failures present severe localized hazards in closed ro-ro spaces and that CFD tools can reliably reproduce transient pressure fields and safety distances for use in risk and design evaluations.

## 5.5 CNG, LPG vehicle and FCV fire modelling

The modelling of hazardous consequences from hydrocarbon releases, such as natural gas or LPG, has a long and well-established history rooted in the development of the oil and gas industry. The well-known Yellow Book (TNO, 2005) provides analytical methods for calculating the physical effects of such releases. Beyond these analytical and empirical formulations, a range of validated engineering tools, such as EFFECTS (Gexcon), FRED (Shell), and Phast (DNV), are available to model phenomena including gas release and dispersion, vapour cloud explosions, jet fires, fireballs, and BLEVE events. Those engineering tools are well recognized in land-based energy and chemical industries and associated Authorities. They are used to assess the consequences of hazardous phenomena mainly in open air and with limited effects of geometry for the purpose of facility siting, safety case or QRA. More advanced analyses typically rely on Computational Fluid Dynamics (CFD), which enables detailed simulation of flow dynamics, combustion, and explosion behaviour. Numerous well-developed and validated CFD models exist to simulate the consequences of compressed natural gas or LPG incidents, including (but not limited to):

- Gas dispersion: FDS from NIST, FLACS-CFD from Gexcon, KFX from DNV, Phast-CFD from DNV.
- Jet fire: FLACS-CFD from Gexcon, KFX from DNV.
- Gas explosion: EXSIM from DNV, FLACS-CFD from Gexcon.

For the past years, numerous research projects have been conducted on hydrogen safety. The European Hydrogen Safety Panel (EHSP, 2023) and French National Institute for Industrial Environment and Risks (INERIS, 2025) provide valuable guidance and a comprehensive state of the art related to modelling of physical effects of release of hydrogen. The centre of Hydrogen Safety Engineering and Research (HySAFER) from the University of Ulster hosts several free e-tools (available online (HySAFER, 2025)) that can be used to estimate hazard distances related to an unignited or ignited jet of hydrogen, rupture of a compressed hydrogen storage tank, or to estimate the dynamics of a storage tank during blowdown. The Sandia National Laboratories has developed an open source tool, HyRAM+ (Sandia, 2025), that integrates experimentally validated models of various aspects of release behaviour and flame physics of compressed hydrogen. This tool can be used to estimate hydrogen jet plume, gas accumulation in an enclosed space, jet flame or unconfined/confined overpressure. Those two tools are simple to use and are based on analytical or empirical models. A lot of other models and tools exist to model the hazardous

consequences of hydrogen. In particular, the aforementioned software for hydrocarbons have also encountered recent developments for hydrogen applications and are used to design safe hydrogen mobility infrastructures.

More in relation with ro-ro spaces, the above models and tools can be used to model the set of hazards from CNG, LPG vehicles and FCVs stowed on weather decks. On open deck, analytical, empirical or integral models can provide good estimate of the hazardous consequences and be used early in the design whereas CFD will provide more detailed results and can be used to also model some mitigation measures. For closed and open ro-ro spaces, the simplest models can still be used to provide order of magnitude and first insight of the consequences, but the validity of the results can be questionable due to the unique environment of ro-ro spaces (e.g. very large, enclosed space, forced mechanical ventilation, etc.). In enclosed or semi-enclosed spaces, CFD models should be used by risk engineers rather than the latter ones.

To be noted that the International Association of Classification Societies (IACS) is currently working on recommendations for gas dispersion analysis required for the use of hydrogen or ammonia as alternative fuel on board ships (IACS, 2025). The recommendations for hydrogen gas dispersion modelling developed in the frame of that work by IACS may be adapted to a certain extent and on a case-by-case basis to the modelling of gas dispersion in ro-ro spaces and on weather decks.

## 5.6 Fire spread modelling, vehicle to vehicle in ro-ro spaces

Recent numerical studies have advanced the understanding of fire spread mechanisms between vehicles in confined or semi-enclosed environments such as ro-ro spaces. These models primarily use Fire Dynamics Simulator (FDS) or coupled thermal runaway models to study ignition, heat transfer, and secondary ignition events.

CNRS (Barré, Carlotti, & Guibaud, 2024) conducted a numerical investigation of the influence of thermal runaway modelling on car park fire hazard, applying the results to a Lithium-ion Manganese Oxide (LMO) battery system. The study demonstrated that the thermal runaway representation (single-cell vs. multi-cell energy release) strongly affects predicted fire growth, radiative heat transfer, and the probability of vehicle-to-vehicle ignition. Models that by explicitly coupling of battery reaction kinetics with CFD-based fire spread produced more realistic transient heat fluxes and gas temperatures than simplified empirical fire sources.

Temple & Anderson (2022) (BREND 2.0 project) extended a simplified approaches to ro-ro space environments, modelling vehicle-to-vehicle ignition sequences under varying ventilation and vehicle spacing conditions (Temple & Anderson, 2022). The simulations showed that in confined decks, radiative and convective heat fluxes can exceed 30–50 kW/m<sup>2</sup> at adjacent vehicle surfaces—sufficient for secondary ignition within 5–10 minutes without suppression.

Together, these studies show that vehicle spacing, ventilation rate, and battery chemistry are critical factors controlling fire spread rates in ro-ro space environments, and that realistic modelling of thermal runaway energy release is essential for accurate predictions.

## 5.7 Simulations results on fire spread, vehicle to vehicle in ro-ro spaces, and on impact of safety systems in ro-ro spaces

Several European research programmes - notably LASH FIRE and ELBAS - have conducted detailed FDS simulations and experimental validations to assess the fire spread dynamics and the performance of safety systems in ro-ro ship spaces.

The ELBAS project (Electric vehicle fire safety in maritime transport, 2023–2025) used large-scale experiments and FDS modelling to evaluate fire propagation between EVs, with and without drencher activation (Kleiman, et al., 2022). Results indicated that sprinkler/drencher systems significantly reduce external flame radiation and delay secondary ignition, but smoke stratification and gas toxicity (CO, HF, HCN) remain critical challenges in enclosed spaces.

The LASH FIRE project (EU Horizon 2020) integrated FDS modelling with experimental validation from RISE and SP Fire Research to examine suppression system performance, tenability, and evacuation conditions (Olofsson, Anderson, Svensson, & Ingason, 2023). The models showed that improved ventilation control, drencher system operation, and early detection can reduce deck-wide temperatures and radiation levels by over 60%, extending

tenability times for passengers and crew. However, simulations also highlighted limited drencher system efficiency against shielded EV fires (e.g. undercar fires or within wheel arches), emphasizing the need for fire detection localization and targeted suppression.

Overall, results from ELBAS, LASH FIRE, and BREND 2.0 converge on a few key findings:

- Fire spread between vehicles in ro-ro spaces is primarily driven by radiative coupling and confined heat accumulation.
- Ventilation and drencher system activation timing critically affect both propagation and gas toxicity levels.
- Thermal runaway-specific source terms and battery chemistry models improve prediction accuracy.

Fire suppression and smoke(/gas) extraction systems can delay but not completely prevent fire propagation without early detection or physical compartmentalization.

## 6. Conclusion

This chapter provides the main conclusions from the regulatory review and from the technical and scientific review. The last section summarizes the identified scientific and technical data per safety area in order to support the on-going work on safe transportation of AFVs on ro-ro ships.

### 6.1 Conclusions from the regulatory review

Since the initial revision of the EMSA Guidance for AFVs in ro-ro spaces, issued in 2022, advances in maritime regulatory landscape have addressed some of the needs of transporting AFVs on board ships. Even though there is some consensus on the hazards posed by the carriage of AFVs, especially EVs containing lithium-ion batteries, different safety philosophies have been applied by the regulatory bodies depending on experience and specificities of ship-type designs.

In general, the literature tends to agree that a combination of heat and smoke fixed detection systems coupled with a water-based fire-extinguishing system are a reliable solution to detect, cool down and prevent the fire spread in case of lithium-ion batteries thermal runaway events. However, for vehicle carriers which are generally not equipped with water-based fire-extinguishing systems or, for container carriers, where the accessibility to the batteries inside a container is complicated, alternative solutions are proposed such as increasing the capacity of the fixed gas-based fire-extinguishing system. As can be seen in Chapter 4, this solution, among others, is currently being studied from a technical and scientific perspective.

From the guidelines issued by the industry community and insurances, the prevention and mitigation of fire risks is also coming from operational constraints such as the verification of the battery conditions during the loading stage or crew training. These points are difficult to verify and therefore difficult to encompass in the regulatory framework.

Based on this regulatory report, some knowledge gaps are surfacing leading to the need of scientific and technical studies, experiments and modelling on specific items such as the efficiency of gas- and foam-based fire-extinguishing systems.

Lastly, from the review of the land-based reference documents, it was found that most of the measures for the safe transportation / use of AFVs on land are common with maritime. However, some interesting recommendations solely found in land-based can be highlighted and further investigated for adoption in maritime (Table 11).

