Thermal Analysis of Plug-in Hybrid Vehicle Batteries in Car Carrier Cargo Holds: Implications for Mitigating Fire Risk

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Concerns have arisen over the potential for fires in electric cars (EVs) during maritime transport, particularly following recent incidents involving car carrier fires. The aim of this study is to provide a clearer picture of the environmental conditions that affect electric vehicles during transport at sea and to provide insight on how to improve maritime practices related to fire risks from battery thermal runaway. This study examines the thermal behavior of Plug-in Hybrid electric vehicle (PHEV) batteries during a one-month voyage on a car carrier. Temperature data from 95 PHEVs distributed across two decks (one near the vessel's fuel tanks and one nearer to the superstructure) were analyzed to investigate potential correlations among the temperatures of the sea, outside air, ambient hold, and fuel tank surface. The research shows that PHEV battery temperatures correlate with sea, air, ambient hold, and fuel tank surface temperatures to various degrees, with notable spatial variability across the vessel. Sea temperature effects are most prominent near the starboard side, while passive ventilation on the port side creates a localized cooling microclimate with negative correlations. On upper decks, outside air and ambient hold temperatures show strong correlations, especially where direct sunlight exposure and limited airflow create warmer zones, though anomalies under ventilation hatches show the existence of microclimates within. Proximity to heated fuel tanks on lower decks increases PHEV battery temperatures, confirming their impact, but there is a need for more detailed monitoring and localized analysis. The correlation analysis indicates that PHEV battery temperatures are strongly influenced by environmental factors. Spatial variability across decks shows that localized conditions, such as proximity to heat sources and passive ventilation, play a big role in potential battery heat buildup. Current stowage practices are inadequate for PHEVs as they lack identification standards, temperature monitoring records, and data collection. The author calls for revised protocols, including ventilation-aware placement, vertical separation of PHEVs, and sharing temperature data among vehicle carriers for a database buildup.

KEY WORDS
~ Car carrier
~ Electric vehicles
~ Thermal runaway
~ BEV battery temperature
~ Vehicle transport
~ Reducing fire risk

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1. INTRODUCTION

With the increasing popularity of electric and hybrid vehicles, the worldwide maritime industry is encountering unprecedented challenges (Łukasz & al., 2023). These vehicles represent significant progress in reducing greenhouse gas emissions, but transporting them via roll-on/roll-off (ro-ro) ships introduces additional safety hazards, particularly concerning the thermal behavior of lithium-ion batteries (Tukes, 2024). Recent conflagrations on car carriers, such as the *Felicity Ace* in 2022 and the *Fremantle Highway* in 2023, have underscored the necessity of promptly addressing these hazards (MSC 109, 2024). The incidents, attributed to electric cars (EVs) or plug-in hybrid electric vehicles (PHEVs), resulted in significant losses and highlighted the inadequacies of existing fire safety measures, as well as the distinct characteristics of battery-powered vehicles compared to conventional vehicles (Węglarz *et al*., 2024).

Ro-ro vessels are particularly susceptible to flames due to their expansive car decks, high vehicle capacity, and limited firefighting resources (Węgrzyński, 2021; Sun *et al*., 2020). These vessels have predominantly transported conventional internal combustion engine (ICE) automobiles for an extended period. The emergence of electric vehicles (EVs) and plug-in hybrid vehicles (PHEVs) has complicated matters (CNBOP, 2023). Lithium-ion batteries that power these vehicles may experience thermal runaway, an exothermic reaction that is self-sustaining and can result in fires, explosions, and the emission of toxic gases. (Kleiman *et a*l., 2021) Battery fires are significantly more challenging to extinguish than those involving internal combustion engine vehicles, as they generate their own oxygen and require substantial water to cool the ignited cells (CNBOP, 2023). Severing the air supply or employing foam-based systems are two prevalent methods for extinguishing fires; however, they are ineffective against battery fires (Yuan *et al*., 2021). Ro-ro vessels present significant challenges due to their confined conditions and limited free space, which can facilitate the rapid spread of fires and complicate firefighting efforts (KG PSP, 2023). The challenge of fire protection on ro-ro vessels significantly differs from those in other environments, such as underground garages or urban areas (Derski, 2023).

The likelihood of battery fires is elevated on ro-ro ships due to confined spaces, a significant volume of vehicles, and insufficient access to firefighting apparatus (Boehmer *et al*., 2021). The distinct risks associated with electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) differ from those of internal combustion engine (ICE) vehicles, necessitating a re-evaluation of safety protocols.

This study aims to address a significant gap by examining a unique dataset collected from a car carrier that transported PHEVs over the course of a month. The dataset documents the temperatures of the batteries, which were obtained with a handheld FLIR E4 thermal camera, the air within the cargo hold, and the external air at 12-hour intervals. This study examines the correlations among these variables to identify patterns and risk factors that may increase the likelihood of fires.

As the demand for PHEVs rises, carriers need to think about changing or adjusting how they do business to make sure these vehicles are transported safely. The study provides empirical examples of PHEV battery behavior during transit and proposes strategies to mitigate fire risks on car carriers, including enhanced ventilation and revised stowage configurations.

This study represents a significant advancement in addressing the fire hazards associated with transporting PHEVs on car carriers.

1.1. Literature Analysis

Historical research on vehicle fires aboard ro-ro ships suggests that used automobiles are more prone to catch fire. Yan Cui *et al*. have done live fire tests on two PHEVs to learn more about how they work and what they are like. (Yan Cui *et al*., 2022). Their results provide a reason to undertake more tests to develop new flame-holding materials for PHEVs. A study from Korea indicated that a lot of cargo fires on ro-ro ships between 2018 and 2022 were caused by secondhand cars, which commonly had poor wiring or old batteries (Kima & Jeon, 2023). There were a lot of accidents that started at port premises where fires were breaking out after the vehicles had been loaded for transit. Bao *et al*. highlighted the typical causes of fires in second-hand ICE vehicles, which include malfunctioning electrical systems, repairs that were put off, and external ignition factors (Bao *et al*. 2023). Around two thirds of vehicle fires on ro-ro decks were attributed to aging electrical circuits.

It is particularly difficult to put out PHEV battery fires because of the risk of reignition, which can persist for over 24 hours (Tukes 2024). Currently, there is no universal system for putting out BEV battery fires, as conventional extinguishers cannot counteract the oxygen generated by decomposing battery cells (Arvidson, Westlund, 2023). Thermal imaging cameras are frequently used to monitor battery conditions and detect early signs of overheating (Kleiman *et al*., 2021). However, these steps are reactive, not preventive, which underscores how crucial it is to establish proactive plans to decrease fire risks.

