SAFE TRANSPORTATION OF ALTERNATIVE FUEL VEHICLES BY SEA

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Abstract: *World trade statistics show that almost 90 percent of all goods are shipped by sea. The global shift toward sustainable transportation has led to an increased demand for the shipping of alternative fuel vehicles (electrical, hybrid, Plug-in hybrid electric, Hydrogen fuel cell) across the seas. While environmentally friendly, these vehicles come with unique considerations and challenges when it comes to safe maritime transport. Ensuring the secure shipment of electric and hybrid vehicles requires a comprehensive approach that encompasses battery management, proper stowage and securing on board ships, compliance with regulations, and emergency response planning.*

Transporting electric and hybrid vehicles by sea requires careful planning and consideration to ensure the safety of the vehicles, the ship, and the environment. Roll-on/roll-off (Ro-Ro) ships are commonly used for the vehicles transportation, including electric and hybrid ones.

Keywords: *Maritime transport, alternative fuel vehicles, Ro-Ro ships, ship safety, fire fighting*

БЕЗОПАСЕН ТРАНСПОРТ НА ПРЕВОЗНИ СРЕДСТВА С АЛТЕРНАТИВНО ГОРИВО ПО МОРЕ

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Резюме: *Световната търговска статистика показва, че почти 90 процента от всички стоки се превозват по море. Глобалното преминаване към устойчив транспорт доведе до повишено търсене на транспортиране на превозни средства с алтернативно гориво (електрически, хибридни, Plug-in хибридни електрически, с водородни горивни клетки) по море. Въпреки че са екологични, тези превозни средства идват с уникални съображения и предизвикателства, когато става въпрос за безопасен морски транспорт. Осигуряването на сигурна доставка на електрически и хибридни превозни средства изисква всеобхватен подход, който включва управление на батериите, правилно товарене, подреждане и укрепване на борда на кораба, спазване на разпоредбите и планиране на реакция при извънредни ситуации.*

Транспортирането на електрически и хибридни превозни средства по море изисква внимателно планиране и обмисляне, за да се гарантира безопасността на

превозните средства, кораба и околната среда. За превоз на автомобили, включително електрически и хибридни, обикновено се използват Ро-ро кораби.

Ключови думи: *Морски транспорт, превозни средства с алтернативно гориво, Ро-ро кораби, безопасност на кораба, борба с пожари*

1. Introduction

As the world shifts toward greener transportation solutions, the logistics of moving Alternative Fuel Vehicles (AFVs) by sea will continue to evolve, with an increased focus on safety, efficiency, and sustainability [10]. According to the latest studies, the global AFVs market size was valued at USD 172950 million in 2022 and is forecast to a readjusted size of USD 447490 million by 2029 with a CAGR of 14.5% during review period. Hydrogen vehicles see dwindling sales in 2023, a total of 9,619 hydrogen fuel cell electric vehicle sales were registered around the world between January and July 2023.[1] Worldwide sales of electric vehicles (EVs) grew by 49% to 6.2 million units in first halve of 2023 [1,4]. EVs constitute 16% of the global light vehicle market, marking a significant increase of 12.4% from the same period of 2022 with China is leading producer as well as market. Europe is the second largest EV market, with a 24% share and 1.5 million units shipped, mainly by sea.[2] EVs are projected to match the sales of internal combustion engine (ICE) vehicles by 2030, and to surpass them by 2040.[3] The global Li-ion battery market is expected to grow by over 30% annually from 2022 to 2030.[4]

The definition of "alternative fuel vehicle" refers to:

- Battery-powered electric vehicles (pure electric vehicles) (BEVs) – powered only by electrical battery. Usually are fitted with a lithium-ion traction battery which is encapsulated and shielded by the vehicle's body. The battery pack consists of various battery modules which in turn are comprised of several (often hundreds or even thousands) battery cells.
- Plug-in hybrid electric vehicles (PHEVs) – a hybrid electric vehicle with rechargeable batteries that can be restored to full charge by connecting a plug to an external electric power source. It can rely on either electric motors or a

[1] https://www.marketreportsworld.com/
[2] https://www.canalys.com
[3] https://resources.sw.siemens.com/
[4] https://www.mckinsey.com/

conventional ICE for propulsion. The presence of the electric power is intended to achieve either better fuel economy than a conventional vehicle or better performance.