Table 11. Additional safety measures from land-based. Note: “/” = No additional relevant measure from land-based was found in comparison to maritime. “✓” = Recommended in land-based situations. “■” = Can be used but with caution

Fire safety area	Fire safety topic	Additional measure(s) found in land-based references documents	Comments
<b>Ignition prevention or mitigation</b>	Vehicle identification	/	
	Conditions of carriage (incl. new, used, damaged)	✓ SoC < 30% (note: transport of damaged lithium-ion batteries by air is forbidden, see 3.3.8)	For transportation of lithium-ion batteries by air.
	Charging of EVs onboard	✓ Maximum charging limit	For EVs.
	Ventilation	/	
<b>Detection</b>	Fixed fire detection and fire alarm	✓ Multi-sensor type detectors (not only smoke and heat detectors) ✓ Performance criteria to test fire detection system	For EVs.
	Video monitoring	/	
	Fire patrol	/	Fire patrol requirement was found specific to maritime.
	Gas detection	✓ Acoustic detection	For gas fuelled vehicles.
	Thermal runaway detection	N/A	No risk control measures found in the land-based reference documents.
<b>Fire-fighting</b>	Fixed fire-extinguishing systems	/	
	Manual fire-fighting equipment (incl. personnel protection)	✓ UHP, battery pack flooding device ✓ High-voltage protection ■ Fire blanket (note: not recommended by IAFF until further research)	For EVs. The feasibility, practicability and utility of the measures should be further demonstrated in maritime environment.
	Operations, procedures	✓ Fire-fighting strategies ✓ Operational ventilation procedure ✓ Submerging or water container (for EVs)	The land-based fire-fighting strategies should be adapted to maritime environment. The use of submerging or water container on board ships sounds infeasible but can be foreseen at the harbour.
	Training and drills	/	
<b>Containment</b>	Structural fire protection / Safety distance	✓ Safety distance or physical barrier ✓ More stringent fire curves	The feasibility, practicability and utility of safety distance or physical barrier (internal ro-ro spaces) should be further demonstrated in maritime environment.
	Explosion protection	/	

Fire safety area	Fire safety topic	Additional measure(s) found in land-based references documents	Comments
Evacuation	-	/	

## 6.2 Conclusions from the technical and scientific review

### The fire severity of battery electric vehicles

Free-burn fire tests conducted by Lecocq, *et al.* (2012), Watanabe, *et al.* (2012) and in the E-TOX project (Willstrand, *et al.*, 2020) indicates that the peak heat release of a battery electric vehicle fire is comparable to that of a vehicle with an internal combustion engine, given similar sized vehicles. Free-burn fire tests conducted by Lam, *et al.*, (2016) showed that the peak heat release rates for the internal combustion engine vehicle models used in the tests were higher than those for their battery electric vehicle counterparts and that the peak heat release rates occurred similar to or earlier. It seems that a vehicle with a full fuel tank produces a greater hazard in terms of heat release rate than does a vehicle with a battery pack.

None of these tests included battery electric vehicles having an energy capacity (40 kWh or larger) associated with modern vehicles. Recent testing at RISE presented by Arsava, *et al.* (2025) with a modern passenger battery electric vehicle indicates a somewhat higher peak heat release rate than the battery electric vehicle tests described above.

A paper by Hodges, *et al.* (2024) presents a theoretical model to extrapolate currently available test data from vehicle fire tests to evaluate the fire hazard associated with larger passenger vehicles. The paper concludes that no significant difference was observed in the heat release rates between similarly sized internal combustion engine vehicles and battery electric vehicles, but the predicted heat release rates for both vehicle types significantly exceeded existing design guidance. Although the theoretical model may be shown to be excessively conservative in future testing, it indicates an alarming trend in the fire protection industry, where the hazard posed by single passenger vehicles may exceed existing design guidance.

Gap: Large-scale free-burn fire testing to evaluate the heat release rates of larger types of battery electric vehicles like pickups, freight trucks and buses.

### The characteristics of AFVs fires / explosions

Battery thermal runaway in EVs produces a wide range of gases, including carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), hydrogen (H<sub>2</sub>) and volatile organic compounds (VOCs). The gas composition is of interest both for detection and for understanding the explosion hazards. The gas composition, but also the volume and production rate is affected by the battery system design, SoC, cell format, cell aging and cell chemistry. Thus, these parameters will influence the risk for explosion of a battery in thermal runaway. Research exists on explosion risk with battery systems in compartments, but no research was identified related to the large size of a ro-ro space. This is clearly identified as a knowledge gap.

In the view of environmental issues, run-off water from BEV and ICEV fire tests contained high levels of toxic substances, including PFAS, nickel, cobalt, lithium, manganese, fluoride, and lead. The water showed acute toxicity to aquatic species.

In the event of fire exposure of gas fuelled vehicles (H<sub>2</sub> and CNG), they may result in jet flames due to the controlled release of gas through the pressure relief device. If this device fails to function, there is a risk of gas tank explosion. Jet flames from compressed gas tanks have in research been in the range of 1-10 m and last for a short period (minute) of time. Temperatures above 1367°C has been reached. There is a lack of studies investigating if and how jet flames and pressure vessels explosion influence the ship structure.

## Early detection of fire root causes: Fire and gas detection

Ongoing initiatives around the world are focusing on the early detection of fire root causes, such as thermal runaway events resulting from battery failures, using various detection technology. Small scale tests promise that gas detection of gas emissions from thermal runaway of a battery cell is possible and relatively easy. Detection in a large space and detection of EV battery fire is a significant task and not well documented in scientific experiments. Safety measures for early detection of thermal runaway are key to limit thermal propagation and prevent spread between vehicles. However, early detection is important for all types of fires or events that can lead to fire, and it is anticipated that any new detection technology required in ro-ro spaces will complement the current requirement for smoke and heat detectors. In submissions to IMO, technologies such as video fire detection, battery management system (BMS) monitoring or temperature-based detection methods are mentioned in a positive way. However, scientific studies are lacking to validate the effect in a ro-ro space.

## Manual fire-fighting equipment, tools and procedures

**Fire hose nozzles:** The use of different types of fire hose was tested in different projects. As expected, it was found that semi-rigid fire hoses of smaller diameter are much easier to deploy and to handle in most cases (in comparison to fire hoses of larger diameter or to lay flat hoses). However, reducing the diameter may affect pressure, water flow and throw length. The BREND report (2019) concludes that handheld systems and water curtain systems are two tactical options, and one cannot replace the other. Handheld systems are needed for fire-fighters to be able to position the water curtain, but when operating the water curtain nozzle, no personnel is required. A water curtain nozzle therefore enables personnel to perform other tasks while it is active.

**Portable water curtain devices:** From field tests, the deployment of a portable water curtain was found to be challenging, even impractical in vehicle carriers, in a fire situation with presence of heat and smoke, and crew members need to be well trained and prepared. To be effective, the device shall be strategically placed between vehicles and close to the vehicle on fire. After testing different deployment strategies, it was found that the device should be placed with a rod or rope from a safety distance. The device should also be made of rigid materials. For example, plastic was found too fragile to be dragged. The fire hose feeding the device should be deployed in manner to avoid curving or being blocked by tires when pressurized. Larger diameter of fire hose can help with that matter thanks to their greater stiffness.

**Fire blankets:** Fire blankets were tested in the ELBAS (2022) and LASH FIRE (2023) projects to smother flames by cutting off the oxygen supply to both the exterior fire and the underlying battery pack in an EV. The use of a fire blanket will need at least two crew members and a minimum space between cars. In a developed fire stage, two protective hose operators are required if water shielding is needed during the application of the blanket. Fire blankets can also be used to cover a vehicle not on fire to protect it from being involved in fire. However, recent testing (2025) by NFPA's Fire Protection Research Foundation and UL's Fire Safety Research Institute has raised concerns regarding accumulation of unburnt combustible vapours under the fire blanket cover, creating an explosion hazard.

**Battery pack water flooding devices:** The use of battery pack water flooding devices are generally more complex than water curtain devices and their use require extensive training and safety measures when used. Their use will require that the members of the fire team to be in direct vicinity of the battery electric vehicle to manually pierce the battery pack and they can therefore be exposed to potential hazards. In the ELBAS project (2022), it was found that some of the tested devices were not suitable for the available space in ro-ro spaces or not suitable for the battery pack or battery module configuration.

**Brine-based fire-fighting system:** In addition to the findings above, one test with a device that discharges super-cooled salt water at  $-19^{\circ}\text{C}$  is described. The commercial name of the concept is the Battery Briner system. The salt solution is used as a coolant on board ships as a secondary fluid in large refrigeration installations and is therefore readily available in large quantities. The system has been installed on the car deck of a specific ship, with normal fire hydrant connections for hoses. The system relies on a device with nozzles, which fire-fighters or crew can push into the burning car (by breaking the windows) and flood the interior at a rate of 250 l/min. It is believed that the high conductivity of the salt and water solution also supports cooling of the battery and its environment, thereby reducing the risk of fire propagation. It can be remarked that there is no data supporting that the salt solution is in fact more effective than regular salt or fresh water.

**Fire-fighting procedures:** From field and onboard tests, it was found that time is the key. Early fire detection and confirmation, timely activation of fixed fire-extinguishing system and early notification to local emergency services (when at port) should be reflected in the ship procedures. The use of the fixed fire-extinguishing system should be the primary mean to contain the fire spread. Manual fire-fighting was found nearly impractical in the space of origin of the fire in vehicle carriers and should only be attempt for rescue purpose. However, for boundary cooling from the deck above or below the zone in fire, manual fire-fighting was deemed relevant. Lastly, at port, it was found that communication, cooperation and exchange of information between all the involved parties (in particular with the local emergency services) were crucial.