Węglarz *et al*. examine how to reduce the risk of fires on ro-ro ships with regard to electric car fires (Węglarz et al., 2024). Studies in Denmark on maritime fire safety have demonstrated that specialist firefighting tools can assist in putting out PHEV fires aboard ships (Kleiman et al., 2021). Two common strategies to put out these kinds of fires are to let the battery burn out on its own or to entirely submerge the PHEV in substantial amounts of water, frequently necessitating thousands of liters. Research indicates that diverting water streams beneath the car is the most effective method for extinguishing fire; however, this can be challenging due to the position of the battery in certain electric vehicles (Lefebvre, L. 2013; González et al., 2023). For instance, some models with twin power sources have battery packs located in different parts of the vehicle (Boehmer et al., 2021).

To mitigate these hazards, industry organizations and governmental bodies have commenced developing guidelines to improve the safety of transporting BEVs and PHEVs. The European Maritime Safety Agency (EMSA) published its Guidance on the Carriage of Alternative Fuel Vehicles in Ro-Ro Spaces in 2022. This recommendation categorizes alternatively powered vehicles into two classifications: electric and gas-powered. It emphasized the necessity for risk assessments and methods to mitigate those risks. (EMSA, 2022). Despite these initiatives, a significant deficiency in empirical data about the behavior of BEV and PHEV batteries during maritime transport persists, hindering the establishment of clear, evidence-based protocols for mitigating fire risks within the industry.

Recognizing these challenges, new safety standards for ships carrying electric vehicles are being developed and were submitted to the International Maritime Organization's (IMO) Maritime Safety Committee (MSC 109, 2024) in December 2024 for consideration and approval. To implement these regulations effectively, it is essential to understand the behavior of BEV and PHEV batteries during transportation and the factors that lead to fires.

1.2. Methodology

This study examines temperature data acquired from plug-in hybrid electric vehicles on a car carrier during a month-long journey. The objective of data collection was to assess potential fire risks associated with PHEV battery temperatures during maritime transport.

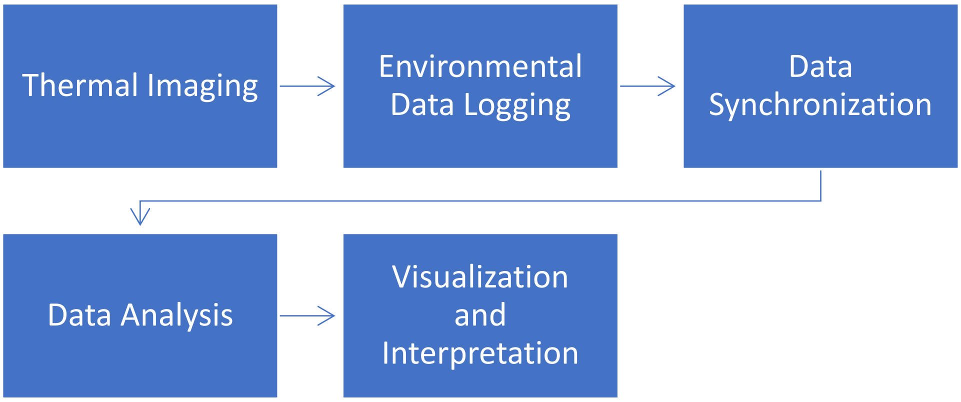

Figure 1 Data acquisition workflow

1.2.1. Data Collection

The data was collected on a car carrier with a capacity of 6,000 vehicles. The vessel is equipped with a foam-based fire-suppression system and ventilation systems across all 12 decks, capable of circulating air in and out. However, these ventilation systems were not activated during the transit period; they were only used while the vessel was in port. No insulation existed between the decks of the car carrier or between the cargo holds and the external environment. Vehicles were stowed densely, with approximately 10 cm between mirrors and 30 cm between bumpers.

Figure 2. Standard vehicle stowage on board Pure Car Carriers

Data collection focused on 95 PHEVs, consisting of both Toyota and Lexus models, distributed across two of the vessel's decks: Deck 1 (Figure 3) and Deck 11 (Figure 4). Deck 1, the lowest deck, is situated directly above the heated fuel-oil tanks, while Deck 11 is located closer to the superstructure, but it is not the topmost deck (the topmost being Deck 12, which is under the weather deck). These decks were selected to illustrate the maximum and minimum potential temperature variations within the cargo hold. Approximately 300 vehicles occupied each of these decks, with the PHEVs interspersed among them. The precise location of each monitored PHEV on the decks is known and will be used for spatial analysis.

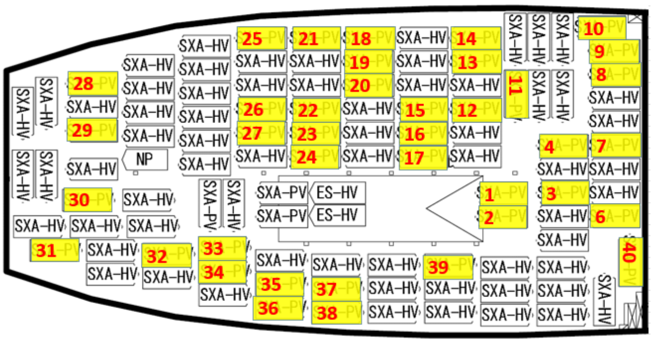

Figure 3. Numbers and locations of 40 selected PHEVs on Deck 1 Hold 3

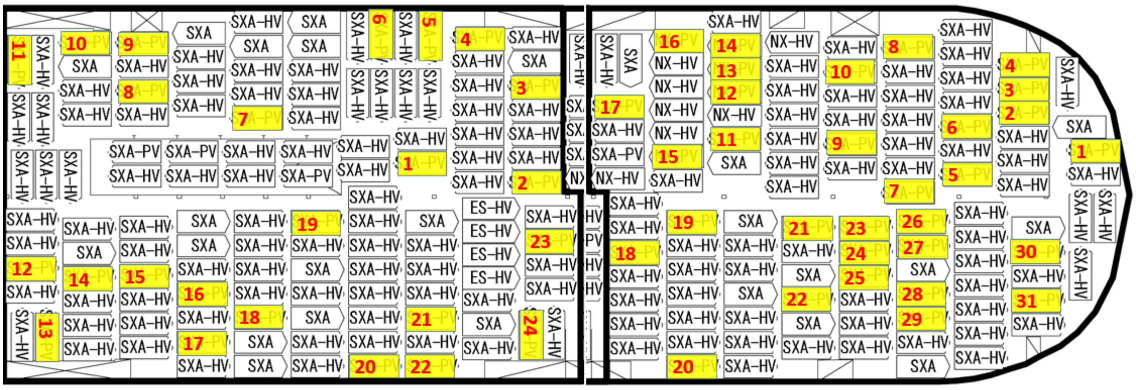

Figure 4. Numbers and locations of 24 selected PHEVs on Deck 11 Hold 2 and 31 PHEVs on Deck 11 Hold 2

