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Review of accident causes and hazard identification report

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Abstract

A background study concerning fire causes in ro-ro spaces was performed and subsequently used as input for a Hazard Identification (HazId) workshop. The main takeaways from the background study are:

- The ship's equipment is rarely the cause of fire–rather, the ship's cargo is generally the culprit;
- Electrical fault originating in the ship's cargo is the most common cause of fire in ro-ro spaces;
- Although refrigerated units typically constitute a rather limited proportion of all the carried cargo onboard, it is, according to statistics, the most hazardous type of cargo, in terms of probability, but also severity;
- While electrical failures in internal combustion engine vehicles constitute an apparent hazard, especially if the vehicles are in poor condition, there is little, if any, data that suggests electrical vehicles are more prone to fire than internal combustion engine vehicles; and
- Gas leak in Alternatively Powered Vehicles that leads to fire is a rare occurrence.

The background study comprised the analytical component of the hazard identification and was subsequently complemented with a creative element, i.e. the HazId workshop which ensured that the identified hazards were not confined to those which have materialized in the past. The workshop also focused on identifying potential safety measures. Examples include advancing technologies like drones, supplying ro-ro space personnel with dedicated thermal cameras, improved routines e.g. avoiding long cables and cable routing, and using only ship cables i.e. prohibiting passengers from using their own cables. These findings will be used as input to define conditions for manual screening of cargo fire hazards and effective fire patrols as well as describing methods for automatic screening and identification of cargoes, amongst other things.

Several potential fire origins were identified, refrigeration units being one of them. Taking into account that refrigeration units are more prone to fire than other types of cargo, and that refrigeration unit fires tend to be more severe, it is likely wise to put special focus on refrigeration units. A fair amount of work on this topic has already been conducted in the EMSA-funded FIRESAFE studies, which naturally served as reference in LASH FIRE.

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Content

Executive summary

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Problem definition

Ro-ro ships are an important component of the global maritime transportation system, but concerns have been raised over the number of significant fire incidents on ro-ro ships in recent years. This has prompted the International Maritime Organization (IMO) and maritime stakeholders to underscore the importance of improving the fire safety in ro-ro spaces. To date, only a limited number of studies focusing on these issues have been conducted. These studies have, to a varying degree, analysed critical aspects in previous ro-ro ship fires, thereby shedding some light on common fire causes in ro-ro shipping.

There is also a need to address the challenges ahead, including the ongoing cargo transformation involving alternatively powered vehicles. Moreover, these fire safety challenges are not limited to ro-ro passenger ships but apply to all types of ro-ro ships, including vehicle carriers and general ro-ro cargo ships. Hence, there is a need to update the fire protection of ro-ro ships from a wide and long-term perspective.

Technical approach

A literature review of studies addressing fire causes on ro-ro ships was carried out to summarize the most common vehicle fire hazards and lessons learned from recent studies. Furthermore, heavy vehicle fire incident data were summarized along with preliminary results of the statistical analysis. These studies were carried out in order to ensure all the participants of the planned Identification (HazId) workshop were informed about state-of-the-art. The literature review of studies addressing fire causes on ro-ro ships was circulated to the participants two weeks prior to the HazId workshop, held at RISE in Borås, Sweden on 11–12 December 2019. The preliminary results of the statistical analysis of heavy vehicle data was presented during the HazId, which was attended by a wide variety of experts. The HazId was based on Failure Mode and Effects Analysis (FMEA), which is a common procedure in risk management. It is a structured approach and was used to identify sources of fire initiation and hazards worsening consequences of fires in ro-ro spaces. Results from a previous HazId involving RISE (then SP) and Stena Line, addressing the same issue, were used as a starting point for the HazId. The results from the background study and HazId were subsequently complemented with a review of 11 selected maritime accident reports.

Results and achievements

The HazId result contains a list of fire causes, fire origins, failure modes and safety measures. A distinction was made between the terms *fire cause* and *fire origin*. The latter corresponds to the spatial origin of the fire, e.g. engine compartment of a car, whereas the former was defined in one of the following 7 categories:

- Overheating;
- Liquid leakage;
- Gas leakage;
- Electrical faults;
- Thermal runaway;
- Self-heating or chemical reaction; or
- Unsolicited activity.

Fire cause is thus a generic categorisation of the type of occurrence that may lead to ignition. Each fire cause was associated with various fire origins, failure modes (e.g. slipping v-belt) and safety measures (e.g. sensors in the trailer). Fire causes and fire origins were not quantified during the HazId procedure. The aim was rather to provide, to the extent possible, a complete picture of the various hazards in ro-ro spaces. Certain common fire causes have nonetheless been quantified in previous studies, which were reviewed in the background study that was circulated to the HazId participants two weeks prior to the workshop. Some important takeaways from the background study were:

- The ship's equipment is rarely the cause of fire; rather the ship's cargo is generally the culprit;
- Electrical fault originating in the ship's cargo is the most common cause of fire in ro-ro spaces;
- Although refrigeration units typically constitute a rather limited proportion of all the carried cargo onboard, it is, according to statistics, the most hazardous type of cargo, in terms of probability but also severity;
- While electrical failures in internal combustion engine vehicles constitute an apparent hazard, especially if the vehicles are in poor condition, there is little, if any, data that suggests Electrical Vehicles are more prone to fire than internal combustion engine vehicles; and
- Gas leaks in Alternatively Powered Vehicles that lead to fire appear to be a rare occurrence.

These results, as well as the results from the HazId, will be used as input to define conditions for manual screening of cargo fire hazards and effective fire patrols as well as for describing methods for automatic screening and identification of cargoes, amongst other things. This is directly related to the strategic objective of LASH FIRE, which is "to provide a recognized technical basis for the revision of international IMO regulations, which greatly enhances fire prevention and ensures independent management of fires on ro-ro ships in current and future fire safety challenges".

Contribution to LASH FIRE objectives

The IMO recently adopted the strategic plan for 2018-2023, which highlights the importance of integrating new and advancing technologies in the regulatory framework. One of the objectives of LASH FIRE is to support the aforementioned strategic plan, in part through this deliverable. This deliverable will furthermore lay the groundwork for achieving the following two objectives in particular:

> *Objective 3 → LASH FIRE will provide a **technical basis** for future revisions of regulations by **assessing risk reduction and economic properties of solutions**.*
>
> *Objective 1 → LASH FIRE will strengthen the **independent** fire protection of **ro-ro ships** by developing and validating effective **operative and design** solutions addressing **current and future** challenges in **all stages of a fire**.*

In order to develop effective operative and design solutions, it is crucial to gain an understand of the various fire hazards that exist in ro-ro spaces. This knowledge will contribute to achieving the verifiable action goals of actions related to ignition prevention (WP08), effective manual operations (WP06) as well as the development of the holistic ro-ro ship fire risk assessment model in WP04.

Exploitation and implementation

The results will be used within LASH FIRE to identify technologies that may help to reduce the risk of fire in ro-ro spaces. This includes better placement algorithms, automatic screening methodologies, heat detection sensors and recommendation on electrical connections.

The deliverable will furthermore highlight the different types of cargo that are typically found in ro-ro space. This is particularly important given that cargo placement on deck relative to other cargoes is an important aspect of reducing the overall risk of fire in ro-ro space. The identified hazards and technologies will support the work in WP08 which aims to provide guidelines and recommendations on cargo placement on deck to reduce risks from combination of certain cargoes and transport units. In parallel with this, the results will also be exploited by WP06 to recommend better equipment for fighting fires in initial stages which will guarantee more efficient handling of a fire on board without recourse to external intervention.

These results may be used to influence regulatory and standardisation bodies. This is particularly relevant in the context of refrigeration units which, relative to other type of cargo, are strongly associated with increased risk of fire.

1 List of symbols and abbreviations

ABS	Anti-lock Braking System
AC	Air Conditioning
APV	Alternatively Powered Vehicle
BEV	Battery Electric Vehicle
BLEVE	Boiling Liquid Expansion Vapour Explosion
CGH2	Compressed Hydrogen Gas
CNG	Compressed Natural Gas
DG	Dangerous Goods
DME	Liquefied Dimethyl Ether
DPF	Diesel Particulate Filter
DRI	Direct Reduced Iron
EMSA	European Maritime Safety Agency
EV	Electric Vehicle
GoE	Group of Experts
grt	Gross register tonnage
HEV	Hybrid Electric Vehicle
HGV	Heavy Goods Vehicle
ICEV	Internal Combustion Engine Vehicle
IMO	International Maritime Organization
LH2	Liquefied Hydrogen Gas
LIB	Li-ion Batteries
IUMI	International Union of Marine Insurance
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MAIB	Marine Accident Investigation Branch
PHEV	Plug-in Hybrid Electric Vehicle
PRV	Pressure Relief Valve
PRD	Pressure Relief Device
RCM	Risk Control Measure
RCO	Risk Control Option (a certain combination of RCMs)

2 Introduction

Main authors of the chapter: Kujtim Ukaj, RISE

There have been several significant ship fires in recent years, leading to growing concerns among Flag States, marine insurers and the International Maritime Organization (IMO). As early as in 2008, Cefor reported that between 2003–2007, roughly 2 % of insurance claims were attributed to fire or explosion, while comprising almost 10 % of the total claims cost (Cefor, 2008). Of increasing interest are fires that occur in ro-ro spaces, which have proven to be challenging to detect, extinguish and contain. According to an analysis prepared by Cefor (2014) based on compiled insurance claims data from the Nordic Marine Insurance Statistics (NoMIS) database, fires have occurred in more than one percent of the vessels belonging to the *Car/Ro-ro* segment, which is substantially higher than the other ship categories. More than half of these fires originated in the vessels' cargo spaces, and approximately 40 % of the fires resulted in insurance claims that exceeded $500,000 (Cefor, 2014). There is hence a considerable financial incentive from industry to improve the fire protection in ro-ro spaces, but in order to do so, a thorough understanding of the hazards that exist in ro-ro spaces is needed. The aim of this study was to provide a basis and outline a scope for forthcoming studies within LASH FIRE which aspire to develop and implement cost-effective methods and technologies to reduce the likelihood of fire ignition in ro-ro spaces. The end goal being to provide a recognized technical basis for the revision of international IMO regulations, aimed at enhancing fire prevention in ro-ro spaces. Part of the groundwork that contributes to achieving that goal is presented herein, commencing with a review of previous studies concerning fires in ro-ro spaces, followed by a Hazard Identification in which the aforementioned background study served as input.