Gap: Tools, equipment, training and tactics to confront fire in larger types of battery electric vehicles like pickups, freight trucks and buses, where equipment as fire blankets or battery water flooding devices are difficult to apply.

### Drencher and automatic sprinkler system performance

A straightforward comparison of the fire suppression performance of a deluge water spray system ('drencher system') for fires involving gasoline-fuelled and battery electric vehicles in test conditions as equivalent as possible with actual conditions onboard was undertaken by RISE in the LASH FIRE project (2023). The overall conclusion from the tests was that a fire in an electric vehicle (passenger cars) does not seem to be more challenging for the water spray system design used in ro-ro cargo and special category spaces than a fire in a gasoline-fuelled vehicle of comparable size. It was also concluded that full fire extinguishment of vehicle fires is typically not possible with an over-head deluge water spray system. When the application of water is intentionally stopped, resources should be available to undertake manual fire-fighting efforts.

Automatic fire sprinkler testing by RISE was undertaken in the LASH FIRE project (2022), including fires in passenger cars and a freight truck. The performance of the tested systems was effective, but none of the vehicles were battery electric vehicles.

Gap: Large-scale fire testing to evaluate the performance of drencher systems on larger types of battery electric vehicles like pickups, freight trucks and buses. Note: same gap for larger ICEVs.

### Water mist system performance

The submittal (SSE 10/INF.10) from China to the Sub-Committee on Ship Systems and Equipment (2023) describes a fire suppression test conducted using a fixed-installed high-pressure water mist system under a 2.5 m ceiling. The system had an array of sixteen open nozzles at the ceiling. A passenger car mock-up as described in MSC.1/Circ.1430 was constructed, consisting of a vehicle body steel sheet structure, combined with target screens made from plywood panels positioned at each side of the mock-up to mimic adjacent vehicles. A lithium-ion battery pack was positioned in the middle and rear of the mock-up, placed on top of a heating plate. The overall conclusion from the three tests is that a high-pressure water mist fire suppression system could effectively suppress the fire in the passenger car mock-up, limit the average gas temperature at the ceiling and prevent target plywood panels to the side of the mock-up to ignite. However, it can be remarked that it does not seem that the battery pack was "built-in" and shielded from the application of water to the degree expected in an actual battery electric vehicle and the mock-up did not contain additional combustible materials as plastics, rubber, lubricants, flammable liquids, etc. associated with an actual vehicle. The overall fire severity is therefore probably less than anticipated in reality.

A submittal (SSE 7/INF.11) from China to the Sub-Committee on Ship Systems and Equipment (2020) describes water mist testing inside a freight container. The fire test source consisted of a passenger car mock-up similar to that described above. Five repetitive tests were conducted, including three tests using NMC and two tests using LFP chemistry battery cells. In all five tests, the flames were extinguished immediately after system discharge. The battery pack did not re-ignite in any of the tests. For these tests, it can also be remarked that an actual battery electric vehicle design is very different compared to the mock-up used in the tests.

In the ELBAS project (2022), a low-pressure water mist utilizing open nozzles installed at the ceiling (2.4 m high) of the test compartment was tested. The battery electric vehicle used in the test was not in good condition and as soon as the water mist system was activated, the temperature on the battery dropped as well as in the smoke layer above the vehicle and the surrounding vehicles. According to the report, the temperature drop in the battery was most likely due to the bad condition of the vehicle allowing droplets to reach the battery pack which would otherwise be better shielded. It was concluded that a fixed-installed water mist system may not fully extinguish a battery electric vehicle fire. However, it can limit the spread of the fire, such that the shipboard fire-fighters can

approach and continue fire-fighting with traditional extinguishing methods, possibly combined with appropriate specialized tools.

A commercial floor-mounted, water-based fire suppression system designed to prevent fire spread to adjacent vehicles and structures was identified (2025). The system consists of a unit with a fire detection system and water spray nozzles that is installed at the parking area of individual vehicles in for example a parking garage. The system has undergone independent third-party certification validating performance against a battery electric vehicle thermal runaway scenario. It can be remarked that the performance against a fire starting inside a vehicle does not seem to have been evaluated.

Gap: Large-scale fire testing to evaluate the performance of water mist systems using actual battery electric vehicles. Note: same gap for larger ICEVs. Larger types of vehicles will be particularly challenging for water mist systems due to higher fire loads and larger ceiling heights.

### High-expansion foam system performance

The submittal (SSE 9/INF.4) from Japan to the Sub-Committee on Ship Systems and Equipment (2022) describes a fire suppression test conducted with an outside-air high-expansion foam system utilizing a single battery electric vehicle (passenger car). The vehicle had a lithium-ion battery pack with an energy capacity of 24 kWh. It was concluded that the fire was suppressed by the high-expansion foam, and although the foam could not stop the thermal runaway of the battery pack, it successfully prevented fire ignition of flammable gaseous electrolyte from the battery and suppressed the fire. Therefore, it is judged that high-expansion foam fire-extinguishing systems are effective in preventing propagation of heat from a vehicle on fire if the vehicle is submerged in the foam.

The submittal (SSE 11/INF.5) from Japan to the Sub-Committee on Ship Systems and Equipment (2024) describes fire suppression testing with an outside-air high-expansion foam system using a fire test source that simulates a fire in vehicles (but not battery electric vehicles). Tests mimicking fire in both a single vehicle and in multiple vehicles were conducted. The results of the fire suppression tests indicate that an outside-air high-expansion foam system providing a nominal filling rate of 1 m/min can suppress fires in up to five vehicles. No delays in foam spreading speed or fire suppression time were observed during the tests. This suggests that systems with the same foam filling rate could potentially suppress fires involving even more vehicles.

Gap: Large-scale fire testing to evaluate high-expansion foam systems on larger types of battery electric vehicles like pickups, freight trucks and buses. Note: same gap for larger ICEVs. The (elevated) position of battery packs at the roof of battery electric buses may result in a challenging scenario for high-expansion foam.

### Carbon dioxide system performance

The submittal (SSE 7/INF.11) from China to the Sub-Committee on Ship Systems and Equipment (2020) includes a short report on a series of fire detection and fire suppression system tests using a battery pack. Four repetitive tests using carbon dioxide were conducted, two tests using NMC and two tests using LFP chemistry battery cells. In all four tests, the flame was extinguished immediately after the discharge. However, after a period of time, the battery pack re-ignited and the fire could not be controlled in two of the NMC tests and one of the LFP tests. In the other test using LFP chemistry, the battery pack did not re-ignite, and only the overcharged module was damaged.

The performance of fixed-installed carbon dioxide systems during vehicle fires on ro-ro vehicle carriers was documented in the first part of the COFFEE project (2024). From 2013 to 2023, at least 22 severe fires started in the cargo space of ro-ro vehicle carriers. In eleven of the 22 fires, information verifies that a carbon dioxide system was used, and in five case the fire was suppressed or extinguished. For the cases when fire was not extinguished, a long delay time combined with the fact that the space was not sufficiently sealed may explain the poor performance. One of the 22 fires probably originated in a new production electric vehicle, but this ship was protected by a high-expansion foam system. The ship capsized and sank in early March 2022. The COFFEE project is currently investigating fire suppression performance of carbon dioxide, aiming at conducting large-scale fire tests with battery electric vehicles in 2026.

Gap: Large-scale fire testing to evaluate the performance of carbon dioxide systems using actual battery electric vehicles. Note: same gap for larger ICEVs. This will be done in the COFFEE project using passenger cars. Larger types of battery electric vehicles may pose additional challenges, the (elevated) position of battery packs at the roof of battery electric buses may result in premature fire re-ignition (as carbon dioxide is heavier than air). From the field experience discussed above, it can also be noted that a fire during loading or unloading implies conditions that the carbon dioxide system cannot actually handle.

### Numerical physical-chemical-mathematical models and simulations

Numerical modelling of electric vehicle fires has become a critical tool for understanding and mitigating emerging fire safety challenges in maritime and confined environments. State-of-the-art studies demonstrate that integrating multi-physics simulations—encompassing thermal runaway behaviour, heat transfer, gas dispersion, and toxic species formation—enables more accurate assessment of hazards in ro-ro spaces and in enclosed spaces. CFD tools such as FDS provide high spatial and temporal resolution for analysing smoke movement and tenability, while consequence modelling software like Phast and EFFECTS offers rapid assessment capabilities for risk evaluation and land-based regulatory compliance. Other CFD tools than FDS, e.g. FLACS-CFD, KFX or EXSIM, were found to be capable to simulate the consequences of hazards of gases produced during a thermal runaway in BESS enclosure or the consequences of a TPRD activation in an enclosed space.

CFD tools are deemed more relevant to model what can happen in closed and open ro-ro spaces than empirical or analytical tools. Simpler tools, like Phast, Effects, e-tools or HyRAM+ for hydrogen, were found more limited (mainly applied to open air, limited effects of geometry) but to be able to provide quicker results and be used to screen hazardous scenarios prior to CFD calculations or to provide order of magnitude of hazardous phenomena. Moreover, those simpler tools often include source term model (e.g. off-gases release rate during thermal runaway) and therefore can be used as inputs to CFD tools. Research from projects including BREND 2.0 (2021), LASH FIRE (2023), and ELBAS (2022) highlights that ventilation control, vehicle spacing, and early suppression activation are critical in limiting fire spread and maintaining survivable conditions. Continued coupling of experimental data with advanced simulation frameworks will be essential to refine predictive models, improve safety system design, and establish standardized methodologies for AFV fire risk assessment in the maritime sector.