Temperatures were recorded every 12 hours (at midnight and noon) over the course of a month. A handheld FLIR E4 thermal camera was used to measure the temperature in the vicinity of each vehicle's battery. The following settings of the thermal camera were used: emissivity of the thermal camera was set to 0.67 (for anodized Aluminum, black and dull); parameters for reflected apparent temperature were set to default; distance between the camera and the object of measurement was set to 0.5 m; Device accuracy is 2° C or ±2 % of reading, for ambient temperature 10° C to 35° C and object temperature above +0° C. While the same operator conducted all measurements, some variability in the precise measurement location on the battery casing is acknowledged. The temperature was measured on the external shell of the vehicle in the vicinity of the battery pack, which was covered by protective casing. This method provides an indirect measure of the battery's internal temperature.

1.2.2. Dataset

The dataset includes the battery temperatures for the 95 monitored PHEVs, along with the following environmental temperatures: outside air temperature (ranging from 17° C to 31° C), sea temperature, cargo hold air temperature, and the temperature of the fuel-oil tanks port and starboard beneath Deck 1 (ranging from 30° C to 48° C). The temperatures of the batteries ranged from 23° C to 40° C. While outside humidity was described as "relatively high," specific humidity readings were not available for analysis. The battery charge levels of the PHEVs at the time of loading onto the vessel are unknown.

1.2.3. Analysis Approach

This study primarily employed correlation analysis to investigate the relationships between PHEV battery temperatures and various environmental factors during the car carrier's voyage. This method was chosen because it allows for the quantification of the strength and direction of linear relationships between continuous variables. This is essential for understanding how environmental conditions affect battery temperatures.

1.2.4. Correlation Analysis

Correlation analysis was conducted to find out the strength and direction of the relationship between battery temperatures and the following environmental factors:

- Outside air temperature
- Sea temperature
- Cargo-hold air temperature
- Fuel-tank temperature (Deck 1 only)

Pearson's correlation coefficient (Pearson's *r*) was chosen for this study because it effectively quantifies the strength and direction of linear relationships between the continuous temperature variables. Given that the study aims to understand how changes in environmental factors (sea temperature, air temperature, etc.) linearly correspond with changes in PHEV battery temperatures, Pearson's *r* is a straightforward and comprehensible method to assess these relationships. This method is particularly suitable for identifying trends and dependencies within the dataset, facilitating a comprehensive examination of the thermal dynamics influencing battery behavior. Pearson's *r* is a statistical measure that quantifies the extent to which two variables change together. Two entities with a high score (near +1) exhibit significant similarity. A Pearson score approaching zero indicates that two variables are not correlated. Two objects that correlated inversely (i.e., one falling when the other rises) would have a Pearson score near –1. The Pearson correlation coefficient is calculated by dividing the covariance of the two variables by the product of their standard deviations:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \qquad \text{……………………………………(1)}$$

where,

n = Quantity of information;
$\sum x$ = Total of all values for the first variable;
$\sum y$ = Total of all values for the second variable;
$\sum xy$ = Sum of product of the first and the second values;
$\sum x^2$ = Sum of squares of the first value;
$\sum y^2$ = Sum of squares of the second value.

This calculation effectively normalizes the relationship, allowing for comparisons across different datasets and variables with varying scales (Boslaughet et al., 2008). The Pearson correlation for two objects with paired attributes sums the product of their differences from their object means and divides the sum by the product of the squared differences from the object means.

All correlation coefficients (*r*) were tested for statistical significance using Fisher's *z*-transformation. For each correlation, the *z*-value was computed as:

$$z = 0.5 \times \ln\left(\frac{1+r}{1-r}\right) \text{ ……………………………………(2)}$$

with a standard error (SE) of $1/\sqrt{n-3}$, where *n* is the number of paired observations. The 95% confidence interval (CI) for *z* is calculated as:

$$z_{CI} = z \pm 1.96 \times SE \text{ ……………………………………(3)}$$

which is then back-transformed to obtain the 95 % CI for *r*:

$$r_{CI} = \frac{e^{2z_{CI}-1}}{e^{2z_{CI}+1}} \text{……………………………………(4)}$$

The statistical significance of each correlation coefficient was evaluated using a *t*-test to determine whether the observed relationship between variables could have arisen by chance. The *t*-statistic for each Pearson correlation was computed as:

$$t = r \times \sqrt{\frac{n-2}{1-r^2}} \text{……………………………………(5)}$$

The degrees of freedom are determined as:

$$df = n - 2 \text{……………………………………(6)}$$

The *p*-value is derived from the *t*-distribution with the calculated degrees of freedom (6):

$$p = 2 \times \left[1 - T_{cdf}(|t|, df)\right] \text{……………………………………(7)}$$

where T_{cdf} is the cumulative distribution function of the *t*-distribution. The factor of 2 accounts for a two-tailed test, which checks both positive and negative correlations.

The corresponding *p*-value was then obtained to quantify the probability of observing a correlation at least as strong as *r* under the null hypothesis of no relationship (r = 0). A small *p*-value (typically < 0.05) indicates that the correlation is statistically significant, implying that the association between the variables is unlikely to have occurred by random variation alone. Reporting *p*-values together with the 95 % confidence intervals ensures a balanced interpretation, combining the strength and direction of association (*r*) with the level of confidence and statistical reliability of the observed effect. This dual approach enhances transparency and robustness in assessing the strength and certainty of thermal relationships within the dataset.

Spatial analysis will involve comparing battery temperatures on Deck 1 and Deck 11 to identify any significant differences or 'hot spots. Given precise knowledge of the vehicle locations, heat maps will be generated to visualize the temperature distribution across the two decks.

Following the methodology outlined in the previous section, the collected temperature data was analyzed to investigate the relationships between PHEV battery temperatures and various environmental factors during the car carrier's voyage. The study examined overall trends, assessed the strength and direction of correlations, analyzed spatial patterns throughout the cargo decks, and investigated how factors such as deck position and proximity to fuel tanks may influence outcomes.