3 Frequency of fire

Main authors of the chapter: Kujtim Ukaj, RISE

Papanikolaou, Bitha, & Eliopolou (2015) analysed 10 841 serious accidents that occurred during the period 1990–2012, involving merchant passenger and cargo ships built after 1980. They used data from IHS Seaweb and found that the frequency of fire or explosion that led to serious accidents for *ro-ro cargo ships* and *ro-ro passenger* ships was 3.32E-03 and 3.49E-03 per ship year, respectively. Leroux et al. (2018) found that 132 ro-ro passenger ship fire accidents were recorded in EMSA's database between 2002 and 2016, which corresponds to a frequency of 1.89E-02 fires per ship year. Of the 132 reported accidents, 37 originated in ro-ro spaces, which amounts to 5.28E-03 fires in ro-ro spaces per ship year. Utilising information from international databases, class records, EMSA marine casualty reports, incident reports and interviews with owners, DNV-GL studied accidents which had occurred between 2005 to 2016 and found that the frequency of ro-ro space fires in ro-ro passenger ships, ro-ro cargo ships and *vehicle carriers* above 4,000 grt was 2.0E-03, 1.19E-03 and 0.91E-03, respectively (2016). Similarly, based on casualty historical data obtained by the Lloyds Maritime Information Unit (LMIU) for the period 1994 to 2004, the SAFEDOR study (2008) found that the frequency of fire or explosion and serious accidents due to fire or explosion was 8.28E-03 and 3.23E-3 per ship year, respectively. A summary of the findings from previous studies is summarized in Table 1.

Table 1: Summary of studies addressing ro-ro ship fires.

Description of casualty	Study	Data	Ship category	Frequency (fire/shipyear)	Period analysed
Ro-ro passenger					
Fire or explosion	SAFEDOR (2008)	Lloyds Maritime Information Unit (LMIU)	Ro-pax above 1,000 grt	8.28E-03	1994-2004
Serious accident due to fire or explosion	SAFEDOR (2008)	Lloyds Maritime Information Unit (LMIU)	Ro-pax above 1,000 grt	3.23E-03	1994-2004
Fire or explosion in ro-ro space	SAFEDOR (2008)	Lloyds Maritime Information Unit (LMIU)	Ro-pax above 1,000 grt	0.99E-03	1994-2004
Serious accident due to fire or explosion	Papanikolaou et al. (2015)	IHS Seaweb	Ro-pax	3.49E-03	1990-2012
Ship fire	FIRESAFE II (2018)	EMSA data	Ro-pax	1.89E-02	2002-2016
Ship fire in ro-ro space	FIRESAFE II (2018)	EMSA data	Ro-pax	5.28E-03	2002-2016
Ship fire in ro-ro space	DNV GL (2016)	a)	Ro-pax above 4,000 grt	2.0E-03	2005-2016
Ro-ro cargo					
Serious accident due to fire or explosion	Papanikolaou et al. (2015)	IHS Seaweb	Ro-ro cargo	3.32E-03	1990-2012
Ship fire in ro-ro space	DNV GL (2016)	a)	Ro-ro cargo above 4,000 grt	1.19E-03	2005-2016
Vehicle carrier					
Ship fire in ro-ro space	DNV GL (2016)	a)	Vehicle carrier above 4,000 grt	0.91E-03	2005-2016
a) International databases, class records, EMSA marine casualty reports, incident reports, interviews with owners					b)

4 Fire causes in ro-ro spaces

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There has been a limited number of studies to date which have addressed the causes of fire in ro-ro spaces. However, the few studies that have been conducted present a consistent picture. Having reviewed 38 reported cases of fire in ro-ro spaces from 1995 to 2010, the UK Marine Accident Investigation Branch (MAIB) found that a significant number of the accidents were caused by electrical faults in the ship's cargo (Marine Accident Investigation Branch, 2011; The North of England P&I Association, 2017), as illustrated in Figure 1. Refrigeration units were identified as a common source of electrical failure, even though they typically represent a small proportion of vehicles carried on board (DNV GL, 2016). Similarly, a study conducted by DNV-GL (2016) revealed that almost 1 in 5 fires with known causes had started in refrigeration units. In 2017, the International Union of Marine Insurance (IUMI) issued a position paper, noting that:

> "Casualty data clearly indicates that a very high percentage of ro-ro fires emanate from the vehicles themselves, specifically from trailer refrigeration units, cab fires and electrical and engine fires, rather from the cargo itself." [1]

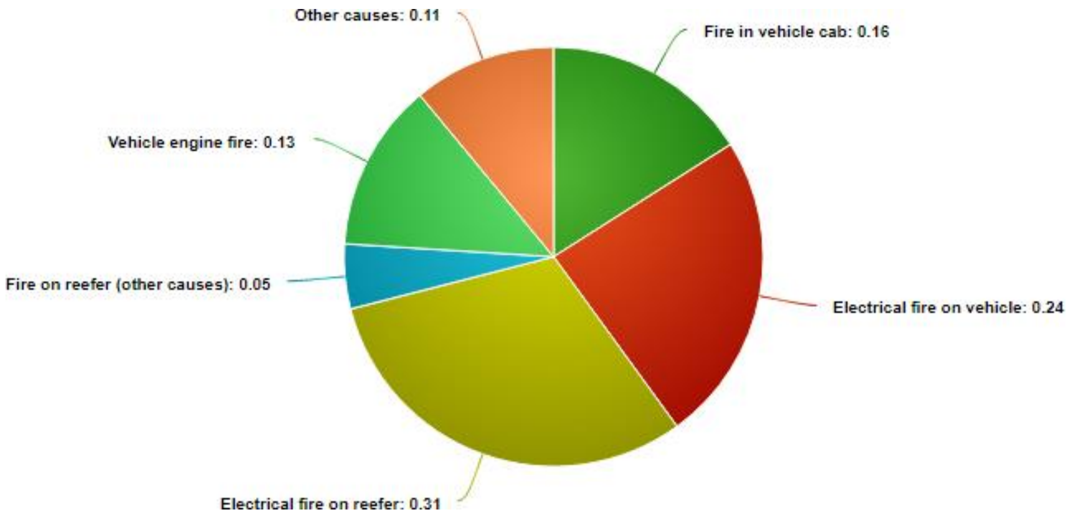

Figure 1: Ignition sources, as identified by MAIB in their investigation of fire in ro-ro space (Marine Accident Investigation Branch, 2011).

The aforementioned paper from IUMI presents a summary of ignition sources, see Figure 2, and builds upon the investigation conducted by the IMO-FSI Correspondence Group on Casualty Analysis (2012). The resulting report by the correspondence group was further analysed in 2015 by a Group of Experts (GoE), consisting of European Flag State representatives and maritime accident investigation bodies, on the initiative of the European Maritime Safety Agency (EMSA). The GoE concluded that *Electrical Fire as Ignition Risk* and *Fire Extinguishing Failure* were the most significant fire risk contributors, triggering European Maritime Safety Agency (EMSA) to commission the FIRESAFE studies — the most comprehensive public studies on ro-ro space fire safety to date.

[1] In general, ship operators classify all goods carried aboard the ship as "cargo", whether it is a vehicle, trailer, pallet, oil, etc. In this particular instance, cargo refers to the goods and materials carried by a truck or van that has been driven or rolled onto the vessel.

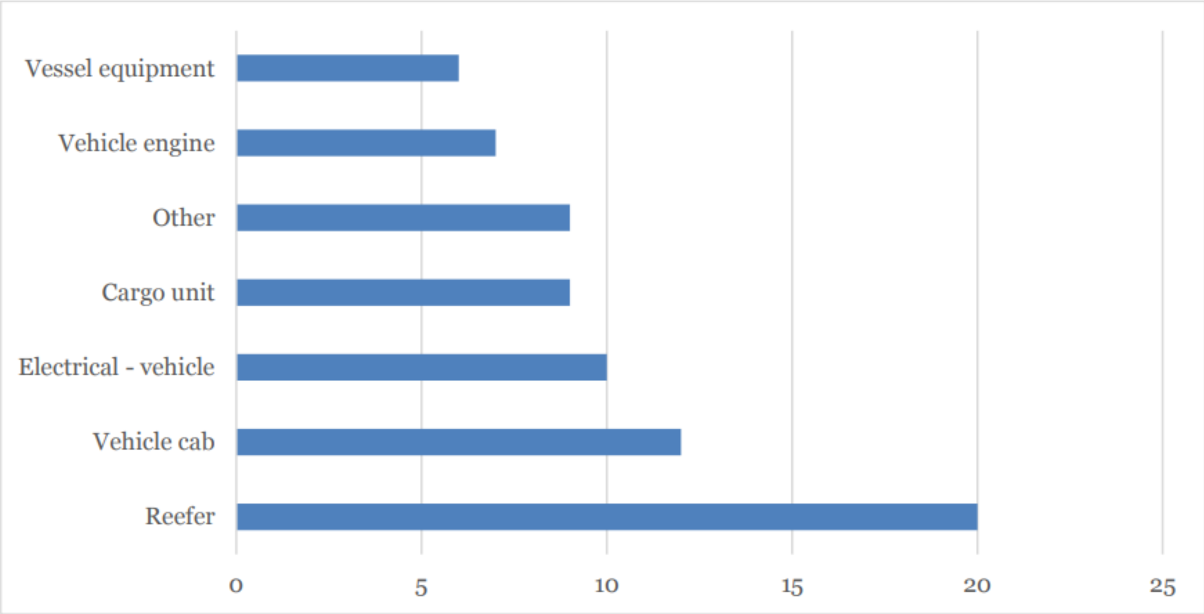

Figure 2: Ignition sources on ro-ro vehicle decks 1994–2011 based on FSI 21/5. (Source: IUMI)

5 The FIRESAFE studies

Main authors of the chapter: Kujtim Ukaj, RISE

Commissioned by EMSA, the FIRESAFE studies were aimed at improving the fire safety of ro-ro passenger ships in light of growing concerns about fires in ro-ro space. The studies were conducted by Bureau Veritas, RISE Research Institutes of Sweden and Stena Rederi, spanned 3 years and were concluded in late 2018. The studies shed light on several aspects of ro-ro space fire safety, including ignition sources, fire detection, decision-making, extinguishment, fire containment and evacuation. The following sections provide a summary and analyses of the FIRESAFE studies in the context of ignition sources in ro-ro spaces and the effects of cargo on fire development.