There are some under-represented areas in current research, some of these are listed below.

1. Suppression interaction with electric vehicle fires: Quantified, validated models for drencher / water-mist / fire monitors on pack fires (cooling of shielded packs, HF/HF (aq) behaviour, re-ignition) are limited; most studies show tenability benefits but do not mechanistically model battery cooling/penetration or HF neutralization/absorption in seawater spray. See also comments on drencher system limitations in ro-ro space scenarios.
2. Toxic species chemistry and deposition at sea: HF/HCN/acid gas generation, condensation, absorption, and surface reactions (salt-laden humidity, spray, drainage) are under-modelled; species are often tracked as passive scalars without deposition/chemistry, and validation data at shipboard conditions are scarce. (Jang, *et al.* (2025) note the difficulty matching multi-species chemistry.)
3. Ejecta from battery thermal runaway represents a major missing element in maritime electric vehicle fire modelling. Current CFD frameworks capture gas, heat, and toxicity well but overlook the ballistic, fragment, and secondary ignition mechanisms that could critically influence fire spread, drencher reliability, and crew safety aboard ships.
4. Predictive source terms for battery TR in CFD (not “imposed”) where many studies inject heat release and species yields from experiments rather than predicting them from abuse physics (kinetics, venting, jetting, fragmentation). Jang, *et al.* (2025) explicitly fall back to using measured HRR and species as inputs. This is still a useful approach; however, it is not predictive for new chemistries, pack designs, or shielding.

There are others missing topics; however, these are out of the scope of the present research such as fully e.g. coupled multi-physics simulations of cell TR to tenability where local conditions may interact with the TR propagation.

### 6.3 Mapping of knowledge

This last section of the conclusions provides a summary of the scientific and technical knowledge identified by the authors of the study. Although not exhaustive, this mapping aims at supporting the on-going work at IMO by sharing references to “*data of scientific reports and studies, new technologies, [...] on fire incidents of new energy vehicles, including BEVs*” (SSE 11/WP.1).

The mapping is organising as it follows:

- Column #1: Safety area as close as possible as EMSA guidance on AFVs and IMO instruments chapters;
- Column #2: Identified scientific and technical data relevant for each safety topic. Some additional information on the knowledge (e.g. if based on numerical simulations or experimental tests, scale of tests) are provided, when relevant;
- Column #3: Proposal(s) for further research based on the reviews conducted in Chapter 3, 4 and 5;
- Column #4: Any comments that may be useful to the readers;
- Column # 5 & 6: Hyperlinks to the sections of the report where the regulations, rules, guidelines or where the scientific and technical are further detailed; and finally
- A colour code is provided to clearly indicate to the readers the degree of knowledge on each safety topic and where further research are needed (based on an assessment from the authors):

Small gap	= limited research needed
Medium gap	= on-going research or further research needed
Large gap	= no or little research

6.3.1 Ignition prevention

Safety areas	Identified scientific and technical data	Proposal for further research	Comments	For more details	
				Reg.	Tech.
<ul style="list-style-type: none"> <li>Condition of carriage</li> </ul>	<ul style="list-style-type: none"> <li>A lot of scientific literature exist on influence of SoC of li-ion batteries on fire hazards</li> </ul>	<ul style="list-style-type: none"> <li>Li-ion batteries: Needs for better understanding and clear conclusions related to fire risk (early ignition) vs. explosion risk (delayed ignition)</li> <li>New technologies / chemistries of battery, new EV fire safety standards to come</li> </ul>	<ul style="list-style-type: none"> <li>SoC EVs: Aviation recommends (and will soon requires) 30%</li> <li>SoC gas fuelled vehicles: No rupture for SoC at 33% or below</li> </ul>	<p>3.2.2.4 3.3.8</p>	<p>4.3.2 4.3.5 4.3.8</p>

6.3.2 Detection

Safety areas	Identified scientific and technical data	Proposal for further research	Comments	For more details	
				Reg.	Tech.
Fixed fire detection and fire alarm	See below per technology	<ul style="list-style-type: none"> <li>In general, more large-scale tests are needed + to better investigate the special features of ro-ro spaces (large space volume, ventilation, hindered battery pack...)</li> <li>Couple test results with numerical modelling to refine predictive models</li> </ul>		3.2.3.1 3.3.3.1	
<ul style="list-style-type: none"> <li>Smoke and heat detectors</li> </ul>	<ul style="list-style-type: none"> <li>STARSS, 2025-2027 / standardized tests in a test compartment in lab + numerical simulations</li> <li>EDOT, 2024-2026 / lab test then large-scale EV test for most promising technologies</li> <li>LASH FIRE WP9, 2019-2023 / lab cell-scale test</li> <li>ELBAS, 2021-2022 / field EV-scale test</li> </ul>	<ul style="list-style-type: none"> <li>Comparison with other detection technologies ← <u>on-going research by EDOT and STARRS</u></li> </ul>	<ul style="list-style-type: none"> <li>Note: sample extraction smoke detection for PCTC</li> </ul>		4.4.2 4.4.3 4.4.4 4.4.6
<ul style="list-style-type: none"> <li>Video fire detection (VFD)</li> </ul>	<ul style="list-style-type: none"> <li>SSE 11/16/1, 2024 (South Korea &amp; IUMI) / land-based</li> <li>LASH FIRE WP9, 2019-2023 / lab cell-scale test</li> </ul>	<ul style="list-style-type: none"> <li>Validation experiments</li> <li>Comparison with other detection technologies</li> </ul>			4.4.4 4.4.8 4.4.9
<ul style="list-style-type: none"> <li>Thermal cameras</li> </ul>	<ul style="list-style-type: none"> <li>EDOT, 2024-2026 / lab test then large-scale EV test for most promising technologies</li> <li>LASH FIRE WP9, 2019-2023 / lab cell-scale test,</li> <li>ALBERO, 2018-2021 / lab test + demonstrator</li> </ul>	<ul style="list-style-type: none"> <li>Comparison with other detection technologies</li> </ul>			4.4.4 4.4.6 4.4.7

TECHNICAL AND REGULATORY REVIEW

Safety areas	Identified scientific and technical data	Proposal for further research	Comments	For more details	
				Reg.	Tech.
<b>Gas detection</b> (for LPG, CNG vehicles and FCVs)			<ul style="list-style-type: none"> <li>As soon as the gas fuelled vehicle is parked, only leak for TPRD is possible</li> </ul>	3.3.3.4	
<b>Thermal runaway detection</b>	<ul style="list-style-type: none"> <li>See review of scientific literature conducted by EDOT</li> </ul>			3.2.3.5	
<ul style="list-style-type: none"> <li>BMS related detection</li> </ul>	<ul style="list-style-type: none"> <li>STARSS, 2025-2027 / evaluation workshop</li> <li>EDOT, 2024-2026 / electrochemical impedance spectroscopy</li> <li>SSE 11/INF.7, 2024 (China)</li> <li>SSE 10/INF.8, 2023 (China)</li> </ul>	<ul style="list-style-type: none"> <li>Policies and legal obstacles of data sharing</li> </ul>	<ul style="list-style-type: none"> <li>Note: Dependent on both ship system and vehicle system</li> </ul>	3.3.3.5	4.4.10
<ul style="list-style-type: none"> <li>Battery pack temperature monitoring</li> </ul>	<ul style="list-style-type: none"> <li>SSE 11/INF.7, 2024 (China) / onboard test</li> <li>SSE 10/INF.8, 2023 (China)</li> </ul>				4.4.10
<ul style="list-style-type: none"> <li>Gas detection</li> </ul>	<ul style="list-style-type: none"> <li>STARRS, 2025-2027 / standardized tests in a test compartment in lab test + numerical simulations</li> <li>EDOT, 2024-2026 / lab test then large-scale EV test for most promising technologies</li> <li>LASH FIRE WP9, 2019-2023 / lab cell-scale test</li> <li>ELBAS, 2021-2022 / field EV-scale test</li> <li>ALBERO, 2018-2021 / lab test + demonstrator</li> </ul>	<ul style="list-style-type: none"> <li>Species to be tracked, cross sensitivity of sensors ← <u>on-going research by EDOT and STARRS</u></li> <li>Performance in ro-ro space, e.g. large volume of ro-ro space, ventilation vs. sensibility of sensor</li> <li>Placement and distance of sensors ← <u>on-going research by EDOT and STARRS</u></li> <li>Comparison with other detection technologies ← <u>on-going research by EDOT and STARRS</u></li> </ul>		3.2.3.4	4.4.3 4.4.4 4.4.6 4.4.7
<b>Video monitoring</b> (for fire confirmation and localization)	<ul style="list-style-type: none"> <li>LASH FIRE WP9, 2019-2023 / General, not specific to AFVs</li> </ul>			3.2.3.2 3.3.3.2	
<b>Fire patrol</b>	<ul style="list-style-type: none"> <li>LASH FIRE WP6, 2019-2023</li> </ul>			3.2.3.3 3.3.3.3	

