
Safety Considerations and Fire Prevention along the Transportation Chain of Electric Vehicles

Master's Thesis in Shipping and Marine Technology

Andreas Peters

Samuel Stüber

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY



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Master's Thesis 2024

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Examiner: Henrik Ringsberg, PhD / Associate Professor / Instructor Maritime Logistics

Supervisor: Henrik Ringsberg, PhD / Associate Professor / Instructor Maritime Logistics

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Department of Mechanics and Maritime Sciences

Division of Maritime Studies

412 96 Göteborg, Sweden

Gothenburg, Sweden, 2024

Abstract

From a seafarer's perspective, one of the worst things to happen on board a vessel is a fire. Accidents in the recent past involving car carriers transporting electric vehicles have triggered the question of the safety of transporting electric vehicles on ocean-going ships. Thus, this thesis explores the transportation chain of electric vehicles, involving the handling of electric vehicles at each of the steps in the export transportation chain. Additionally, risk factors along the transportation chain in addition to preventive measures are explored at each step. For this, a literature review is combined with a case study in the Gothenburg region. Literature on the fields of the management of batteries, firefighting and handling of electric vehicles, and the general management of the transportation chain is reviewed. The case study involves expert interviews with 12 interviewees from stakeholders along the transportation chain from the manufacturer onto the RoRo- or RoPax vessels. In the case study, the suggestions found in published literature are compared with the actual procedures in practice to reveal similarities and differences. It is discovered that the handling of electric vehicles is not materially different from the handling of vehicles with an internal combustion engine. For each step in the transportation chain, individual risk factors are identified, in addition to risk factors affecting the entire transportation chain. These are the 12V/24V batteries in the electric vehicles, human error, and a lack of information flow between the various individual stakeholders. Similarly, preventive measures at each step in the transportation chain are identified in addition to overarching preventive measures. A state of charge in the vehicle's battery of less than 50%, training and education, and communication between stakeholders are suggested as preventive measures in order to prevent the ignition of the electric vehicles and to make the transportation chain safer.

Keywords: *Electric Vehicles, Transport Safety, Fire Prevention, Maritime Transportation, Transportation Chain, Multimodal Transport, Risk Factors, Safety Measures, Battery Safety*

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List of Abbreviations

BMS	Battery Management System
EV	Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
IMO	International Maritime Organization
Li-Ion	Lithium-Ion
MSC	Maritime Safety Committee
PPE	Personal Protective Equipment
RoPax	Roll-on/Roll-off and Passengers
RoRo	Roll-on/Roll-off
RQ	Research Question
SOC	State of Charge
SOLAS	Safety of Life at Sea

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Terminology

Factor	“An element which enters into the composition of something; a circumstance, fact, or influence which contributes to a result” (Oxford English Dictionary, 2024)
Multimodal Transport	“Carriage of goods by two or more modes of transport.” (United Nations Economic Commission for Europe, 2000)
Preventive risk controls	“Preventive controls are designed to limit the possibility of an undesirable hazard event occurring” (Hopkin, 2018)
Risk	“Risk is used to signify negative consequences” (Hopkin, 2018)
Risk Management	“Coordinated activities to direct and control an organization with regard to risk” (ISO 31000:2018)
Risk Source	“Element which alone or in combination has the potential to give rise to risk” (ISO 31000:2018)
Safety	“The state of being protected from or guarded against hurt or injury; freedom from danger” (Oxford English Dictionary, 2024)

1 Introduction and Background

From a seafarer's perspective, one of the worst things to happen on board a vessel is a fire. Far from civilization and help, the crew is often on their own in fighting the fire. In the summer of 2023, such a situation occurred on board the 'MV Fremantle Highway' (Kirby, 2023). Likely triggered by an electric vehicle, the vessel caught fire but could eventually be towed to port and safety (Kirby, 2023). In combination with new legislation by the European Union (European Parliament, 2022) an increase in the number of electric vehicles (EV) is expected. According to this legislation, no new vehicles with an internal combustion engine can be registered from 2035 onwards (European Parliament, 2022). Therefore, incidents like the one on 'MV Fremantle Highway' might occur more frequently in the future. Consequently, the question is brought up how these could be prevented and the transportation of EVs made safer for the crew, the vessel and the environment.

The 2023 report by the Intergovernmental Panel on Climate Change, abbreviated as IPCC, confirmed that global warming has been caused by human actions, through the emission of greenhouse gases. The surface temperature in the observed period (2011-2020) was 1.1°C above the reference period (1850-1900). The current mitigation ambitions in place by country states make it unlikely that the global warming can be kept within the 2.0°C limit, as set in the Paris accord (Intergovernmental Panel on Climate Change, 2023).

The transportation industry is a key sector in the reduction of greenhouse gas emissions. Transportation as a sector contributed 16.2% to global greenhouse gas emissions in 2016 [CO₂eq]. Thereof, road transportation alone was responsible for ~73%, or 11.9% of global greenhouse emissions respectively (Ritchie & Roser, 2023). With the European Union aiming to achieve net zero emissions by 2050, a change in the transport sector is necessary. This sector is responsible for 20% of the European Union's CO₂ emissions (European Parliament, 2022). Since battery electric vehicles are currently the most preferred alternative to internal combustion engine vehicles (ICEVs), the amount of transported EVs will increase in the future (European Parliament, 2022).

In order to comply with the 17 Sustainable Development Goals set out by the United Nations in 2015 (United Nations, 2015), the development of new and climate-neutral propulsion solutions for all kinds of road vehicles is necessary. As described above, the preferred alternative

to the ordinary combustion engine is the electrical power-driven vehicle. When EVs are produced for export, they are usually transported via ocean-going ships to their destination. It is essential that all vehicles are handled carefully to ensure a safe journey and to deliver them undamaged at their destination. Apart from heavy weather during the sea transport, fire is one of the greatest hazards on board merchant ships. Unlike fires in ICEVs, the battery fire of an EV is much more difficult to extinguish and has a great potential for reignition (Dorsz & Lewandowski, 2021). Furthermore, in comparison to the fire in an ICEV, the temperature development is much higher. How difficult it is to extinguish a fire on a vessel could be witnessed at the end of July 2023 when the ‘MV Fremantle Highway’ caught fire in the North Sea (Kirby, 2023). The fire on board ‘MV Fremantle Highway’ started on 25 July 2023 in the North Sea. The source of ignition is unknown, but “an audio recording emerged of one rescue worker suggesting it had started in the battery of an EV and ‘it appears an electric vehicle exploded too’” (Kirby, 2023). However, the only way to get a fire within a lithium battery under control is with excessive cooling. “Once the onboard battery is involved in fire, there is a greater difficulty in suppressing EV fires, because the burning battery pack inside is inaccessible to externally applied suppressant and can re-ignite without sufficient cooling” (P. Sun et al., 2020).

Since the EU decided on a ban of the possibility to register new vehicles with a combustion chamber from 2035 (European Parliament, 2022), EVs are an important step towards a more sustainable society. New systems for firefighting, handling and transporting of EVs are cost-intensive to develop and implement. Additionally, new regulations for ships and terminals to increase safety will also need to be published. This involves the International Maritime Organization (IMO), especially the sub-committee Maritime Safety Committee (MSC).

Despite the risk of EV fires on board, a limited number of studies have been published so far (Brzezinska & Bryant, 2022; Sturm et al., 2022; P. Sun et al., 2020). While P. Sun et al. (2020) emphasises that fires in lithium batteries are hard to extinguish, Sturm et al. (2020) investigated the temperature development of a battery fire within an enclosed space, more precisely a road tunnel. Additionally, Brzezinska and Bryant (2022) reviewed vehicle fires and simulated computer-based models of smoke and temperature distribution. But there is still a gap in the literature on how to prevent the self-ignition of vehicle batteries in the terminals and on board of ships. This poses an increased threat to ships and terminals handling those vehicles for export and import. Therefore, it is important to explore how to prepare the firefighting departments near the terminals and to equip ships with appropriate firefighting systems.

1.1 Purpose and Research Questions

The purpose of this Master's thesis is to explore the practice of handling EVs for export in the Gothenburg region. The main aim is to explore the current process steps in place along the transportation chain of EVs, from the manufacturers to the terminal and onto the ocean-going vessel. Secondly, the risk factors along the transportation chain, focusing on the risk for accidents and self-ignition of EVs, are explored. As third aim, the fire prevention measures, i.e. preventive risk controls along the transportation chain, on the shore side as well as on board of Roll-on/Roll-off (RoRo) and Roll-on/Roll-off and Passengers (RoPax) vessels are explored. Hereby, the fire prevention measures are explored with regard to their sufficiency. This shall serve as basis for the development of suggestions for changes in order to lower the risk of ignition of EVs at each step in the transportation chain and thereby enable a safer transport.

In order to achieve the purpose, the following three research questions (RQ) are formulated:

Research Question 1

How are electric vehicles handled along the various steps of the export transportation chain (manufacturer, road transport, terminal, ship)?

Research Question 2

Which risk factors exist along the steps of the transportation chain, which could cause the ignition of electric vehicles?

Research Question 3

What preventive measures could be implemented during the various steps of the transportation chain to reduce the risk of ignition of electric vehicles?

1.2 Delimitations

In the following paragraphs the delimitations of this Master's thesis project are presented.

Based on the location of Chalmers University of Technology, the thesis is geographically limited to the companies operating in the region around the City of Gothenburg.

Moreover, the thesis is limited to the examination of newly manufactured vehicles for export only. Therefore, the import of vehicle parts, such as batteries, other intermediate products or raw materials is not considered.

Additionally, the transportation chain is only examined from the manufacturer to the export terminal, and onto the ocean-going vessel. The sea part of the transportation chain is only considered until the vessel enters the Vessel Traffic Service area at its port of destination. All port operations including pilotage, berthing and the discharge operations as well as the further transportation into the hinterland from the port of discharge are excluded from the study.

The focus lies on the development of processes and risk management solutions, rather than on the development of new engineering solutions. This might include the presentation and proposal of existing, but not implemented fire prevention and/or firefighting systems.

Furthermore, the study is time-limited to the spring semester of 2024, a total number of 22 weeks.

1.3 Structure of the Thesis

The structure of the thesis is as follows: After the introduction and background, the methodology is explained. This includes the research approach and the description of the case study conducted in this study. In the following frame of reference, the current academic state of knowledge in the relevant research fields is presented. Thereafter, in the results and analysis section, the interview results are then linked to the academic background. The results are then further discussed in the subsequent chapter, before the RQs are answered in the conclusion chapter and an outlook on potential future research paths is given.

2 Methodology

The research consists of a literature review in combination with a case study. With regards to the main aim of this study, the preventive measures, firefighting systems and procedures in case of a fire, that are currently in place, will be explored. Hereby, it will be investigated which different measures are implemented at the step of the manufacturer, the terminal, and the shipping company respectively, i.e. along the entire transportation chain.

2.1 Research Approach

The research process follows mostly the abductive approach, as outlined by Spens & Kovács (2006). This is a relatively new research field, and recently, accidents on board ships involving EVs have frequently been reported in the news (Chapter 1). Therefore, the literature is being used as basis for developing answers to the RQs, while it is being acknowledged that the data from the interviews might change or expand these significantly (Andreewsky & Bourcier, 2000; Spens & Kovács, 2006). Due to the novelty of the research topic, a qualitative approach has been selected as research method for this thesis.

A case study of a transportation chain (Chapter 2.2) and the RQs together form the foundation of the structure of the research process. This is depicted in the form of a matrix, with the RQs denoted on the Y-axis and the individual steps of the transportation chain on the X-axis. When aligning the RQs with the steps along the transportation chain, it becomes obvious that $4 * 3 = 12$ open fields (points of interest) need to be addressed (Table 1). Hereby, the processes within the manufacturer have been marked in grey in the table, since they are out of the main scope of this thesis, but still form an essential part of the transportation chain.

Table 1: *Research matrix*

	← Multimodal Transportation chain of EVs →				
	<i>Manufacturer</i>	Road Transport	Terminal and Storage	Loading	Sea Leg
Research Question 1					
Research Question 2					
Research Question 3					

By combining different methods, in this case a literature review and interviews with experts within the field of this study, the probability to uncover unknown aspects of the studied problem is increased (Dubois & Gadde, 2002). Hereby, the literature review is the foundation of this thesis and represents the academic state of knowledge. Moreover, the literature is categorized as described in detail in Chapter 2 and entered into the matrix shown in Table 1. Since the amount of identified literature is not equally distributed across the twelve points of interest, interview questions are then developed to fill the gaps of knowledge in the matrix. Additionally, the academic state of knowledge can thereby be compared to real-world practices and potential discrepancies can be identified.

The literature review is the foundation on which the thesis' theoretical framework builds upon (Webster & Watson, 2002). Hereby, a systematic literature search for peer-reviewed documents by using pre-defined keywords, so called queries, was conducted in the Scopus database. Firstly, inclusion and exclusion criteria (Table 2) were formulated, to evaluate the results from the queries. Secondly, the formulated queries were then searched within "Article title, Abstract, Keywords" on Scopus and sorted by relevance (Table 3). The purpose of this detailed documentation of search patterns is to provide a comparable search process as described by Brocke et al. (2009).

Table 2: *Inclusion and exclusion criteria*

Inclusion Criteria
1 Headline is relevant for one of the Research Questions
2 Abstract is relevant for one of the Research Questions
3 Document is written in English (Swedish only accepted selectively)

Exclusion Criteria
1 Not accessible through Chalmers University of Technology or Chalmers Library
2 Headlines stating vessel types other than RoRo / RoPax / Car Carrier
3 Document is of visibly low quality

The initial literature search in Scopus was conducted on 23 January 2024 and delivered in total 23,289 results. It was decided to limit the screening of headlines to the first five pages for each

query, which led to a maximum of 50 documents. Considering this, 786 headlines were read, and with view on the inclusion and exclusion criteria, 124 documents were identified as potentially relevant for this study. In the next step the abstracts of the 124 documents were read and 84 papers were eliminated. The remaining 40 papers were read thoroughly. At the end of this process, 18 documents (Table 4) were included for the thesis. A further nine papers were considered as relevant but were not included and therefore disregarded, as these could not be accessed with the licenses from Chalmers University of Technology or Chalmers Library.

Besides journal articles, conference proceedings and other relevant grey literature sources were also considered in the literature review, if they were relevant, reputable and of high quality (Webster & Watson, 2002). This was decided due to the novelty of the research topic.

Table 3: *Initial literature search*

Query	Results	Headlines read	Abstracts read	Documents read
((Electrical AND Vehicle) OR EV) AND Transportation	6,971	50	5	1
((Electrical AND Vehicle) OR EV) AND Transport AND Chain	826	50	5	2
((Electrical AND Vehicle) OR EV) AND Shipping	55	50	3	0
((Electrical AND Vehicle) OR EV) AND Fire AND Prevention AND (Port OR Terminal)	1	1	1	1
((Electrical AND Vehicle) OR EV) AND Fire AND Prevention AND (Car OR Bus OR Truck)	7	7	2	2
((Electrical AND Vehicle) OR EV) AND Fire AND Prevention AND (Vessel OR Ship OR Ferry OR RoRo OR RoPax OR Car Carrier)	0	0	0	0
((Electrical AND Vehicle) OR EV) AND Fire AND Firefighting	7	7	2	1
((Electrical AND Vehicle) OR EV) AND Fire AND Handling	17	17	9	5
((Electrical AND Vehicle) OR EV) AND Handling AND (Terminal OR Vessel OR Ship OR Ferry OR RoRo OR RoPax OR Car Carrier)	4	4	0	0
((Electrical AND Vehicle) OR EV) AND Fire	598	50	16	4
((Electrical AND Vehicle) OR EV) AND Ignition	757	50	14	4
((Electrical AND Vehicle) OR EV) AND Risk AND Factor AND Transport	54	50	10	2
Risk AND Management AND (Port OR Terminal)	7,938	50	12	5
Risk AND Management AND (Car OR Bus OR Truck)	4,644	50	1	0
Risk AND Management AND (Vessel OR Ship OR Ferry OR RoRo OR RoPax OR Car Carrier)	193	50	7	1
Firefighting AND System AND (Vessel OR Ship OR Ferry OR RoRo OR RoPax OR Car Carrier)	1	1	1	0
Firefighting AND System AND (Port OR Terminal)	49	49	5	1
Firefighting AND System AND Road	81	50	12	8
Firefighting AND System AND (Car OR Bus OR Truck)	58	50	0	0
Logistics operations AND Port Terminals	525	50	14	3
Logistics operations AND (Vessel OR Ship OR Ferry OR RoRo OR RoPax OR Car Carrier)	116	50	4	0
Port operations AND (Vessel OR Ship OR Ferry OR RoRo OR RoPax OR Car Carrier)	357	50	1	0

An overview of the results and included documents from the initial search is given in Table 4.

Table 4: *Initial literature included in this thesis*

Queries	Results	Headlines read	Abstracts read	Documents read	Documents included
22	23,289	786	124	40	18

Additionally, backward- and forward-snowballing were conducted between 26 January and 14 February 2024 in order to capture further relevant documents in this research field, which were not found by the initial search in Scopus. This focused only on the 18 documents which were actually included for the thesis. The term snowballing describes the backward- and forward search by using a document's reference list or the citations of that specific document after publication in order to find more papers within a field (Webster & Watson, 2002; Wohlin, 2014). Hereby, the 'cross-reference snowballing' method as described by Geissdoerfer et al. (2018) was applied. The snowballing process was hence built up as follows: A screening of the titles in a document's reference list in view of which keyword appeared in the headlines was done. Afterwards, the as potentially relevant identified documents' abstracts were read and based on the pre-defined criteria presented in Table 2, included or excluded from this study (Geissdoerfer et al., 2018). This process is to be repeated in a loop with the newly found documents until no new relevant documents are found anymore (Geissdoerfer et al., 2018). This was slightly adapted for the thesis. Due to time constraints, only two backward loops and one forward snowballing loop were conducted. During the forward loop, the focus laid on the most relevant documents and to fill remaining gaps. Within all stages of the literature search, duplicates were immediately filtered out. The result of the further search is presented in Table 5.

Table 5: *Backward and forward search results*

	Abstracts read	Documents read	Documents included
Backward Search	107	73	41
Forward Search	14	8	7

Through the Scopus search with the pre-defined search terms, in combination with the snowballing process, a total of 66 documents were obtained.