5.1 The first FIRESAFE study

In 2016, based on the findings from the GoE, EMSA commissioned the first FIRESAFE study, which comprised two parts–*Electrical Fire as Ignition Risk* and *Fire Extinguishing Failure.* The former aimed to outline a range of cost-efficient safety measures that would help to reduce the number of fires arising from electrical failures in cargo stowed in ro-ro spaces. To that end, a fault tree describing ignition sources leading to fire in ro-ro spaces was developed. Input to the fault tree was extracted from three filtered datasets involving 140 cases of fire in ro-ro spaces in total, all of which occurred during the period 1994–2016. The developed fault tree is presented in Figure 3 and illustrates that, inter alia, approximately 60 % of all reviewed ro-ro ship fires were caused by electrical faults. Furthermore, roughly 90 % of the fires which occurred in ro-ro space originated in the ship's cargo, over one third of which were caused by refrigeration units, as illustrated in Figure 4.

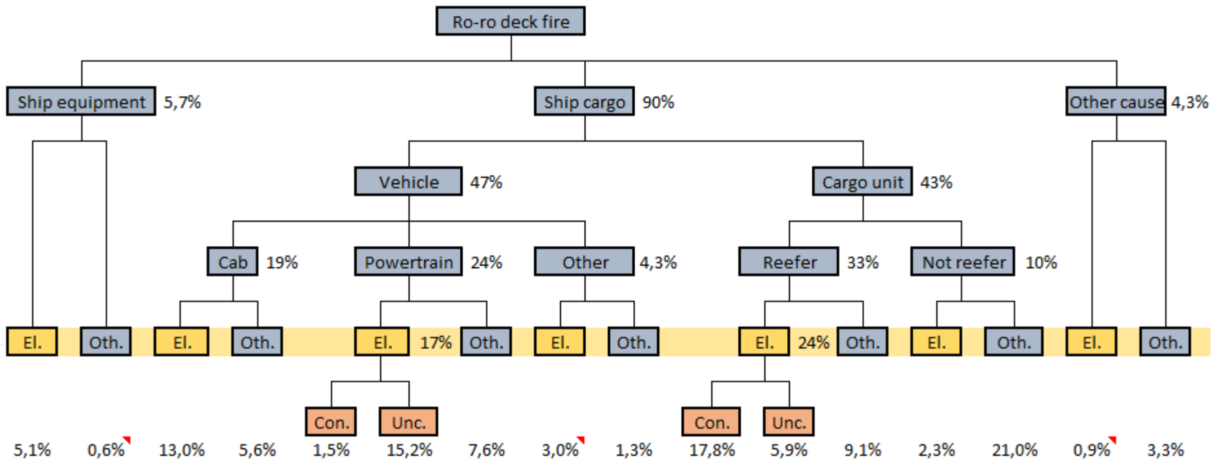

Figure 3: Fault tree risk model developed in the first FIRESAFE study, detailing ignition sources leading to ro-ro space fire.

For comparison, Li and Spearpoint (2007) studied statistics of vehicle fires in enclosed car parks in New Zealand and found that approximately 25 % of the vehicle fires were thought to have been caused by electrical faults, roughly the same as the proportion of vehicle fires caused by arson. It should be noted that passengers are typically prohibited from accessing ro-ro spaces during voyage, which might explain why arson is not as common on-board ships as in enclosed car parks.

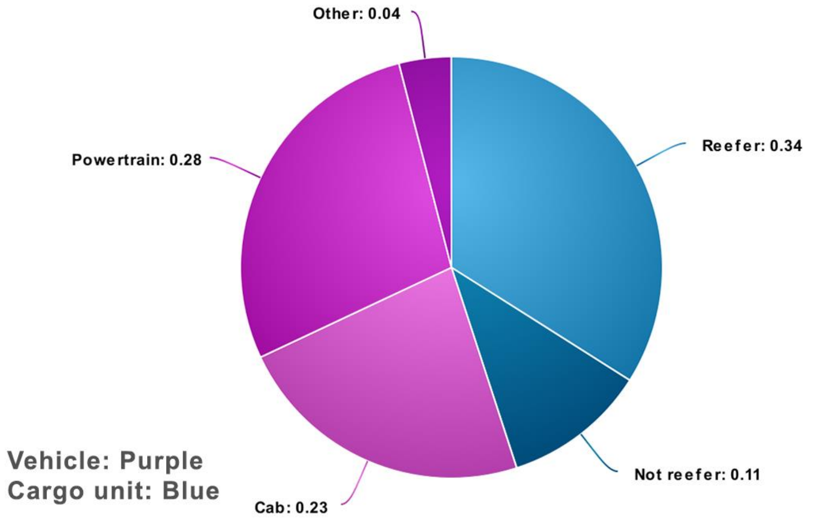

Figure 4: The specific origins of fires related to the ship's cargo (90 %), which includes the cargo unit and the vehicle – excluding fires caused by "ship equipment" and "other causes" (in total 10 %).

An aim of the *first* FIRESAFE study was to investigate cost-effective measures that would increase the chances of successful deployment of the drencher system (Wikman, et al., 2016). Fault trees were developed for both closed and open ro-ro spaces. The probability of successful extinguishment for both types of spaces was assumed to be dependent on whether the decision to deploy the drencher system was early or late in relation to the fire growth rate. As defined by Wikman et al. (2016):

> "'Early' means that the system has been activated early enough to have a certain chance to extinguish the fire. 'Late' means that the fire is already too developed, and that it is too late to have a chance to extinguish it. However, the fire can still be suppressed."

Figure 5 illustrates the fault tree for the *extinguishment/suppression failure in case of "early decision" in a closed ro-ro space*. The values assigned to the bottom nodes were based on expert judgement and literature values, if available (Wikman, et al., 2016).

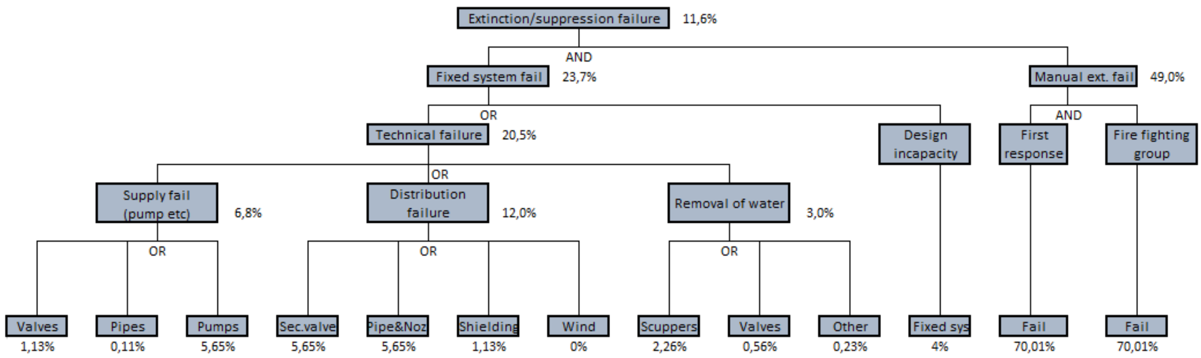

Figure 5: Extinguishment/suppression fault tree developed in FIRESAFE.

Analysing each causal factor leading to extinguishment/suppression failure is beyond the scope of this review, which instead focuses on ignition sources and the effects of cargo on fire development. With regard to the effects of cargo on fire development, it can be deduced from Figure 5 that there are a few causal factors that are directly or indirectly related to the cargo. They are described below.

5.1.1 Blocked scuppers leading to stability issues

Dislodged goods and produce from trailers as well as debris from the fire may block ro-ro space drains (scuppers), causing water to accumulate, which reduces the ship's stability and limits fire-fighting efforts (Marine Accident Investigation Branch, 2011). In 2006, MS al-Salam Boccaccio capsized when blocked scuppers caused water from fire-fighting to accumulate on vehicle deck, resulting in the death of more than 1,000 people (Panama Maritime Authority General Directorate of Merchant Marine Casualty Investigation Branch, 2006). In 2010, 4 years after the deadly MS al-Salam Boccaccio accident, a fire broke out on the vehicle deck of MV Commodore Clipper. While there were no deaths as a result of the fire, dislodged potatoes from some of the trailers caused scuppers to become blocked, destabilizing the ship which consequently put limitations on fire-fighting efforts (Marine Accident Investigation Branch, 2011).

5.1.2 Failure by first responders and fire-fighters to extinguish the fire

The tight stowage of lorries, trailers and vehicles in ro-ro space leaves little room for first responders and fire-fighters to access the fire (Bram, Millgård, & Degerman, 2019). Reduced visibility from thick smoke as well as debris from the fire may further restrict access to the fire (Marine Accident Investigation Branch, 2011). If the fire impinges on a pressure vessel, e.g. the gas tank of a CNG vehicle, the risk of a jet fire or explosion may put severe limitations on manual fire-fighting efforts. Extinguishment efforts may furthermore be constrained if the seat of the fire is confined inside a trailer, container or a vehicle, thereby making it inaccessible and difficult to extinguish (Bram, Millgård, & Degerman, 2019).

5.1.3 Shielding of nozzles leading to water distribution failure

The efficiency of a drencher system may be limited if the distribution of water is obstructed by a closed-top, high-sided vehicle (Bram, Millgård, & Degerman, 2019; Murdoch, Jenkins, & Anderson, 2018), as illustrated in Figure 6.

Figure 6: Drencher spray obstructed by cargo (Bram, Millgård, & Degerman, 2019).

5.2 The second FIRESAFE study

A second FIRESAFE study was initiated by EMSA in 2017, focusing on fire detection, decision-making, containment and evacuation—subject matters which were not covered by the first FIRESAFE study. Similar to the first FIRESAFE study, fault trees were developed to quantify failures contributing to fire in ro-ro spaces. Cargo-related factors contributing to detection failure, delayed decision for extinguishing system activation and containment failure are provided in the following sections. Causal factors leading to evacuation failure were, in the review herein, determined to be unrelated to the ship's cargo and were thus excluded from the analysis.

5.2.1 Fire detection

A cargo fire that develops rapidly, produces a limited amount of soot or starts inside a cargo unit or cabin may cause detection failure (Leroux, et al., 2018). A fire that develops rapidly leaves little time for successful first response activities. As the fire increases in size, the chances of manually extinguishing the fire decrease. Rapid fire growth may occur as a result of for example thermal runaway in lithium-ion batteries, or due to the combustion of any gas or liquid (Leroux, et al., 2018).

Most fuels produce a significant amount of soot, which is a by-product of incomplete combustion. Notable exceptions include alcohols and flammable gases, which generally produce less soot than solid fuels (Leroux, et al., 2018). Methanol, in particular, produces very little soot which may delay fire detection. However, fire in a ro-ro space will generally involve several different fuels which are likely to generate a significant amount of soot (Leroux, et al., 2018). Delayed detection may also occur if the fire develops inside the cargo unit or vehicle (Leroux, et al., 2018); however, oxygen deficiency within a confined space may cause the fire to self-extinguish.