6.3.3 Fire-fighting

Safety areas	Identified scientific and technical data	Proposal for further research	Comments	For more details	
				Reg.	Tech.
<b>Fixed fire-extinguishing system</b>				3.2.4.1 3.3.5.1	
<ul style="list-style-type: none"> <li>Drencher (or deluge) and automatic sprinkler system</li> </ul>	<ul style="list-style-type: none"> <li>LASH FIRE WP10, 2019-2023 &amp; MSC 107/INF.5, 2023 (Interferry) / EV-scale test</li> <li>ELBAS, 2021-2022 / numerical simulations</li> <li>ALBERO, 2018-2021 / battery pack-scale test</li> </ul>	<ul style="list-style-type: none"> <li>Performance on larger EVs, like pickups, freight trucks and buses (i.e. larger battery pack and potential different battery position)</li> </ul>	<ul style="list-style-type: none"> <li>MSC.1/Circ.1430: revised for modern vehicles, e.g. water flow rate improved, possibility for automatic activation</li> <li>Mainly RO-PAX, RO-RO. Note: automatic sprinkler systems (not drencher) for PCTC tested in LASH FIRE (ICEV test)</li> </ul>		4.8.2 4.8.3 5.7
<ul style="list-style-type: none"> <li>Water mist system</li> </ul>	<ul style="list-style-type: none"> <li>SSE 10/INF.10, 2023 (China) / EV mock-up test</li> <li>ELBAS, 2021-2022 / EV-scale test</li> <li>SSE 7/INF.11, 2020 (China) / EV mock-up test</li> </ul>	<ul style="list-style-type: none"> <li>Performance in very large, enclosed space (i.e. ro-ro space) and adequacy of distribution rate</li> <li>Performance on larger EVs, like pickups, freight trucks and buses</li> </ul>	<ul style="list-style-type: none"> <li>Mainly RO-PAX, RO-RO</li> <li>Closed ro-ro space</li> </ul>		4.6.3 4.8.5 4.8.6
<ul style="list-style-type: none"> <li>Ground water spray system (i.e. system spraying water from the deck/floor)</li> </ul>			<ul style="list-style-type: none"> <li>Low TRL</li> </ul>		4.8.4
<ul style="list-style-type: none"> <li>High-expansion foam system</li> </ul>	<ul style="list-style-type: none"> <li>STARSS, 2025-2027 / inside air foam system, EV-scale test</li> <li>SSE 9/INF.4, 2022 &amp; SSE 11/INF.5, 2024 (Japan) / outside air foam system, EV-scale &amp; EV mock-up test</li> <li>SSE 7/INF.11, 2020 (China) / EV mock-up test</li> </ul>	<ul style="list-style-type: none"> <li>Performance under actual marine conditions</li> <li>Performance on larger EVs, like pickups, freight trucks and buses, and/or when the battery is located at the top of the vehicle</li> </ul>	<ul style="list-style-type: none"> <li>RO-RO, PCTC</li> </ul>		4.9

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Safety areas	Identified scientific and technical data	Proposal for further research	Comments	For more details	
				Reg.	Tech.
<ul style="list-style-type: none"> <li>Carbon dioxide systems</li> </ul>	<ul style="list-style-type: none"> <li>COFFEE, 2024-2026 / cell-scale then EV-scale test</li> <li>SSE 7/INF.11, 2020 (China) / EV mock-up test</li> </ul>	<ul style="list-style-type: none"> <li>Adequacy of concentration of CO<sub>2</sub> (45%) and number of discharge (1) ← <u>on-going research by COFFEE</u></li> <li>Performance vs. timing of release ← <u>on-going research by COFFEE</u></li> <li>Performance on larger EVs, like pickups, freight trucks and buses</li> <li>Crew user studies on PCTC to reduce human error and support timely, effective action in fire scenarios such as activation of system</li> </ul>	<ul style="list-style-type: none"> <li>RO-RO, PCTC</li> <li>Only closed ro-ro space</li> </ul>		4.10
<p><b>Manual fire-fighting (incl. personnel equipment)</b></p>	<ul style="list-style-type: none"> <li>"Fire Safety of Batteries and Electric Vehicles" project from FSRI (UL, 2025) / land-based</li> <li>'Assessment of EV Firefighting Techniques and the Impact on Stranded Energy' project from NFPA (NFPA, 2025) / land-based</li> </ul>		<ul style="list-style-type: none"> <li>A recent exercise on board a PCTC found manual fire-fighting nearly impractical in the space of origin of the fire</li> </ul>	3.2.4.2 3.3.5.2	
<ul style="list-style-type: none"> <li>Fire-fighting gear</li> </ul>	<ul style="list-style-type: none"> <li>"Emerging Issues Related to Personal Protective Equipment" project from FSRI (FSRI, 2025) / land-based</li> <li>SSE 11/INF.6, 2024 (South Korea) / land-based</li> <li>LASH FIRE WP6, 2019-2023</li> <li>Safe and Suitable Firefighting project, 2020-2021</li> </ul>	<ul style="list-style-type: none"> <li>All vehicle fires produce toxic smoke and soot. Conclude on difference between ICEVs and EVs as regards as human and gear exposure to chemical hazards</li> <li>Conclude on reutilization of fire-fighting gear after EV fire (e.g. strong smell even after many washing)</li> </ul>			

Safety areas	Identified scientific and technical data	Proposal for further research	Comments	For more details	
				Reg.	Tech.
<ul style="list-style-type: none"> <li>Existing equipment (e.g. fire extinguishers, fire hoses)</li> </ul>	<ul style="list-style-type: none"> <li>SSE 11/INF.6, 2024 (South Korea) / land-based</li> <li>INERIS, 2024 (Lecocq &amp; Bordes, 2024) / land-based</li> <li>LASH FIRE WP6, 2019-2023 / field test</li> <li>BREND, 2018-2019 / lab and field test</li> </ul>	<ul style="list-style-type: none"> <li>Performance on larger EVs, like pickups, freight trucks and buses</li> </ul>			4.6.2
<ul style="list-style-type: none"> <li>Brine-based fire-fighting system</li> </ul>	<ul style="list-style-type: none"> <li>SSE 11/16, 2024 (Faroes) &amp; (Radulescu &amp; Firkic, 2023) / field test</li> </ul>	<ul style="list-style-type: none"> <li>Conclude on safe deployment in ro-ro space (e.g. better understanding of risk of explosion)</li> <li>Feasibility on larger EVs and/or when the battery is located at the top of the vehicle</li> </ul>			4.6.5.5
<ul style="list-style-type: none"> <li>Battery pack water flooding devices</li> </ul>	<ul style="list-style-type: none"> <li>MSB, 2023 / land-based, battery pack-scale</li> <li>ELBAS, 2021-2022 / field EV-scale test</li> </ul>	<ul style="list-style-type: none"> <li>Conclude on safe deployment in ro-ro space (e.g. better understanding of risk of explosion)</li> <li>Feasibility on larger EVs and/or when the battery is located at the top of the vehicle</li> </ul>			4.6.3 4.6.5
<ul style="list-style-type: none"> <li>Fire blankets</li> </ul>	<ul style="list-style-type: none"> <li>NFPA, 2025 / land-based</li> <li>LASH FIRE WP6, 2019-2023 / field test</li> <li>ELBAS, 2021-2022 / field test</li> <li>ALBERO, 2018-2021 / field test</li> </ul>	<ul style="list-style-type: none"> <li>Conclude on safe deployment / removal in ro-ro space (e.g. better understanding of risk of explosion)</li> <li>Feasibility on larger EVs</li> </ul>			4.6.3 4.7
<ul style="list-style-type: none"> <li>Portable water curtain</li> </ul>	<ul style="list-style-type: none"> <li>LASH FIRE WP6, 2019-2023 / field test</li> <li>ELBAS, 2021-2022 / field test</li> <li>ALBERO, 2018-2021 / lab and field scale</li> <li>BREND, 2018-2019 / field tests</li> </ul>				4.6.2 4.6.3 4.6.4

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Safety areas	Identified scientific and technical data	Proposal for further research	Comments	For more details	
				Reg.	Tech.
<ul style="list-style-type: none"> <li>Portable “underbody water spray equipment” or drones</li> </ul>	<ul style="list-style-type: none"> <li>SSE 11/INF.6, 2024 (South Korea) / land-based</li> <li>ELBAS, 2021-2022 / field test</li> </ul>		<ul style="list-style-type: none"> <li>Low TRL</li> </ul>		4.6.3
<b>Operations, procedures</b>				3.2.4.3 3.3.5.3	
<ul style="list-style-type: none"> <li>Fire-fighting/emergency response</li> </ul>	<ul style="list-style-type: none"> <li>Learnings of a vehicle carrier fire simulation in the port of Emden, SSE 11, 2024 (Germany) / PCTC</li> <li>FerrySafe23 / RO-PAX</li> <li>LASH FIRE WP6, 7, 2019-2023 / general, not specific to AFVs</li> <li>ELBAS, 2021-2022 / RO-PAX</li> <li>BREND, 2018-2019 &amp; BREND 2.0, 2020-2022 / mainly RO-PAX</li> </ul>	<ul style="list-style-type: none"> <li>Onboard studies that enable virtual analysis of crew behaviour, coordination, and decision-making during fire scenarios to identify bottlenecks, and improve training and ship design</li> </ul>	<ul style="list-style-type: none"> <li>Few data on PCTC identified</li> <li>Ship-specific</li> </ul>		4.11.1
<ul style="list-style-type: none"> <li>Ventilation for fire-fighting</li> </ul>	<ul style="list-style-type: none"> <li>LASH FIRE WP11, 2019-2023 / general, not specific to AFVs, numerical simulations</li> <li>ELBAS, 2021-2022 / RO-PAX, numerical simulations</li> <li>BREND 2.0, 2020-2022 / mainly RO-PAX, numerical simulations</li> </ul>	<ul style="list-style-type: none"> <li>Data mostly identified from numerical simulations, field test may provide more knowledge</li> <li>Explosion mitigation strategies</li> </ul>	<ul style="list-style-type: none"> <li>Ship-specific</li> </ul>		5.3 5.7
<ul style="list-style-type: none"> <li>Post fire-fighting management, incl. fire water management, decontamination of equipment and gear, removal of vehicle(s)</li> </ul>	<ul style="list-style-type: none"> <li>FerrySafe23 / RO-PAX</li> <li>LASH FIRE WP6, 2019-2023</li> <li>E-TOX, 2019-2020 &amp; E-TOX 2, 2021-2022</li> </ul>				4.3.2 4.3.3
<ul style="list-style-type: none"> <li>Re-ignition prevention</li> </ul>	<ul style="list-style-type: none"> <li>STARSS, 2025-2027 / re-ignition monitoring during inside air foam system, EV-scale test</li> <li>LASH FIRE WP6, 2019-2023</li> </ul>	<ul style="list-style-type: none"> <li>Safe transportation of damaged batteries and/or EVs</li> </ul>	<ul style="list-style-type: none"> <li>Can be linked to new equipment, like fire blankets, portable water curtain, but not only</li> </ul>		