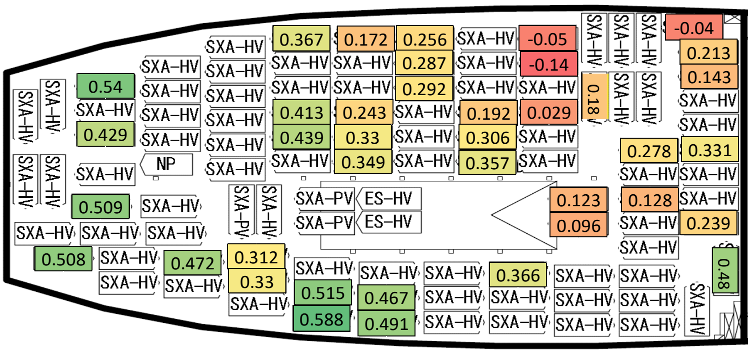

Figure 5. Spatial distribution of correlation coefficients between PHEV battery temperature and sea temperature across Deck 1 Hold 3 (Color gradient indicates correlation strength (e.g., green for strong positive, yellow for weak, red for negative.)

As illustrated in Figure 5, the correlation analysis revealed several associations between battery temperature and sea temperature. While a majority of vehicles exhibited positive correlations, indicating a tendency for battery temperature to increase with sea temperature, the strength of these correlations varied considerably across the cargo hold. The average correlation coefficient for sea temperature was 0.2947 on Deck 1.

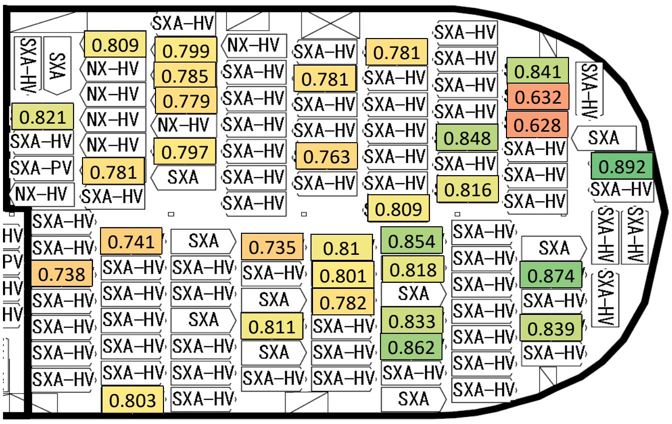

Figure 6. Spatial distribution of correlation coefficients between PHEV battery temperature and air temperature across Deck 11 Hold 1 (Color gradient indicates correlation strength.)

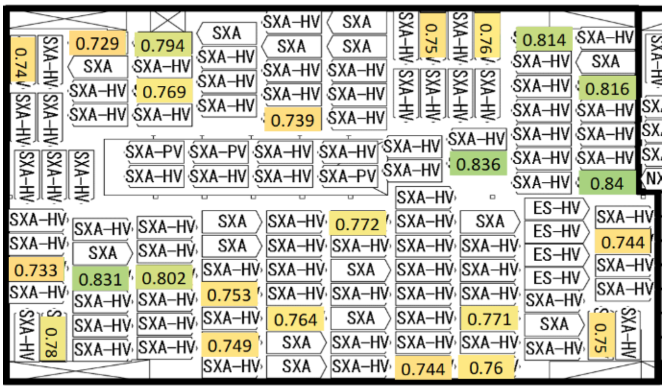

Figure 7. Spatial distribution of correlation coefficients between PHEV battery temperature and air temperature across Deck 11 Hold 2 (Color gradient indicates correlation strength.)

Figures 6 and 7 represent the spatial distribution of correlation coefficients for the outside air temperature. Similar to the patterns observed for sea temperature, air temperature correlations also exhibited spatial variability, with regions of stronger positive correlation and areas of weaker correlation. The average correlation coefficients for air temperature were 0.7955 and 0.7725 on Deck 11 for Hold 1 and Hold 2, respectively.

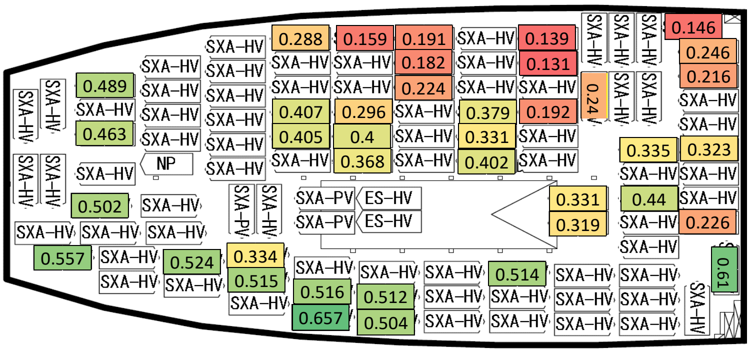

Figure 8. Spatial distribution of correlation coefficients between PHEV battery temperature and hold air temperature across Deck 1 Hold 3 (Color gradient indicates correlation strength.)

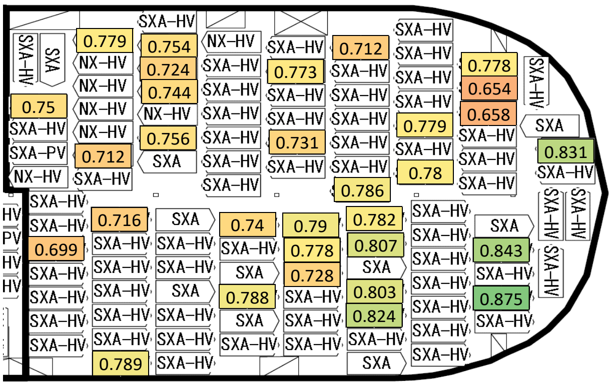

Figure 9. Spatial distribution of correlation coefficients between PHEV battery temperature and hold air temperature across Deck 11 Hold 1 (Color gradient indicates correlation strength.)

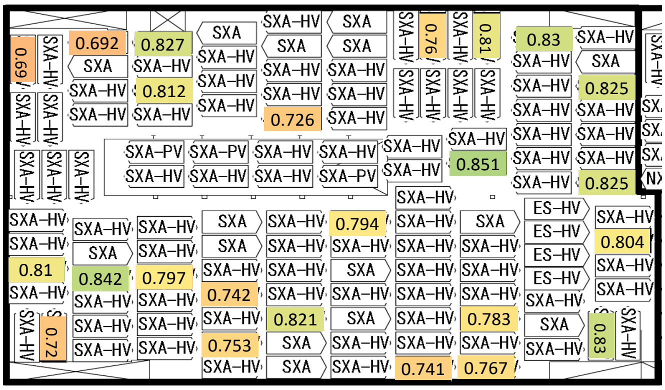

Figure 10. Spatial distribution of correlation coefficients between PHEV battery temperature and hold air temperature across Deck 11 Hold 2 (Color gradient indicates correlation strength.)