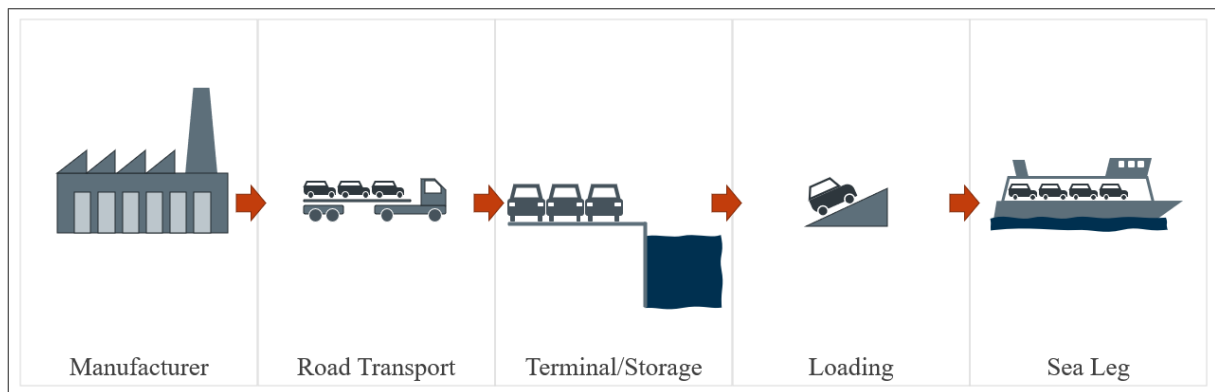
2.2 Case Study

Gothenburg combines the needed key industries, port facilities, and with Chalmers University of Technology a supporting academic institute to conduct this Master's Thesis. Specifically, in Gothenburg the following companies are located: the manufacturers of electric vehicles, Volvo Buses in Viared, Volvo Car AB in Torslanda, Volvo Trucks in Tuve, and additionally the Gothenburg RoRo Terminal AB and Logent AB on the northern bank of the river Göta Älv, which provide the terminal infrastructure for global export. Less than one hour north of Gothenburg, the terminal of Wallhamn AB is located on the island of Tjörn which also facilitates the export of vehicles. Moreover, Stena Line's RoPax terminals are located on the southern bank of the river Göta Älv, offering connections from Sweden towards Germany and Denmark. Therefore, this work will examine the transportation chain from the manufacturer to the terminal, onto the ocean-going vessel, and on the sea leg.

2.2.1 Case Study Description

The case study within this thesis is based on the aforementioned literature review, combined with interviews. The aim of the case study is to generate detailed insights by thoroughly examining the transportation chain of EVs in practice (R. K. Yin, 2018).

The transportation chain has been selected as means of graphic representation of the transport work, since it facilitates a good visualization. Furthermore, it serves as structure for the literature review as well as the primary research, and helps to structure the following sections along the transportation chain and the RQs. The transportation chain is especially useful for the depiction of intermodal transports, when goods are transported from a customer or factory via truck, rail or barge to the terminal and then loaded onto the ocean-going vessel (Lumsden et al., 2019). The book chapter as well as the figure from Lumsden et al. (2019) and from Pencheva et al. (2022) served as foundation for the development of Figure 1. This was however expanded to incorporate also the work from Jansson & Shneerson (1982), who put more emphasis on the processes within the terminal, which are also relevant for this thesis. Since this thesis is delimited to the export side and ocean leg only, and does not consider the influence of legislators and other authorities on the transportation chain, the multimodal transportation chain can therefore be visualized as follows:

Figure 1: *Multimodal transportation chain for the export of EVs*

Adapted from Jansson & Shneerson (1982, p.10), Lumsden et al. (2019, p.414), Pencheva et al. (2022, p.63)

For this thesis, this is regarded as a multimodal transportation chain instead of an intermodal transportation chain, since the goods (vehicles) are handled themselves rather than in intermodal loading units (United Nations Economic Commission for Europe 2000).

2.2.2 Interviews

Semi-structured interviews were conducted with a total of twelve (12) experts, divided into eight (8) interviews. Of the interviewees, two (2) were female and the remaining ten (10) were male. The interviews took place in interviewees' offices (5), via Microsoft Teams (2), or via telephone (1), and some were supported by a walk around in the different facilities. The duration of the interviews varied between 8 min and 36 min. The participants were selected based on the relevant experience they possessed concerning the field of the study and were affiliated to one step in the transportation chain (Table 6). Semi-structured interviews are also referred to as qualitative interviews and are therefore a good choice for a qualitative research (Blumberg et al., 2011). The interviewer has a set of questions which he/she wants to ask the interviewee, but this interview style also leaves room for the interviewee to delve into other topics, which could also be relevant for the researcher (Blumberg et al., 2011).

Table 6: *List of interviewees*

Interview number	Date	Person [anonymised]	Company [anonymised]	Position in the company	Years of experience in that position
1	11.03.2024	Interviewee A1	Company A (RoRo Shipping Line)	Cargo Officer	7 Years
1	11.03.2024	Interviewee A2	Company A (RoRo Shipping Line)	Chief Mate	2.5 Years
2	11.03.2024	Interviewee B1	Company B (Terminal Operator)	Terminal Administration	8 Years
3	12.03.2024	Interviewee A3	Company A (RoRo Shipping Line)	Chief Mate	14 Years
4	14.03.2024	Interviewee C1	Company C (EV Manufacturer)	Intro Engineer	10 Years
4	14.03.2024	Interviewee C2	Company C (EV Manufacturer)	Intro Engineer	5 Years
5	15.03.2024	Interviewee D1	Company D (RoPax Shipping Line)	Naval Architect	5 Years
6	19.03.2024	Interviewee E1	Company E (Logistics Operator)	Finished Vehicle Logistics	2 Years
6	19.03.2024	Interviewee E2	Company E (Logistics Operator)	Operators Manager for Logistics	3 Years
6	19.03.2024	Interviewee E3	Company E (Logistics Operator)	Foreman	8 Years
7	21.03.2024	Interviewee F1	Company F (EV Manufacturer)	Finished Vehicle Distribution	2.5 Years
8	11.04.2024	Interviewee B2	Company B (Terminal Operator)	Stevedore	10 Years

According to (Bryman et al., 2022, p.431)

As a first step, an interview guide was developed (Blumberg et al., 2011). An interview guide ensures that the researcher always asks the same questions in the single interviews and thereby covers all relevant areas. But, as described above, in semi-structured interviews there is also room to ask follow-up questions based on the flow of the conversation and the background of each interviewee (Blumberg et al., 2011; Bryman et al., 2022). Additionally, towards the end of each interview, the interviewee was offered the opportunity to add whatever he/she would like to add which had not been covered by the questions. This way, additional important areas could be detected (Patton, 2015). When formulating an interview guide, it should be ensured that the interview guide covers all questions that need to be addressed in the interviews, that the questions asked are not too narrow but rather give the interviewees the opportunity to elaborate and that the questions are formulated in an easily understandable language (Blumberg et al., 2011; Bryman et al., 2022). The interview guide includes all areas to be covered in the interviews, and can be provided to the participants beforehand so that they can prepare for the interview (Bryman et al., 2022). In this work, an interview guide has been developed in a Microsoft Excel spreadsheet. Before each interview, the relevant questions were selected based on the interviewee's position and background. The spreadsheet helped to ensure that after all interviews were conducted, all questions were covered and no blank spots remained. The complete set of questions, assigned to the different steps of the transportation chain / interviewees and sorted according to the RQs, is available in Appendix I.

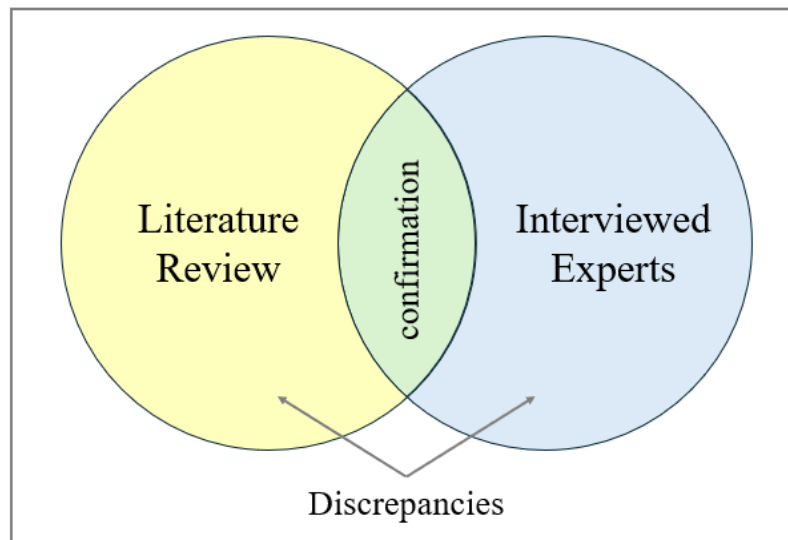
To ensure a high quality of answers during the interview, the questions were sent in advance to the participants. On one hand it informs the interviewees about the purpose and aim of the interview, on the other hand it enables them to prepare themselves (Bryman et al., 2022). The authors were not interested in assessing spontaneous reactions of participants on certain questions. The focus laid on gaining knowledge about specific processes and routines in the handling of EVs along the transportation chain (Bryman et al., 2022). Furthermore, prior the interview started, each interviewee was informed about the ethical considerations related to their personal data and the voice recording. This includes the confidential treatment of sensitive personal data as name, company and voice recording with limited access to the authors only, to inform about the purpose and ensure that the interviewee appreciated her/his contribution to the research (Bryman et al., 2022). The ethical treatment of interview data and personal information was ensured through a consent form which was signed by all interviewees prior the interview recording.

The interviews were conducted by the authors themselves. This can be classified as an interview being conducted by “insiders” (Demirci, 2024) due to the previous knowledge and industry experience from the authors. The advantage of that is that interviews by insiders usually deliver more meaningful data (Demirci, 2024). In this research, the interviews were recorded with a mobile phone recording app for both in-person interviews and digital/telephone interviews. Recording and transcribing interviews ensures that all important areas are covered. E.g. when taking notes, important aspects might be omitted (Bryman et al., 2022). When recording the interviews, the interviewer can focus completely on the conversation and ask follow-up questions, where necessary. Therefore, a digital recording, with the interviewees’ consent was selected. Furthermore, in each interview, relevant information of the participant, such as position, years of experience in that position and company (anonymised) were noted (Blumberg et al., 2011; Bryman et al., 2022). After the interview, the transcribed text file was sent to each participant for validation and comments.

2.3 Data Analysis

In this thesis, the major risk factors at each of the steps of the transportation chain are investigated. The focus is hereby on risk factors which can lead to immediate or delayed ignition of the electric vehicles during the transport. The identified risk factors and the current preventive measures are compared with each other, and potential mismatches and discrepancies are identified. For this purpose, a literature review and interviews with experts from every step in the transportation chain are conducted.

The ability to compare and combine key elements from different qualitative sources is of essential importance. Since this study remains within the qualitative sphere of research, the blended design explained by Fusch et al. (2018) is appropriated. Hereby, a comparison between the literature review and held interviews is conducted. The aim is to find aspects where the theoretical knowledge from the literature and the practical routines are matching, but more interestingly, where mismatches are revealed. An illustration of the comparison is shown in Figure 2.

Figure 2: Comparison of literature review and expert interviews

Own illustration (indicative only, the graphic does not represent actual ratios)

In the literature review, thematic analysis has been used for analysis of the documents, as it offers a useful tool for the analysis of large sets of sources and for the identification of so-called ‘themes’. For this purpose, a spreadsheet was constructed in Microsoft Excel to structure the reading and to assign ‘concepts’ or ‘themes’ to each article (Braun & Clarke, 2006; Webster & Watson, 2002). The setup of the table was based on Webster & Watson (2002). The phases of the thematic analysis as described by Braun and Clarke (2006) have been followed during the thematic analysis of the literature. A similar approach has been described by Webster and Watson (2002). In a ‘concept-centric’ literature review, the results are grouped around concepts discovered among the different articles (Webster & Watson, 2002). Since a similar approach to a literature review analysis has been described by Gupta and Sharma (2022) and Jones et al. (2011), which are both economic/business research papers, it was regarded as suiting to this study.

Based on the literature, eight different themes were defined and the documents sorted respectively. In alphabetic order these themes are (1) Battery Fire Hazards [3.1.1], (2) Battery Safety [3.1.2], (3) Fire Detection- and -Fighting Systems [3.2.1], (4) EV Fire Handling [3.2.2], (5) Multimodal Transport and RoRo Operations [3.3.1], (6) Onboard Handling [3.3.2], (7) Management of Accidents and Fires on RoRo Ships [3.3.3] and (8) Terminal Risk Management [3.3.4]. To visualize the literature review process and clarify how the documents contribute to answering the RQs, a matrix (Table 1) was designed. The transportation chain is labelling the

X-axis and the three RQs are labelling the Y-axis. Afterwards, suitable themes were assigned to every XY-position, i.e. point of interest (Table 7).

Table 7: Literature review matrix

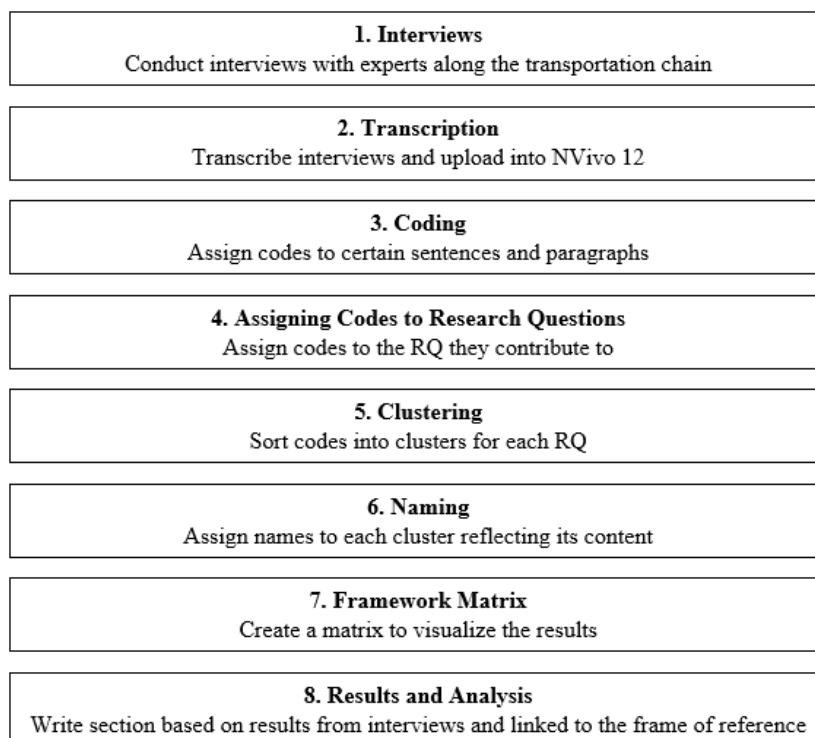
	← Multimodal Transportation chain of EVs →				
	<i>Manufacturer</i>	Road Transport	Terminal and Storage	Loading	Sea Leg
How are electric vehicles handled along the various steps of the export transportation chain (manufacturer, terminal, ship)?	(4)	(4), (5)	(4)	(4)	(4), (6)
Which risk factors exist along the steps of the transportation chain, which could cause the ignition of electric vehicles?	(1)	(1)	(1), (8)	(1), (8)	(1), (6), (7)
What preventive measures could be implemented during the various steps of the transportation chain to reduce the risk of ignition of electric vehicles?	(2)	(2)	(2), (3)	(2)	(2), (3), (6)

In order to fill the gaps left in the transportation chain matrix and to confirm the findings from the literature review, expert interviews were conducted. The results from the literature review were compared with the results from the interviews, as to develop recommendations for making the transportation chain safer (the purpose of this work).

Qualitative interviews produce a large quantity of text which needs to be analysed. For the analysis, e.g. thematic analysis or grounded theory can be used (Bryman et al., 2022). For this research, thematic analysis has been selected, since it has already been used in the literature review stage and hence warrants a solid foundation for this work. Similar to the literature review, in the transcripts of the interviews, first ‘codes’ were assigned to the text passages and later from these ‘codes’, overarching ‘themes’ (‘clusters’) were derived (Braun & Clarke, 2006; Bryman et al., 2022). Afterwards, the extracted information was used to contribute to filling the transportation chain matrix.

For the analysis of the interviews, NVivo 12 software was employed. The above-mentioned steps were translated to the software and data processing as follows: Firstly, the transcribed interviews were uploaded into NVivo. Then, the interviews were coded by assigning codes which represented certain sentences/paragraphs and at the same time contributed to the thematic RQs. After all interviews had been coded, the codes were assigned to the three RQs. Within each RQ, afterwards the codes were grouped into clusters. Hereby, the code with the highest frequency was assigned to cluster one. Then the following code was compared to the first one and if covering a similar topic, grouped in the same cluster. If not, it was assigned to cluster two. This process was continued until all codes were assigned to clusters. In the end the clusters were reviewed and a name assigned to each. Afterwards, the underlying information for the codes from the interviews was downloaded from NVivo. This was facilitated in the form of a matrix ('framework matrix'), where the Y-axis contained all interviews and the X-Axis contained all clusters of the RQ. This matrix was generated and downloaded for each RQ and then facilitated the writing process of the results and analysis chapter. The approach is illustrated in Figure 3.

Figure 3: *Flowchart of analysis approach*



Own illustration

3 Frame of Reference

In this chapter, the frame of reference is presented.

3.1 Management of Batteries

In the sub-chapters, battery-related topics are presented.

3.1.1 Battery Fire Hazards

The greatest hazard of a Lithium-Ion (Li-Ion) battery is the thermal runaway. This phenomenon describes an increase in temperature of the battery's internal cells, which may lead to an exothermic reaction and an uncontrolled rise of the battery's temperature (Baird et al., 2020; Bisschop et al., 2019; Held et al., 2022; Kong et al., 2018; Larsson, 2017). The temperature range at which a thermal runaway starts is 150-200°C (Kong et al., 2018; Larsson, 2017). Such a thermal runaway can have serious consequences such as the release of smoke and gas, or even lead to an explosion which results in a fire (Baird et al., 2020; Bisschop et al., 2019; Larsson, 2017; Willstrand et al., 2020). While the temperature rises, the pressure inside the battery rises, too. To prevent the battery from exploding, an overpressure release valve is built in which releases the gases from the battery (Sturk & Hoffmann, 2013). More details on the internal safety measures are described in Chapter 3.1.2.