5.2.2 Decision making

Successful first response is highly contingent on the speed of detection. Poor accessibility in general due to the tight stowage of cargo is exacerbated by low visibility due to smoke, which creates a challenging environment for decision-making (Leroux, et al., 2018). Critical decisions can be delayed if the situation assessment requires information about cargo and vehicles around the fire scene (Leroux, et al., 2018). However, in practice, the decision to carry out first response is rarely influenced by available cargo information (Leroux, et al., 2018). This may however change as Alternatively Powered Vehicles (APVs), which introduce new hazards, become more common (Englund, Rylander, & Duran, 2017).

5.2.3 Containment

In general, containment depends mainly on the ship's design and structure rather than the ship's cargo. Nonetheless, the nature of the stowed cargo may in some cases cause a more rapid fire development, which increases the risk of containment failure.

6 Ro-ro space cargo

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6.1 Vehicles

Vehicles constitute a major source of fire in ro-ro spaces. Ignition, which is commonly the result of electrical failure (Wikman, et al., 2016), may occur in the vehicle's engine compartment, chassis or cab. The engine compartment contains the battery, normally a 12V DC negative ground system (International Association of Arson Investigators, 2018); it is worth noting that the battery supplies power to certain electrical circuits even after the engine is shut off (International Association of Arson Investigators, 2018). Live circuits may include battery to starter, and ignition switch to clock, cigarette lighter, onboard computers and aftermarket accessories (International Association of Arson Investigators, 2018). Abnormal electric current in these circuits may be the result of damaged cables, overloaded electrical equipment, faulty repairs/installations or inappropriately rated components (Murdoch, Jenkins, & Anderson, 2018; International Association of Arson Investigators, 2018). Additional equipment in the cabin such as Christmas trees, lights, TVs, laptops and cabin heaters may further increase the risk of fire. However, a fire that develops inside the cab will likely self-extinguish due to oxygen deprivation, provided that the side windows and other potential openings are kept closed (Swedish Accident Investigation Authority, 2019). Current practice on vehicle carriers is although to keep the driver side window down, in case of electrical faults in the vehicle. Fans that are still operating on vehicles that have been loaded may also require special attention (Murdoch, Jenkins, & Anderson, 2018).

Apart from electrical faults, mechanical failure such as overheated brakes, tires, and bearings may also lead to fire (International Association of Arson Investigators, 2018). The combination of fluid line failure, i.e. deteriorating lines that carry lubricant or hydraulic oil, and overheated parts is a common cause of fire in vehicles in general (U.S. Department of Transportation, 2013). The aforementioned risk is likely much lower in stationary vehicles. During voyage, cargo shift leading to contact between vehicles may damage fuel tanks and electrical systems, increasing the risk of fire (The North of England P&I Association, 2017).

6.1.1 Used vehicles

A significant proportion of vehicle fires are caused by electrical faults. Used vehicles that await shipment in a port area for an extended period of time are exposed to corrosion-inducing elements which may lead to the deterioration of electrical and wiring systems, which in turn may increase the likelihood of fire (The North of England P&I Association, 2017). Reconnecting an electrical system that has been idle to a charged battery increases the probability of electrical failure (The North of England P&I Association, 2017). Measures which may assist in isolating the circuit, thereby preventing arc faults, include removing the key and disconnecting the battery (The North of England P&I Association, 2017). Disconnecting the battery on a large number of vehicles is however not always feasible. Leaving the key in stop/park may not be enough to isolate circuits (The North of England P&I Association, 2017). Additionally, used vehicles may contain combustible materials such as gas canisters, jerry cans, and welding equipment which may contribute to fire growth (The North of England P&I Association, 2017).

6.1.2 New vehicles

New vehicles on vehicle carriers are normally shipped with their batteries connected and keys in their ignition (The North of England P&I Association, 2017). To reduce the likelihood of unwanted electrical faults, many new vehicles are fitted with a transportation mode which enables turning off internal circuits during transportation (The North of England P&I Association, 2017).

6.2 Special vehicles & machines

There are various types of non-conventional vehicles and machines that also require consideration, including tractors, wheel loaders, sky lifts, process machines, forest vehicles, forklifts, military vehicles and recreational vehicles. Some special vehicles are fitted with a main power switch, allowing operators to turn off the power supply entirely.

Hydraulic machinery like wheel loaders, tractors and forest vehicles rely on hydraulic fluid to transfer power and drive machinery. Although most hydraulic fluids are combustible (Yuan, 2006), they are typically considered much less flammable than middle distillates (Mushrush, Willauer, Bailey, Hoover, & Williams, 2006). Middle distillates, e.g. diesel, kerosene and jet fuel, are fractions of petroleum with boiling points in the range 175 °C to 375 °C (Hemighaus, 1998).

A high-pressure leak of a petroleum-based hydraulic fluid may result in an atomized spray or mist of oil droplet that may subsequently ignite upon impingement onto a hot surface (Mushrush, Willauer, Bailey, Hoover, & Williams, 2006). Yuan (2006) demonstrated through various experiments that the minimum surface temperature required for hydraulic oil spray to ignite was between 350 °C to 440 °C. Yuan however also noted that the obtained results may not apply to other conditions since hot surface ignition is a complex phenomenon that depends on the spray properties, ignition source power and location, and local flow conditions.

Examples of hot surfaces that may cause ignition of oil particles include hot turbochargers, exhaust manifolds and diesel particulate filter (DPF) systems. A DPF system may reach temperatures of up to 600 °C during the oxidization of particulate matter (WorkSafeBC, 2015). This process, known as regeneration, is performed to reduce the soot load, and may increase the risk of fire (WorkSafeBC, 2015), especially if there are combustible materials in close proximity.

Apart from hydraulic machinery, special attention should also be paid recreational vehicles and military vehicles. The latter may include ammunition, while the former often contains propane tanks, used for refrigerators, furnaces, ovens and stovetops. Possible safety measures include disconnecting the gas tanks and closing the main valves (Englund, Rylander, & Duran, 2017).

6.3 Alternatively powered vehicles

Alternatively powered vehicles (APVs) can be divided into four categories based on what they are powered by:

- Liquid fuels e.g. Ethanol, Methanol, Biodiesel and other alcohols;
- Liquefied gas e.g. Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), Liquefied Hydrogen Gas (LH2) and Liquefied Dimethyl Ether (DME);
- Compressed gas e.g. Compressed Natural Gas (CNG) and Compressed Hydrogen Gas (CGH2); or
- Electricity e.g. battery and fuel cell.

Alternative liquid fuels share similar properties with conventional transportation fuels regarding fire and explosion hazards but differ in some respects from the other fuel types mentioned above. One major difference is how the fuels are stored in the vehicle.

Vehicles powered by liquids and gases kept under high pressure

Liquefied and compressed gases that are kept under pressure in steel or composite containers are subject to gas leaks, and in the case of liquefied gases, venting of boil-off gas (Edeskuty & Stewart, 1996). Vehicles powered by fuels held in pressure vessels are normally stowed on the weather deck to prevent the accumulation of flammable gases in case of accidental gas release (Englund, Rylander, & Duran, 2017). There is limited data in literature concerning accidental release of liquids and gases that are kept under high pressure. Brezinska (2019) noted that LPG car installations are often in poor condition, and that gas leaks occur frequently, particularly at the pipe joints. Experiments (Brzezinska, 2019) and simulations (Brzezinska, 2019; Schoor, Middha, & Bulck, 2013) have shown that accidental release of LPG from a car in an enclosed area poses a significant fire and explosion hazard. However, having analysed a total of 138 accidents involving CNG powered vehicles between 1976–2010, the U.S. Department of Transportation (2013) concluded that the cause of fire could, in most cases, be attributed to other sources than a leaking CNG fuel system. Most fires were in fact "started by an electrical short, stuck brakes (which ignited a tire), or leaking gasoline, diesel fuel, or hydraulic fluid impinging on a hot engine or exhaust components" (U.S. Department of Transportation, 2013).

Containers, or tanks, for compressed gas are designed to withstand high pressures; however, excessive pressure build-up may occur due to for example an external fire impinging on the container, causing the temperature of the contents to increase rapidly. If the temperature or pressure reaches a certain threshold, a safety mechanism in the form of a pressure relief device (PRD) activates, allowing the fluid to flow out of the system (Li Y. Z., 2018). As the flammable fluid is ejected out of the system, it may give rise to a *jet flame* or mix with the surrounding air to form an explosive mixture (Li Y. Z., 2018). The discharge of pressure-liquefied gas may, in contrast to compressed gas, also result in a *pool fire*. Another more severe outcome is *Boiling Liquid Expansion Vapor Explosion* (BLEVE). The *Center for Chemical Process Safety* has defined BLEVE as "an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure" (Baker, et al., 2010). Vessel failure, i.e. complete and sudden loss of containment, may occur due to heat exposure causing the initiation and propagation of local cracks on the vessel shell (Baker, et al., 2010). Although a pressure release mechanism reduces the likelihood of explosion, a number of experiments have demonstrated that a functioning pressure release mechanism does not necessarily prevent BLEVE from occurring (Baker, et al., 2010).

Electric vehicles

Electric vehicle (EV) is a term that includes battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs). BEVs rely entirely on electric energy for propulsion whereas the latter two combine an internal combustion engine with an electric motor (Sun, Bisschop, Niu, & Huang, 2019). There are various battery technologies that can be used to power the electric motor in EVs. Li-ion batteries (LIBs) have emerged as the preferred technology in EVs due to their superior energy density and capacity. However, concerns have been raised about their safety following numerous EV fires in recent years (Sun, Bisschop, Niu, & Huang, 2019). In April 2019, a Tesla Model S spontaneously ignited in an underground garage in China. The incident happened approximately one year after a similar incident involving the same make and model had caught fire under analogous circumstances in China's Chongqing Municipality (CGTN.com, 2019). According to the Chinese State Administration for Market Regulation, there were more than 40 EV fire incidents in China in 2018 (Bloomberg.com, 2019), which at the time had an EV stock of approximately 2.6 million (Center for Solar Energy and Hydrogen Research Baden-Württemberg, n.d.). Sun, Bisschop, Niu, & Huang (2019) have reviewed a selection of the EV battery fire incidents that occurred in 2018. Most of the reviewed incidents involved EVs that caught fire during charging (Sun, Bisschop, Niu, & Huang, 2019).