- Hybrid electric vehicles (HEVs) – powered alternatively or simultaneously by electric motor and ICE (petrol, LNG or Hydrogen)
- Hydrogen Fuel Cell vehicles (FCEVs) – uses hydrogen fuel for power, generated by converting the chemical energy of hydrogen to mechanical energy [5], either by reacting hydrogen with oxygen in a fuel cell to power electric motors or, less commonly, by hydrogen internal combustion.

Basic characteristics of different types AFVs:

BEVs: They rely on being recharged from an external power source, typically a specialised charge point, and are the greenest way to drive, with no tailpipe emissions. Usually the big battery is positioned under the car between two axles). Electric vehicles have extensive safety systems that will automatically shut down the power and isolate the battery pack when a collision or a short circuit is detected. An important safety feature of EV battery packs are in-built battery management systems (BMS). The BMS monitors and controls the battery and is a crucial factor in ensuring EV safety. It safeguards both the user and the battery by ensuring that the cell operates within its safe operating parameters. [9].

PHEVS: Usually their batteries are smaller than a pure-EV, but also have a conventional petrol or diesel power engine. A PHEV can run on the engine alone, but are most efficient when used in electric mode as much as possible.

HEVs: Some varieties of HEV use an ICE to turn an electrical generator, which either recharges the vehicle's batteries or directly powers its electric drive motors. Fire safety issues are further complicated by the fact that the two energy supply systems are located in one vehicle body. Many HEVs reduce the emissions by shutting down the engine at idle and restarting it when needed (start-stop system). If the engine is not used to drive the car directly, it can be geared to run at maximum efficiency, further improving fuel economy. There is a variety of HEV types and the degree to which an electric function is used: parallel hybrids (the ICE and the electric motor are both connected and simultaneously transmit power to drive the wheels), series hybrids (only the electric motor drives the wheels, and a smaller ICE works as a generator to power the electric motor or to recharge the batteries), full hybrid (it can run only on ICE, only on an electric motor, or a combination of both. LNG is stored in a thermos tank at

-162°C and at around 5-20 bars pressure to minimize heating of the gas which causes the pressure to rise which is vented to avoid tank rupture. Once parked the liquid starts to heat up and, unless the engine is started, venting of the pressure build up will eventually occur (boil-off). CNG/CBG is often stored in a gas tank of 200 bar pressure.

FCEVs: Although rare, they are also classed as electric cars. They do not require charging, and refuelling takes only a few minutes, similar to refilling at a petrol station. However, this needs to be done at a dedicated refuelling site. Hydrogen is stored compressed or in fuel cells at higher pressures, 350 bar or 700 bar. Hydrogen is colourless and odourless and burns with a very hot flame (about 2000°C). [11].

AFVs are transported mainly by RoRo (Roll-on/Roll-off) vessels, which basically are two types – PC/TC (Pure Car and Truck Carriers) and RoRo/RoPax (RoRo which carry also passengers with their vehicles). They have significant differences in their design; hence many safety measures, risk control options and incident responses are different on these ship types. The differences between them are:

PCTCs are purpose-built vessels for the transportation of different types of rolling cargo, e.g. new and used passenger cars and trucks, heavy construction equipment, and other heavy loads. There is a different risk associated with "used vehicles" – at times they may have not passed some kind of safety inspection but are being shipped to the vessel, even sometimes without knowledge of the crew. Usually are configured with 10-13 decks for the loading of different vehicle types. The height between the decks can be adjusted depending on the types of vehicles being transported. The height of the vehicle decks is extremely low to reduce the loss of cargo space. Adjustable decks further optimize the cargo space. The vehicles are loaded with very little space between them (30 cm bumper-to-bumper and 10 cm between side mirrors) (Fig. 1a). This impedes quick access to specific cars.

A challenge specific to RoPax vessels is the cargo they carry (Fig. 1b). Vehicles as cars, buses and excavators are often are not new but used and may have hidden damages which are impossibly to detect upon loading. It is a difficult to visually check at the terminals which units are safe to carry and which ones may not be safe. A particularity of RoPax vessels is the growing interest by passengers to have the possibility to charge EVs on board. [9].