A fire in a Li-Ion battery mainly starts due to an "internal cell short circuit" (Bisschop et al., 2019), as a result of one of the following events. In the literature three main events are identified which can result in an internal short circuit and therefore lead to a thermal runaway. It is either a (1) thermal-, (2) electrical- or (3) mechanical event (Baird et al., 2020; Bisschop et al., 2019; Feng et al., 2018; Sturk & Hoffmann, 2013; P. Sun et al., 2020; Taylor et al., 2012; Zhang et al., 2022). Another event is a defect of the battery due to manufacturing failures (Baird et al., 2020; Bisschop et al., 2019; Kong et al., 2018; Taylor et al., 2012).

(1) Thermal events: When the surrounding temperature, the external temperature, of a Li-Ion battery is higher than the internal temperature, the battery may be triggered to heat instead of cool (Bisschop et al., 2019; Willstrand et al., 2020). A source which triggers a battery to heat up can be a nearby fire (Bisschop et al., 2019; Gehandler et al., 2017). Circumstances which favour the rise of the internal temperature can be a poor design of the battery or insufficient ventilation (Christensen et al., 2021). Moreover, besides high temperatures, even too low tem-

peratures can lead to an increase of the battery's internal resistance which might trigger a thermal runaway (P. Sun et al., 2020). The optimal temperature for the Li-Ion battery to work at is between 20°C and 30°C (P. Sun et al., 2020).

(2) Electrical events: The charging level of a Li-Ion battery is defined as “state of charge (SOC)” (Bisschop et al., 2019) with an optimal operational level between 0-100%. Nevertheless, due to the capacity of the battery, it is possible to exceed the operational level, above as well as below. This overcharging or over-discharging of the Li-Ion battery can lead to an internal circuit and start a thermal runaway (Bisschop et al., 2019; Taylor et al., 2012; Willstrand et al., 2020). An internal “Battery Management System” (BMS) (Christensen et al., 2021; P. Sun et al., 2020) shall prevent the battery from exceeding its operational limits. When the BMS fails, an overcharging or over-discharging is possible (Christensen et al., 2021).

(3) Mechanical events: A mechanical deformation, which describes a permanent deformation, of the Li-Ion battery can lead to an internal circuit and start a thermal runaway (Bisschop et al., 2019). Such deformation can occur in a “crash or ground impact” (Bisschop et al., 2019). However, P. Sun et al. (2020) state in their paper that the batteries are well enough protected not to take serious harm in a crash, but that a high acceleration can result in a fire. Besides a car crash, objects on the road can damage the battery and even high G-forces can trigger a thermal runaway (Christensen et al., 2021).

As mentioned above, in the event of a thermal runaway smoke and gases are released from the battery. More precisely, a wide range of various toxic, corrosive and flammable substances are set free (Long et al., 2013). The type and amount of leaked gases is highly dependent on the battery's SOC (Held et al., 2022; J. Sun et al., 2016). A list of the gases is presented in Table 8.

Table 8: *Gases released during a thermal runaway*

Compound	Formula	Reference
Carbon-Monoxide	CO	(Baird et al., 2020; Held et al., 2022; Larsson et al., 2017; P. Sun et al., 2020)
Carbon-Dioxide	CO ₂	(Baird et al., 2020; Held et al., 2022)
Methan	CH ₄	(Baird et al., 2020; Held et al., 2022; P. Sun et al., 2020; Willstrand et al., 2020)
Polyvinylidene Fluoride	C ₂ H ₂ F ₂	(Larsson et al., 2017)
Propane	C ₃ H ₈	(Baird et al., 2020; Held et al., 2022)
Hydrogen	H	(Baird et al., 2020; Larsson et al., 2017)
Dihydrogen	H ₂	(Held et al., 2022; P. Sun et al., 2020; Willstrand et al., 2020)
Hydrogen Fluoride	HF	(Larsson et al., 2017; Willstrand et al., 2020)
Phosphorus Pentafluoride	PF ₅	(Larsson et al., 2017)
Phosphoryl Fluoride	POF ₃	(Larsson et al., 2017)

Furthermore, not only gases are released, but the smoke also contains “specific metals [...] depending on the battery cell chemistry“ (Willstrand et al., 2020). These metals are presented in Table 9.

Table 9: *Metals contained within the smoke during a thermal runaway*

Element	Formula	Reference
Cobalt	Co	(Held et al., 2022; Willstrand et al., 2020)
Lithium	Li	(Willstrand et al., 2020)
Manganese	Mn	(Held et al., 2022; Willstrand et al., 2020)
Nickel	Ni	(Held et al., 2022; Willstrand et al., 2020)

An EV fire consists of several threats to the people who are designated to extinguish the fire. One discussed issue is the question if a battery electricizes the water which is used by the firefighters. Sturk and Hoffmann (2013) could not find any evidence for a such a threat in their study. But a proven threat are the toxic substances to which the firefighters are exposed during

their duty. The reason is that the firefighters' personal protective equipment (PPE) is not designed for such a duty and therefore the substances contaminate their clothing (Szymtke et al., 2022). Szymtke et al. (2022) could prove by blood samples from firefighters that even if the clothes were washed after the duty they were still contaminated. The recommendation is to decontaminate them with chemicals. Moreover, Hydrogen Fluoride is potentially dangerous due to its ability to be absorbed by the skin (Willstrand et al., 2020). The ordinary firefighters' PPE is designed to withstand flames and high temperatures but not toxic substances, for such case chemical protection suits are designed. For the situation in which flames and high temperatures occur simultaneously to toxic gases, none of the suits is sufficient (Willstrand et al., 2020).

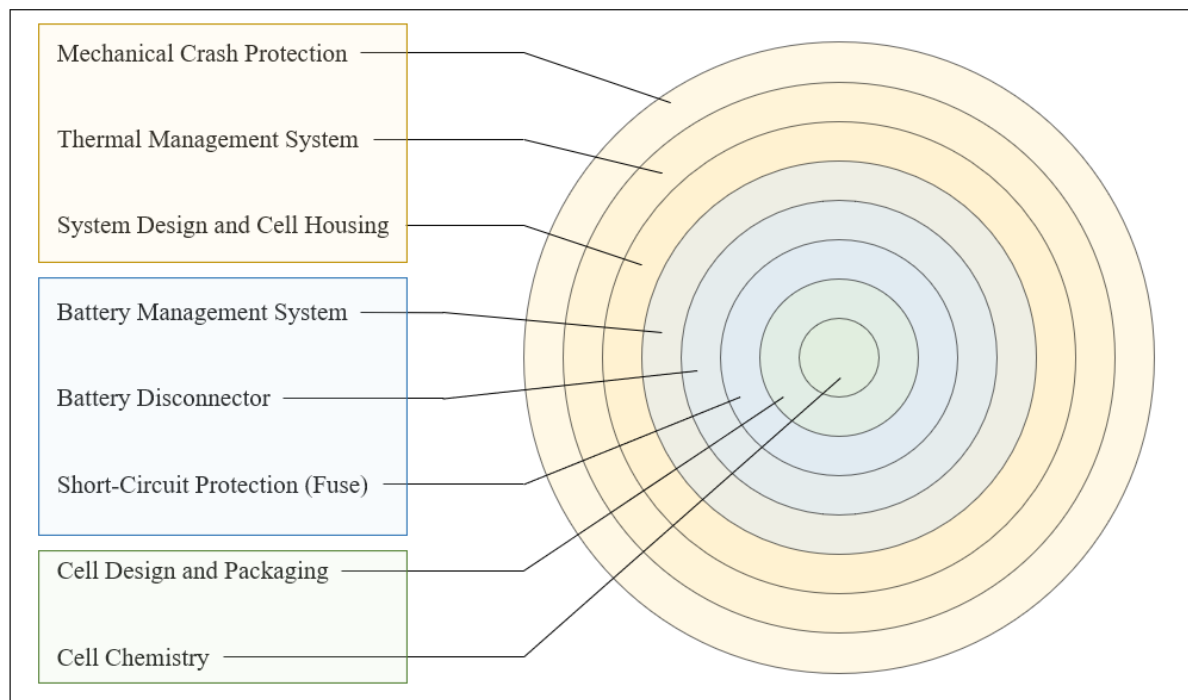
The toxicity of the released substances is dependent on the SOC, and the literature shows that the higher the SOC is, the greater is the potential danger (J. Sun et al., 2016). Nevertheless, Larsson (2017) suggests not to overestimate the risk of Li-Ion batteries, the topic is just very large in the media. To the same conclusion comes a study conducted by Bisschop et al. (2020), EVs do not cause a higher fire hazard compared to ICEVs. Hassan et al. (2023) studied car fires in Australia and came to the conclusion that EV fires are "significantly lower than the average fire frequency for all vehicle fires" (Hassan et al., 2023).

3.1.2 Battery Safety

As described in Chapter 3.1.1, a wide range of different events can lead to a battery fire. This is only the case if the Li-Ion battery is not correctly protected (Honey et al., 2013). When Li-Ion batteries are used in different kinds of vehicles, they are exposed to a potentially hazardous environment for the battery itself, such as e.g. a frequent change in humidity and temperature (Larsson et al., 2016). Therefore, it is important that the battery is protected accordingly by using different safety measures (Larsson et al., 2016).

The literature states that in most of the cases where a Li-Ion battery catches fire spontaneously, the reason is "related to poor manufacturing and design procedures and/or inadequate electronic control systems, BMS, and power transmission control systems" (P. Sun et al., 2020). Nevertheless, the battery needs to be protected against different kinds of threats, the safety measures preventing the battery from damage must be installed in different stages. This reaches from the cell's chemistry to outer case of the battery and these layers can be illustrated as an onion presented in Figure 4 (Larsson et al., 2016).

Figure 4: *Li-Ion battery safety onion*



Adapted from Larsson et al. (2016, p. 11)

At the cell level it is distinguished between the chemical part and the physical part. The chemical part of the battery cell contains all three elements the fire triangle consists of (Gehandler et al., 2017; Larsson & Mellander, 2017; Zhang et al., 2022): with the flammable organic electrolyte it contains combustible material (Larsson & Mellander, 2017), the cathode releases oxygen (Bisschop et al., 2019) and a thermal runaway provides the needed heat for self-ignition. Therefore, it is important to choose the electrolyte wisely because it has an influence on the battery's safety. Hereby, the reviewed literature emphasizes to use a "non-fluorine salt" (Larsson et al., 2016), "adding flame retardants to the electrolyte" (Kong et al., 2018) and to use a "high flash point electrolyte" (Kong et al., 2018) or, simply to use a "less flammable or non-flammable electrolyte" (Bisschop et al., 2019). Willstrand (2022) writes that much research on the cell level has been conducted, but it is important to continue the improvement of safety. The next safety measure at the cell level is the physical design and package of the cell. Three designs are commonly used: the cylindrical, the hard prismatic or the pouch one (Bisschop et al., 2019; Larsson & Mellander, 2017; P. Sun et al., 2020; R. Yin et al., 2023). Hereby, it is important to consider the location of the cells in relation to each other and its wiring to prevent the transmission of heat from one cell to another (Bisschop et al., 2019).

Furthermore, the Li-Ion battery is equipped with many different technical safety installations which shall protect the battery in case of a malfunction. Besides electrical components like fuses (Kong et al., 2018), current interruption devices (Ouyang et al., 2019) and shutdown separators (Kong et al., 2018), Li-Ion batteries have a BMS (Bisschop et al., 2019; Christensen et al., 2021; Larsson & Mellander, 2017; P. Sun et al., 2020). Due to the relatively small range in which the battery operates at its best, a temperature between 20°C to 30°C, SOC between 0% to 100%, and the fact that the battery contains flammable liquids, the installation of a BMS is important (Larsson & Mellander, 2017). The purpose of the BMS is not to protect the battery from thermal- or mechanical abuse, but against electrical abuse (Bisschop et al., 2019; Gehandler et al., 2017; Larsson & Mellander, 2017). Christensen et al. (2021) divide the BMS duty into four main tasks: (1) monitoring, (2) protection, (3) computation and (4) communication.

(1) Monitoring: The BMS continuously controls the battery's operation to ensure that it stays within the safe limits (Christensen et al., 2021).

(2) Protection: This function prevents the battery from exceeding the safe limits of operation by receiving information from the monitoring system (Christensen et al., 2021).

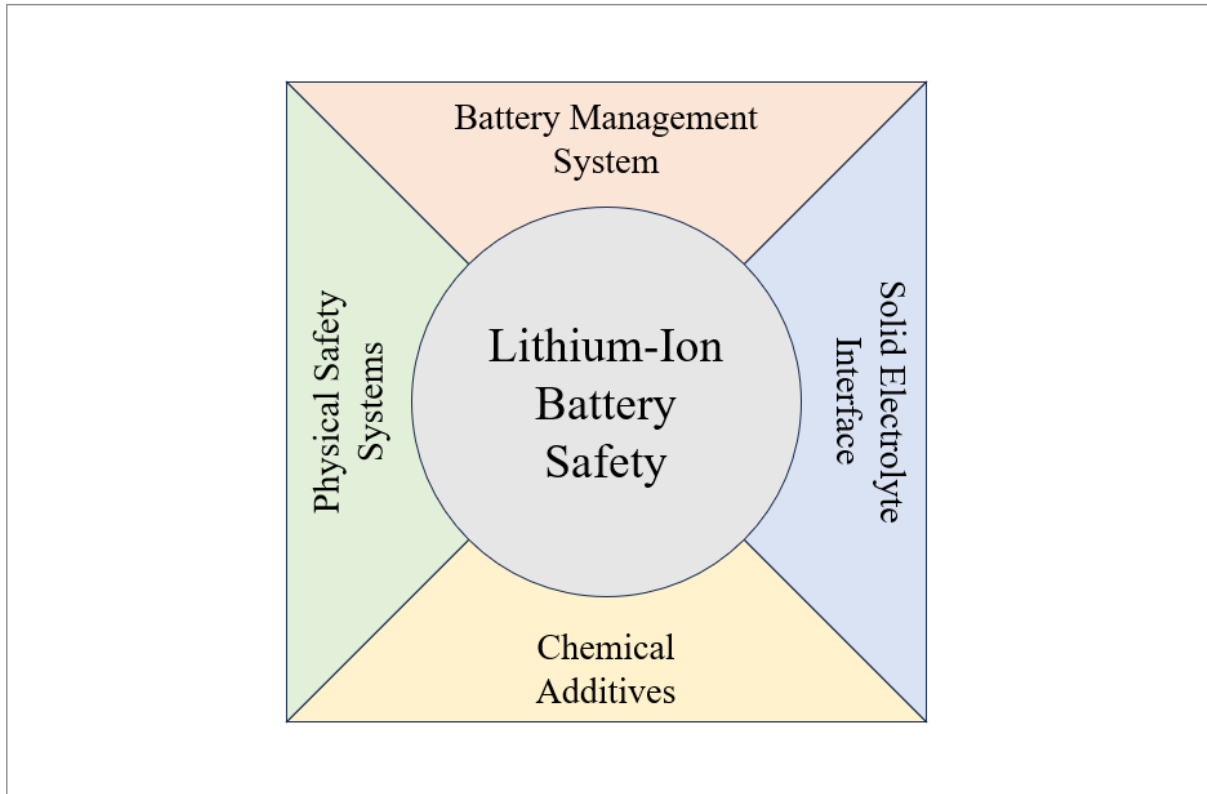
(3) Computation: At this level the collected data from the monitoring system are processed and, in case it is necessary, transferred to the protection system which triggers its activation (Christensen et al., 2021).

(4) Communication: The communication system logs the collected data from the monitoring system and provides the user with the information (Christensen et al., 2021).

Besides the safety measures on a chemical base and the technical overwatch of the systems functions, Li-Ion batteries are additionally equipped with mechanical safety installations. At this point the safety vent is to name (Kong et al., 2018; Ouyang et al., 2019). In case of a thermal runaway, the pressure inside the battery rises and the safety vent will be activated and the overpressure released (Ouyang et al., 2019). Additionally, Li-Ion batteries are equipped with a "Positive Temperature Coefficient" element (Ouyang et al., 2019). The working principle is as follows: in case a high current flows through the element, its temperature will rise and generate a high resistance until the current drops to normal again (Ouyang et al., 2019). This prevents the

battery from any harm caused by an abnormal electrical event. All four parts contributing to the safety of a Li-Ion battery are illustrated in Figure 5.

Figure 5: Battery risk management system for Li-Ion batteries



Adapted from Christensen et al. (2021, p. 11)

Additionally, the topic of re-ignition is widely discussed in the literature. There is a consensus that a re-ignition might occur when the flames are extinguished but the temperature inside the battery is still high (Kong et al., 2018), or the battery did not burn out completely during the event of a fire (Bisschop et al., 2019). Such a re-ignition can even start days after the original fire is extinguished (Bisschop et al., 2020).

The aspect of safety considerations during the marine transport of Li-Ion batteries is explored by Yin et al. (2023). If the Li-Ion battery is not mounted to a vehicle and transported on a car carrier respectively on a RoRo- or RoPax vessel, it is shipped on a container vessel. In order to prevent an abnormal electrical event from occurring, the Li-Ion battery is transported “in an open circuit state” (R. Yin et al., 2023). This leaves the remaining threats to a thermal- and mechanical event. Thermal events are caused by heat transfer from outside of the container to the inside (R. Yin et al., 2023), e.g. a high air temperature or a heated fuel oil tank in the vicinity.

Mechanical events are triggered by external forces impacting the Li-Ion battery (R. Yin et al., 2023), e.g. high G-forces caused by heavy sea or the rough handling of containers during the loading and discharging operation in the port.

3.2 Firefighting and Handling

In the sub-chapters, fire detection and -fighting system-related objects are presented.

3.2.1 Fire Detection and -Fighting Systems

Every vessel is equipped with fixed fire detection and -fighting systems in accordance with Safety of life at sea (SOLAS) Chapter II-2, Construction - Fire protection, fire detection and fire extinction (International Maritime Organization, 2002; The Standard Club Ltd, 2021). In the “Fire safety on ferries” Master’s guide by The Standard Club Ltd (2021) the authors explain that the car decks are monitored by smoke detectors instead of flame- or heat detectors. Furthermore, the car decks of ferries are equipped with “high expansion foam” extinguishing systems, while RoRo ships have a fixed CO₂ system (The Standard Club, 2021).