Charging of electric vehicles on board ro-ro passenger vessels has been identified as a potential fire hazard (DNV GL, 2016), possibly in part due to the accident involving M/S Pearl of Scandinavia. On November 16, 2010, a fire broke out on board the ro-ro passenger vessel M/S Pearl of Scandinavia. The following investigation found that the fire originated in the battery pack of a rebuilt Nissan that was connected to the vessel's power supply (Balleby, 2011). As a result of the accident, several Danish ro-ro passenger ship operators introduced policies to prohibit charging of electrical vehicles on board their vessels (Transportstyrelsen, 2018). In 2018, the Swedish Transport Agency issued a guideline which addressed charging of electric vehicles on board Swedish ro-ro passenger vessels (Transportstyrelsen, 2018), remarking in regards to the actions taken by Danish ro-ro passenger ship operators "Swedish Transport Agency (STA) does not support this policy and electric vehicles can be charged on-board Swedish flagged ro-pax vessels." Nonetheless, many ship operators do not offer or allow charging of electric cars on board ro-ro passenger vessels (DNV GL, 2016).

Although EVs are becoming more common on our roads, there is currently insufficient data to determine whether EVs are more prone to fire incidents than conventional vehicles. Larsson et al. (2016) have nonetheless argued that the limited data indicates that EVs might in fact be less prone to fire than vehicles powered by internal combustion engines. In a report prepared for the US National Highway Traffic Safety Administration, Stephens et al. (2017) drew a similar conclusion, noting that the "severity of fires and explosions from the accidental ignition of flammable electrolytic solvents used in Li-ion battery systems are anticipated to be somewhat comparable to or perhaps slightly less than those for gasoline or diesel vehicular fuels." It is however worth mentioning that the average fleet age is considerably lower for EVs than for Internal Combustion Engine Vehicles (ICEVs). An older fleet contains a larger proportion of vehicles in unsatisfactory condition which are more prone to fire (Li & Spearpoint, 2007). As the EV fleet ages, an increase in fire incidents may follow. This increase may however be offset by newer, better and more firesafe battery technologies.

6.4 Heavy good vehicles and buses

Heavy goods vehicles (HGVs) and buses are subject to many of the same failures that can be found on personal vehicles, e.g. electrical faults, overheated brakes or bearings, oil and other flammable fluid leaks, etc. One significant difference is that HGVs may carry dangerous goods, including goods that can react with air and release energy without the presence of an ignition source. This type of reaction, known as self-heating, may occur in e.g. oil seed cake, coal, direct reduced iron (DRI) and metal turnings (Sanders, n.d.). Dangerous goods also include unstable chemicals that decompose over time, generating heat, which eventually may lead to "thermal runaway" (Sanders, n.d.).

6.4.1 Refrigeration units

Refrigeration units, commonly referred to as reefer units or reefers, are commonly subject to electrical faults and constitute a significant fire hazard in ro-ro spaces (Wikman, et al., 2016; DNV GL, 2016). Electrical malfunction may occur due to a faulty/damaged cable, connection, or unit and can develop to cause ignition (see Figure 7). Not only are refrigeration units that are connected to a power supply more likely to catch fire than other sources of ignition, four out of the five major ro-ro passenger ship fires in recent years have been caused by electrical failure in refrigeration units[2] (DNV

[2] Electrical failure in refrigeration unit includes failure related to the cable or connection.

GL, 2016). Three of those resulted in total loss of the ship, all of which occurred on open ro-ro spaces (DNV GL, 2016). Open ro-ro spaces are particularly vulnerable to increased fire growth, as was concluded in FIRESAFE II (2018) and RO5 (2020), due to the unlimited access to oxygen permitted by the side openings. Ro-ro space fires caused by refrigeration units are particularly noteworthy since refrigerated cargo constitute a rather limited proportion of all the carried cargo. In a study performed by Germanischer Lloyd and Stena (2013) it was estimated that vehicles with refrigeration units comprised 10 % of all transported lorries.

The hazardous nature of refrigeration units was highlighted in the EMSA-funded FIRESAFE studies, which identified the following risk control options (RCO):

- **Robust connection boxes**
    - Involves installing, upgrading and maintaining connection boxes. Features include earth fault breakers, increased maintenance of connection boxes, IP-class (e.g. IP56), individual circuit breakers, individual and interlocked switches, and secured cables.
- **Only ship cables**
    - Aims to reduce the likelihood of short circuit in cables and adapters, overheating due to wrong size and arc faults due to damaged cables by prohibiting unknown cables from being connected to the ship. Cables should be treated as consumables and routines for maintenance and exchange of cables should be developed.
- **IR camera**
    - Detection of overheating equipment due to e.g. electrical fault can be improved by supplying ro-ro space personnel with dedicated (no sharing) portable thermographic cameras during fire rounds or upon suspicion of fire.
- **Training for awareness**
    - Expand ongoing training processes and training programs to include fire hazards related to substandard installations and other sources of electrical faults, e.g. damaged connections/cables. The training program should also include routines for reviewing units and how to handle risk.
- **Only crew connections**
    - Cables should only be connected and disconnected by trained crew, who through training and routines, can reduce the likelihood of fire through proper control of, care for and maintenance of cables, as well as the ability to identify faulty and risky connections. Routines include e.g. avoiding long cables and cable routing.
- **Cable reeling drums**
    - By placing cable reeling drums in appropriate locations in the ceiling of the RoRo space, it is possible to protect cables from damage during loading or other deck activity.

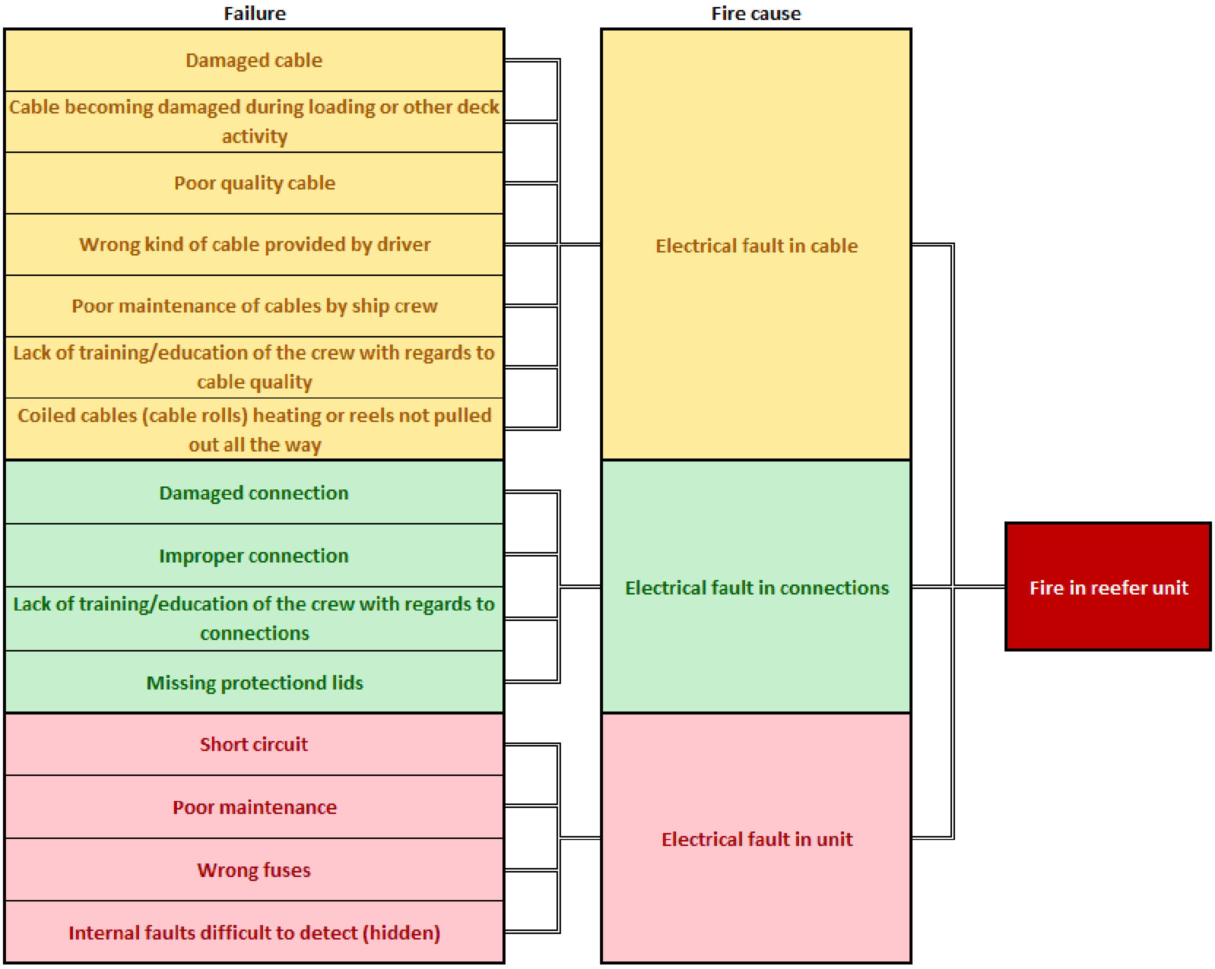

Figure 7: Refrigeration unit failure modes and their relation to fire cause. Based on data from the report Stena Line HAZID Study - Transport of Alternatively Fuelled Vehicles (2015).

7 Case studies

Main authors of the chapter: Eric de Carvalho, BV

A review of 11 selected maritime accident reports has been carried out. Those marine accidents occurred between February 2008 and February 2017. They are related to fire in ro-ro space for 7 Ro-pax, 2 ro-ro cargo and 2 Pure Car Carriers. The review of maritime accident reports and the outcomes of the background study are in line and raise the same conclusions.

Source of ignition

From the reviewed maritime accident reports, fire originated from personally owned conventional car, second-hand conventional car, electrical car (former conventional car rebuilt by the owner to an electrical car), truck, refrigeration unit or goods (petrol from a jerrycan). All vehicles were located in closed ro-ro spaces except in one accident when a refrigeration unit was located in an open ro-ro space, as per the ship's policy (Lisco Gloria). Note that in two accidents (Commodore Clipper and Stena Spirit), the refrigeration units where the ignition occurred were located in closed ro-ro spaces. For the Commodore Clipper, there were too many refrigeration units for the upper (open) ro-ro space capacity. One fire originated from the weather deck (Britannia Seaways).

The exact origin or cause of the fire was for some accidents unknown (Lisco Gloria, Pearl of Scandinavia and Und Adriyatik). It is often the case when the ship suffers a high level of damages. The ignition sources of the reviewed fires were car engine including battery (Mecklenburg-Vorpommern, Victoria Seaways and Honor), ABS module (Courage), battery pack in charge of an electrical car (Pearl of Scandinavia), heating system (Und Adriyatik), truck refrigeration unit (Stena Spirit), truck refrigeration unit cable provided by the ship (Commodore Clipper), goods such as jerrycan (Britannia Seaways) or ship equipment such as light fixture (Urd).