 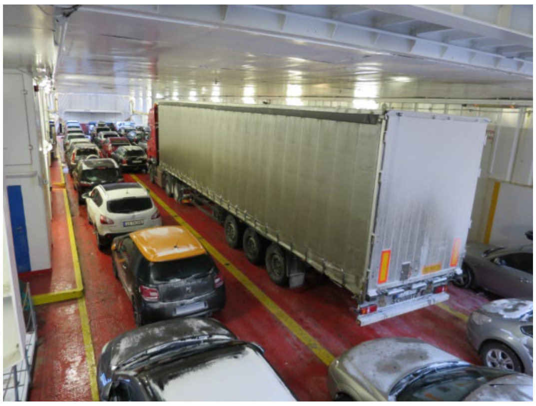

Fig.1. Cargo on deck a) PCTC b) RoPax

2. Safe loading of AFVs

Transporting Alternative Fuel Vehicles (AFVs) by sea is becoming increasingly important as the global focus on sustainable and eco-friendly transportation grows. Moving towards sustainable transport also means that the transportation of AFVs onboard ships is performed at a high safety standard, mitigating risks to the crew, the ship and the environment. Whether it is BEVs, FCEVs, or other alternative fuel-powered automobiles, the logistics of their sea transport involve unique considerations, navigating a set of unique challenges.

The crew plays a pivotal role in ensuring the safe loading of EVs onto these vessels. The crew's preparation for shipment of AFVs starts with pre-loading inspection. It should be carried out prior to loading, while cargo is still on the prier. The information on the type of fuel or energy supply should be provided during booking and confirmed at the check-in if possible. All AFVs should be clearly identified with a marking system that the master and all the crew are familiar with. During this inspection the crew should to verify that the battery of BEVs are not damaged or defective, there are no alarms active in its battery management system, other AFVs are free from any leakages of fuel/gases, to ensure that the power sources are properly secured and disconnected before loading. If a battery is damaged, a small amount of fluid may leak from under the vehicle as it is liquid-cooled, typically with glycol-based automotive coolant. Any fluid leakage must be investigated immediately and should prompt further action following the investigation. BEVs which are damaged in any way that may impact on the battery system should not be loaded on board. Bodywork scrapes, damaged headlights, windscreen cracks etc. do not impact the battery system and could be accepted. Pre-loading inspection should not impede or delay cargo operations.

Stowage and securing: Efficient stowage planning is essential for maximizing the cargo capacity of a Ro-Ro ship while maintaining safety standards. Ship operators and cargo planners should collaborate to design stowage plans that consider the weight, dimensions, and specific features of EVs. For instance, BEVs are approximately 25% heavier than vehicles with ICE; the difference in weight is between 200 and 500 kg. This may result in deck loading limitations being exceeded and could adversely affect the stability of the vessel, therefore should be considered when stowing the vehicles in weight and stability calculations to minimize the potential negative impact on vessel stability. [3]. On the other hand, EVs with low ground clearance should be clearly labeled as this can present loading and discharging challenges arising from the vessel's ramps, inner slopes, or deck appendages – it can lead to battery damage with all consequences. Usually, unless loaded in separate compartment AFVs are note separated from other cars with ICEs, therefore they should display clear and precise identification on the windshield detailing the battery and power supply type. Operators should consider the use of drivers' information about number of AFVs loaded onboard and may include details to separate pure electric vehicles from hybrid vehicles. The driver should also identify if there are any error messages or other indications of possible faults on the vehicle for example dashboard warnings before loading AFVs on the vessel. The crew shall be well informed where these vehicles are stowed. Depending on the make and model of a hybrid or electric vehicle a battery isolation switch may be fitted within the cabin of the vehicle. If fitted then this should only be activated once the vehicle is parked and secured.

AFVs should be stowed in a way that will allow patrols direct access to all such vehicles. In addition, when they are stowed in Ro-Ro spaces or special category spaces any repair works in such spaces should not be carried out, with particular attention to those activities implying the use of naked flames or fire ignition sources. AFVs may use gaseous fuels such as hydrogen or compressed natural gas so the cargo area should be well-ventilated and equipped with gas detection systems to monitor potential leaks.

EVs must be securely fastened during transportation to prevent movement and potential damage.