The correlation analysis with ambient hold air temperature (Figures 8, 7, and 10) revealed a pattern mostly consistent with the previous observations. However, the magnitude of positive correlations appeared to be somewhat higher, indicating a more direct influence of hold air temperature on battery temperatures. Once more, spatial variations were observed, highlighting the complexity of the thermal environment within the cargo hold. The average correlation coefficients for hold temperature were 0.3576 on Deck 1, and 0.7634 and 0.7853 on Deck 11 for Hold 1 and Hold 2, respectively.

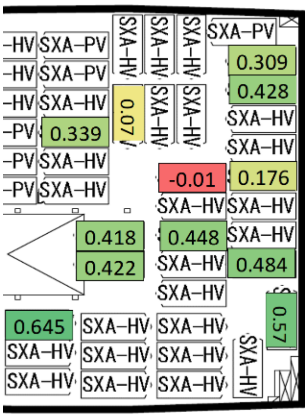

Figure 11. Spatial distribution of correlation coefficients between PHEV battery temperature and fuel tank temperature on Deck 1 Hold 3 (Color gradient indicates correlation strength.)

The correlation between fuel tank temperature (Figure 11) and other variables for cars on Deck 1 provided more insights into the impact of heat on the lower deck. As anticipated, a positive correlation was observed for many vehicles, confirming the influence of the fuel tanks as a heat source. The average correlation coefficients for fuel tank temperature were 0.2862 for the port side and 0.4980 for the starboard side.

2. RESULTS

This section presents the findings of the correlation analysis between PHEV battery temperatures and various environmental factors measured during the car carrier's voyage. The results are organized by environmental factor, highlighting overall trends, spatial variations, and potential explanations for the observed patterns.

2.1. Sea Temperature

A moderate positive correlation existed between the battery temperature and the sea temperature on Deck 1, Hold 3 (Figure 3). This indicates that, generally, battery temperature increases in conjunction with rising sea temperature, consistent with basic thermodynamic principles. However, the strength of this relationship varied significantly across the hold, ranging from -0.16 to 0.588. A particularly strong positive relationship was observed for vehicles located nearest to the starboard side of the hold, with correlation coefficients approaching 0.588. This suggests that these vehicles are more directly influenced by the ambient temperature fluctuations associated with changes in sea temperature. Conversely, a cluster of vehicles adjacent to the ventilation fan on the port side exhibited negative correlation coefficients, some as low as -0.16. This counterintuitive finding can be explained by the localized cooling effect of the ventilation system. The airflow, differing in temperature from the ambient hold temperature, significantly alters the thermal dynamics in this area. This localized cooling creates a microclimate where battery temperatures respond differently to changes in sea temperature compared to vehicles further away from the ventilation fan. The observed variation in correlation strength underscores the importance of considering localized environmental factors within the cargo hold, even within relatively small distances. Such localized variations may result from variations in airflow, proximity to other heat sources (or lack thereof), or even the specific stowage position relative to structural elements of the vessel. Furthermore, the possibility of measurement inconsistencies, while less likely given the consistent methodology, cannot be entirely ruled out.

2.2. Outside Air Temperature

Outside air temperature exhibited a significantly stronger positive correlation with battery temperature compared to sea temperature. This supports the expectation that ambient air temperature plays a more direct role in influencing battery temperatures, particularly on the upper decks. The mean correlation coefficients for air temperature on Deck 11 indicate a direct and significant influence of air temperature on battery temperatures in the upper cargo holds. This strong correlation is consistent with the general understanding of heat transfer principles, as the batteries, being exposed to the surrounding air, would be expected to equilibrate.

However, despite the high average correlation, some degree of variability in correlation strength was observed across Deck 11 (Figure 6). Notably, the highest correlation coefficients were observed for vehicles located at the foremost part of the vessel. This spatial pattern can likely be attributed to the vessel's route, which took it from Japan to the Suez Canal and so exposed the forward part of the vessel more towards the south. During this transit, the bow of the vessel would have been more directly exposed to solar radiation compared to the sides. This prolonged and direct exposure to sunlight would result in a greater transfer of radiant heat to the vehicles located fore, leading to a stronger correlation between air temperature and their battery temperatures.

Interestingly, a localized anomaly was observed for two vehicles, vehicle numbers 2 and 3 of Deck 11 Hold 1, also located fore on the vessel. Despite the general trend of strong positive correlations in this area, these two vehicles showed marginally lower correlation coefficients. This anomaly can potentially be explained by the presence of a ventilation hatch located directly above these vehicles. While this hatch was kept closed at all times, it is theorized that the additional space provided by the hatch above the standard deck height might create a localized microclimate. This extra space could allow warmer air to accumulate at the top, potentially resulting in slightly cooler air being present closer to the deck floor, where the batteries are located. This cooling effect is possibly increased by the fact that the entirety of the deck is filled with 5 cm holes for lashings, and as such, slightly cooler air from lower decks would also pass underneath the two vehicles, further contributing to the localized cooling beneath the ventilation hatch. This localized temperature difference could explain the lower correlation with the general ambient air temperature. However, this explanation raises a further question of why the vehicle number 4, located nearby but not directly under the hatch, does not exhibit the same behavior. While it is unclear why the same principle did not apply to vehicle number 4, it is important to note that the vehicle was not located directly under the ventilation hatch. This suggests that the localized cooling effect, if present, is highly specific to the area directly beneath the hatch.

2.3. Cargo-Hold Air Temperature

Cargo-hold air temperature, measured only at the geometric center of each hold, presents a limited perspective on the thermal microclimates that likely exist across the entirety of each deck. While the correlation analysis with hold air temperature showed a general pattern similar to that observed with air temperature, it is crucial to acknowledge that these centrally measured values may not be fully representative of the temperature variations experienced by individual vehicles in different locations within the holds. Despite this limitation, the analysis provides some valuable insights.

The average correlation coefficients suggest that hold air temperature, as measured at the central location, is also a significant factor influencing battery temperatures, particularly on Deck 11. The high correlation coefficients on Deck 11 (averaging around 0.77 - 0.78) indicate a strong relationship between the centrally measured hold air temperature and the battery temperatures of the vehicles on that deck. The similarity of these values to those observed for outside air temperature on Deck 11 enhances the likelihood that the centrally measured hold air temperature serves as an accurate indicator of the general ambient air temperature on the upper deck, at least in the center of the hold.

However, the correlation observed on Deck 1 (0.3576) is notably weaker than on Deck 11 and weaker than the correlation observed between Deck 1 vehicles and sea temperature. This discrepancy likely reflects the complex thermal environment on Deck 1, where the proximity to the fuel tanks introduces a substantial confounding factor. The centrally measured hold air temperature on Deck 1, being influenced by the fuel tanks below, may not accurately capture the temperature variations experienced by individual vehicles situated at different distances from this significant heat source. Therefore, while the correlation analysis with hold air temperature provides some general insights, the limitations of the centrally measured data, particularly on Deck 1, must be carefully considered when interpreting these results.