The causes of ignition were either mechanical (blockage of a V-belt for Stena Spirit or steel to steel contact for Britannia Seaways), electrical (poor or wrong electrical connection of a ship's refrigeration unit cable for Commodore Clipper or of a light fixture for Urd, and arcing then ignition of plastic casing, short-circuit of ABS module due to brake fluid leaking from the master cylinder reservoir cap for Courage, fault in the start solenoid for Honor, bad insulation of power wires for Victoria Seaways or defective (conventional) battery for Mecklenburg-Vorpommern) or unknown.

Detection

It is difficult to assess the effects of cargo on detection because the time between ignition and detection cannot be easily evaluated. From the review of the maritime accident reports, it was although found that cargo can mislead the detection and the assessment of the origin of the fire. During the Pearl of Scandinavia's accident, the first alarm sounded for a section adjacent to the section where the fire originated. The battery explosion spread hot fragments above the flooding door, causing ignition of vehicles on the other side. In addition to that, those trailers were carrying plastic pipes which produced heavy smoke. All detectors shortly activated, and the detection system was overloaded. It was not possible to use CCTV due to the heavy smoke.

First response

In most of the reviewed accidents, first response was not attempted or not possible due to rapid fire growth. Rapid spread of fire was made easier by the high fire load created by the combustible cargo, small space between cargo, and by the large oxygen volume (by definition of closed ro-ro space and weather deck) or unlimited oxygen supply (by definition of open ro-ro space). Untenable conditions were quickly created, forcing a runner not equipped with breathing apparatus to abandon the scene of the fire (Und Adriyatik).

Among cargo that fed the fire and was involved in quick spread of fire, the following were reported (not exhaustive): refrigeration curtain-side and webbing stapes of the truck (Commodore Clipper), potatoes (Commodore Clipper), chicken necks (Lisco Gloria), plastic pipes (Pearl of Scandinavia), refrigeration chamber's insulation (Stena Spirit) / lorry's tarpaulin (Urd), petrol (Britannia Seaways), clothing and household items carried by the car (Mecklenburg-Vorpommern), etc.

When first response is attempted, the configuration of cargo can make this task inefficient such as what occurred during the Stena Spirit accident. The watchman started to extinguish the fire with a powder extinguisher, but the powder did not reach the area of the flames, since the flames were on the truck roof.

Decision
In Urd's accident report, it was noted that no vehicle towage plan was established, which is a common loading procedure. So, to establish the flammability of the cargo, the license plate of the lorry in fire was transmitted to the master, who consulted the cargo documents in order to identify the cargo.

Extinguishment
For the same reason mentioned above with regard to first response i.e. quick fire spread due to high fire load and large or unlimited amount of oxygen, manual firefighting intervention may not be attempted or possible. During Commodore Clipper's accident, high cargo density blocked the access to the seat of the fire; when at port, the firefighting teams together with crew and stevedores unlashed and removed undamaged trailers to gain access. During Britannia Seaways' accident, the cargo lashings came loose as the fire progressed, potentially adding more obstacles to firefighters' work.

Firefighters' equipment may be inadequate for a type of cargo. During Britannia Seaways' accident, it was not possible to penetrate effectively two containers still developing heat by means of fireman's axes, and the specially designed spears did not fit with the ship's couplings and could not be connected to the ship's fire main. Then, angle grinders were used with success.

Cargo and fire debris were reported to clog the scuppers causing stability issue (Commodore Clipper and Lisco Gloria). For Commodore Clipper, a balance was made between activation of the drencher system to extinguish the fire, but drencher water caused Commodore Clipper to list and stopping the drencher system enhancing stability, but the fire grew in intensity. The main debris were potatoes. During its voyage, Commodore Clipper was full of trailers loaded with potatoes.

Containment
During Pearl of Scandinavia's accident, the battery explosion spread hot fragments above the flooding control door igniting vehicles in another section.

Evacuation
During Commodore Clipper's accident, evacuation of passengers at port was not possible because, firstly, the evacuation route passed through the main vehicle deck with the fire and, secondly, the

density of vehicles on the upper deck precluded passengers from using the gangway. Therefore, it was deemed safer to keep the passengers on board until the fire was extinguished.

8 Ro-ro space Hazard Identification workshop

Main authors of the chapter: Kujtim Ukaj, RISE

A HazId workshop was held at Research Institutes of Sweden in Borås on 11–12 December 2019. The focus of the HazId was fire ignition in ro-ro spaces and cargo fire hazards. The experts gathered are presented in Table 2, along with their expertise. A more comprehensive résumé of each participant can be found in ANNEX A.

Table 2. Hazid workshop participants.

Name	Organisation	Area of expertise
Franz Evegren	RISE	Alternative fire safety design, risk assessment, ro-ro ship fire safety, methanol fire safety, new energy carriers, lightweight materials
Lotta Vylund	RISE	Firefighting tactics, fires in alternatively powered vehicles, risk assessment, fire cause investigations
Ulrika Millgård	RISE	Human factors, safety, design
Kujtim Ukaj	RISE	Dangerous goods, alternative fire safety design, lightweight materials, ro-ro ship fire safety
Boris Durán	RISE	Machine Learning, cognitive robotics, autonomous systems
Jérome Leroux	BV	Formal Safety Assessment, ro-ro ship fire safety, maritime accident data analysis
Blandine Vicard	BV	Rule development and international rule follow-up (fire safety and structural assessment)
Eric de Carvalho	BV	Fire and gas safety, LNG, risk analysis
Mads Bentzen Billesø	DFDS	Maritime safety information and vessel management, e-navigation, digitalization, ship design
Jonas Carlsson	STL	Marine engineering
Arie Krijgsman	STL	Technical projects in marine industries
Covadonga Suárez	SASEMAR	Training in maritime safety domain, ship handling and manoeuvre, ship simulators
Jaime Bleye	SASEMAR	Marine firefighting, LNG emergency spill response, firefighting tactics
África Marrero del Rosario	CIMNE	Computational Fluid Dynamics (CFD), ship emissions, maritime transport
Ángel Priegue	CIMNE	Information and Communication Technologies, software development
Francisco Rodero	CIMNE	Database design and implementation, software development and modelling and simulation of transportation systems

A spreadsheet was developed (taking into account results from a previous HazId in the FIRESAFE studies (Leroux, et al., 2018) on the same subject) prior to the HazId workshop to guide the procedure and for documentation of results. The spreadsheet and the HazId procedure were based on a Failure Mode and Effects Analysis (FMEA), which is commonly used in risk management.

As can be seen from the documented results presented in ANNEX B, fire causes were grouped into 7 categories, represented by the bottom nodes in Figure 8. The bottom nodes have been coloured to distinguish between causes that depend on another failure to develop into a fire (blue nodes), and those which do not (orange nodes). As illustrated by the diagram, leakage of gas or liquid will not cause a fire to develop unless there is an ignition source present. The ignition source can be in the form of an overheated car part, sparks, friction due to cargo shift, etc. Similarly, overheating will not lead to fire development unless the overheated part is impinged upon flammable substances, such as gas or liquid leakage. Another possible scenario is one where the overheated part itself is made of combustible material, e.g. a tyre, in which case overheating unaidedly may develop into a fire. This is similar to fires caused by electrical faults, thermal runaway, self-heating and unsolicited activity, which likewise do not depend on other failures for a fire to develop.

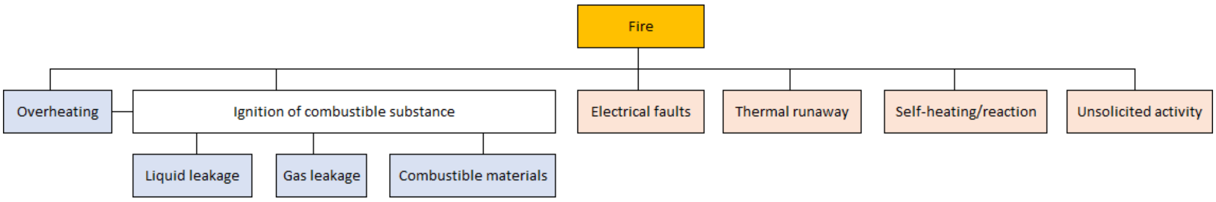

Figure 8: Simple tree describing different fire causes in ro-ro spaces.

9 Summary of hazard identification and discussion

Main authors of the chapter: Kujtim Ukaj, RISE

Below follows a summary and discussion in relation to the identification of hazards in Borås, Sweden on 11-12 December 2019. The different fire causes illustrated by the bottom nodes in Figure 8 served as starting point during the hazard identification. The fire causes were examined systematically to ensure all the relevant aspects of fire prevention and recovery were addressed. Findings from the background study were also considered in the discussion.

It is clear from previous studies that refrigeration units constitute the most significant hazard in ro-ro spaces, despite the fact that some refrigeration units are fitted with sensors that can detect heat and temperature deviations. The most common types of refrigeration units are drop trailers and accompanied trailers; proportions vary depending on the route. There seems to be a trend toward more drop trailers, which however is also considered to be a greater fire hazard than the accompanied trailers[3]. A drop trailer will on the other hand be inspected when it comes through the terminal whereas accompanied units are not subjected to the same kind of scrutiny.

There are instances where a refrigeration unit may appear to be in questionable condition, but it is generally kept onboard if it runs properly when connected. It is often difficult to make an assessment on their condition, however, especially when they are already onboard. Damages to the trailer may have occurred during loading, e.g. if the trailer got stuck on the ramp. Moreover, unlike cars, refrigeration units are not required by law to undergo regular inspections on land. There is nonetheless a possibility for carrying out onboard inspections and sending back units which appear to be in dubious condition. It is worth mentioning that refrigeration units are not allowed to be powered by their diesel generators (which drives the compressor) when loaded in closed ro-ro spaces. Running the diesel generator is only allowed in open ro-ro spaces and on weather deck. Leakage of diesel from the generator can be difficult to detect, especially on weather deck, due to wet weather, ice, AC-water etc. According to Stena representatives, leakage is however not an issue and the amount of fuel powering the generator at any given time is limited.

It was suggested during the workshop that tools which are currently used to fight forest fires can potentially be applied within the maritime segment. One such technology is drones—a topic that came up regularly during the workshop. It is worth keeping in mind that any new technology involving machines powered by electricity, e.g. drones, may also be potential sources of ignition. The matter of driving versus flying drones was emphasized in light of *lifting gases* (e.g. hydrogen) potentially becoming more common in ro-ro spaces. While for example a gas sniffer mounted on a driving drone may detect heavy gases, lifting gases would go undetected. Furthermore, as the presence of lifting gases becomes more prevalent in ro-ro spaces, it may require a re-definition of hazardous areas for ventilation and EX-classed equipment.