Safety areas	Identified scientific and technical data	Proposal for further research	Comments	For more details	
				Reg.	Tech.
<b>Training and drills</b>				3.2.4.4 3.3.5.4	
<ul style="list-style-type: none"> <li>■ Training</li> </ul>	<ul style="list-style-type: none"> <li>■ LASH FIRE WP6, 7, 2019-2023</li> <li>■ ELBAS, 2021-2022 / RO-PAX</li> <li>■ ALBERO, 2018-2021 / RO-PAX</li> </ul>	<ul style="list-style-type: none"> <li>■ Onboard studies that enable virtual analysis of crew behaviour, coordination, and decision-making during fire scenarios to identify bottlenecks, and improve training and ship design</li> </ul>	<ul style="list-style-type: none"> <li>■ Few data on PCTC identified</li> </ul>		4.11.2
<b>Fire-fighting at shore</b>	<ul style="list-style-type: none"> <li>■ Learnings of a vehicle carrier fire simulation in the port of Emden, SSE 11, 2024 (Germany) / PCTC</li> <li>■ FerrySafe23 / RO-PAX</li> </ul>			3.2.4.5	

6.3.4 Containment

Safety areas	Identified scientific and technical data	Proposal for further research	Comments	For more details	
				Reg.	Tech.
<ul style="list-style-type: none"> <li>Structural fire protection</li> </ul>	<ul style="list-style-type: none"> <li>LASH FIRE WP11, 2019-2023 / general, not specific to AFVs</li> <li>RoBound, 2021 (Mindykowski, 2021) / general, not specific to AFVs</li> </ul>	<ul style="list-style-type: none"> <li>Adequacy of fire curve (ISO 834), of A-class division as defined in FTP code, to be further evaluated</li> </ul>		<p>3.2.5.1 3.3.6.1</p>	
<ul style="list-style-type: none"> <li>Explosion risk and mitigation</li> </ul>	<ul style="list-style-type: none"> <li>COMBAT, 2024-2025 / BESS level</li> <li>BESAFE, 2024 / BESS level</li> <li>INERIS, 2023 (Lecocq, 2023) / BESS level</li> </ul>	<ul style="list-style-type: none"> <li>Lack of data about compartment explosion in very large, enclosed space (i.e. ro-ro space) + hazards of confined explosion inside the vehicle (= protection of crew members and fire-fighters)</li> <li>Adequacy of A-class division as defined in FTP code to be further evaluated</li> </ul>		<p>3.3.6.2 3.3.6.2</p>	<p>4.3.7 4.3.8</p>

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## Appendix A General description of AFVs

A general description of the different types of AFVs can be found on: <https://afdc.energy.gov/fuels>.

[Battery Electric Vehicle \(BEV\):](#)

### All-Electric Vehicle

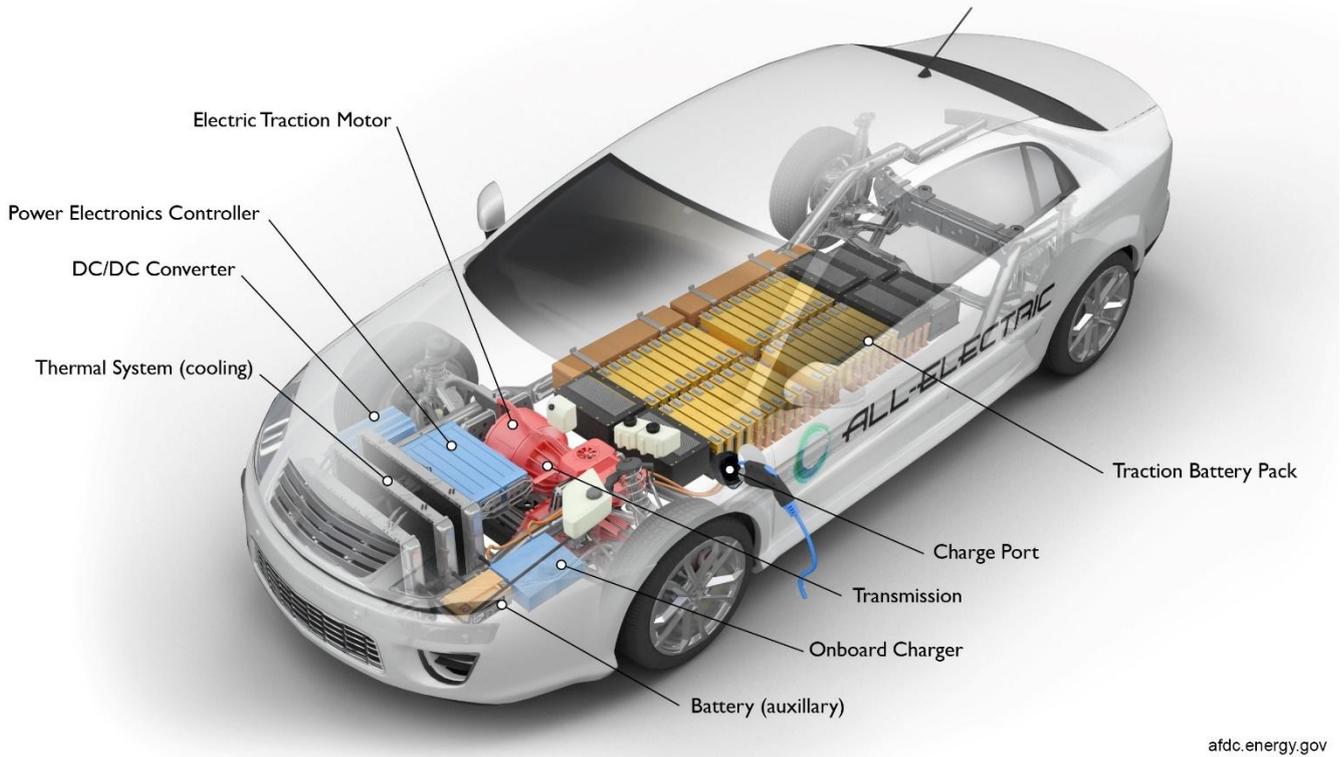


Figure 32. General description of BEV (from US Department of Energy).

<https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work>

Different safety systems are installed on board a BEV such as a thermal management system, a battery management system (BMS)... A BMS is an “*electronic system associated with a battery which has functions to control current in case of overcharge, overcurrent, overdischarge, and overheating and which monitors and/or manages the battery's state, calculates secondary data, reports that data and/or controls its environment to influence the battery's safety, performance and/or service life*” (IEC 62619:2022).

[Liquefied Petroleum Gas \(LPG\) vehicle:](#)