3. Fire precautions for transportation of AFVs

The efforts for cleaner road transport in the world adds new risks for ship operators as a rich mix of fuels and batteries will be onboard Ro-Ro's and RoPax vessels. Main fire-related characteristics AFVs are:

BEVs: While the likelihood of fires for BEVs is very low compared to fires from ICE vehicles (about 60 times less likely to catch fire), the fires involving BEVs reach full potential in a shorter period in comparison and can reach temperatures of more than 1600O C, hot enough to burn metals like aluminium, commonly used in BEV construction to reduce weight. Typically flames shoot upwards and outwards simultaneously. [2]. During the fire, toxic and highly corrosive hydrogen fluoride and hydrogen chloride gases are released. Electric cars with large Li-Ion batteries in general burn for a particularly long time. Increased temperature caused by fire, physical damage or internal shortcut could lead to thermal runaway is a chain reaction within a battery cell that can be very difficult to stop once it has started. This chemical reaction produces even more heat, which drives the temperature higher, causing further chemical reactions that create more heat. In thermal runaway, the battery cell temperature rises incredibly fast (milliseconds). The energy stored in that battery is released very suddenly. This chain reaction creates extremely high temperatures (around 400^{O} C).

PHEVS: Additionally to mentioned battery features, there dangers, connected with presence of liquefied fuels: jet flames from Pressure Release valve (PRV) activation, gas tank integrity loss and gas leak, pressure vessel explosion, fire ball, etc.

FCEVs: Much higher tank pressure than CNG can lead to leaks, which could lead to accumulation of flammable or even explosive hydrogen air mixtures for a short period. Rupture of pressure tank can cause very high concentrations of hydrogen in the vicinity of the car. Enclosed spaces could accumulate enough hydrogen-air mixture for a large explosion. There could be more ignitable, higher flammability and explosivity than conventional fuels and natural gas.

General fire precautions on board Ro-Ro vessels are aimed to early detection of possible fire by means automatic sensor system and physical patrolling.

Fixed fire detection system: It is a fire and gas detection system, which incorporates detecting sensors, located in almost all ship's compartment and a control panel on the Bridge. Depending on fire dangers there are different types of sensors: infrared (for detecting flames and changes in temperature), smoke and gas. Furthermore, a big advantage will be installing of closed-circuit television (CCTV) which can incorporate a flame recognition system. Usually activating a sensor will trigger a sound signal on the system panel. Very important principal of operating the fire detecting system is to consider any alarm as real one until physically proven that it is false.

Fire patrol: During sea passage the crew shall perform regular fire patrolling, which frequency and procedures are depending on company policy, as the International Maritime Organization (IMO) regulations in SOLAS Convention [8] are quite vague. In the general case, patrolling begins immediately after sailing and is carried out once per watch, i.e. at 4-hour intervals. If some AFVs are considered to pose an increased risk, frequency should be increased and the cargo spaces where they are loaded may be inspected at more frequent intervals. Crew members performing fire patrol duties should be familiarised in the basic characteristics and safety aspects of AFVs. They should be especially alert to AFVs related signs such as smoke/heat emitted from parts of vehicle where a battery is normally located, popping sounds from battery cells caused by a thermal runaway, sounds related to opening of over pressure valves on CNG or LNG tanks, leakages or gas smell. On RoPax ships attention should be paid also to suspected unauthorized connection to ship electric system for charging of batteries. The patrolling personnel should wear proper attire and use dedicated equipment: handheld VHF radios, explosion-proof flashlights, it is good if they are provided with portable thermal imaging cameras.

4. Fire-fighting AFVs fires

Ships means for firefighting are limited to:

Fire extinguishers: Basically Ro-Ro cargo decks are equipped with dry-powder extinguishers, but for the areas with loaded AFVs preferably should be used dry-chemical and CO_2 types.

Fire blankets or Fire Shields: They are made from fire-resistant materials and their function is to prevent spreading of fire to neighboring cars. Blankets are large size, big enough to cover several cars, the shield are used to separate the place of burning vehicles. These means should be distributed in the respective areas in advance in order to be applied to the accidental car manually by fire fighting team very fast. Fire blankets cannot stop the thermal runaway in the battery module from continuing but the combustion of other vehicle construction materials can be stopped by the blanket and the flying away of particles is reduced.

Ship's fire main: It is sea-water based system of pipes and hydrants. The water is delivered by main or emergency fire pumps and distributed all over the ship. Different accessories could be attached to the hydrants – fire hoses with nozzles, portable sprinklers, foam applicators, etc. The system is used mainly for cooling burning materials as well for boundary-cooling of adjacent bulkhead. Water has excellent cooling effects and it can be an effective way of cooling EVs batteries with thermal runaway or to prevent a tank catching fire, although is difficult to direct water jet or spray on BEVs batteries or LNG/CNG/Hydrogen tanks because they are typically installed in lower sections of vehicle chassis or inside the trunk. Even so, spraying water on burning vehicles surrounding can be an excellent way of preventing fire spread. If an EV caches fire while charging, before applying water fire fighting the electricity shall be cut off. To fire main is connected also the fixed sprinkler system but the sprinklers are mounted on the ceiling above the cars, so they can perform only general cooling. Basic drawback of using fire main for firefighting is the possible negative consequences from accumulating of large amount sea water – reducing the reserve buoyancy and adverse effect on ships stability caused by water free surface.