2.4. Fuel-Tank Temperature

For vehicles located on Deck 1, the correlation with fuel tank temperature provided valuable insights into the thermal impact of the fuel tanks on nearby PHEV batteries. The analysis focused specifically on the 12 vehicles (numbers 01, 02, 03, 04, 06, 07, 08, 09, 11, 12, 39, and 40) positioned above the fuel tanks in use during the voyage: HFO-3(P) and HFO-3(S). These tanks are heated during the voyage to the optimal viscosity for enhanced flow. The positive correlation confirms the expected trend: as the fuel tanks are heated, the battery temperatures of vehicles on top also tend to increase.

However, the analysis also revealed some intriguing anomalies. Two vehicles, numbers 04 and 07, exhibited unexpectedly low correlation coefficients. This deviation from the general trend can be attributed to the location of these vehicles above a pipe passage and not directly above a fuel tank. The pipe passage is a narrow and low shaft that runs beneath the deck along the vessel's centerline, providing access to the fuel and ballast tanks for maintenance and inspection. This passage, while considered an enclosed space and rarely ventilated, is filled with hot air from the surrounding tanks. Therefore, the air temperature of the pipe passage would be less influential, which would explain the non-existent correlation between fuel tank temperature and the battery temperatures of vehicles 04 and 07.

Another noteworthy observation was the unexpectedly low correlation coefficient for vehicle 11. While this vehicle is located above the fuel tanks, its correlation with fuel tank temperature was significantly lower than that of neighboring vehicles. Currently, there is no clear explanation for this anomaly. It is possible that measurement error or other unidentified localized factors might have contributed to this unexpected behavior. Further investigation is required to ascertain the source of this discrepancy, either using more comprehensive temperature measurements or an examination of the vehicle's distinctive characteristics.

The correlation analysis of the fuel tank surface temperatures indicates that the heated fuel tanks on Deck 1 significantly influence the temperature. The observed positive correlations for most vehicles underscore the importance of considering the proximity of PHEVs to heat sources when planning cargo stowage. However, the presence of anomalies and localized variations emphasizes the complexity of the thermal environment within the cargo hold and the need for more comprehensive data and analysis to fully understand the connection of the various factors affecting battery temperatures.

3. DISCUSSION

3.1. Interpretation of Results

3.1.1. Overall Significance of Correlation Analysis

The observed correlations, while varying in strength, illustrate the complex environment with contributing factors such as sea temperature, air temperature, hold temperature, proximity to heat sources (fuel tanks), and localized ventilation effects. This understanding is crucial for developing effective strategies to mitigate fire risks associated with the maritime transport of PHEVs.

3.1.2. Relating Findings to Thermal Runaway Potential

The observed positive correlations between battery temperature and environmental factors like sea temperature, air temperature, and fuel tank surface temperature indicate the potential for thermal runaway in PHEV batteries during maritime transport. While the specific temperature thresholds for thermal runaway vary depending on battery chemistry and design, it is widely acknowledged that elevated temperatures significantly increase the risk. The observed correlations, particularly the strong positive correlations with air temperature and fuel tank surface temperature, highlight the need for careful monitoring and control of environmental conditions within the cargo holds to minimize the risk of thermal runaway.

3.1.3. Implications of Spatial Variations

The spatial variations in correlation coefficients observed across the cargo decks reveal the significant influence of localized factors on battery temperatures. The presence of both positive and negative correlations, even across relatively small distances, indicates that the thermal environment within the hold is not uniform. Factors such as proximity to ventilation fans, location relative to heat sources such as fuel tanks, and even the specific stowage position relative to other cargo or structural elements can create microclimates with distinct temperature dynamics. This spatial variability underscores the importance of considering not just the average environmental conditions but also the localized variations when assessing fire risk and developing mitigation strategies.

3.1.4. Impact of Ventilation (or Lack Thereof)

The presence of negative correlations near ventilation fans, particularly on Deck 1, demonstrates the potential for localized cooling effects due to natural ventilation. However, the fact that the vessel's ventilation systems were not operational during the voyage raises concerns about the potential for heat accumulation within the cargo holds. The lack of active ventilation could exacerbate the influence of heat sources like the fuel tanks and contribute to elevated battery temperatures, particularly in areas with no natural ventilation.

3.2. Limitations

While this study provides valuable insights into the thermal behavior of PHEV batteries on car carriers, it is essential to acknowledge its limitations. These limitations may hinder the applicability of the results to different contexts; hence, they should be considered when formulating suggestions and interpreting the findings.

- Lack of Comparative Data: This study represents one of the first attempts to systematically collect and analyze temperature data from PHEVs on a car carrier. As such, there is a lack of comparative data from other voyages or vessel types, which limits the ability to assess the extent to which the observed patterns are typical or unique to this specific voyage and vessel.

- Unknown Battery Charge Levels: The battery charge levels of the PHEVs at the time of loading were unknown. Battery charge level can influence the thermal behavior of the battery, and the absence of this information introduces a potential confounding factor. It is possible that batteries with higher charge levels might exhibit different thermal responses compared to those with lower charge levels. The absence of precise data on the PHEV battery charge levels introduces a key limitation in interpreting the observed temperature patterns. Battery state of charge (SoC) directly influences thermal behavior — cells with higher SoC are more prone to self-heating, elevated internal resistance, and accelerated temperature rise when exposed to ambient or radiant heat. Without this information, it is not possible to fully distinguish whether measured temperature differences stem from environmental exposure, vehicle placement, or intrinsic electrochemical conditions. Nevertheless, the consistency of thermal trends across multiple vehicles and deck locations suggests that ambient and structural factors, rather than SoC variability, were the dominant contributors to the observed temperature gradients.

- Potential Variability in Thermal Camera Readings: While the same operator conducted all measurements with the FLIR E4 thermal camera, some variability in the precise measurement location on the battery casing is acknowledged. This variability could introduce slight discrepancies in the temperature readings, potentially affecting the accuracy of the correlation analysis. Additionally, the use of a hand-held thermal camera, while offering convenience and flexibility, may not provide the same level of precision as more sophisticated fixed-mounted thermal imaging systems.

- Centrally Measured Hold Air Temperature: Hold air temperature was measured only at the geometric center of each hold, which may not fully represent the temperature variations experienced by individual vehicles in different locations within the holds. This limitation could particularly affect the interpretation of correlations on Deck 1, where the proximity to the fuel tanks likely creates significant temperature gradients.