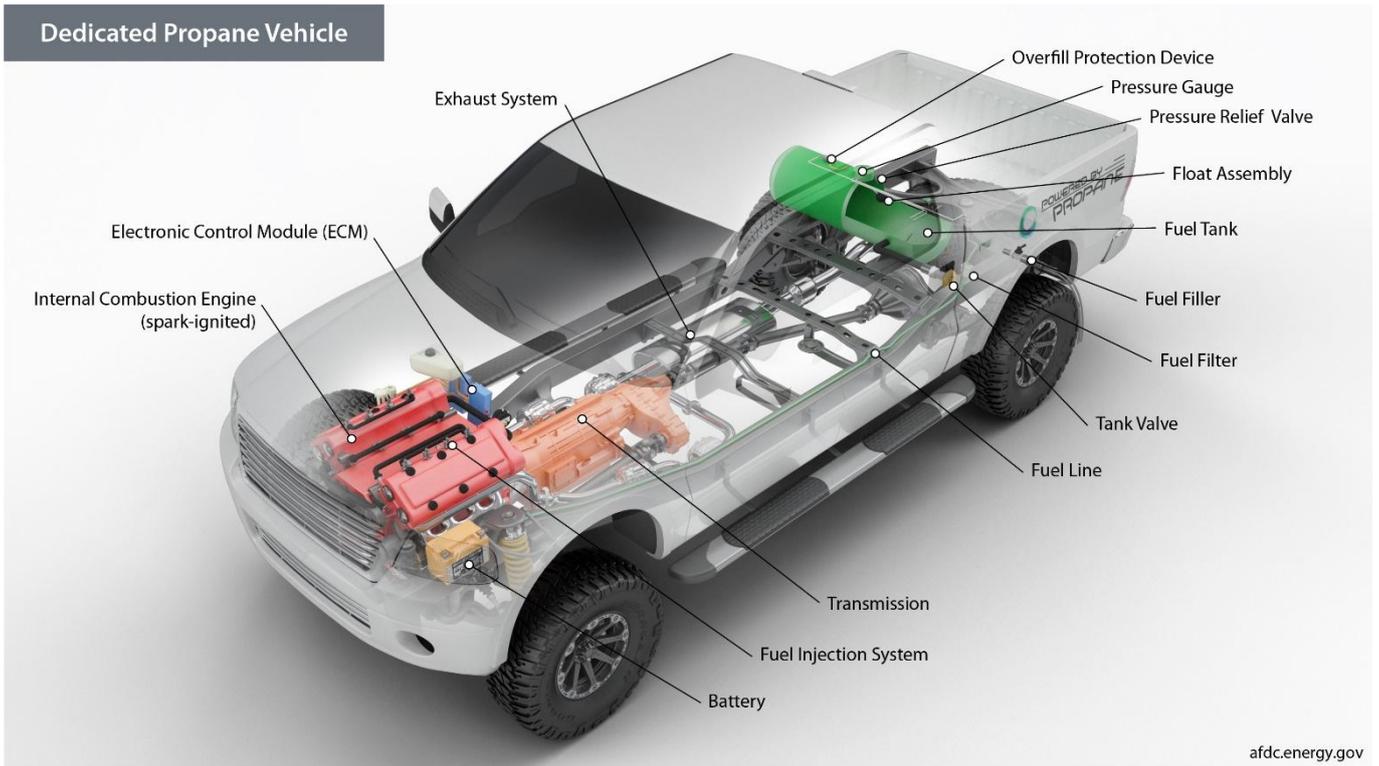


Figure 33. General description of LPG vehicle (from US Department of Energy).

<https://afdc.energy.gov/vehicles/how-do-propane-cars-work>

Compressed Natural Gas (CNG) vehicle:

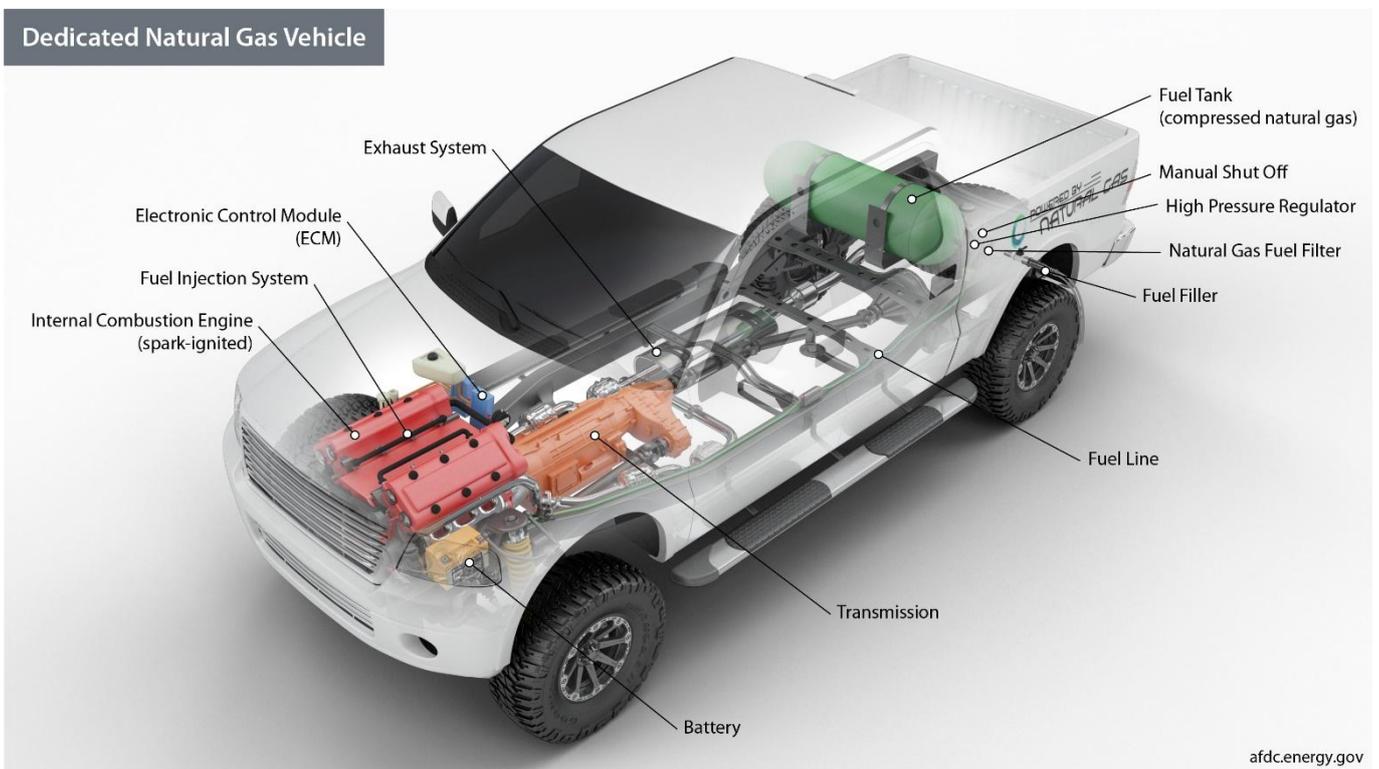


Figure 34. General description of CNG vehicle (from US Department of Energy).

<https://afdc.energy.gov/vehicles/how-do-natural-gas-cars-work>

Fuel Cell Vehicle (FCV):

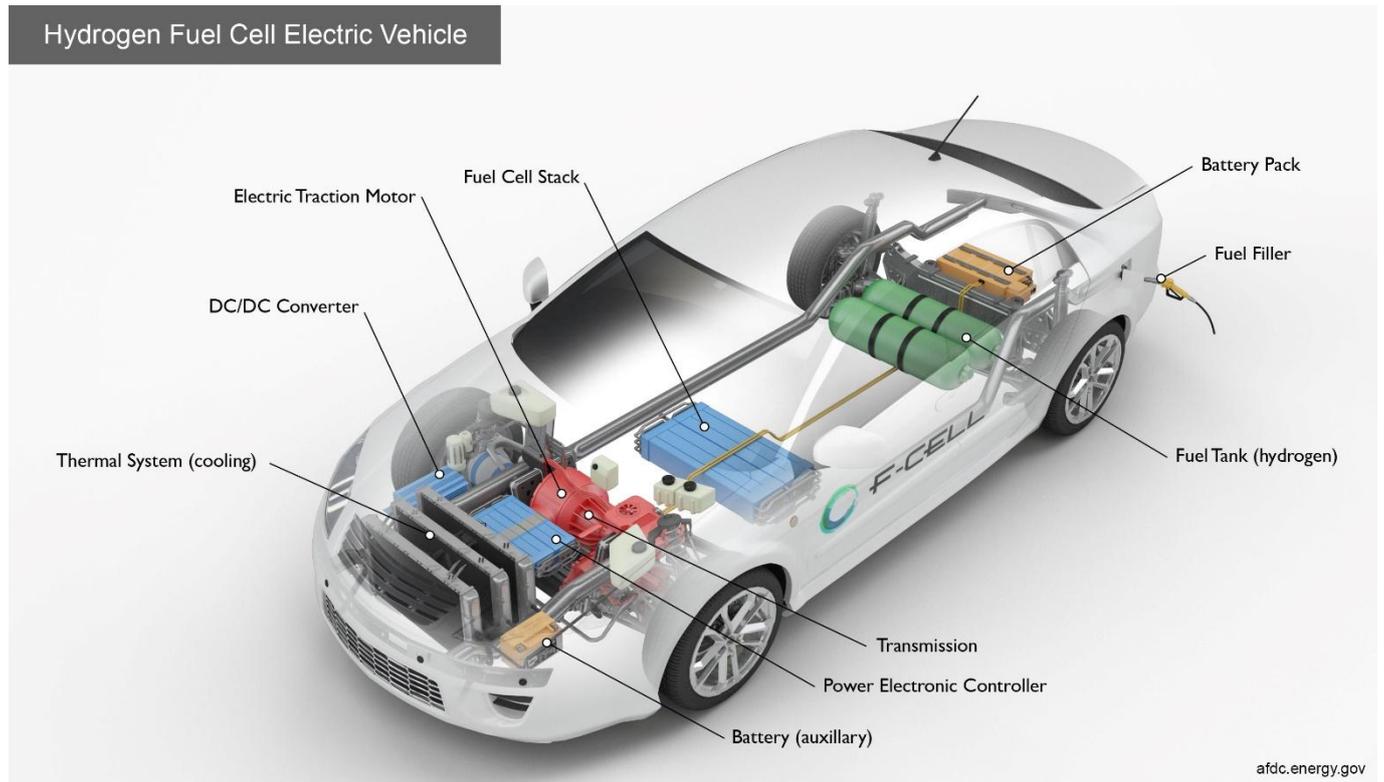


Figure 35. General description of FCV (from US Department of Energy).