The design of a road tunnel and the car deck of a ship are quite similar in terms of that both are a longitudinal space which is confined to both sides and the top. Therefore, some findings of the fire safety of road tunnels can also be adopted to RoRo ships. The literature highlights that a tunnel is a special environment with unique challenges when it comes to the detection and extinguishing of fires (Kashef et al., 2009; Liu et al., 2010). Both articles investigate the advantages and disadvantages of the following fire detection systems: (1) Fiber optic heat detector, (2) Optical flame detector, (3) Heat detector, (4) Smoke detector and (5) Camera observation. To enable valid evaluation, full-scale experiments were conducted. The performance of the five systems differed depending on a wide range of variables like location, source, size and expansion rate of the fire (Kashef et al., 2009).

Besides the fire detection in confined spaces as described above, others investigated in experiments the efficiency of different fixed firefighting systems for onboard use to extinguish battery fires inside the engine room. Andersson et al. (2018) concluded that a fixed sprinkler or water mist system is not enough to extinguish a fire which started inside a battery cell, simply because the water cannot reach the source of the fire. If a high-expansion foam or nitrogen gas is added to the water, it might increase the possibility of extinguishing the fire, but the cooling effect which prevents the fire from spreading further would be reduced (Andersson et al., 2018). This

is backed by the findings of Magdolenová (2021), who found out that a fixed high pressure water mist system in a road tunnel reduces the temperature significantly, which disables the fire's ability to spread further. Bisschop et al. (2021) performed a similar experiment with a fixed firefighting system on gaseous base. They found out that the risk for the fire to spread from one module to another module was reduced and it is therefore a good approach. However, the scene of fire needs still to be cooled by water (Bisschop et al., 2021). Ditch and Zeng (2019) conducted full-scale fire experiments with energy storage systems based on Li-Ion batteries. Their findings show that a fixed sprinkler system is capable of keeping even a large scale fire under control (Ditch & Zeng, 2019).

The findings of Andersson et al. (2018) and Bisschop et al. (2021) are proven by the work of Zhang et al. (2022). Every firefighting system has its own advantages and disadvantages, e.g. if the cooling effect is high, the ability to extinguish the fire is low, some agents are electrically conductive and others produce toxic gases (Zhang et al., 2022). The best-performing fire extinguishing agent in the experiments conducted by Zhang et al. (2022) was liquid nitrogen. It can reach the inside of the Li-Ion battery cell, has a good cooling effect, does not produce toxic gases and is, compared to other gases, inexpensive. The disadvantage of liquid nitrogen is the storage and transportation (Zhang et al., 2022). However, since Li-Ion battery fires are coming along with a wide range of challenges, Bisschop et al. (2021) raise the question if every EV fire needs to be extinguished in view of the flammable gases which might be produced in contact with water and the risk of explosion.

3.2.2 EV Fire Handling

A common problem which firefighters are facing when they arrive to a scene of a fire involving vehicles, is to identify if it is an EV or ICEV, since there is no industrial standard for that (Long et al., 2013; Stave & Carlson, 2017). The different types of vehicles vary in the characteristics of how they behave during an event of fire. Moreover, the location of the Li-Ion battery pack differs between the various manufacturers (Stave & Carlson, 2017). During the study of Stave and Carlson (2017), they interviewed among others the fire brigade in Gothenburg with a focus on how EV fires are handled and if they are well-prepared for the challenges connected to EV fires. The response was that they receive good and useful information from Volvo Cars, but their knowledge about the other manufacturers is limited to their own experience. Besides the mentioned problem, Stave and Carlson (2017) highlight the lack of information about how to extinguish EV fires, what kind of gases develop during a fire and the risks occurring when the

Li-Ion battery comes into contact with salt water. While Long et al. (2013) ascertain that no best practices exist in how to handle EV fires, Stave and Carlson (2017) verify that water became the standard procedure for firefighting.

Hoffmann (2014) conducted an experiment in which he investigated the different reactions of a Li-Ion battery when it comes into contact with fresh- and salt water. Due to the internal safety measures of the battery, the main conductor is switched off when a battery comes in contact with fresh water, while the electrical power remains stored inside (Hoffmann, 2014). A completely different behaviour is noted when the battery gets in contact with salt water. Hoffmann (2014) found out that the battery discharges its complete electrochemical energy within 15 minutes while the flammable electrolyte remains. Furthermore, different hydrogen chlorine compounds are formed during this process (Hoffmann, 2014; Willstrand et al., 2020). Furthermore, the salt water is contaminated by Zinc-, Iron-, Copper- and Aluminium-Ions after its contact with the Li-Ion battery (Hoffmann, 2014). The above-presented study by Stave and Carlson (2017) identified the potential risks of an EV after the contact with salt water as a problem.

The lack of information on how to extinguish or control an EV fire is explained by Kong et al. (2018). It is highlighted that the conducted research focuses on how to ensure a safe transportation of batteries, therefore they are tested under extreme conditions in terms of mechanical-, thermal- and electrical abuse (Kong et al., 2018). Furthermore, Kong et al. (2018) suggest that the aim should shift towards answering the question how the flammability of batteries can be brought under control and to identify potential firefighting suppressants.

Moreover, to deal with a fire which has its source of ignition inside a Li-Ion battery is very difficult. As described earlier, it contains all three elements which are required for a fire to burn on its own (Zhang et al., 2022). The only solution is either to ensure that a thermal runaway is prevented from happening or to limit its damage (Gehandler et al., 2017). Therefore, the fire triangle must be interrupted, which means one of the three elements needs to be eliminated (Gehandler et al., 2017; Zhang et al., 2022). A possible solution for this problem is given by Bisschop et al. (2020), they suggest to install a fixed firefighting system inside the Li-Ion battery. The big advantage would be to hinder the fire to reach very high temperatures (Bisschop et al., 2020). However, the continuous development of gases inside the battery cannot be limited by this device. The design of the Li-Ion battery pack is optimized to protect the battery from external damage, but limits the access to its core in case of a fire (Gehandler et al., 2017).

3.3 Management of the Transportation Chain

In the sub-chapters, transportation chain-related objects are presented.

3.3.1 *Multimodal Transport and RoRo Operations*

‘Intermodal transport’ has been defined as “the movement of goods in one and the same loading unit or road vehicle, which uses successively two or more modes of transport without handling the goods themselves in changing modes” (United Nations Economic Commission for Europe, 2000). The successful implementation of intermodal transport requires the standardization of infrastructure, handling units and technical solutions (Mindur & Mindur, 2022). A transport can be referred to as ‘multimodal transport’, if the goods are carried by two or more different transport modes (United Nations Economic Commission for Europe, 2000). Furthermore, it should be noted that “the adoption of standards improves logistics efficiency in the management of cargo, control, and service marketing, and it facilitates access to port terminal users in the maritime sector” (Ringsberg & Lumsden, 2016). When introducing standards in the handling of RoRo cargo, such as trailers, the communication of the company management to the employees impacts their response to the new standard (Ringsberg & Lumsden, 2016).

In their paper, Flodén and Woxenius (2021) analyse the stakeholders involved in the (land) transportation of dangerous goods and how these can contribute to the overall safety of the entire system. When handling dangerous goods as general cargo, the operators (of e.g. trucks) often are unaware that they are picking up dangerous goods before they reach the client’s loading zone and only then receive that information (Flodén & Woxenius, 2021). Their research further reveals that a large number of stakeholders is involved in the transportation of dangerous goods cargo. The primary stakeholders (e.g. consignor, consignee, intermodal transport operators) are required in order for the system to work (Flodén & Woxenius, 2021). In case of incidents, the crucial role of rescue and emergency services has also been highlighted. Good cooperation and communication between all stakeholders increases the safety of the system and further prepares for emergency situations (Flodén & Woxenius, 2021). It is however pointed out, that information technology and communication systems are often insufficient for the handling of dangerous goods (Flodén & Woxenius, 2021).

In the following, the RoRo processes are explained in more detail. In RoRo shipping, the cargo is rolled onto the vessel either via its own wheels (in the case of vehicles) or on special chassis or trailers (Kaptan, 2022). The vessels usually have ramps either at the bow, at the side, or at

the stern of the vessel, sometimes also in multiple locations. On board the ship, the cargo is driven or pulled to its stowage position and cargo deck via internal ramps or lifts. There, the cargo is lashed to the vessel, e.g. with chains or tensioners (Kaptan, 2022). The sequence of activities in the terminal in the RoRo process can be categorized into three overarching steps: First, the planning considers the availability of human and material resources. Second, the actual import and export, i.e. loading and unloading are conducted. Third, the clients are billed and the payment is received (Mabrouki et al., 2013, 2014). Since the handling of trailers and cars on RoRo vessels has certain similarities (since they are transported on the same vessel), it is reasonable to also look at this process in more detail. When managing export trailers, the logistics process chain is made up of the following consecutive steps within the RoRo terminal: “arriving, transporting, receiving, inspecting, outbound staging, loading, and shipping operations” (Ringsberg & Lumsden, 2016).

3.3.2 Onboard Handling

When transporting EVs on RoRo ships, a failure in a Li-Ion battery presents a significant fire hazard. Additionally, failure by staff to follow set-out procedures and heavy sea state can also contribute to onboard fires (Fu et al., 2023). In line with the literature reviewed in Chapter 3.1.2, a fire in a Li-Ion battery emits toxic gases, is very hard to extinguish, and reaches high temperatures (Germanischer Lloyd, 2013). Therefore, appropriate loading-, onboard handling-, and oversight procedures are required which enable safe transportation of the EVs (Bao et al., 2023; Fu et al., 2023; Kaptan, 2022; NTSB, 2021).

In the summer of 2023, the IMO MSC, during its 107th session, approved for future adoption an amendment to SOLAS Chapter II-2 (International Maritime Organization, 2023a). This took place, after the IMO ‘Sub-Committee on Ship Systems and Equipment (SSE)’ completed the review of Chapter II-2 of the SOLAS regulation in the beginning of 2023. This included the ‘Fire Safety Systems’ code, which should reduce the number of incidents, and their consequences, on board RoRo- and RoPax ships to a minimum (International Maritime Organization, 2023b). According to the proposal, passenger ships constructed after 01 January 2026 are required to have the following installed: “a fixed fire detection and fire alarm system to be provided for the area on the weather deck intended for the carriage of vehicles; an effective video monitoring system shall be arranged in vehicle, special category and ro-ro spaces for continuous monitoring of these spaces; structural fire protection in passenger ships carrying more than 36 passengers, including fire insulation of boundary bulkheads and decks of special category and

ro-ro spaces; and a fixed water-based fire-extinguishing system based on monitor(s) to be installed in order to cover weather decks intended for the carriage of vehicles” (International Maritime Organization, 2023b).

In their report, compiled for the German Federal Ministry of Transportation, the Germanischer Lloyd (2013) distinguishes between two kinds of electric vehicles during the transportation on board ships: Those that are transported without their batteries being charged during the ocean transportation and those, whose batteries are being charged during the ocean transportation (Germanischer Lloyd, 2013). The latter hereby present a higher risk for ignition and fire (Germanischer Lloyd, 2013). EVs should therefore not be allowed to charge during the ocean transport, as to prevent fire and potentially explosions (Wu et al., 2021). In case the EVs are nevertheless being charged during the transport, the power supply to the entire deck should be accessible from outside so that it can be switched off from a safe distance in case a fire breaks out (Germanischer Lloyd, 2013).

When loading EVs on board a RoRo- or RoPax vessel, it is imperative, that the stevedores and longshoremen follow the loading procedures set out by the ship operator. This was one of the recommendations by the United States National Transportation Safety Board (2021) after the fire on Höegh Xiamen (Chapter 3.3.3). Nevertheless, the ship operator (in the form of the chief mate and crew) should also check and monitor these operations (National Transportation Safety Board, 2021). It was further suggested that ship operators and technical managers should ensure that their lashing procedures contain detailed instructions on the handling of batteries (in that case referring to regular car batteries in ICEVs) (National Transportation Safety Board, 2021). Bao et al. (2023) advise for the loading and unloading procedure of EVs, that special attention should be placed on the prevention of collisions or impacts involving EVs in order not to potentially damage the battery (Bao et al., 2023). Furthermore, the battery should ideally be disconnected once the EV has been parked on the loading deck and the cables should be secured and covered. Additionally, extra lashings should be placed on EVs, so that movement and shifting during the transport can be prevented. Lastly, charging during the journey should be prohibited (Bao et al., 2023). This however rather concerns RoPax vessels than pure RoRo vessels. When loading vehicles on board a RoRo ship, accidents can occur e.g. when drivers bump against the steel walls on board the vessel or scrape loading ramps with the bottom of the car. A typical cause for these accidents is human error due to fatigue (Kaptan, 2022). Kaptan (2022) hence gives the following recommendations (excerpt) in order to prevent accidents during the

loading operations on board RoRo vessels: An “electronic fatigue risk assessment procedural infrastructure” should be implemented in order to prevent accidents caused by fatigue of dockworkers and/or crewmembers (Kaptan, 2022). Secondly, the communication during the loading process should be clear and concise. Standardised hand gestures and verbal expressions are recommended and continuous training should ensure that everybody involved in the operation has the same knowledge. Lastly, vehicle drivers should be educated on a ship-by-ship basis. Since each ship has its own design, the important points to consider when driving the vehicles on board should be highlighted to the drivers for each individual ship (Kaptan, 2022).

As per suggestions by the Germanischer Lloyd (2013), EVs should be marked, both visually and in the cargo manifest/loading plan, so that the crew and emergency responders can quickly identify those cars in an emergency. Thereby, the crew could also change their approach, e.g. regarding the choice of PPE and firefighting tactic, in case a fire breaks out (Germanischer Lloyd, 2013). EVs should be parked in special lanes, so that the identification of the vehicle type is made easier. That way, the fire detection and firefighting systems in that area could be adjusted to match the needs of that cargo. Moreover, they should be parked separately from any dangerous goods on board (Germanischer Lloyd, 2013). The International Union of Marine Insurance (2017) also recommends to screen and secure the cargo, to mark the areas where EVs are parked on deck, and to ensure that the crew is trained in fire detection and fire response (International Union of Marine Insurance, 2017).

Rodero and Marrero (2023) developed an algorithm which should assist during the stowage planning and loading of EVs. Their “cargo distribution algorithm” (Rodero & Marrero, 2023) calculates the stowage plan with the lowest possible overall risk for an onboard fire, based on vehicle types. Hereby, the information whether a vehicle is “an alternative fuel vehicle or not”, presents the first step and a very relevant information for the process (Rodero & Marrero, 2023). However, they acknowledge that often the information required, such as the propulsion type for a vehicle, is missing since the space on board is booked per lane meter and customers are hesitant to share further information (Rodero & Marrero, 2023). On board the RoRo vessels, fire detection systems should be sensitive in order to detect gases being released from defect Li-Ion batteries, even before the thermal runaway process has concluded and set the battery on fire. This way, a potential fire can be detected quite early and the affected vehicle can be cooled down, before the fire has the chance to spread over to other vehicles in the proximity (Germanischer Lloyd, 2013). Nonetheless, it is difficult to detect gases on open or weather decks and

furthermore, the firefighting operations on these decks are challenging due to the flow of air (Germanischer Lloyd, 2013; International Union of Marine Insurance, 2017).

3.3.3 Management of Accidents and Fires on RoRo Ships

On RoRo- and RoPax ships, there are four main types of hazards: Collision, grounding, capsizing and fire or explosion (Antão & Guedes Soares, 2006). With regard to the location, where the incidents happen, in the period from 2014-2021, ~45% of incidents or casualties involving ships within the European Union occurred during the port stay of the vessels. This includes the mooring and unmooring, loading and unloading and other alongside operations (European Maritime Safety Agency, 2022). While the occurrence of fires on board ships is relatively seldom, the consequences can potentially be severe, especially on ships also transporting passengers (Antão & Guedes Soares, 2006; Wang et al., 2021).

In order for a fire to start, oxygen, a flammable substance or fuel, and heat are required. This is referred to as the “fire triangle” (Antão & Guedes Soares, 2006; Gehandler et al., 2017; Larsson & Mellander, 2017; Zhang et al., 2022) (Chapter 3.1.2). When all three of those components are available, a fire can start. As soon as one of them is removed, this can cause the fire to be extinguished (Antão & Guedes Soares, 2006). From a time perspective, ship fires can be classified into three different categories: “Catching fire, fire spread and fire out of control” (Wang et al., 2021). A fire can have many different causes or starting points. According to Baalisampang et al. (2018), the causes of fire on board ships can be categorized as human error, thermal reaction, mechanical failures and electrical fault. They further highlight that human error is responsible for 48% of onboard accidents and hence reducing human errors for accident prevention is crucial (Baalisampang et al., 2018). Their findings revealed that human actions that triggered fires on board ships usually occurred during maintenance activities, such as welding. They hence suggest the design of equipment in a way that reduces the probability of human error, as well as the location and design of workspaces which increases human reliability (Baalisampang et al., 2018). However, Antão & Guedes Soares (2006) argue that human error has a lesser impact on fire incidents than e.g. on groundings or collisions. In a different paper, the causes of fire on board are discovered to be “improper loading vehicle condition, lack of understanding and structural limitations of fixed fire extinguishing systems, failure to detect fire in a timely manner, inadequate fire patrols” (Kim & Jeon, 2023). The movement and shifting of cargo during the transport hence presents a relevant ignition hazard. This can be caused by e.g. heavy rolling and swell on board the ship. In the observed period between 2005-2016,

10-20% of fires on RoRo-, RoPax- and Car Carrier vessels broke out due to shifting of the cargo (DNV GL, 2016). Generally, underwriters for marine insurance could observe an increase in the number of fires on RoRo- and RoPax vessels and it has also been pointed out that these vessel types are more prone to fires than others (International Union of Marine Insurance, 2017). Additionally, higher speed during the sea leg of the transportation chain can lead to higher operational risks (Antão & Guedes Soares, 2006).

Marrero et al. (2022) conducted an analysis of fires on board RoRo vessels in order to identify risk categories and causes of ignition on board. Their focus had been on fires originating in the cargo space and starting in the vehicles or cargo being transported. One risk category has been identified as EVs with spontaneous ignition due to thermal runaway. A second risk category is cargo involving dangerous goods which is not properly stowed and lashed and could therefore be subject to movement during the sea transport. A third risk category centres around recreational vehicles which pose multiple fire hazards (Marrero et al., 2022). Furthermore, owing to the design of RoRo vessels, the firefighting operations on board are aggravated. This is due to the fact that the vehicles are tightly loaded, enabling a fire to spread quickly while on the other hand making the detection of a potential fire harder (Kim & Jeon, 2023). Moreover, the transportation of EVs and the potential for thermal runaway exacerbates the situation (Kim & Jeon, 2023).