Water mist: It is high pressure water system with cooling and smothering effect. The applicators could be fixed on the ceiling or portable ("mist nail" or "mist lance"). High pressure water mist systems very suitable because they disperse the fire-fighting agent very evenly throughout the affected place, also allowing it to reach covered areas (Fig. 2a). For AFVs the lance is more applicable because it can pierce the cars window or trunk cover and spray the mist over its floor for cooling the battery or tank respectively. The mist lance is very useful for fighting fire on car, transported in container. (Fig. 2b)

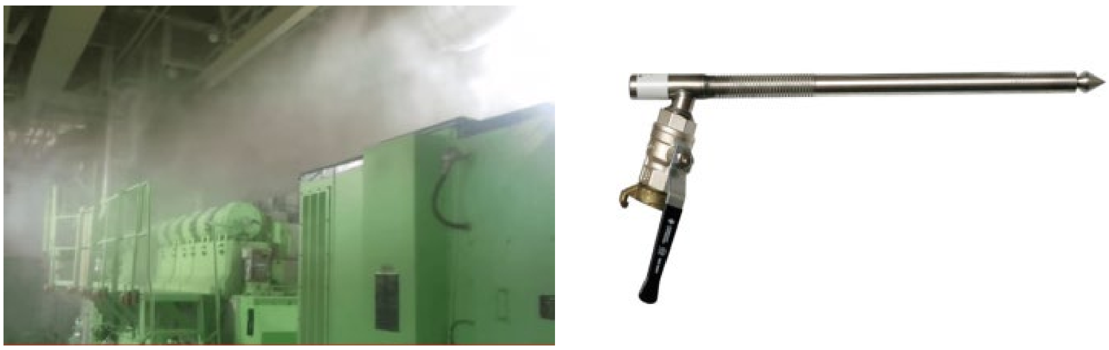

Fig. 2 a) Water mist in action; b) "Mist nail" (Lance)

Fixed fire systems: Fixed fire systems usually are applied in case that manually f the fire cannot be controlled, but sometimes could be considered their use first rather than manual firefighting by the crew. Almost all such systems are called "volumetric" because they fill the entire volume of the compartment, pushing the air out. The typical ship's fixed fire system is based on CO_2. Basic drawback of CO_2 system is its lethal effect on humans, therefore before releasing the gas all crew have to leave the place and to be accounted for. Another type "volumetric" system is the high-expansion foam. More modern systems also fill the room, but require a much smaller concentration of gases for this, and therefore are not dangerous for people who may be left there. They are called „Fire suppression systems". Such systems use gases such as Nitrogen, exhaust gases (inert gas system), Halon, Freon, HFC-227ea, FM 200 (HFC 227), Novec 1230, as well as aerosols.

Crew training: Training the crew on handling emergencies, such as fighting fires is critical for ship's safety. SOLAS Convention [8] determines that each crew member shall participate at least in one fire drill per month. As shipping is changing, evolving with the new cargoes with new fuels, it is becoming clear that crew training has to also evolve, they need to know more about the risks of new challenges and to be able to cope with them. Crew involved in firefighting should be capable of recognizing AFVs, understand the risks posed by them and be aware of the possible consequences if they catch a fire. Specialised response to such fires should be risk assessed and should be incorporated into the vessels fire drills schedules. Drills should be as close to reality as possible and to include all feasible scenarios, including fire out of control and ship abandon.

5. Conclusions

The global shift toward sustainable transportation has led to an increased demand for the shipping of electric and hybrid vehicles across the seas. While environmentally friendly, these vehicles come with unique considerations and challenges when it comes to safe maritime transport. The growing AFVs market and future's emission control will be pushing ship-owners to make investments for safer and more efficient transport operations. Ensuring their secure shipment requires a comprehensive approach that encompasses battery management, packaging, compliance with regulations, and emergency response planning. By addressing these aspects comprehensively, stakeholders can contribute to the sustainable and secure maritime transport of these vehicles, further promoting the global shift towards eco-friendly transportation solutions.

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