As has been stated previously, electrical faults are a major source of fire. Some of those faults arise from damaged cables. Cable reeling drums are therefore, according to Stena representatives, particularly useful since they reduce the likelihood of cables being damaged by cargo during loading operations. In relation to this, it was also mentioned that some ships make their own cables onboard.

If ignition cannot be prevented, detecting a fire quickly becomes vital. Handheld thermal cameras are commonly brought up in this context. There is however a small delay in measuring temperature with this type of technology, and a good torch might therefore be better suited for this purpose. A new method involving a matrix of sensors on the floor to detect heat was also briefly mentioned as a potential technology to reduce the risk of fire.

For all vehicles it was concluded that the main fire hazards were associated with non-manufactured installations, e.g. home-made electrical installations (e.g. lights, heaters, etc. in trucks) or home-made, rebuilt or vintage vehicles. Some vehicles have a lot of added installations and electric equipment in cabins. In general, vehicles containing excessive electric equipment, vehicles with aftermarket parts and accessories, vehicles in poor condition, and vehicles of delayed passengers should be treated as high risk vehicles.

Some common types of vehicles carried in ro-ro spaces include cars, buses, trucks, recreational vehicles (RVs) and tractors. The latter are mostly new or reconditioned equipment. With regards to RVs, mobile homes are generally considered more hazardous than caravans. As for car drivers, they comprise a different group in terms of risk profile than bus and truck drivers. As an example, it might be difficult to convey certain information to an elderly person, which is exacerbated by the fact that modern systems in cars can be challenging to fully understand. This may cause some passengers to not understand the instructions provided to them. Truck and bus drivers are on the other hand professional drivers and generally have a better command and understanding of their vehicles. With regards to buses vis-à-vis trucks, it has been noted that buses generally have much longer unfused battery cables than trucks; from the main switch by the driver to somewhere in the cabin (about 5 m, compared to about 0.5 m in a truck).

It is not uncommon for truck drivers to stay in the cabin on short voyages. Although there are strict rules against passengers in ro-ro spaces during voyage, it is very difficult to enforce the rules since security cannot check the units and it is not permitted to open doors or break locks to ensure that drivers are not staying in their vehicles. Still, even if all passengers leave their cabs, there is the possibility that electrical equipment left behind in vehicles/trucks is charging or in standby mode. This may increase the risk of electrical faults, which in general are difficult to detect. Electrical faults may also arise due to cargo shift causing vehicles to bump into each other, thereby possibly damaging components such as fuel tanks or pipes. Cargo shift may also generate friction and sparks, which could subsequently ignite leaked or spilled fuels, such as methanol or LNG. The latter is particularly insidious if it is transported as Dangerous Goods (DG), since it does not contain odorizers and therefore does not have a smell.

There are already quite thorough inspections for DG, and in general, DG is given much more attention to prevent damage and accidents than other cargo. There is e.g. a separation software used on some ships which alleviates loading of DG and compliance with regulations. In case fire involving DG occurs, fire patrols are trained to not approach the fire. If the fire occurs on weather deck, it is–on some ships–possible to fight the fire with water monitors, but it must be considered that some DG should not be extinguished with water on these decks. According to ship operators at the workshop, improper weight declaration is typically a more serious concern.

10 Conclusion

Main authors of the chapter: Kujtim Ukaj, RISE

There has been a limited number of studies to date which have focused on fire safety in ro-ro spaces. The studies reviewed herein paint a consistent picture, namely that electrical fault is the most significant cause of ignition in ro-ro spaces, accounting for approximately 60 % of all fires in ro-ro spaces according to FIRESAFE. Marine casualty data also shows that electrical faults in refrigeration units are particularly hazardous, which is not least evident by the fact that four out of the five major ro-ro passenger ship fires in recent years have been caused by electrical faults in refrigeration units. This includes faults in the cable connecting the refrigeration unit to the power supply as well as the connection itself. Ship operators should pay special attention to refrigeration units that are connected to the ship's power supply, which, according to the data, are more likely to fail and result in fire. Taking into account that refrigerated units typically constitute a rather limited proportion of all the carried cargo, an estimated 10 % according to a study (Securius & Kähler, 2013), it is reasonable to conclude that risk reduction in ro-ro spaces should focus on improving the safety of transporting refrigerated units. This either means lobbying for inherently safer refrigeration units or providing the ship's crew with both the skills and the tools to quickly detect and extinguish fires in refrigeration units. Examples include innovative technologies like drones, supplying ro-ro space personnel with dedicated thermal cameras, improved routines addressing e.g. avoiding long cables and safe cable routing, and using only ship cables i.e. prohibiting passengers from using their own cables.

Another common source of fire in ro-ro space is the vehicles, especially those which are in poor condition and thereby more prone to electrical faults and leaks. Since electrical fault is a common source of fire, it might be inclined to assume that EVs are therefore more prone to fire than conventional vehicles. However, this premise is not supported by (the limited amount of) research, which instead suggests that EVs are less prone to fire than conventional vehicles. Two things are particularly important to bear in mind though:

1. The EV fleet is considerably younger than the ICEV fleet, making the comparison somewhat skewed in favour of the latter; and
2. While EVs may be less prone to fire than conventional vehicles in general, only statistical data of stationary vehicles should be considered in order to determine whether EVs are less prone to fire than conventional vehicles in ro-ro space.

With regard to the second point, a large number of vehicle fires occur as a result of collision. It is thus perhaps not surprising that vehicles that contain fuel may burn more readily following a collision than vehicles powered by Li-ion batteries. It would, in the context of the current study, be more relevant to explore data of fires in stationary vehicles—data which is currently not available. Further research is thus needed to establish whether a transition to EVs from ICEVs will bring about an increase in vehicle fires in ro-ro spaces, assuming all other factors remain constant.

11 References

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13 ANNEXES

13.1 ANNEX A

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13.2 ANNEX B

Fire cause	Fire origin	Failure	Signatures	Specific safety measures	General safety measures
Overheating	Reefer	Slipping V-belt (poor maintenance), couplings, compressor failure, bearings	Heat, temperature deviation	* Check the temperature on the panel of the reefer for temperature deviations * Heat sensors before loading, the cargo passes a space in conjunction with boarding where heat can be detected * Sensors in the trailers / on the reefer units (?) * Connect smart sensors on reefers with surveillance network (e.g. WiFi) * Make the cables stand out (e.g. color) so they can be distinguished from ordinary cables * Smart power cables that can detect faults in the cable, e.g. temperature deviations * Frequent control (Frequencer)	* Training to be aware of dangerous cargo that aren't necessarily considered dangerous * Support system for the fire patrols to remember or make notes of cargo or different hazards, take notes consistenly, so this information can be passed onto other crew members or next round * Heat detection (Handheld IR camera) * Heat camera on drone or rail * Drones in port area with detectors mounted * Fixed (separate or as part of CCTV) or handheld IR cameras could give quick detection (it is however difficult to "see" the cargo since it is often loaded with small gaps)
	Vehicle	Bearings, brakes, tires, cooling failure of exhaust system, belts, compressor failure, fuel heater, stop-engine fans and heaters, particle filter glowing, catalyst smouldering fire, regeneration in particle filter, parking heaters	Heat radiation	* Ensuring of cooling time - usually check-in and embarkation time is sufficient but it could be necessary to require e.g. to stay on the key X mins before embarking? * Special awareness by crew of the increased risk of late arrivals - routine for identifying late arrivals * Allowing to leave engine on for X mins for vehicles coming directly on-board * Information that particle filter regeneration is forbidden on-board * Increase frequency of fire patrols within first hour when the risk of fire is the highest due to overheating * Fire patrols looking out for tires that are semi-flat causing friction heat * Keep track of makes/model that have been recalled due to fire concern * Be aware of signatures, e.g. blue smoke from turbocharger, oil on exhaust, general cleanliness * Incentivize leaving the cab * Increase separated beds / capacity of cabins to make sure drivers leave their vehicles * Older vintage (and rebuilt) cars may not have electrical engine cooling fans running after engine stop and should therefore be given special attention * Information that diesel, cabin heating is prohibited	* Automatic scanning of hot spots on vehicles as they embark on the ship * Before loading, check the vehicle by running it through a frame/"gate"
Liquid leakage	Vehicle fluids	Hydraulic oil, wiper fluid, cooling liquid, AC gas, breaking fluid, de-icing alcohol, brake fluid, cargo shift	Smell, gas vapour		* Good torch to detect leakage * Gas sniffers for example on drone * Dog patrol during voyage * Similair to on airlines, inform passengers repeatedly during and before embarkation of hazards/good practice/what not to do/report certain things that may increase the fire risk * Efficient procedure for managing a leakage * Provision of ventilation and limitation of ignition sources in accordance with regulations * Future vessels could be designed with double ramps to allow for flexible loading and unloading
	Vehicle fuel	Leakage from corroded tank, pipe, connections, gasket due to age or mechanical damage, overloading of vehicle, overfilling of fuel (ramp tilt, sun, heel/trim...), accident (could also be caused on-board due to use of wrong lane etc.), spare fuel container (jerry cans), cargo shift	See above	* Portable fuel containers and added fuel tanks (with a hose to the conventional fuel tank) should be refused or stored in a safer location * Awareness of the factors which give increased risk of fuel leakage (fuel price difference between countries, hot days, heavy seas, on tilted ramps, on main deck...)	
	Dangerous goods	Mechanical failure, broken seals, hit by another truck/collision, collision by ship (due to ramp design, DG is usually stored on port side, where collision happens to be most common), cargo shift	See above	* Prioritizing loading of DG in the middle of the ship and as far as practicable avoiding loading DG along the ship sides (in particular port side) where collision damage mainly occurs * Additional lashing of cargo close to DG * Rejection of certain DG classes depending on the weather conditions * Loading DG easily accessible (which may be in contradiction to not loading DG along the ship sides, as suggested above * Distance requirement between reefers and DG * Check and make sure/require that LNG tanks have low pressure when embarked	
Gas leakage	Alternative fuel vehicle	LNG boil-off gas, cargo shift, leaky pipe joints	Smell, water mist due to very cold gas (LNG)	* Policy for how to handle venting of LNG from vehicles * Venting from pressure vessels can be detected acoustically or thermally	* EX classed electrical equipment in ceiling or whole space * Gas detectors or sniffers in ceiling * Ventilation system connected to gas detector * Glasses that enable seeing certain gases or leakages * Temperature monitoring to detect cold fluids being vented * Awareness of odours, training e.g. how Natural Gas smells like * Sniffer attached to fire patrol gear/clothing * Automatic driving drones, fitted with detectors and sniffers and other interesting things * Similair to on airlines, inform passengers repeatedly during and before embarkation of hazards/good practice/what not to do/report certain things that may increase the fire risk
	Dangerous goods	See liquid leakage	Smell	See liquid leakage	
	Supplies	Propane tanks, additional gas tanks/spares, gas left on for heating, battery left on to remain heating, electrical connection to ship grid, cooking appliances, gadgets for camping	Smell	* Thorough inspections for gas tanks and spares and instructions/information to close the main valves * Requirement to disconnect the gas tank * Provision of increased ventilation * Offer to connect RVs, but there are way more units than sockets in the summertime * Informaiton pamplets targeted to campers * Close and disconnect the gas tanks valve and seal with tape	