In order to give an example from a real incident, the fire on board the car carrier Höegh Xiamen will be shortly described. As this incident occurred during the loading operations in the port of Jacksonville, Florida, the US government National Transportation Safety Board has published a detailed accident report on the incident (National Transportation Safety Board, 2021). The fire broke out in the aft section of the ship, on a cargo deck and during loading operations while the ship was moored in port. It was caused by a not properly detached battery in a used car. The situation was exacerbated, since the fire detection system had been switched off during the loading operations and had not immediately been switched on again. Additionally, the CO₂ fire extinguishing system was employed too late and was therefore ineffective, as the fire had already spread further (National Transportation Safety Board, 2021). It has been reported that the risk for a fire to start in a new car (ICEV) that is being transported is fairly low. The risk in a used car however is higher (DNV GL, 2016). This is also what caused the fire on the Höegh Xiamen (National Transportation Safety Board, 2021). The stevedores did not follow the es-

established loading protocol and especially not with regard to the battery disconnection procedures. Furthermore, the oversight of the loading operations was inadequate (National Transportation Safety Board, 2021). The fact that used vehicles are exempted from the hazardous materials regulations increased the risk for the ship and crew (National Transportation Safety Board, 2021). The National Transportation Safety Board (2021) also puts forth recommendations for vessel operators. The recommendations target mostly the procedures, e.g. during loading, lashing and battery securing. The main recommendation is the development and improvement of the processes, involving the crew and stevedores (National Transportation Safety Board, 2021).

When it comes to countermeasures in response to fires, additional recommendations to operators can be found in the literature. Through an analysis of fires on RoRo-, RoPax- and Car Carrier vessels, the classification society Det Norske Veritas (then still under the old name DNV GL) developed recommendations for vessel operators. Among the recommendations put forth is that the charging of electric vehicles on board should be prohibited, cargo should be checked before loading and specific focus should be placed on old and/or used cars. Additionally, the crew should be familiarised with the firefighting procedures and these should be practiced regularly (DNV GL, 2016). Based on the identified causes to fires, Kim & Jeon (2023) suggest the following for the prevention of fires in cargo holds and for the improvement of countermeasures: “random checks of the condition of the vehicles scheduled for shipment, improvement of fixed fire extinguishing system, improved fire detection systems and fire patrols” (Kim & Jeon, 2023). Moreover, the cabin, i.e. the section of the ship where the fire broke out, should be sealed off as soon as possible after the fire starts, and ventilation of that part of the ship should be switched off. Additionally, emphasis has been put on crew training (Wang et al., 2021).

3.3.4 Terminal Risk Management

It can be distinguished between two types of risk sources in seaport terminals, those risks caused by natural disasters and risks from operational and safety causes (Nagi et al., 2021). Risk management in ports “is a strategic, capital, and inescapable process, as it affects all aspects of the professional activity” (Dhahri et al., 2022). Through a literature review of the supply chain risk management and the port risk management literature, Dhari et al. (2022) conclude that the risk management in port operations has only seldomly been addressed in the literature. This stands in contrast to supply chain risk management, which has been covered more extensively by academia (Dhahri et al., 2022). Furthermore, the research in the field of the loading and unloading

operations, as well as on the risk assessment of the handling of dangerous goods in seaports is limited (Nagi et al., 2017).

Generally, risk should be reduced since this improves the overall safety and reduces potential negative effects on humans. But there is a balancing between the risk and the potential benefits, and moreover, different stakeholders have different interests and attitudes to risk (Kristiansen & Haugen, 2022). When managing risk, we firstly need to understand what the risk exactly is, and which accidents can be caused by it and in which frequency (Kristiansen & Haugen, 2022).

Risk management plays a key role in ensuring effective operations at seaports and terminals (Dhahri et al., 2022; Mabrouki et al., 2014). An important part of the risk management process is the evaluation of risks (Mokhtari et al., 2012). For the risk management, knowledge of the risk variables (also referred to as risk factors) is imperative. For example, the risk variables in the terminals in the port of Sfax, Tunisia, have been identified and prioritized by Dhahri et al. (2022). The focus hereby lay on the man-made risks. For the port of Sfax, their results show that, “the highest-priority risk variables are the manual handling, disregard for safety aspects, unsafe storage of goods, absence of a prevention system and a rescue organization, neglect of the regulatory aspects of handling equipment, ignorance of good handling practices during the operation of loading and unloading, and inadequate lifting accessories” (Dhahri et al., 2022). According to John et al. (2014), sources of disruption in seaports can be categorized into operational-, security-, technical-, organisational- and natural risk factors (John et al., 2014). Within the operational risk factors, human error in port operations is a major factor which can lead to the disruption of maritime operations and substantial economic losses. Further, lack of equipment maintenance and resulting equipment failures are another source of potential disruption (John et al., 2014). Mokhtari et al. (2012) classify the operational risk factors into six sub-categories on a lower level, namely (1) safety risk factors (e.g. weather conditions), (2) security risk factors (e.g. personal safety), (3) pollution risk factors (e.g. pollution by the ship), (4) legal risk factors (e.g. regulatory changes), (5) human error risk factors (e.g. errors by stevedores or the ship’s personnel), (6) technical risk factors (e.g. lack of equipment maintenance) (Mokhtari et al., 2012). Human errors can be related to lack of knowledge, bad decision-making or missing communication (Trbojevic & Carr, 2000). In their paper, Mabrouki et al. (2013) classify the operational risks into the five categories (1) unloading and storage, (2) unloading and direct delivery, (3) delivery of stored vehicle, (4) loading directly, and (5) planning and preparation

(Mabrouki et al., 2014). Among the most critical risks discovered in the RoRo terminal processes, the ones most relevant for this thesis are infrastructure sizing and capacity sizing, information system failure, error entry, routing plan, a not provided information or not exact information (Mabrouki et al., 2014). Decision makers within terminals should pay specific attention to the critical risks (Mabrouki et al., 2014).

When it comes to the existing risk management concepts in organizations, Nagi et al. (2021) mentioned that there are no clearly distributed responsibilities between the actors and stakeholders in seaports with regards to operational and safety risks. The response to risks is rather decentralized, driven by the variety of risks that exist in this realm (Nagi et al., 2021). Additionally, the risk management often only focuses on the own organization, with a lack of cooperation and collaboration with other organizations and other actors within the ecosystem (Pileggi et al., 2020).

There are different models proposed for risk management within the actors of the seaport ecosystem as well as across the entire system. For example, Trbojevic and Carr (2000) developed a step-by-step approach for risk management in seaports, focusing on hazard management and quantitative assessment of risks in port operations, considering both probabilities and corresponding consequences of risk events. Mokhtari et al. (2012) also developed a step-by-step approach to risk management in ports, however using fuzzy set theory and evidential reasoning approach. Pileggi et al. (2020) propose an ontological model for risk management in seaports. It is suggested that the roles between the different stakeholders in the port environment are clearly distributed and defined, also in order to facilitate easier collaboration between those (Nagi et al., 2021). Additionally, personnel within the different organizations should be well-educated in the field of risk management and procedures and information should be equally available to all members of the organizations (Nagi et al., 2021). When “risk owners” are defined in each organization, the collaboration between the various stakeholders in the port is also enabled and simplified (Nagi et al., 2021).

4 Results and Analysis

This chapter depicts the results of the interviews in connection with the literature presented in Chapter 3. The results are divided into three sub-chapters, wherein the interviews are analysed and linked to the results from the literature review. The presentation follows the steps and activities of the transportation chain as introduced in Chapter 2 (Figure 1).

4.1 Handling of Electric Vehicles along the Transportation Chain

The analysed results are presented based on the four created clusters (1) No distinction between EVs and ICEVs, (2) Loading and storage on board ships, (3) Terminal operation and (4) Road transportation, to represent the codes assigned to them (Appendix II).

It should foremost be noted that the interview results revealed that there was no material difference in handling EVs compared to handling ICEVs or other vehicles at each respective step in the transportation chain. This was stated in all eight interviews, even despite the fact that the main question asked was how EVs are handled, and in the question it was not asked for a comparison with ICEVs. Thus, the results show that along the entire transportation chain, there is no material difference in handling these different types of vehicles, according to the interviews. This was also confirmed by the following two interviewees (B1, F1):

“We don't treat EVs differently in the terminal, for us it's just a car.”

(Interviewee B1)

“It's not really a difference compared to how we ship or operate with a combustion engine. I would say so independently if it's an electric [Vehicle] or a non-electric [Vehicle] then it's the same.” (Interviewee F1)

In line with this, it was mentioned during one of the interviews with an intro engineer (Interviewee C1) from an EV manufacturer (Company C) that they do not differentiate between EVs and ICEVs in production. Nevertheless, there are certain requirements when the battery of an EV is being connected for the first time, since the personnel doing this job would need special training. Additionally, as mentioned by the foreman of the logistics company (Interviewee E3), the handling of EVs is slightly different for the loading and unloading on the truck for transport between the manufacturer and the terminal, due to different torque of the electric engine in lower gear and the higher weight of the EVs compared to ICEVs.

In three of the eight conducted interviews (Interviewees A1, B2, E1), it was also addressed that the number of EVs has been increasing in the recent past. This is in line with the goal from the EU to increase the amount of EVs on European roads, as highlighted in the introduction (Chapter 1). The two following quotes support this finding:

“Now more or less all cars are hybrid or fully electric” (Interviewee A1)

“A lot of cars, it’s electric for today” (Interviewee E1)

The increase of EVs was even positively appreciated by the interviewed stevedore (Interviewee B2), due to the technical aspects and the handling of this type of vehicles, when driving them in the terminal and onto the ship.

With regards to the details about the handling of EVs at different stakeholders in the transportation chain, the clusters 2 to 4, which were derived from the interview results, were assigned to the individual steps, manufacturer, road transport, terminal/storage, loading and sea leg (Figure 1).

Step 1, the manufacturer, marks the beginning of the transportation chain. This information was included in **cluster 1**. According to interviews with the intro engineers (Interviewees C1, C2), the EVs and ICEVs are mixed in production in the factory, they are produced on the same line. There is also no distinction between who can work on these vehicles, as all factory workers can assemble all types of vehicles. However, as soon as the battery is connected, the staff working on these vehicles need special training. In the interview with the finished vehicle distributor (Interviewee F1) from another EV manufacturer (Company F), it was mentioned that from their logistics perspective, they do not distinguish between EVs and ICEVs in terms of shipping or operating the vehicles for export. Thus, according to logistics management of EVs, the vehicles are received when factory complete, so there was no additional information about the production processes before that.

In step 2, after the vehicle leaves the factory, it is transported to the export port by truck, which was addressed during interviews at both EV manufacturers. According to the interviews with the staff from the EV manufacturers (Companies C, F), the road transportation (**Cluster 4**) from the manufacturer to the export terminal begins with the interface between the manufacturer and the transport operator. The finished vehicle distributor (Interviewee F1) also gave a detailed

description of the export process from the perspective of an EV manufacturer. Conducted interviews thus show that finished EVs are stored in a yard outside the factory, until they are assigned to a load and the logistics company is coming for picking up the vehicles. The logistics staff from the manufacturer themselves are actually not allowed to move the EVs. Instead, the loading and lashing of the truck is the responsibility of the logistics operator/carrier but needs to be done according to the manufacturer's rules and standards. Of the conducted interviews, one finished vehicle logistics operator (Interviewee E1), highlighted that before a vehicle is loaded, the truck drivers have a routine to check the vehicles for visual damages. The interview with staff from a logistics company (Interviewee E3) addressed that the actual loading procedure onto the truck is slightly different for EVs compared to ICEVs, since they have more torque and power right from the start and with lower revolutions per minute. In order to avoid the tyres to spin, and to enable a smooth loading operation with no bumping, the trailer needs to be adjusted and lowered a bit. These issues however mostly occur in cold or wet conditions. Furthermore, it was emphasised during the interview with the logistics company (Company E) that, due to higher weight of the EVs, the loading of the trailer needs to be planned and calculated carefully. It is important for the truck driver to consider how the trailer handles with a higher weight. Nevertheless, the higher weight can also be an advantage as the EVs rest more stably on the trailer. Moreover, during the interview with one EV manufacturer (Company F) it was explained that when vehicles are handed over from one carrier to another, respectively from one step in the transportation chain to the next, there is also an inspection.

After the road transportation, the EVs arrive in the export terminal on a trailer, as per the interview with a terminal administrator (Interviewee B1). This marks step 3 in the transportation chain and the information for this was included in **cluster 3** (Terminal). According to the interviews with staff from a terminal operator (Company B), when the vehicles arrive in the terminal for the export, they are first stored in the terminal yard. It was mentioned by the terminal administrator (Interviewee B1) that, due to the high frequency of RoRo vessels arriving and departing the port, the storage duration is tried to be kept below 24 hours, before the vehicles are exported. The parking spaces for the vehicles are marked in order to ensure that the vehicles are not parked too tight to each other and to prevent accidents.

During the interview with the terminal administrator (Interviewee B1), it was also addressed that the car handling is separated from the other RoRo terminal operations, such as handling of trailers, containers, etc., but there is no distinction between different types of vehicles. The

separation towards the other terminal operations is enabled by having different driving paths for the vehicles. The vehicles which are loaded onto the vessel have an own lane to prevent interference and accidents with the other terminal processes. Additionally, only one row of vehicles is handled at a time, in order to avoid collisions and traffic jams. This was also confirmed by the terminal administrator (Interviewee B1) who stated:

“So we try to create different driving paths and so it will not be interfered by the normal operation and by normal operation I mean the trailers and the heavy machinery and secure boxes containers.” (Interviewee B1)

During interviews with a chief mate of a RoRo vessel and a terminal administrator (Interviewees A2, B1), it was mentioned that the speed of the EVs during the transport is restricted to 30 km/h in the terminal. Having special vehicle lanes separated from other terminal operations, in addition to the speed limit, is supported in published literature. The literature review (Chapter 3) showed that collisions or impacts on EVs should be prevented during the loading and discharging procedures, since these could potentially damage the battery. By having separate lanes for vehicles only, this is partly fulfilled, since EVs are still handled in the same lanes as ICEVs, according to the terminal administrator (Interviewee B1). Additionally, it was further explained in that same interview that the different IMO dangerous goods classes are separated from each other on the terminal yard, so that a potential fire could be contained locally, but this rather concerns the general terminal operation and less the EVs. It was further elaborated that while the terminal does have EV charging stations, these are for use by their own and their employees' vehicles only. On the terminal, the EVs to be exported are not being charged before loading them onto the ship and the terminal operator relies on the vehicles arriving with a high enough charge level. An interviewed stevedore (Interviewee B2) also addressed that only when the EVs are completely empty do they have to be charged with a gas generator, but this is an exception and does not occur very frequently.

According to conducted interviews, the EVs are stored in the same areas as ICEVs in the terminal. From the terminal, they are being driven onto the ship and stowed for transport. The loading and storage on board ships has been summarized in **cluster 2** and marks the last step in the export transportation chain.

Interviews with chief officers (Interviewees A2, A3) showed that they are not really responsible for the handling of the cargo and the loading operation. This is done by the stevedores who load

and store the vehicles (and other RoRo cargo) on board, and later also discharge the cargo at the port of destination. Nevertheless, if the vessel's crew notices something out of the ordinary during the loading operation, this will be reported and followed up with the deck officer of the vessel. This was also confirmed by two ship officers (Interviewees A1, A3):

“We are not so much responsible for the handling of the car because it's the stevedores, they load the cars and they discharge the cars.” (Interviewee A1)

“It is the stevedores that do all handling, but we have crew supervising loading operations.” (Interviewee A3)

According to interviews, one problem during the loading operation is the ramp. The ramp can cause bumps on the vehicles, when the angle between the ship and the terminal is too small. This was especially mentioned by one chief officer (Interviewee A2):

“I think the big problem is when driving on board the ramp in the stern because it's like a speed bump.” (Interviewee A2)

Interviews with officers on board the vessel showed that what they can and try to do during the loading operation, is to keep the ramp as flat as possible by adjusting the ballast water throughout the loading operation. This makes not only the work for the stevedores more comfortable but further reduces the risk of heavy bumps of the vehicles on the ramp. Furthermore, with modern vessel types, the ramp is constructed for easier loading, according to the terminal administrator (Interviewee B1). In case a damage occurred during the loading operation or in the terminal, a reporting form will be left inside the vehicles, in order to inform other transportation chain actors that the damage had already been recorded, as pointed out in the interview with a terminal administrator (Interviewee B1).

Once the vehicles are on board, they are stowed in closed cargo decks and separated from hazardous cargo, as highlighted by one interviewed chief officer (Interviewee A3). This is something that can be influenced by the vessel, by issuing onboard loading requirements. However, within the lanes it is not differentiated between EVs and ICEVs. This is in contrast to published recommendations presented in the literature review (Chapter 3). According to these, the EVs should be parked in dedicated lanes, which should be marked, so that the identification of vehicle types is made easier.

When it comes to the separation of EVs from sources of heat, such as heated fuel tanks, on both vessels of the RoRo shipping line (Company A), the interview results demonstrate that this is not really considered during the stowage planning for the onboard storage. However, this is relevant when considering the risk of thermal abuse triggered by external heat sources, confirmed by published literature (Chapter 3). With regards to the lashing of EVs, the analysed interviews addressed that EVs are neither lashed on RoRo- nor on RoPax vessels. On the one hand, since it is not distinguished between EVs and ICEVs and on the other hand because the lashing of all vehicles would take a long time and require additional human resources. This was also confirmed by two interviewees (A2, D1):

“If we lash actually there's a lot of damages and also it takes a lot of time and there is no resources for it.” (Interviewee A2)

“[...] we have a 12-hour journey, what can we expect in that period of time [...] I would say [we] never lash cars.” (Interviewee D1)

Additionally, the interviews showed that lashings were not required due to the service the vessels were sailing on, with only short (mostly coastal) ocean stretches. This stands in contrast to the published description of the RoRo process in the literature (Chapter 3), which shows that cargo is lashed to the vessel with e.g. chains. Interview results show that from the manufacturer's point of view, the vehicles can (if they are) only be lashed in certain ways so as not to damage the vehicle. Moreover, one naval architect (Interviewee D1) confirmed that, even though EVs are usually not lashed for the sea leg, rubber wedges can be put underneath the last vehicles in the block, in case a loading deck is only partially loaded. This serves to prevent the vehicles from coming free and thereby also holding the other vehicles in place and preventing many vehicles from sliding over the deck. As per the interview with a chief mate (Interviewee A3), EVs are often transported together with other trailers on RoRo vessels. The lashing requirements of trailers are dependent on the weather (i.e. wave height) and the position on board the ship and follow IMO guidelines.