<https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work>

## Appendix B Regulatory review (other than maritime) – List of reviewed documents

Table 12. List of reviewed documents related to road tunnels, car parks and BESS regulations – EVs

Year	Author of document	Title of document	Scope	Type of document	Countries	Notes	Ref.
2015	NFPA	Emergency Field Guide	Emergency response	Guidelines	USA		(NFPA, 2015)
2018	DGSCGC	Guide pratique relatif à la sécurité incendie dans les parcs de stationnement couverts ouverts au public	Enclosed car parks	Guidelines	France		(DGSCGC, 2018)
2019	City of London Corporation	FSGN 63 - Guidance on the installation of fast, rapid and super vehicle charging units	Charging stations	Standards, Guidelines	UK		(City of London Corporation, 2019)
2020	NFPA	Modern Vehicles Hazards in Parking Garage and Vehicle Carrier	Car parks	Review	USA	All types of vehicles	(Boehmer, Klassen, & Olenick, 2020)
2020	NTSB	Safety risks to Emergency responders from LI battery fires in Electric Vehicles	Emergency response	Review	International, USA		(NTSB, 2020)
2020	SDIS86	Fire service operational handbook - Emergency response on vehicles	Emergency response	Guidelines	France		(SDIS86, 2020)
2022	Conseil Général de l'Environnement et du Développement Durable	Le renforcement de la protection incendie dans les parkings couverts	Charging stations	Review	France		(CGEDD, 2022)
2023	ARUP	T0194 – Covered car parks - fire safety guidance for electric vehicles	Enclosed car parks	Guidelines	UK		(ARUP, 2023)

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2023	ARUP	Electric Vehicles (EVs) and Charging Infrastructure - Technical Info on Fire Safety	Charging stations	Review	Australia, Netherlands, USA, UK		(ARUP, 2023)
2023	Fire Forum	Code de bonne pratique Sécurité Incendie – Véhicules Electriques dans les parkings	Car parks	Standards, Guidelines	Belgium		(Fire Forum, 2023)
2023	Fire Protection Association	RC59: Recommendations for fire safety when charging electric vehicles	Charging stations	Recommendations	UK		(FPA, 2023)
2023	National Fire Research Institute	Electric Vehicle Fire Response Guide	Emergency response	Guidelines	South Korea		(NFA, 2023)
2023	NFPA	NFPA 88A - Standard for Parking Structures	Car parks	Regulations, Standards	USA	All types of vehicles	(NFPA, 2023)
2023	RISE	Electric Vehicle Fire Safety in Enclosed Spaces	Car parks, road tunnels	Review	Australia, New Zealand, Sweden, USA	All types of vehicles	(Hynynen, et al., 2023)
2023	TotalEnergies	FABIG TM105 - Managing battery hazards in EV charging infrastructure and industrial assets	Outdoor charging station	Best practices	France		(Roosendans & Dutertre, 2023)
2024	NFPA	Classification of Modern Vehicle Hazards in Parking Structures & Systems	Car parks	Review	International, USA, other	All types of vehicles	(Olenick, Klassen, & Hussain, 2024)
2024	MSB	Räddningsinsats där litiumjonbatterier förekommer	Land-based	Guidelines	Swedish		(MSB, 2024)
2024	NIPV	FABIG TM108 - Electric vehicles fires: Statistics, parking structures & incident response	Charging stations	Review	Netherlands		(Hessels T. , 2024)
2024	TotalEnergies	FABIG TM108 - Technological risk management for multi-energy service stations	Outdoor charging station	Best practices	France		(Do, 2025)

2025	DBI	Battery Energy Storage Systems (BESS) - Overview of guidelines from Denmark, Belgium, Sweden, UK, USA and other selected countries	BESS	Review	Denmark, Belgium, Sweden, UK, USA and other		(Æbelø, Funk, Livkiss, Gallas-Hulin, & Sauca, 2025)
2025	European Commission	Fire safety - Electric vehicles and charging infrastructure	Charging stations	Review	European countries		(EC, 2025)
2026	NFPA	NFPA 502 - Standard for Road Tunnels, Bridges, and Other Limited Access Highways	Road tunnels	Regulations, Standards	USA	All types of vehicles	(NFPA, 2026)

Table 13. List of reviewed documents related to road tunnels and car parks – LPG, CNG vehicles, FCVs

Year	Author of document	Title of document	Scope	Type of document	Countries	Notes	Ref.
2008	NFPA	Fire Protection Handbook	LPG and CNG fuelling stations	Review	USA	LPG and CNG vehicles	(NFPA, 2008)
2015	NFPA	Emergency Field Guide	Emergency response	Guidelines	USA	LPG, CNG vehicles and FCVs	(NFPA, 2015)
2017	RISE	Risks associated with alternative fuels in road tunnels and underground garages	Enclosed car parks	Review	Sweden	LPG, CNG vehicles and FCVs	(Gehandler, Karlsson, & Vylund, 2017)
2018	DGSCGC	Guide pratique relatif à la sécurité incendie dans les parcs de stationnement couverts ouverts au public	Enclosed car parks	Guidelines	France	FCVs	(DGSCGC, 2018)

PUBLICATION TITLE

2020	NFPA	Modern Vehicles Hazards in Parking Garage and Vehicle Carrier	Car parks	Review	USA	All types of vehicles	(Boehmer, Klassen, & Olenick, 2020)
2020	SDIS86	Fire service operational handbook - Emergency response on vehicles	Emergency response	Guidelines	France	LPG, CNG vehicles and FCVs	(SDIS86, 2020)
2022	HyTunnel	Pre-normative research for safety of hydrogen-powered vehicles and transport through tunnels and similar confined spaces	Road tunnels	Recommendations from R&D project	European countries	FCVs	(Brauner, et al., 2022)
2023	NFPA	NFPA 88A - Standard for Parking Structures	Car parks	Regulations, Standards	USA	All types of vehicles	(NFPA, 2023)
2023	RISE	Electric Vehicle Fire Safety in Enclosed Spaces	Car parks, road tunnels	Review	Australia, New Zealand, Sweden, USA	All types of vehicles	(Hynynen, et al., 2023)
2024	HyTRA	Hydrogen powered vehicles in a tunnel accident - Risks and consequences	Road tunnels	Recommendations from R&D project	Austria	FCVs	(Aggarwal, et al., 2024)
2024	NFPA	Classification of Modern Vehicle Hazards in Parking Structures & Systems	Car parks	Review	International, USA, other	All types of vehicles	(Olenick, Klassen, & Hussain, 2024)
2024	TotalEnergies	FABIG TM108 - Technological risk management for multi-energy service stations	Outdoor fuelling stations	Best practices	France	CNG vehicles and FCVs	(Do, 2025)
2026	NFPA	NFPA 502 - Standard for Road Tunnels, Bridges, and Other Limited Access Highways	Road tunnels	Regulations, Standards	USA	LPG, CNG vehicles and FCVs	(NFPA, 2026)

Table 14. List of reviewed documents related to multimodal transportation of AFVs

Year	Author of document	Title of document	Notes	Ref.
2019	United Nations	Proposal to add state of charge (SOC) provision to large lithium-ion cells and batteries during transportation		(UN, 2019)
2022	United Nations Economic Commission for Europe	Regulation No. 100 - Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train	Paragraph 6.5 <i>Fire resistance</i> + Paragraph 6.15 <i>Thermal propagation</i> + Annex 9E <i>Fire resistance</i>	(UNECE, 2022)
2023	United Nations	Recommendations on the transport of dangerous goods		(UN, 2023)
2023	United Nations	Manual of tests and criteria	Part III, Sub-Section 38.3 <i>Lithium metal, lithium ion and sodium batteries</i>	(UN, 2023)
2023	United Nations Economic Commission for Europe	UN Global technical regulation No. 13 - Hydrogen and Fuel Cell Vehicles	Paragraph 5.1.4 <i>Verification test for service terminating performance in fire</i> + Paragraph 6.2.5 <i>Test procedures for two localized/engulfing fire test</i> + Paragraph 7.2.3 <i>Verification of service-terminating conditions: bonfire</i> + Paragraph 7.4.3 <i>Verification test for service-terminating performance due to fire</i>	(UNECE, 2023)
2023	European Union	Regulation (EU) 2023/1542 – “EU Battery Regulation”		(EU, 2023)

PUBLICATION TITLE

2024	Pipeline and Hazardous Materials Safety Administration	Lithium battery test summaries (TS)		(PHMSA, 2024)
2024	Pipeline and Hazardous Materials Safety Administration	Lithium battery guide for shippers		(PHMSA, 2024)
2024	United Nations Economic Commission for Europe	Regulation No. 134 - Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen-fuelled vehicles (HFCV)	Paragraph 5.4 <i>Verification test for service terminating performance in fire</i> + Annex 3 Paragraph 5 <i>Test procedures for service terminating performance in fire</i>	(UNECE, 2024)
2025	International Air Transport Association	Battery Guidance Document		(IATA, 2025)
2025	United Nations Economic Commission for Europe	Agreement concerning the international carriage of dangerous goods by road (ADR treaty)		(UNECE, 2025)



**European Maritime Safety Agency**

Praça Europa 4  
1249-206 Lisbon, Portugal  
Tel +351 21 1209 200  
Fax +351 21 1209 210  
[emsa.europa.eu](http://emsa.europa.eu)