- Lack of Precise Humidity Data: While outside humidity was described as ‘relatively high’, specific humidity readings were not available for analysis. Humidity can influence battery performance and thermal behavior, and the lack of precise humidity data limits the ability to fully assess its potential impact on the observed temperature patterns.

- Lack of Internal Battery Temperature Data: The study relied on measuring the temperature on the external shell of the vehicle in the vicinity of the battery pack, which provides an indirect measure of the battery's internal temperature. Direct measurement of the internal battery temperature was unfeasible due to the protective casing surrounding the battery pack. This indirect measurement approach may introduce a certain level of error, as the external shell temperature might not perfectly reflect the internal battery temperature.

- These limitations highlight the need for further research with more comprehensive data collection, including:

- Conducting similar studies on different car carriers and routes to gather comparative data;

- Recording the battery charge levels of PHEVs at the time of loading;

- Utilizing advanced thermal imaging systems with fixed-mounted sensors for greater precision;

- Implementing a more distributed temperature measurement approach within the cargo holds to capture spatial variations more accurately;

- Exploring methods for directly measuring internal battery temperatures, potentially through collaboration with vehicle manufacturers.

Despite these limitations, this study provides valuable insights into the thermal behavior of PHEV batteries on car carriers and contributes to the growing body of knowledge on this important safety issue.

3.3. Implications for Maritime Safety

The observed temperature patterns, correlations, and spatial variations highlight the potential risks associated with transporting PHEV vehicles, particularly the risk of thermal runaway in batteries. To mitigate these risks and enhance maritime safety, several key recommendations emerge from this research.

3.3.1. Improved Stowage Procedures

The findings of this study highlight the need for improved stowage procedures for PHEVs on car carriers. The vessel on which this study was conducted had existing procedures for the stowage of battery electric vehicles (BEVs), such as prohibiting their loading on Deck 1 and the topmost deck due to the influence of fuel tank temperatures and heat transfer from the weather deck. Nevertheless, no specific standards or recommendations were in place for PHEVs. This lack of specific guidelines for PHEVs is concerning as the study demonstrates that these vehicles also exhibit significant temperature sensitivities and may be susceptible to thermal runaways.

Furthermore, while procedures were in place on this vessel for temperature monitoring of all BEVs, these procedures did not extend to PHEVs. Moreover, the temperature data usually collected from monitoring of BEVs is not recorded or stored anywhere, precluding its use for analysis and the development of evidence-based stowage practices. The lack of data collection and analysis represents a missed opportunity to gain valuable insights into the thermal behavior of electric vehicles during maritime transport and to refine safety protocols accordingly.

Based on the author's experience and the results of this study, the following recommendations for improved stowage procedures are proposed:

- Clear Identification of Vehicle Propulsion Type: Accurate and readily available information on the propulsion type of each vehicle (PHEV, BEV, HEV, or internal combustion engine) is crucial for efficient fire safety management. The lack of such information can hinder fire patrols and emergency response efforts as crew members may not be aware of the hazards posed by unmarked vehicles. There have been numerous cases where information on the vehicle propulsion system was absent or incomplete, which indicates the need for standardized and comprehensive vehicle identification procedures. This could involve requiring clear labeling on the vehicles themselves, as well as providing detailed vehicle manifests to the vessel's crew.

- Prioritizing Stowage Near Ventilation Shafts: Whenever possible, PHEVs should be stowed in locations near the vessel's ventilation shafts. The natural downward flow of cooler air along these shafts can provide passive cooling to the vehicles located nearby, reducing the risk of heat accumulation and thermal runaway.

- Avoiding Vertical Stacking of Electric Vehicles: To minimize the risk of fire propagation, electric vehicles, including PHEVs, should not be stacked directly above each other on multiple decks. The presence of lashing holes in most decks creates pathways for hot air, flames, and sparks to travel upwards in the event of a fire, potentially igniting vehicles on the deck above and triggering a cascade of thermal runaway events. By avoiding vertical stacking, the risk of fire spreading between decks can be significantly reduced.

- Utilizing Thermal Imaging with Data Recording and Export: The use of thermal imaging instruments with data recording and export capabilities can significantly enhance the monitoring and analysis of battery temperatures. By systematically collecting and analyzing temperature data, operators can gain a deeper understanding of the factors influencing battery temperatures and identify potential hot spots or trends that may warrant adjustments to stowage procedures. This data-driven approach can contribute to the development of more effective and targeted risk mitigation strategies.

- Continuous Temperature Monitoring: The installation of continuous temperature monitoring systems within the cargo holds could provide real-time data on battery temperatures and environmental conditions. This would enable early detection of potential thermal runaway events and facilitate prompt intervention. The monitoring system could be integrated with the vessel's alarm system to alert the crew of any temperature anomalies, allowing for timely response and mitigation efforts.

3.3.2. Operational Decision Support for Maritime Safety

Current maritime regulations offer no clear limits for PHEV battery temperatures at sea, which leaves operators to rely on judgment rather than data. The findings in this article attempt to close that gap with a quantitative decision tool grounded in measured correlations between environmental and battery temperatures. The temperature of 45° C is suggested as a ‘watch’ level and 55° C as an ‘action required’ threshold. These limits are intentionally conservative, providing early warning well before the onset of thermal instability. In case the PHEV battery exceeds its threshold in two consecutive readings, the crew should increase ventilation, isolate affected decks if possible, and initiate continuous monitoring. This approach transforms temperature data into actionable safety intelligence, something crews can use now without waiting for future regulation. The results in this study have shown that the rise of battery temperature is directly linked to the rise of the ambient temperature; in hot voyages, even modest ambient increases can push batteries into the risk zone.

4. CONCLUSIONS

This study has provided valuable insights into the thermal behavior of PHEV batteries on car carriers, showcasing the potential risks associated with their transport and the need for enhanced standards for transportation. The correlation analysis revealed substantial connections between battery temperatures and various environmental factors, including sea temperature, air temperature, hold temperature, and proximity to heat sources such as fuel tanks. The spatial variations in correlation coefficients emphasized the complexity of the thermal environment within the cargo hold and the influence of localized factors such as ventilation and stowage position.

The findings of this study have important implications for the maritime industry, particularly for car carriers involved in the transport of PHEVs. To enhance safety and mitigate the risk of fire incidents, a multi-faceted approach is required. Crucially, addressing the challenges posed by the maritime transport of PHEVs necessitates a collaborative approach. The maritime industry, including car carriers, vehicle manufacturers, regulators, and research institutions, is encouraged to work together to develop and implement best practices. This collaboration could involve:

- Sharing data and research findings on battery thermal behavior and fire risks;
- Developing standardized testing and certification procedures for electric vehicles intended for maritime transport;
- Establishing clear guidelines and regulations for the stowage, ventilation, and fire suppression requirements for PHEVs on car carriers;
- Conducting joint training programs for crew members on the safe handling and transport of electric vehicles.