In the literature (Chapter 3), it was further recommended that ship operators should ensure that their lashing procedures contain detailed instructions on how to handle the batteries in ICEVs, i.e. if and how to disconnect them. According to the interview with the intro engineer (Interviewee C2), the manufacturer provides information on how to turn off the electric system for

the transport. Nevertheless, no information on this procedure was found in the interview data from the interviews with the RoRo- and RoPax shipping lines.

4.2 Potential Risk Factors along the Transportation Chain

The codes assigned to RQ2 were sorted into seven clusters: (1) State of charge during transport, (2) Battery fire hazard, (3) EV identification, (4) Experience with the transport of EVs, (5) Risks from different types of vehicles, (6) Trust in other stakeholders involved in the transportation chain of EVs, and (7) Damages caused by mechanical abuse (Appendix III). In the following paragraphs, the clusters are described with statements of the interviewed experts along the export transportation chain and compared with results from the literature review (Chapter 3).

During the interviews, special attention was paid to explore how the different stakeholders along the transportation chain handle the three main trigger events of a thermal abuse. These key risk factors for a thermal runaway in the EV's battery, as found in the literature (Chapter 3) are: (1) electrical event, (2) thermal event, and (3) mechanical event.

Cluster 1 (State of charge during transport) contains the three codes (1) State of charge, (2) Onboard charging and (3) Operational issues from empty batteries.

According to the interview with the intro engineer (Interviewee C1), the EV manufacturer (Company C) receives the Li-Ion batteries from a production facility with a SOC of 20%. For a safe transportation of EVs 'The Association of European Vehicle Logistics, ECG' recommends a SOC of 50% (Interviewee F1). This ensures that the vehicles can be loaded and unloaded onto the trucks for the road transport, as well as onto the ship for the sea transport. However, one intro engineer (Interviewee C2) mentioned that the terminals require a SOC of 50% while the finished vehicle distributor (Interviewee F1) mentioned that other customers ask for a lower SOC, but never above 50%. As presented in the literature (Chapter 3), it is pointed out that the SOC level is an essential risk factor. Published studies show that the higher the SOC is, the greater is the potential risk, therefore it is recommended to transport EVs with an as low as possible SOC. Two interviewed participants (Interviewees E2, F1) highlighted that a certain SOC level is needed for the EVs to be driven on and off the trucks and the vessels during the transport from the manufacturer to the customer. According to the interview results, it is not possible to reduce the SOC to an absolute minimum, from a practical perspective.

However, one of the interviewees highlighted that it is hard for the entire global vehicle industry to agree on a certain SOC level:

“[...] we are constantly sharing and pushing and using the ECG recommendations so the latest that ECG have, that's what we're using in our standards.”
(Interviewee F1)

The interviews show that all EVs leave the factory of the EV manufacturer (Company C) with a SOC of 50%. The charging station on the yard is programmed so that it stops the charging process when the battery reaches 50%. Moreover, three of the interviewees (B1, B2, E2) stated that if an EV's battery's SOC is too low and the vehicle is not starting, it needs to be charged by the responsible stakeholder in the transportation chain. However, according to these interviewees, such a particular case is very uncommon. It was mentioned during the interview with a logistics operator (Interviewee E2) that such an event occurred two or three times out of around a thousand moved vehicles. But it is a problem if an EV is not starting when it is supposed to be loaded onto a trailer.

According to the interview with the terminal administrator (Interviewee B1) at the terminal operator (Company B), it was emphasised that the SOC level is an issue. In that interview it was mentioned that EVs should not be shipped over long distances with a SOC below 50%. The person named as an example vehicles which arrived from a country outside of Europe with a very low SOC, but still enough to drive them from the ship onto the trucks. As stated in the literature (Chapter 3) it is possible for a Li-Ion battery to drain below 0% which might trigger a thermal runaway. The terminal operator (Interviewee B1) pointed out that the BMS is designed to prevent such an event, this is confirmed by published studies (Chapter 3).

In line with published literature (Chapter 3), good communication between all stakeholders is crucial when transporting dangerous goods. During the interviews, a lack of information flow was identified at various steps along the transportation chain, which poses another risk factor. For example, on board of the RoRo shipping lines' vessels (Company A) the SOC's of the loaded vehicles are not known, it is assumed that the vehicles' SOC's are between 30% and 40%. The charging of EVs on these vessels is prohibited during the transport, this is in line with published recommendations (Chapter 3). However, the analysed interviews showed that only brand-new vehicles are loaded and transported on board of the RoRo shipping line's vessels. Interviews also showed that differently to the RoRo vessels, the RoPax shipping line's vessels transport

mostly in-use EVs with an unknown SOC and only sometimes new EVs. Furthermore, the interview with the naval architect (Interviewee D1) revealed, that as a pilot project six charging stations were installed on one of the vessels in their fleet. The charging is conducted with cables provided by the vessel and the stations are connected to the ship management system. This ensures a constant control of the charging process as well as the SOC level and complies with recommendations presented in the literature review (Chapter 3), to be able to switch of the power supply from a safe distance.

Cluster 2 (Battery fire hazard) contains four codes which are: (1) Battery fire danger, (2) Thermal abuse requirements, (3) 12V/24V battery hazard and (4) Thermal abuse unlikely in Sweden.

The interview conducted with two intro engineers (Interviewees C1, C2) at an EV manufacturer (Company C), explained the hazard of the 24V battery in detail. The installed components in vehicles receive their needed power from the 24V battery, if this battery is empty, it will drain power from the 600V battery. Depending on the transportation duration from the manufacturer to the destination port it might happen that the 600V battery arrives empty. To prevent this from happening, a detailed instruction on how to switch off the 24V battery is printed onto the steering wheel's cover and shall be followed by the stevedores loading the vehicles on board. This described procedure follows the recommendations published in the literature (Chapter 3), that the battery shall be disconnected after the EV is loaded onto the vessel. As greatest fire hazard, the 24V, respective 12V, batteries were mentioned by one intro engineer and the naval architect (Interviewees C1, D1). One of the intro engineers (Interviewee C2) also explained that for a Li-Ion battery to enter into the state of a thermal runaway it needs a trigger event, it does not start by itself. For example, such an event might be a production failure or contaminations within the Li-Ion battery (Interviewee C2). The possibility of a production failure resulting in a thermal runaway is in accordance with published studies (Chapter 3). Furthermore, one of the intro engineers (Interviewee C2) explained that the Li-Ion batteries have several safety layers to prevent a fire from breaking out. One mentioned example by that interviewee was that if a battery's module catches fire it will burn off and isolate itself from the other modules, this prevents the fire from spreading further inside the battery. According to published literature (Chapter 3), this limits the exothermic reaction and the uncontrolled rise of temperature. It is a protection system which is similar to a fuse and burns off if the temperature rises and stops the charging/discharging process. Published studies (Chapter 3) show that this process starts at an internal temperature of 50°C to 70°C and will hinder the overcharging or over-discharging. The most likely

trigger of a thermal runaway is the overcharging of a Li-Ion battery, which was also addressed by one of the interviewed intro engineers (Interviewee C2):

“[A battery] won't just start to have a thermal runaway. [...] When it happens, it's most likely if you're charging a battery and you have an overcharge. That's I think that's the most common.” (Interviewee C2)

The two interviewed intro engineers (Interviewees C1, C2) at one EV manufacturer (Company C) explained that their EVs have five 600V batteries installed, which are containing thousands of cells. They further pointed out that, during a thermal runaway, each cell can produce 5 to 8 Liters of gases, which results in a total volume of $\sim 40\text{m}^3$. Moreover, during that interview it was emphasised that the greatest hazard for people is not the fire itself, because it takes time until the gases ignite, but the flammable and toxic gases produced during a thermal runaway. A detailed list of produced and released gases is presented in Chapter 3 (Table 7). The analysed interview conducted at one EV manufacturer (Company C) states that, to prevent the batteries from mechanical abuse, all batteries of large EVs are protected by strong metal beams. This follows the published recommendation set out in the literature (Chapter 3) that all batteries should be well protected to not take harm when involved in a crash.

Three interviewees (B1, C2, D1) mentioned the 12V/24V battery as main risk factor for draining the EV's battery. One interviewee at the terminal operator (Interviewee B1) explained that the routine is to leave the keys inside the vehicles while they are parked on the yard or on board the vessels. Additionally, it was highlighted during that interview that the seat protection cover might trigger the seat's sensors to assume a person is sitting inside the vehicle. According to the terminal administrator (Interviewee B1) these two factors can drain the battery. It was further mentioned that EVs with an empty battery need a booster to be started.

According to published literature (Chapter 3), a nearby fire is named as a possible heat source which can ignite an EV (thermal abuse). This was confirmed by the interview at the RoPax shipping line. In the interview with the naval architect (Interviewee D1), it was pointed out that there is usually enough time for preventing a nearby fire from igniting an EV, since it takes longer time to ignite an EV's battery compared to igniting an ICEV's fuel tank. Additionally, published literature (Chapter 3) states that an ambient temperature of 20-30°C is the optimal temperature for the Li-Ion battery to work. The two intro engineers (Interviewees C1, C2) pointed out that in a trial the required temperature to start a thermal abuse was evaluated to be

between 35-40°C for seven days in a row, 24 hours per day and that these high temperatures are usually not reached during the transport. Interviewees from the logistics operator and the terminal operator (Interviewees B1, E1) agree that the temperature in Sweden is too low to trigger a thermal abuse of a Li-Ion battery.

Cluster 3 (EV identification) contains two codes which are: (1) Difficult distinction between EVs and ICEVs and (2) Identification of EVs.

Published literature (Chapter 3) addressed that a common problem and potential risk source is that firefighters are missing a clear recognition sign on EVs. The interview with the intro engineer (Interviewee C2) from an EV manufacturer (Company C) pointed out that all EVs contain orange cables, this is a definite identification mark in case of an emergency. It was explained in the interview at that EV manufacturer (Company C) that all systems connected to the 600V battery are marked with a hazard voltage emblem. Additionally, the manufactured vehicles at this factory have stickers on the outside which indicate them as EVs.

In addition, results from the interview with the terminal administrator (Interviewee B1) revealed that all vehicles are treated the same and it is not distinguished between different types of vehicles. Due to the wide range of various propulsion systems (ICEV, EV and hybrid solutions), the question was raised when a distinction should be made. During the interviews with ships' officers (Interviewees A1, A2) it was mentioned that no information about the type of vehicle (ICEV, EV, or hybrid) is stated in the loading list. The only option to identify the types of vehicles is by entering the cargo hold and looking at them directly. This stands in contrast to recommendations stated in published literature (Chapter 3).

Cluster 4 (Experience with the transport of EVs): The fourth cluster contains all information related to the experience with the transport of EVs. It contains one code which is: (1) No EV accidents in road transportation. During the interview with the logistics operator (Company E), the finished vehicles logistics administrator (Interviewee E1) stated that they never experienced any accidents or fires involving EVs during the road transportation.

Cluster 5 (Risk from different types of vehicles) contains four codes which are: (1) ICEV vs. EV hazards, (2) Electrified parking brakes, (3) Refusal of damaged vehicles and (4) Risk from damaged or used cars.

Analysed interviews addressed a difference in the hazard of ICEVs vs. the hazard of EVs. For example, one intro engineer (Interviewee C2) from an EV manufacturer (Company C) highlighted that if a fire starts, it usually starts in the 12V/24V battery, independently of the type of vehicle. This statement confirms the results of the published studies (Chapter 3), which emphasised that EVs are not posing a greater danger compared to ICEVs. Furthermore, the terminal administrator (Interviewee B1) from the terminal operator emphasised that ICEVs are also hazardous and that the public has found a way to manage these risks.

One interviewee (E1) from a logistics operator highlighted the electrical parking brake as another issue. It was noticed that for one particular car model the electrical brake was not really activated. This was a problem during the transportation on the trucks. Furthermore, it was stated during that interview that modern cars are becoming more electrified, even the brake systems.

During the interview on board of one RoRo vessel, the cargo officer (Interviewee A1) mentioned that only undamaged vehicles are transported and vehicles with bigger damages are refused to load. Moreover, the interviewed terminal administrator (Interviewee B1) explained that minor damages like scratches are documented and this information is passed on to the next stakeholder in the transportation chain. According to one interviewee (D1), used cars are transported on a trailer, but EVs with a damaged battery are not allowed to be transported in such a way. The damaged battery must be transported according to the 'International Maritime Dangerous Goods Code', separately from the car. It was emphasised by the interviewed naval architect (Interviewee D1) that there is still a gap, and a procedure on how to transport damaged EVs is lacking.

Cluster 6 (Trust in other stakeholders involved in the transportation chain of EVs) contains five codes which are: (1) Trust in manufacturers to produce safe EVs, (2) Having to rely on customer information for DG, (3) Transfer of responsibility to other stakeholders, (4) Trust in carriers to safely store EVs on board and (5) Lack of information for emergency handling.

While the manufacturer has to rely on the battery producer to deliver safe batteries, the terminal administrator (Interviewee B1) highlighted that the terminal needs to rely on the manufacturer to deliver safe vehicles. One interviewee (F1) from an EV manufacturer (Company F) pointed out that the manufacturer's responsibility for the vehicles' safe transportation is transferred to the carrier at the factory yard. The analysed interview with the logistics company showed that the truck drivers are unsure how to inspect vehicles before loading them onto a trailer. These

interviewees (E1, E3) agreed that it is important to consider topics related to the safety. The published literature (Chapter 3) describes that risk management is often only conducted for the internal use within an organisation, but not shared with other stakeholders involved in the overarching process chain, in this case the transportation of EVs.

Cluster 7 (Damages caused by mechanical abuse): A mechanical abuse is an event in which the battery is mechanically damaged and affected in its physical integrity (Chapter 3). Such impacts on the battery can occur during the various loading operations along the transportation chain, e.g. on and off the ramp of the truck on the way from the manufacturer to the terminal, or on and off the ramp of the vessel for the sea transport. Interviews with a chief mate (Interviewee A2) and the foreman in the logistics company (Interviewee E3) confirmed that the ramp is a crucial point during the loading process:

“I think the big problem is when driving on board the ramp in the stern because it's like a speed bump.” (Interviewee A2)

“[...] but to prevent damages, so we have we lower the trailer before we load every time and then we can adjust the ramps to go over more smoothly. To avoid damaging it at all.” (Interviewee E3)

The battery on an electric car is located underneath the vehicle, as mentioned during the interview with the naval architect (Interviewee D1). The aforementioned chief mate (Interviewee A2) and the foreman (Interviewee E3) elaborated in the interviews that in order to prevent bumps during the loading process, it is tried to keep the ramp's angle as large as possible. On board of the RoRo shipping line's (Company A) vessels the angle is adjusted by re-distributing the ballast water. This procedure and care is fully in line with published recommendations (Chapter 3) which show that special attention must be paid in order to avoid any harm from happening to the battery during the loading and unloading operation.

Moreover, besides the hazard of a physical impact on the battery, a high acceleration might be harmful. Published literature (Chapter 3) highlights that strong G-forces can cause a mechanical abuse, e.g. when a ship is rolling in a heavy sea state. Due to the short sea legs in the RoRo shipping line's services, the loaded vehicles are not lashed. It was mentioned during the interviews with the ships' chief officers (Interviewees A2, A3) that if the weather, especially during

the wintertime, is too bad, then trips are cancelled and the vessels remain alongside. This prevents the vehicles from shifting and even trailers from moving and becoming a potential threat to the EVs.

4.3 Preventive Measures to Reduce the Risk of Ignition of Electric Vehicles

The assigned codes were sorted into the seven clusters, (1) Safety infrastructure, (2) Battery protection, (3) Fire countermeasures and firefighting dangers, (4) Training and education, (5) Shoreside implemented measures, (6) Guidelines and communication, and (7) Weather routing (Appendix IV). Here, the clusters are described with statements of the interviewed experts and compared with the suggestions found in the literature (Chapter 3).

Cluster 1 (Fire detectors) contains five codes which are: (1) Fire detectors, (2) Fire patrols, (3) Sprinkler system, (4) Emergency procedures and (5) Onboard monitoring system.

Published literature (Chapter 3) addressed that one of the greatest dangers on board a vessel is a fire and that being able to detect a developing fire in an early stage increases the chances for the crew on board to control and to potentially extinguish it. During the interviews with the experts along the transportation chain, questions about their fire detection systems, routines and fighting systems were asked. It was confirmed by the naval architect (Interviewee D1) that early detection is crucial for preventing a fire to spread and for being able to launch effective countermeasures.

“[...] early detection is everything and if we can find the problem before we have a fire, that's really good.” (Interviewee D1)

The analysed interview with the intro engineers (Interviewees C1, C2) from one EV manufacturer (Company C) shows that the factory is equipped with smoke detectors and additional fire alarms which can be triggered manually. It was further explained that the correct behaviour in case of a fire is part of the safety training for all employees. The terminal administrator (Interviewee B1) stated that the complete terminal yard is monitored with cameras 24 hours per day. This is relatively similar to the detection systems used by both shipping companies. According to the interviews, the RoRo shipping line and the RoPax shipping line have comparable technical detection systems on board. The interviews with officers from the RoRo shipping line (Interviewees A1, A2, A3) showed that the vessels are equipped with smoke- and heat detectors,

portable multi detectors for the crew and the car decks are monitored with a camera system. While the interview with the RoPax shipping line's naval architect (Interviewee D1) showed that their vessels are equipped with smoke- and heat detectors and one infrared camera connected to the fire alarm system. It was further mentioned in that interview that many cameras would be needed to monitor the entire car deck. According to the interview with the naval architect (Interviewee D1), a change in temperature is a very local phenomenon with a very low probability. Combined with the large number of cameras needed to monitor the entire car deck, it is a costly and less feasible solution. It was explained during the interview with the naval architect (Interviewee D1) that the infrared camera is very sensitive and detects temperature differences of 0.1°C, but it must have a direct visual contact. Before the infrared camera can detect the rise of a temperature, a malfunctioning battery entering a thermal runaway must first heat up the deck plate underneath the vehicle and the increase in temperature has to spread beyond the boundary of the vehicle in order for the camera to be able to detect it.