Electrical faults	Electrical systems in vehicle	Squeezed cables, installation fault, internal arcing, cargo shift, fault in the starter motor solenoid, damaged starting battery, damaged power supply cable, diode failure, damaged brake booster motor, damaged alternator, aftermarket accessories, faulty reparation/installations, battery left on to remain heating, electrical connection to ship grid More vibration exposure to buses generally cause more damaged cables and electrical faults, climate system often activated remotely/with a timer before embarkation	Smoke, heat radiation, smell	* Detection and suppression system in the engine compartment (work only when running?) * Older vintage (and rebuilt) cars may not have electrical engine cooling fans running after engine stop and should therefore be given special attention * Information that diesel, cabin heating is prohibited * Before loading, check the vehicle by running it through a frame, or by the use of a drone that detects hot spots etc * Isolate the battery of certain high-risk vehicles * Single out trucks that are warmer than other trucks due to activated cabin heaters with the help of a heat camera * Offer to connect RVs, but there are way more units than sockets in the summertime * Certain vehicles (e.g. Forklifts) have a high risk of squeezed and damaged isolation on cables * Certain vehicles (e.g. forklifts) have large battery packs	* Information to drivers to switch off the main power (some cabin installations may still have power, e.g. in case they are run by a separate cable directly on the battery) * Arc fault detection device * Check for "smart" installations in vehicles coming on-board - but what action??? * Warm up the whole ro-ro space (Improbable) * Awareness of most common sources of ignition, train crew members on what to look for and the proper measures * Important that windows are closed in case of fire since this could mitigate fire growth - instructions and inspection/training/routine. * Fire patrols (training also for fire response on how to act upon fire in various cargo, e.g. to turn off main power of truck or disconnect main power of reefer unit) * Drivers association to implement standard for signs for main switch * Rebate if main power switch exists * Maintenance - Make sure installations are correct * Not use overly long cables * Check fuses * Earth faults * Provision of increased ventilation * Control of lashing - Important to do lashing properly in the beginning, taking into account the weather forecast * Inspection of damaged equipment
	Electrical equipment & supplies	Christmas trees, lights, fans, TV, laptop, heating system that malfunctions, cooking supplies/appliances		* Instruction to turn off cab heaters and other electrical equipment	
	Reefer	Squeezed cables, installation fault, internal arcing, cargo shift		* Impact the quality and safety of cargo: - Affect regulations for haulers to keep reefers up to date - Affect drivers' associations to ensure that drivers check and keep their equipment well maintained - Affect the truck/unit association to introduce a standard for checking their units - Affect the standard reefer units to implement alarm in case of deviations in temperature or electrical failure (make reefer units more failsafe), should give a warning whether visual or if it's connected to the system onboard	
Thermal runaway	Electrical vehicle	Charging, spontaneous combustion	Acuostic		*Different type of sensors that detect specifically battery gases *Acuostic detection *Heat sensors *Portable sensors / detection boxes for certain high risk vehicles for enhanced detection by different signatures *Pre-sceening prior to embarkation, perhaps in conjunction with action plan on how to handle potential hazards
	Dangerous goods	Spontaneous combustion			
Self-heating or chemical reaction	Dangerous goods	Wet hay, coal, etc., friction and vibrations, ammunition		* Placing of cargo where fire safety is increased and not by other high risk cargo * Require DG trucks to cool down before embarking - time for check-in and embarkation could be sufficient but it could also be necessary to have them stay on the key X mins before embarking? * Incentives to declare goods (rebate?, to be allowed off the ship first?) * Keep track of self-heating and self-decomposing DG, scraps and batteries (Class 9 DG), some explosives (Class 1) may be sensitive to vibrations	* Control / random check of goods * Fire patrols making visual and smoke smell (hand-held gas detectors, IR camera) * Affect regulatory agencies
	Reefer cargo	Cooling failure, wrong instructions from ashore regarding heating/cooling (usually cargo damage is the only consequence and only at long crossings)		* Logging of temperatures and connected alarm in case of deviation	
Unsolicited activity	Stowaways	Cooking facility, heating, smoking, security not allowed to check cargo/units		* Inform authorities at the destination of suspicious cargo. * Fire patrols listening/being aware for noises. * Heartbeat sensors. * Dog patrols. * Authority to check cargo or routine to contact police to make checks * Play annoying sound to make it impossible to sleep in ro-ro space during voyage (truck drivers) * Incentivize leaving the cab * Increase separated beds / capacity of cabins to make sure drivers leave their vehicles * Port security inspecting vehicles/ISPS	
	Arson	Security is not allowed to check cargo/units, Terrorist attack, Drums with oil, Gas and oxygen pipes go through the ro-ro space (these should although be closed)		* Fire patrols disturbing arsonist activity * Changed locks on doors to only be able to use card locks, also for lockers and linen stores * Inform passengers to not throw cigarette butts overboard	
	Campers	Cooking/use of electrical appliances, heating system		* Food and cabin included in ticket if possible. * Loud noise to avoid campers * Directed noise. * Procedure to inform the hauler and black list the driver/truck.	

System	Desired function	Affecting conditions	Challenges | Examples of cargo in parentheses	Potential safety measures
Detection	Quick detection Precise detection Fire monitoring/assessment Reliability		* Alcohol or other fuels which produce limited/no smoke (methanol, ethanol, hydrogen) * Quickly developing fuels/goods will make it difficult to achieve early detection (see above) * Delayed detection may also occur if the fire develops inside the cargo unit or vehicle * Smoldering fires difficult to detect (Under the engine compartment, self heating substances, self-decomposing substances) * High production of thick smoke causing several detectors to activate (solids, plastics, diesel) * Explosive cargo causing spread of fire making it difficult to detect fire origin (EV, pressure tanks) * Obstructed detectors (High-sided cargo)	* Flame detectors (UV/IR/flickering) * Heat detection e.g. IR camera * Follow the policy with regards to maximum height of cargo * Add directed fire patrols in areas with extra high cargo
First response	Fire/detection confirmation Fire assessment Early fire fighting Quick response Safe response Localization (e.g. unit, drencher zone) Identification of cargo burning and type of fire	* Spacing	* False alarms - often due to running diesel generators * Difficult to see what type of fire it is (electrical, battery, DG, pool fire, new energy carriers), due to e.g. small separation of cargo/difficulties to access or large amount of smoke or heat * Tight stowage of lorries, trailer and vehicle in ro-ro space leaves little room for first responders and fire-fighters to access the fire * A fire that develops rapidly leaves little time for successful first response activities. Rapid fire growth may occur as a result of for example thermal runaway in lithium-ion batteries, or due to the combustion of any gas or liquid * Fires underneath a truck (flammable liquids) * Fires on top of trucks make it difficult to reach * Difficult to reach the seat of the fire with exintiguishment equipment due to the size of cargo and tight stowage	* Assembly of fire squad as soon as you get the alarm (at least from spaces with few false alarms) * It should be possible to keep the walk-ways clear (in particular on old vessels without raised walkways) * CCTV system could be used to backtrack where the fire started * Redesign to make ventilations trunks flush with the main frame * Requirements for minimum separation of cargo * Lighter and more mobile equipment
Decision-making	Quick decisions Coordination Based on good information/data	* Equipment (carried and fixed) * Training of crew (in particular fire patrol) * Possibilities for communication (radio functionality etc.) * Accessibility on cargo deck	* Poor accessibility in general due to the tight stowage of cargo is exacerbated by low visibility due to smoke, which creates a challenging environment for decision-making (Plastics, diesel) * Critical decisions can be delayed if the situation assessment requires information about cargo and vehicles around the fire scene (AFVs, DG) * Unspecified/wrong cargo declaration delaying decision to activate drencher due to risk of causing a reaction of water and substance that reacts with water (Alkali metals, EVs, batteries)	
Extinguishment	Swift possibility for activation Reliable system Sufficient capacity Safe system	* Cargo height (distance to nozzles) * Design discharge density and nozzle distribution	* Cargo right below drencher heads (no distance between), shielding extinguishing water distribution * Training for decision-making on what system to activate, depending on DG plan * All kinds of DG on weather deck, also such that should not be extinguished with water (Alkali metals, certain peroxides, fertilizer [AN]) * Clogging of scuppers, leading to de-activation of extinguishing system (Produce, paper rolls) * Paper rolls will swell and expand in case of water exposure, which may cause damage to the ship structure * Hidden fire / Confined fire / Underneath or inside cabin * All kinds of DG on weather deck, also such that should not be extinguished with water	* Loading procedure where high cargo (trucks/trailers) are mixed with low cargo (cars) * Increased deck height * Routine to prepare beforehand what system to activate depending on the cargo * Development of new procedures * Avoid mixing paper rolls with other cargo (risk of water ingress and swelling) * Development of new procedures with regards to water cannons
Ventilation	Ventilation of hot gases Prevention of oxygen provision Ventilation of combustible gases To keep escape routes clear from smoke		* Cargo producing large amounts of dense smoke (Plastics, diesel)	
Firefighting	Quickly available Effective response Efficient response Safe response	* Fire growth rate (material properties, DG, etc.)	* Tight stowage of lorries, trailer and vehicle in ro-ro space leaves little room for first responders and fire-fighters to access the fire * If the fire impinges on a pressure vessel, e.g. the gas tank of a CNG vehicle, the potential risk of a jet fire or explosion may put severe limitations on manual fire-fighting efforts (AFVs with pressure vessels, dangerous goods [flammable liquids, gases]) * Difficult to access and manually extinguish fire if the drencher is activated * Difficult to access and extinguish confined fires or fires underneath vehicles * Lack of information about different type of cargo, e.g. some are explosive/react with water * Difficult to find a suitable fire fighting media	* Training crew to be aware of the risks associated with pressures vessels * Use of heat camers * Use of tools/equipment that give better reach into/underneath cargo * Pop up nozzles