With the development of a culture of collaboration, knowledge sharing, and continuous improvement, the fire risks associated with PHEVs can be addressed. This collaborative approach is essential to ensure the continued growth and sustainability of maritime trade while safeguarding lives, property, and the environment.

Information from this study can contribute to the database of knowledge on the safe transport of electric vehicles. Further research is needed to expand upon these findings, address the limitations of this study, and develop even more effective risk mitigation strategies.

5. DATA AVAILABILITY

All temperature measurements, Pearson correlation calculations and Fisher transformation data used in this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

Authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

Arvidson, M. and Westlund, Ö. (2023) ‘Water spray fire suppression tests comparing gasoline-fuelled and battery electric vehicles’, Fire Technology, 59, pp. 3391–3414. Available at: https://doi.org/10.1007/s10694-023-01473-w.

Bao, J. et al. (2023) ‘A hybrid approach for quantitative analysis of fire hazards in enclosed vehicle spaces on ro-ro passenger ships’, Sustainability, 15(17). Available at: https://doi.org/10.3390/su151713059.

Boehmer, H., Klassen, M. and Olenick, S. (2021) ‘Fire hazard analysis of modern vehicles in parking facilities’, Fire Technology, 57(5), pp. 2097–2127. Available at: https://doi.org/10.1007/s10694-021-01113-1.

Boslaugh, S. and Watters, P.A. (2008) Statistics in a nutshell: a desktop quick reference. Sebastopol, CA: O’Reilly Media.

ClassNK (2023) Guidelines for the safe transportation of electric vehicles (Edition 1.0). Available at: https://www.classnk.or.jp/hp/pdf/activities/statutory/ev_carriage_safety/gl_ev_carriage_safety_e202412.pdf (Accessed: 10 December 2024).

CNBOP (Scientific and Research Centre for Fire Protection) (2023) Prowadzenie działań ratowniczych podczas zdarzeń z udziałem pojazdów z napędem elektrycznym. Józefów. Available at: https://cnbop.pl/app/uploads/2024/11/Dzialania_ratownicze_pojazdy_elektryczne_2023.pdf (Accessed: 13 December 2024).

Cui, Y. et al. (2022) ‘Characteristics and hazards of plug-in hybrid electric vehicle fires caused by lithium-ion battery packs with thermal runaway’, Frontiers in Energy Research. Available at: https://doi.org/10.3389/fenrg.2022.878035.

Derski, B. (2023) ‘Firefighters about electric car fires’, Wysokie Napięcie. Available at: https://wysokienapiecie.pl/90860-strazacy-o-pozarach-samochodow-elektrycznych/ (Accessed: 10 December 2024).

EMSA (2022) Transportation of alternative fuelled vehicles (AFV). Available at: https://www.emsa.europa.eu/afv.html (Accessed: 23 November 2024).

González-Almeida, J.A. et al. (2023) ‘Transport of electric and hybrid vehicles on board ships: risks and measures to consider for a growing problem’, Journal of Maritime Research, 20(3), pp. 240–250. Available at: https://www.jmr.unican.es/jmr/article/view/876/805.

KG PSP (National Headquarters of the State Fire Service) (2023) Standardowe zasady postępowania podczas zdarzeń z samochodami z napędem elektrycznym oraz hybrydowym. 2nd edn. Available at: https://www.gov.pl/attachment/73a0ca6c-e5d0-4640-8cd0-570bc92fe4ab (Accessed: 28 November 2024).

Kim, K. and Jeon, H. (2023) ‘The causes and responses to cargo hold fire accidents in ro-ro ships using AcciMap’, Journal of International Maritime Safety, Environmental Affairs, and Shipping, 7(4). Available at: https://doi.org/10.1080/25725084.2023.2274227.

Kleiman, A. et al. (2021) The ELBAS project – electric vehicle fires at sea: new technologies and methods for suppression, containment, and extinguishing of battery car fires onboard ships. The Danish Maritime Fund. Available at: https://brandogsikring.dk/files/Pdf/FogU/ELBAS/DBI%20ELBAS%20Report%20-%20Full%20Final%20(rev.%201).pdf (Accessed: 12 December 2024).

Lefebvre, L. (2013) ‘Smart battery thermal management for PHEV efficiency’, Oil & Gas Science and Technology – Revue d’IFP Energies nouvelles, 68, pp. 149–164. Available at: https://doi.org/10.2516/ogst/2012076.

Łukasz, B. et al. (2022) ‘Lithium batteries safety, wider perspective’, International Journal of Occupational Medicine and Environmental Health, 36(1), pp. 3–20. Available at: https://doi.org/10.13075/ijomeh.1896.01995.

Marcheschi, A. (2023) ‘Behind the scenes of the Fremantle Highway salvage mission’, Marine Log. Available at: https://www.chinapandi.com/index.php/en/loss-prevention-menu-en/loss-prevention-content-en/5843-lp-19-2023-a-brief-review-on-fremantle-highway-fire (Accessed: 12 December 2025).

Maritime Safety Committee (MSC 109) (2024) 109th session, 2–6 December 2024.

Sun, P. et al. (2020) ‘A review of battery fires in electric vehicles’, Fire Technology, 56(4), p. 1411. Available at: https://doi.org/10.1007/s10694-020-00958-2.

Todorov, D.M. (2016) Ro-ro handbook: a practical guide to roll-on roll-off cargo ships. Cornell Maritime Press/Tidewater Publishers.

Tukes (2024) Litiumioniakkujen elinkaari [life span of lithium batteries]. Available at: https://tukes.fi/litiumioniakkujen-elinkaari (Accessed: 21 November 2024).

Węglarz, K., Złoczowska, E. and Krasuski, A. (2024) ‘Problems of fire protection in the ro-ro space of roll-on/roll-off ships during an electric vehicle fire: Part 1’, Zeszyty Naukowe SGSP, 2, pp. 109–129. Available at: https://doi.org/10.5604/01.3001.0054.6256.

Węgrzyński, W. (2021) ‘Smoke control of car parks with electric vehicles’, Instal, 7–8, pp. 27–32. Available at: https://doi.org/10.36119/15.2021.7-8.4.

Yuan, S. et al. (2021) ‘A review of fire-extinguishing agents on suppressing lithium-ion batteries fire’, Journal of Energy Chemistry, 62, pp. 262–280. Available at: https://doi.org/10.1016/j.jechem.2021.03.031.