Further, it was explained during the interview with the naval architect (Interviewee D1) that a gas detection system exists, which registers the gas emissions produced by an EV's battery before it starts to burn. This mentioned gas detection system is also recommended by the published literature (Chapter 3).

Published literature (Chapter 3) emphasises that the classic fire patrol is an effective method to detect any abnormalities like smoke and fire on board. During the interviews on board of two different vessels from the RoRo shipping line, the authors received two different answers on the question if fire patrols were conducted. While on board of one vessel, one officer (Interviewee A1) did not mention that any fire patrols were conducted, the chief officer (Interviewee A3) on board of another vessel confirmed that after every watch the watchman is conducting a fire round throughout the whole ship. A different routine is implemented on board of the RoPax shipping line's vessels, where a fire round is conducted on an hourly base, as per the information provided by the naval architect (Interviewee D1). Moreover, the watchmen are trained on what to pay attention to with regards to the EVs. Regular fire rounds should be part of the daily routine, especially during the night hours. Confirmed by published studies (Chapter 3), the absence of, or inadequate fire patrols are a safety risk.

As highlighted in four interviews (Interviewees A1, A3, C1, D1), the main firefighting system at the EV manufacturer (Company C) as well as on board the ships (Companies A, D) is a fixed sprinkler system. The only difference between the system ashore and the one on board is the

used medium. While the vessels use seawater, the shore facility uses freshwater. Since the characteristics of a vessel's car deck compared to a road tunnel do not differ that much, both are longitudinal chambers and airtight sealed to the sides and the top, the literature within these field can be used as a reference. A published study (Chapter 3) described the advantage of a high pressure water mist system, which reduces the temperature inside a road tunnel in the event of a fire significantly. This was confirmed by one interviewee (D1), that the fixed sprinkler system on board is used for boundary cooling. It is important to consider the structural limitations of the fixed firefighting system and it must be well-maintained, which was stressed by the published literature (Chapter 3). Another subject which was discussed during the interviews was based on a published experiment which studied the different effects salt- and fresh water have on a Li-Ion battery and the risk of toxic gases to develop when saltwater is used to extinguish a battery fire (Chapter 3). However, as interviewees (C1, C2) from one EV manufacturer (Company C) countered, the highly flammable and toxic chlorine gas is only forming when the battery's cells come in direct contact with the salt water. Due to the battery's design it is nearly impossible for salt water to reach the cells:

“[...] but then the salt water must go into the battery and the battery is like all other components are IP classed. So you have to have an intrusion into the battery, and that's not so easy.” (Interviewee C2)

“Yes, you must go into the modules and then from the modules it must go into the cells also and that's not so easy. So you have to have the impact on the battery before you get salt water inside the battery.” (Interviewee C1)

Published literature (Chapter 3) points out that it is very difficult to extinguish a battery fire with water. According to a published study (Chapter 3), liquid nitrogen is, due to its characteristics, an excellent choice for extinguishing a battery fire. It is capable of reaching the inside of a Li-Ion battery cell and it can stop the burning process. Furthermore, it has a great cooling effect. However, this published study also points out that the great challenge with liquid nitrogen is the storage and transportation.

During the interviews, stakeholders along the transportation chain have been asked about their emergency procedures. The intro engineers (Interviewees C1, C2) from one EV manufacturer (Company C) described in detail the procedures for various events which might occur: It was explained that if a battery which is attached onto the vehicle chassis starts to emit smoke due to

a defect, the chassis is pulled out from the factory and onto the yard. If a battery is damaged before the assembly process, it is stored in a designated box outside on the yard, 15m away from the production building and monitored for 48 hours. When the time passed without any sign of activity from the battery, the quality department is investigating the battery and contacting the producer to discuss the shipping of the battery. Furthermore, it was pointed out during the same interview that the batteries are installed at the very last step in the production chain, close to a gate for quick response in case of an emergency. Moreover, it was referred to the safety manual, which is available online, which contains emergency procedures e.g. detailed information about escape routes and how to disconnect the electricity in a correct way.

Another stakeholder who described the procedures in case of an emergency was the naval architect (Interviewee D1) from the RoPax shipping line. The training for the crew conducting the fire patrols was explained in detail in that interview: Firstly, if a fire inside an EV is noticed, it is most probably an ordinary car fire and not caused by thermal runaway. Therefore, in such a case it is important to do a quick first response, e.g. if a fire is noticed in the cabin of a car, a fire extinguisher shall be used. But if smoke is noticed from underneath the EV, then it is with very high likelihood the battery that is entering a state of thermal runaway. If a fire can not be extinguished while it is still developing, boundary cooling shall be started. Either manually with fire hoses or by starting the sprinkler system. In summary, the ideal fire response was described as follows by the naval architect (Interviewee D1): if an EV's battery enters into the stage of a thermal runaway, boundary cooling of all vehicles in the vicinity should be established and the battery fire is continuing until it stops by itself when there is no energy left in the battery. With this procedure, it is guaranteed that the battery's energy is used up and a re-ignition is unlikely. A published study (Chapter 3) presents a similar suggestion. There, the question was raised if every EV fire must necessarily be extinguished or if it might not be better to let it burn out while the surroundings are cooled.

Two interviewees (E1, E3) from the logistics operator pointed out that they are very limited in their possibilities to extinguish a car fire on board a truck. The only equipment they have is one fire extinguisher. If an EV's battery catches fire there is nothing they can do themselves.

Cluster 2 (Battery Protection) contains three codes which are: (1) Battery management system, (2) Future battery technology and (3) Safety system within EV design.

The published literature (Chapter 3) describes the various safety layers within a Li-Ion battery in order to protect the battery from malfunctioning. These systems consist of physical installations and electrical programs. During the interview at one EV manufacturer (Company C), it was explained that a too low environmental temperature is not a danger for a Li-Ion battery, it may only start to derate. This statement stands in contrast to published literature (Chapter 3). One intro engineer (Interviewee C2) clarified that if the temperature inside the battery exceeds 50°C to 70°C, the meltdown process starts (Chapter 4.2). Furthermore, it was pointed out during that interview that Li-Ion batteries are only a transition technology, towards a more stable battery. The future batteries could e.g. be LFP batteries, Lithium-Iron-Phosphate batteries.

It was mentioned by one intro engineer (Interviewee C1) that this chemical combination is not less hazardous compared to Li-Ion, but that it takes more time for harmful gases to form:

“It's another chemistry in the batteries. It's as hazardous but it takes longer time. [...] For the gases to build up.” (Interviewee C1)

Safety systems are already considered within the design process, in terms of physical and electrical safety measures, as explained by two intro engineers (Interviewees C1, C2). That interview further showed that the software of the 600V system is part of a smart system. If any fault within the 600V system is detected, the vehicle will not start. This shall prevent the battery from taking damage. Furthermore, one of the several safety systems within the electrical system was explained in the interview with the intro engineers (Interviewees C1, C2). The working principle is that, if a connector loses its contact due to a damage or it gets loose while the power is switched on, then the system will shut down within 100 milliseconds. Another safety measure which was mentioned during the same interview is the way the cables are grounded. It was described as a floating installation where only the components are grounded to the chassis. During the operation, the distance between plus to ground and minus to ground is measured continuously, it was called an active isolation measure. Additionally, the wiring harness itself is another active protective system which will turn off the 600V system when it gets damaged, e.g. by a fire.

A physical protection, which was mentioned by the intro engineer (Interviewee C1) from one EV manufacturer (Company C), are the large crash beams around the battery. According to published literature (Chapter 3), the battery frame is designed in such a way that the cells inside are protected against external physical forces. There are three common designs which are the

cylindrical, the hard prismatic and the pouch one. As stated by published literature (Chapter 3), salt water is reacting with the Li-Ion cells and produces harmful chlorine gas, if it gets into direct contact with the cells. However, the intro engineers (Interviewees C1, C2) from one EV manufacturer (Company C) countered that, when the battery's frame is intact, it is impossible for water to reach the core of the battery. The naval architect from the RoPax shipping line (Interviewee D1) also described the risk from using salt water in the sprinklers as being negligible:

“But the battery is protected underneath the car and the battery itself. In the bigger perspective, in the sense of a car deck fire or even car fire or multi car fire. Then the advantages of the saltwater system compared to any other alternative, what that would be, is so big so it is a negligible extra risk.” (Interviewee D1)

Besides the protective measures for the battery, the vehicles must fulfil other requirements, as per the interview data. During the interview with one EV manufacturer (Company F), the design process of the vehicles and the various considerations which need to be taken into account for ensuring a safe transportation from the manufacturer to the customer were explained by the finished vehicle distributor (Interviewee F1). The EVs' dimensions are limited by the trucks which transport the vehicles from the manufacturer to the terminal. Furthermore, it was stressed in the interview with one of the EV manufacturers (Company F), that the vehicles need to have dampers to withstand bumps during the transport and connection points to attach lashings. The dampers and the lashings prevent the cargo from shifting during the transport. On board the vessels, chains or tensioners are usually used to lash vehicles, as per published literature (Chapter 3). During the interviews with the vessels' officers (Interviewees A1, A2, A3) from the RoRo shipping line, it became clear that vehicles are not lashed during short sea legs. One reason is that it is very time intensive, and it bears the risk of damaging the cargo, which could be costly for the company.

Cluster 3 (Fire countermeasures and firefighting dangers) contains eight codes which are: (1) Car deck ventilation, (2) Dangerous to send in crew for firefighting, (3) Difficult to reach car in case of fire, (4) Fear of onboard fire and loss of control, (5) Firefighting equipment, (6) Own fire brigade in factory, (7) Prevent fire spreading and (8) Proximity to shore and firefighters.

Analysed interviews with interviewees of the two participating shipping companies (Companies A, D) reveal their different attitudes towards the risks associated with transporting EVs.

While the chief officer of one RoRo vessel (Interviewee A3) expressed mostly the concerns that arise when transporting EVs, the naval architect (Interviewee D1) from the RoPax shipping line focused instead on practical procedures and on how potential hazards are handled. The RoPax shipping line's naval architect (Interviewee D1) explained the presence of two different ventilation modes on the loading decks' ventilation system. In case of a detected gas emission without the presence of a fire, the ventilation fans run in a way that the potentially explosive air is evacuated from the car deck. The second function was not specifically explained, just that in a case of an EV fire the 'thermal runaway button' is to be pushed. The chief mate on one of the RoRo shipping line's vessels (Interviewee A3) was not as comfortable with the transport of EVs as the naval architect (Interviewee D1) of the RoPax shipping line was. The chief mate's (Interviewee A3) concerns about the transportation of EVs were actually concerns about the safety of the crew in case of a fire, independently of its origin. When the vessel is at sea and a fire breaks out, there is no professional fire brigade assisting, the crew is on their own. The same interviewee pointed out that it is hard to decide if the crew should be sent to the scene or stay away. More specifically, the accessibility of the scene was highlighted. When the ship is fully loaded, the space between the vehicles is very limited, therefore the chief mate (Interviewee A3) was not sure if the scene could even be reached by the crew. Additionally, the fear of losing control was pointed out in the interview. Concerns were expressed if it was even possible to control a fire and the person referred to fires on board of car carriers which ended catastrophically. It was pointed out by the chief mate (Interviewee A3) that the Swedish and Danish fire brigades are well-trained and can assist in case of a fire, but the concern is what they can do if not one but multiple EVs are on fire.

However, the RoRo- and RoPax vessels are well-equipped with different tools for firefighting, as per the interviews. Nevertheless, as stated in the published literature (Chapter 3), the ordinary firefighting suits are no sufficient protection against the fumes and gases which develop during a Li-Ion fire. One interviewee (A1) on board of the RoRo shipping line's vessel was aware of this fact and reported that they received new clothes which are better suited for the task of fighting EV fires. Furthermore, the vessels received fire blankets and special rods which can be connected to the ship's fire hoses and be put under the car for cooling. The vessels of the RoPax shipping line are equipped with similar tools. One tool which the naval architect (Interviewee D1) highlighted, is a portable sprinkler device, in addition to the fixed sprinkler system, fire hoses and fire blankets. It was mentioned in the same interview that the fire blankets are not especially good for extinguishing fires in EVs, but rather for ordinary car fires.

As per the interview with one EV manufacturer (Company F), they are independent from the public fire brigade, because they have their own internal fire brigade in order to be able to react quickly in case a fire breaks out.

In order to prevent a fire from spreading, all chief mates (Interviewees A2, A3), mentioned that the fixed sprinkler system will be used. During the interview at one EV manufacturer (Company C) it was mentioned that the last step in the production is the one with the greatest potential for a fire, as explained by one intro engineer (Interviewee C2). Therefore, the commissioning takes place inside a fire cell which can be sealed off in an emergency.

As per published literature (Chapter 3), EVs should be parked or stored in specially marked areas inside the terminal and on board the vessels. However, as five out of twelve interviewees (A1, A3, B2, D1, E1) pointed out, this is, due to the increased number of EVs, not feasible.

Cluster 4 (Training and Education) consists of the seven codes (1) Training of production staff, (2) Loading test run for new models, (3) Training for stevedores, (4) Training of transport staff, (5) Crew training for firefighting, (6) Fire brigade training, and (7) Fire brigade visits. The high frequency of codes related to training was driven by asking the respondents how human error was minimized in their step of the transportation chain. This question was asked since human error had been identified in the literature as a frequent source of accidents in loading and other maritime operations. According to a published study (Chapter 3), the reason why human error occurs can be e.g. lack of knowledge or insufficient decision making. The answers to this question focused on various aspects of training, in order to increase the knowledge. However, published literature (Chapter 3) showed that another likely source of human error (during the loading/discharging operation) is fatigue.

The interviews show that in production, and during the preparation of EVs for transport, staff needs special training when physically working with the battery or the electric system (Interviewees C1, C2, F1). Depending on what type of work they are doing on the vehicles, different trainings are required.

The need for training was supported by the finished vehicle distributor (Interviewee F1), who stated the following:

“[...] we have trainings and we have specific technicians that can do that.”
(Interviewee F1)

Interviews with the EV manufacturers (Companies C, F) show that the transport staff are given instructions on how to handle the vehicles, but it has not been mentioned if actual trainings for the staff are conducted. This lies more in the responsibility of the transport provider's management.

According to interviews, both the terminal administrator and the finished vehicle logistics administrator (Interviewees B1, E1) mentioned that it is important to conduct test runs when new vehicle models are launched. These test runs are done on the trucks, i.e. to ensure that the vehicles are not damaged by the lashing equipment used or the trucks themselves. On the vessels, the critical point is the ramp, so here the test runs focus on driving the new vehicle types on and off the vessels in order to find out if there are any areas where the vehicles scratch or bump on the vessels' ramps. The terminal administrator (Interviewee B1) also stated in the interview that the stevedores who actually drive the vehicles onto the vessel also receive training. For the training, they receive instructions from the manufacturer's side on how to handle their vehicles, as this can differ between various manufacturers. The trainings are conducted by the terminal company itself and involves e.g. how to handle the vehicle, or how to park the vehicles.

Onboard crew training has been highlighted in published literature (Chapter 3) as another means for fire prevention. This was confirmed by both staff of the RoRo shipping line as well as staff of the RoPax shipping line during the interviews. According to the interview with one chief mate (Interviewee A3), the crew training however focuses mostly on firefighting procedures:

“I don't have the best solution, but we do regular training. We try to involve the equipment when we have fire drills, we go through the equipment, try, you know, try the fire blankets, try this construction to put under the cars with water and see so everything is working.” (Interviewee A3)

The interviews with one EV manufacturer (Company C) and a terminal operator also revealed that there is cooperation between the stakeholders in the transportation chain and the public fire brigades. The intro engineer (Interviewee C2) of one EV manufacturer (Company C) mentioned that they organize trainings for fire brigades in order to teach them how to handle the different types of vehicles. In the terminal, the fire brigades visit the facilities in order to get familiarised with the area and be prepared in case an incident occurs there, as stated by the terminal administrator (Interviewee B1).

Cluster 5 (Shoreside Implemented Measures) focuses on measures in the terminal and during the road transportation that aim to prevent damages to the EVs or even fires during the transport. It contains the four codes (1) EV fire prevention, (2) Preventive measures during transport, (3) Procedures in terminal to prevent traffic jams in car handling and (4) Speed limit inside the terminal. The interviews show that during the road transportation or at the manufacturer, no additional measures are in place for the protection of EVs. There is one approach applied to all types of vehicles, which includes e.g. hail nets outside the factory for protection of the newly manufactured vehicles, as per the finished vehicle distributor (Interviewee F1). When asked about additional preventive measures for EV fire prevention in the terminal, the terminal administrator (Interviewee B1) responded:

“We have no measures of extra fire protection for EVs.” (Interviewee B1)

Nevertheless, later in the interview with the terminal administrator (Interviewee B1), and also in the interview with the stevedore (Interviewee B2), additional information was revealed which shows that some of these additional preventive measures are actually in place. One example for this is to keep the terminal yard clean and to avoid having a buildup of debris. Additionally, according to the analysed interviews, the transportation of EVs is made safer by having dedicated areas for vehicles in the terminal and by having a speed limit inside the terminal yard and during the loading. This can reduce the risk of accidents, especially since the handling of vehicles is separated from the other terminal operations by having e.g. own lanes only for vehicles. Furthermore, when the vehicles are transported from the yard onto the vessel, only one lane is handled at a given time in order to avoid congestion. In two interviews (Interviewees A2, B1) it was explained that the speed limit in the terminal for the vehicles is 30 km/h and close to the vessel this is further reduced to 15 km/h. This confirms that the recommendations set out in the published literature (Chapter 3) can be found in practice. The published literature (Chapter 3) further highlights that special attention should be placed on the prevention of collisions or impacts involving EVs in order not to potentially damage the battery during the loading and unloading process. This is to reduce the probability of thermal runaway when the battery is being mechanically damaged. Hence, the measures found in the terminal throughout the interviews seem appropriate for the prevention of damages and a potential thermal runaway in the vehicles' batteries.

Cluster 6 (Guidelines and Communication) includes the three codes (1) Communication and best-practice finding, (2) European guidelines for EV handling, (3) Increased demand for information flow.

The interviews and the published literature (Chapter 3) highlight the importance of communication and information sharing for the safe transport of EVs. In the published literature (Chapter 3), the need for increased communication between stakeholders involved in the transportation of dangerous goods has been mentioned. In the interviews it was revealed that, even though EVs are no dangerous goods as per the ‘International Maritime Dangerous Goods Code’, the batteries in the vehicles alone are dangerous goods and hence the EVs should be handled with similar care. It was mentioned by one chief mate (Interviewee A2) how difficult it is to know what types of vehicles are on board, based on the loading list:

“You can't see it. The only way to see it is if you go down into the cargo hold and look at it.” (Interviewee A2)

The interviews show that transparent information sharing and communication between the different stakeholders in the transportation chain could be a way to increase safety during the transportation of EVs. This has apparently already started. As one finished vehicle distributor (Interviewee F1) from an EV manufacturer (Company F) highlighted:

“[The carriers] have more and more asked us for the information on the different type of the vehicle so that they can do [the stowage planning] in a better way.” (Interviewee F1)

In the interview with the finished vehicle distributor (Interviewee F1), it was further mentioned that, when having information on the vehicle types, the carriers can adjust their stowage plans accordingly. Furthermore, during that interview, the ECG Guidelines were mentioned. These guidelines for the transportation of vehicles are distributed by the ‘Association of European Vehicle Logistics’. However, it has not become clear throughout the other interviews if these guidelines are mandatory and followed by all stakeholders in the transportation chain. Another measure in this cluster is the alignment and exchange between the internal departments on the manufacturer’s side, e.g. between the logistics department and the research and development department at one EV manufacturer (Company F). Through this, the requirements for safe transportation could already be considered during the development of the vehicles.

The final cluster, **cluster 7** (Weather routing) stands on its own as the only code assigned to this cluster is the code (1) Weather routing. In the published literature (Chapter 3), the danger of external forces on the Li-Ion battery has been explored. The literature (Chapter 3) revealed that this external force could even be a high G-force on the battery due to heavy seas. Additionally, heavy sea state was also mentioned as a potential source of fire on board in general in the published literature (Chapter 3). Interviews with chief mates (Interviewees A2, A3) pointed out that it is crucial to avoid bad weather, in order to avoid heavy sea states. This way, the carrier also avoids having to pay for potential damages to the vehicles.

The interviews showed that one option how to avoid heavy weather is to stay alongside in port and to postpone the sailing, which was stressed by both chief mates (Interviewees A2, A3):

“If it's so bad weather that we have to go out and the cars start flying, then we should remain in port.” (Interviewee A2)

“I don't know if I can give you a correct answer on that one, but weather forecast, if it's bad weather then we stay alongside.” (Interviewee A3)

It has further been mentioned by one interviewee (A3), that sometimes a few hours of delay can lead to a much calmer sea state. Imperative for that is a good weather forecast. A second option for the avoidance of heavy sea state is to change the route, which was stated by one chief mate (Interviewee A3):

“You can also change route, go more south, go more north.” (Interviewee A3)

Hence, the avoidance of bad weather and thereby steering clear of heavy sea states, by either staying alongside or by changing the route is another potential measure to reduce the risk of EVs igniting during the transport on board the vessels, since the G-forces on the EVs' batteries will be reduced.

4.4 Overview of Key Results concerning RQ2 and RQ3

In order to summarize and visualize the key results related to RQ2 and RQ3, a matrix (Table 10) was developed based on the content of the previous two Chapters 4.2 and 4.3. This includes the major risk factors which were identified along the transportation chain from the literature

review (Chapter 3) as well as from the analysed interviews. Additionally, it shows the key preventive measures which were identified along the transportation chain from the literature review (Chapter 3) as well as from the analysed interviews.

Table 10: Overview of identified risk factors and preventive measures

	← Multimodal Transportation Chain of EVs →				
	<i>Manufacturer</i>	Road Transport	Terminal and Storage	Loading	Ship
Risk factors (RQ2)	Defect batteries	Ramp angle	(Debris in yard)	Ramp angle	Heavy sea state Lack of fire patrols
	12V/24V Battery (for all types of vehicles) Human error Lack of information flow				
Preventive measures (RQ3)	Battery protection	Trials with new car models Adjusting ramp angle	Separation of vehicle handling	Trials with new car models Adjusting ramp angle	Weather routing Safety infrastructure Timely fire response
	Communication Training and education SOC <50%				

5 Discussion

The discussion of the results follows the three research questions in chronological order. As described in the methodology section (Chapter 2.1), the research followed the abductive approach as outlined by Spens & Kovács (2006).

Discussing the results concerning **RQ1**, it should be foremost noted that the handling of EVs is not materially different from the handling of other vehicle types (e.g. ICEVs), which was stated in all eight interviews. Despite the main risk associated with the EV transportation highlighted in the literature review (Chapter 3), i.e. a thermal runaway (Baird et al., 2020; Bisschop et al., 2019; Held et al., 2022; Kong et al., 2018; Larsson, 2017), the interview results (Chapter 4) show that there is no overall difference in the transportation chain. Both EVs and ICEVs are handled alongside. As presented in the literature review (Chapter 3), thermal-, mechanical- or electrical events can damage the Li-Ion battery and trigger a thermal runaway (Baird et al., 2020; Bisschop et al., 2019; Feng et al., 2018; Sturk & Hoffmann, 2013; P. Sun et al., 2020; Taylor et al., 2012; Zhang et al., 2022). The interview results revealed that only minor adjustments are undertaken to counter these risks, e.g. the adjustment of the ramps on trucks and vessels in order to reduce the risk of a mechanical abuse. However, thermal abuse was not considered by the interviewed companies, e.g. vehicles are stowed close to heat sources on board (e.g. heated fuel oil tanks), in contrast to recommendations set out in the literature (R. Yin et al., 2023). This is also due to the fact that the carriers often do not know what type of vehicles they are transporting, since they do not receive this type of information, as per the interview results. Regarding the risk of an electrical abuse, the interview results show that there are many safety mechanisms in place to prevent such. To conclude, the interviewees predominantly viewed the risk level of EVs compared to that of ICEVs as similar. These views are in line with the findings of Bisschop et al. (2020) and Hassan et al. (2023), who emphasised that EVs are not causing a greater danger than ICEVs.

For **RQ2** and **RQ3**, one matrix (Table 10) was developed based on the literature review (Chapter 3) and the results from the interviews (Chapter 4), in order to visualize the most important aspects for each RQ and step in the transportation chain. Individual risk factors for each step in the transportation chain were identified, in addition to overarching risk factors affecting the entire transportation chain. The discussion hereby focuses on the latter.

Regarding **RQ2**, one of the main overarching risk factors which was pointed out in the interviews is the 12V/24V onboard battery. This is shared by both EVs and ICEVs and was mentioned by three interviewees. During the interview with one EV manufacturer, the 12V/24V battery was identified as the most likely fire hazard. Another risk factor is human error, both during the loading operations (Kaptan, 2022) or as potential source of fire on board (Baalispang et al., 2018). In seven of the interviews, it was emphasised that the people who are working along the transportation chain of EVs are specially trained. However, human error in handling cannot be prevented by training alone, e.g. processes on how to notice and prevent fatigue are similarly relevant (Kaptan, 2022). Lack of information is the third risk factor which affects the entire transportation chain. In the interviews with the ship officers it was mentioned that the vessels often neither receive any information about the propulsion systems of the vehicles which they are transporting (EV, ICEV, hybrid-solution) nor about the SOC level of the EVs' batteries. This is in contrast to the recommendation by Flodén & Woxenius (2021) who identify good communication between all stakeholders as crucial for a safe transportation of dangerous goods. However, since the amount of EVs is increasing, which was pointed out during five interviews, the identification of EVs could be only a temporary issue during the transition period from mostly ICEVs to mostly EVs.

With regards to **RQ3**, the overarching preventive measures to reduce the risk of ignition of EVs are good communication, training and education, as well as a SOC level of maximum 50%. The first two hereby mirror the risk factors as discussed in RQ2 (Lack of information flow vs. Communication, and Human error vs. Training and education). Regarding the SOC, the published literature recommends to transport EVs with the SOC to be as low as possible (R. Yin et al., 2023), since a higher SOC causes a greater danger in case of an incident (J. Sun et al., 2016). In contrast to this, the results point out that the SOC also must be as high as necessary for a stable transportation flow and to prevent disruptions due to empty batteries, which was emphasised by four interviewees. Even though this preventive measure is only relevant during the sea leg, due to the focus of this work, the weather routing will be highlighted and discussed here as well. Although weather conditions have been identified as an operational risk factor in the frame of reference (Mokhtari et al., 2012), no preventive measure around this has been found in the literature (Chapter 3). As a result of the interviews however, weather routing has been identified as an effective countermeasure to this risk by both chief mates which were interviewed for this study. As per the results, the sailing route can be adjusted, or the departure can be delayed in order to avoid critical sea state conditions. This is especially relevant, since the vehicles are not

lashed on short sea legs, as per the companies interviewed in this study. This stands in contrast to the recommendations set out in the published literature, to lash vehicles in order to prevent moving and shifting of cargo (DNV GL, 2016).

6 Conclusion

In order to find answers to the three RQs set out for this thesis, a literature review combined with a case study was conducted. The case study focused on the Gothenburg region and included eight (8) interviews with six (6) companies and a total of twelve (12) interviewees.

For RQ1, *'How are electric vehicles handled along the various steps of the export transportation chain (manufacturer, road transport, terminal, ship)?'*, it was discovered in the interviews that the handling of EVs is not materially different from the handling of ICEVs. The manufacturer marks the first step in the export transportation chain. The finished vehicles are picked up at the factory by the logistics operator. They are then transported via truck to the export terminal. There, the vehicles are stored for less than 24h, before they are loaded onto the ocean-going vessel (RoRo or RoPax). On board, no lashings are attached to the vehicles due to the short sailing distances and since attaching lashings would be time- and labour-intensive.

For RQ2, *'Which risk factors exist along the steps of the transportation chain, which could cause the ignition of electric vehicles?'*, the following risk factors could be identified: As per the literature review (National Transportation Safety Board, 2021) and the results of the interviews, the 12V/24V battery has been identified as potential source of ignition in both EVs and ICEVs. Other overarching risk factors across the entire transportation chain are human error (Balisampang et al., 2018; Kaptan, 2022) and lack of information flow (Flodén & Woxenius, 2021). For EVs, the thermal runaway in the battery is a main risk source for ignition of the vehicles (Baird et al., 2020; Bisschop et al., 2019; Held et al., 2022; Kong et al., 2018; Larsson, 2017). This can be triggered by electrical-, thermal- or mechanical events (Baird et al., 2020; Bisschop et al., 2019; Feng et al., 2018; Sturk & Hoffmann, 2013; P. Sun et al., 2020; Taylor et al., 2012; Zhang et al., 2022). The risk factors that were identified at the individual steps in the transportation chain focused mostly on mechanical events, since electrical events were viewed as the responsibility of the battery manufacturer and thermal events were viewed as negligible risk by the interviewees. At the manufacturer, defect batteries (electrical event), and during the road transport the ramp angle (mechanical event) were identified as risk factors. In the terminal, as per the interview results, debris in the yard has been mentioned as minor risk factor. For the loading onto the ship, the ramp angle (mechanical event) has been identified, while on the sea leg heavy sea state (mechanical event) are risk factors for the ignition of EVs during the transport. Moreover, a lack of fire patrols prevents the crew from detecting a developing fire at an early stage and hinders timely countermeasures.

Regarding RQ3, *'What preventive measures could be implemented during the various steps of the transportation chain to reduce the risk of ignition of electric vehicles?'*, overarching measures to prevent the ignition of EVs during transport have been discovered to be good communication between stakeholders in the transportation chain, training and education for everyone involved in the handling of EVs, and a SOC in the transported vehicles' batteries of <50%. Individual preventive measures which are recommended for each step of the transportation chain are as follows: Battery protection (physical and electrical measures) at the manufacturer, trials with new car models for the ramp angle and transport equipment for the road transport, individual storage and separation of vehicle handling from other operations in the terminal, trials with new car models for the ramp angle at the RoRo- and RoPax vessel and adjustment of the ramp angle throughout the loading process, weather routing to avoid heavy sea state on the sea leg, in addition to safety infrastructure on board, e.g. sprinkler systems, fire detection systems, infrared cameras, and timely fire response, with a focus on early detection of potential fires.

6.1 Managerial Implications

In order to counter the main risk factors for ignition of EVs during the transport; the 12V/24V battery, human error, and lack of communication flow, several preventive measures should be in place. Good communication and the exchange of information regarding potential risks and preventative measures are required along the transportation chain. Information on which actions should be taken in case of an incident should be exchanged between the stakeholders. Training and education can alter the perceived risks of transporting EVs by the individuals who are involved in the transportation and prepare them for potential incidents. The SOC of the transported vehicles is suggested to be at a level of 50%, so that the vehicles have enough charge for driving on and off the vessels, but reducing the potential fire energy in the battery.

6.2 Further Research Suggestions

For future work, similar case studies could be conducted in other geographical regions to compare and triangulate the findings. Furthermore, deep-sea shipping (in contrast to coastal RoRo- and RoPax shipping) could be included for a different perspective on the transportation chain. Moreover, one EV manufacturer mentioned the development of new battery types, such as LFP batteries, which would potentially require a different handling approach than Li-Ion batteries.

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Appendices

Appendix I – Assignment of interview questions to the steps in the transportation chain

Interview Question	Manufacturer	Logistic	Storage	Loading	Ship	RQ
How are different EVs handled from an operational perspective at your step of the transportation chain?						RQ 1
Are EVs handled at dedicated areas?						RQ 1
How are EVs lashed on board/on trucks to prevent movements?						RQ 1
How is the potential hazard of a thermal abuse of the Li-Ion batteries during the transport managed?						RQ 2
How is the potential hazard of an electrical/mechanical abuse of the Li-Ion batteries during the transport managed?						RQ 2
How do you reduce human errors in the handling of EVs?						RQ 2
Do you have specific firefighting systems in place where EVs are being handled?						RQ 3
How does the procedure for fire patrols/safety rounds look like?						RQ 3
How are bumps prevented during the [loading, storing, driving] operation?						RQ 3
What preventive measures are in place to reduce the risk of an incident which can result in a fire involving EVs?						RQ 3
Are you aware of the different reactions of a Li-Ion battery in contact with fresh- and salt water?						RQ 3

Appendix II – Research Question 1: Clusters and Codes

Cluster 1 <i>[No distinction between EVs and ICEVs]</i>	Cluster 2 <i>[Loading and Storage on board ships]</i>	Cluster 3 <i>[Terminal Operation]</i>	Cluster 4 <i>[Road Transportation]</i>
<p>No difference in handling EVs and ICEVs</p> <p>Increasing amount of EVs</p> <p>Uptake in EV numbers appreciated by stevedores</p>	<p>Loading operation</p> <p>Lashing of EVs</p> <p>Onboard storage</p> <p>Damage reporting procedure</p> <p>Lashing of trailers</p> <p>Onboard loading requirements</p>	<p>DG cargo separation in terminal</p> <p>Car handling separated from other terminal operations</p> <p>No dedicated area for EVs in production</p> <p>Short storage duration in Terminal</p> <p>Charging of EVs</p> <p>Distance between parked cars in Terminal</p>	<p>Difference in loading EVs on trucks</p> <p>Higher weight of EVs for road transportation</p> <p>Inspection before loading</p> <p>Export procedure</p> <p>Restrictions on who can handle vehicles</p>

Appendix III – Research Question 2: Clusters and Codes

Cluster 1 <i>[State of Charge during transport]</i>	Cluster 2 <i>[Battery Fire Hazard]</i>	Cluster 3 <i>[EV identification]</i>	Cluster 4 <i>[Experience with the transport of EVs]</i>	Cluster 5 <i>[Risks from different types of vehicles]</i>	Cluster 6 <i>[Trust in other stakeholders involved in the transportation chain of EVs]</i>	Cluster 7 <i>[Mechanical damage]</i>
<p>State of charge</p> <p>Onboard charging</p> <p>Operational issues from empty batteries</p>	<p>Battery Fire Danger</p> <p>Thermal abuse requirements</p> <p>12V/24V Battery hazard</p> <p>Thermal abuse unlikely in Sweden</p>	<p>Difficult distinction between EVs and ICEVs</p> <p>Identification of EVs</p>	<p>No EV accidents in road transportation</p>	<p>ICEV vs EV hazards</p> <p>Electrified parking brakes</p> <p>Refusal of damaged vehicles</p> <p>Risk from damaged or used cars</p>	<p>Trust in manufacturers to produce safe EVs</p> <p>Having to rely on customer information for DG</p> <p>Transfer of responsibility to other stakeholders</p> <p>Trust in carriers to safely store EVs on board</p> <p>Lack of information for emergency handling</p>	<p>Risk for mechanical abuse during loading operation</p> <p>Avoiding high G-forces by staying in port</p> <p>Avoiding mechanical damage by securing vehicles</p>

Appendix IV – Research Question 3: Clusters and Codes

Cluster 1 <i>[Safety Infrastructure]</i>	Cluster 2 <i>[Battery Protection]</i>	Cluster 3 <i>[Fire counter-measures and firefighting dangers]</i>	Cluster 4 <i>[Training and Education]</i>	Cluster 5 <i>[Shoreside Implemented Measures]</i>	Cluster 6 <i>[Guidelines and Communication]</i>	Cluster 7 <i>[Weather routing]</i>
<p>Fire detectors</p> <p>Fire patrols</p> <p>Sprinkler system</p> <p>Emergency procedures</p> <p>Onboard monitoring system</p>	<p>Safety system within EV design</p> <p>Future battery technology</p> <p>Battery Management System</p>	<p>Firefighting equipment</p> <p>Prevent fire spreading</p> <p>Dangerous to send in crew for firefighting</p> <p>Difficult to reach car in case of fire</p> <p>Proximity to shore and firefighters</p> <p>Car deck ventilation</p> <p>Fear of onboard fire and loss of control</p> <p>Own fire brigade in factory</p>	<p>Training of production staff</p> <p>Loading test run for new models</p> <p>Training for stevedores</p> <p>Training of transport staff</p> <p>Crew training for firefighting</p> <p>Fire brigade training</p> <p>Fire brigade visits</p>	<p>EV Fire prevention</p> <p>Preventive measures during transport</p> <p>Speed limit in Terminal</p> <p>Procedures in Terminal to prevent traffic jams in car handling</p>	<p>European guidelines for EV handling</p> <p>Communication and best-practice finding</p> <p>Increased demand for information flow</p>	<p>Weather routing</p>

