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Stability of a Ro-Ro Ship: An Assessment of the Impact of Electric Vehicle Transportation

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ABSTRACT

In terms of service lives, ships have the ability to remain operational for extended periods of time, potentially exceeding several decades. Changes in machinery and equipment are dependent on technological improvements. The above change is most noticeable in the components that make up ship systems. Nonetheless, the movement of ships on the water involves research into a variety of topics, including static-dynamic equilibrium and the demands of speed and power. The study focuses on the growing fascination with electric automobiles, which can be ascribed to technology improvements, environmental policies, and the concept's widespread acceptance. As a result, there has been a boom in interest in purchasing electric vehicles and using them for transportation. When conventional internal combustion engine automobiles are considered during the design process of marine vessels that transport land vehicles, it is expected that electric vehicles (EVs) will be primarily transported by Roll-on/Roll-off (Ro-Ro) ships in the foreseeable future. However, weight discrepancies exist between electric vehicles and other models in the same category. The significant weight attributed to batteries emphasizes the significant possibility for advancement in modern battery technology. This research aims to examine the changes in the stability of a Ro-Ro ship carrying an equal number of conventional and electric vehicles and evaluate the effect of transportation of the same total weight of these two vehicle types on ship stability.

Keywords: Electric vehicle transportation, ro-ro ships, ship stability

Bir Ro-Ro Gemisinin Stabilitesi: Elektrikli Araç Taşımacılığının Etkisinin Değerlendirilmesi

ÖZ

Hizmet ömürleri açısından gemiler, potansiyel olarak birkaç on yılı aşan uzun süreler boyunca çalışır durumda kalma kapasitesine sahiptir. Makine ve ekipmanlardaki değişiklikler teknolojik gelişmelere bağlıdır. Gemilerdeki değişiklikler en çok gemi sistemlerini oluşturan bileşenlerde fark edilmektedir. Bununla birlikte, gemilerin su üzerindeki hareketi, statik-dinamik denge ve hız-güç talepleri de dahil olmak üzere çeşitli konuların araştırılmasını gerektirir. Çalışma, teknolojik gelişmelere, çevre politikalarına ve konseptin yaygın kabulüne atfedilebilecek elektrikli otomobillere yönelik artan ilgiye odaklanıyor. Bunun sonucunda elektrikli araçların satın alınması

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ve ulaşımda kullanılmasına ilgide patlama yaşanmaktadır. Kara taşıtlarını taşıyan deniz araçlarının tasarım sürecinde konvansiyonel içten yanmalı motorlu otomobiller dikkate alındığında, öngörülebilir gelecekte elektrikli araçların (EV) öncelikli olarak Roll-on/Roll-off (Ro-Ro) gemilerle taşınması beklenmektedir. Ancak elektrikli araçlar ile aynı kategorideki diğer modeller arasında ağırlık farklılıkları mevcuttur. Pillere atfedilen kayda değer ağırlık farkı, modern pil teknolojisindeki önemli ilerleme olasılığını vurgulamaktadır. Bu araştırma, eşit sayıda konvansiyonel ve elektrikli araç taşıyan bir Ro-Ro gemisinin stabilitesindeki değişiklikleri incelemeyi ve bu iki araç tipinin aynı toplam ağırlıkta taşınmasının gemi stabilitesi üzerindeki etkisini değerlendirmeyi amaçlamaktadır.

Anahtar Kelimeler: Elektrikli araç taşımacılığı, ro-ro gemileri, gemi stabilitesi

1 Introduction

Car carriers, often referred to as vehicle carriers, are specialized marine vessels designed for the primary objective of transporting a diverse range of wheeled vehicles, such as cars, trucks, buses, and similar means of transportation. These vessels are often utilized to transport various combinations of vehicles (Kang et al., 2012). Roll-on/Roll-off (Ro-Ro) vessels are categorized as such based on their resemblance in the processes of loading and unloading. Pure Car Carriers (PCCs) are a type of maritime vessel that is purposefully constructed for the only purpose of transporting vehicles. On the other hand, Pure Car Truck Carriers (PCTCs) are a form of specialist vessels designed to transport a diverse range of wheeled cargo, including vehicles (Yasukawa, 2019). In addition to commercial maritime vessels, a variety of Ro-Ro ships can be found, which include ferries as well as military tanks (Kennedy, 2023). A comprehensive account of several ship designs is provided in the subsequent text.

- A Pure Car Carrier (PCC) is a specialized vehicle that is specifically constructed for the transportation of autos, with a particular focus on new vehicles, to their respective sales regions (Hasegawa et al., 2006).

- The Pure Car Truck Carrier (PCTC) is a specialist maritime vessel specifically engineered for the purpose of transporting a wide range of wheeled vehicles across many ports. This classification comprises a diverse range of vehicles, including automobiles, trucks, tractors, and other wheeled industrial vehicles (Silvanius, 2009).

- The Container Ship and Ro-Ro Ship (ConRo) is a type of vessel that combines the functionalities of a conventional container ship and a Ro-Ro ship, which is specifically built for the transportation of wheeled vehicles (Daduna, 2013).

- The General Cargo and Ro-Ro Ship (GenRo) is a maritime vehicle that exhibits a hybrid configuration, integrating the characteristics of a conventional cargo ship with a Ro-Ro ship. The GenRo ship is typically distinguished from a ConRo ship by its relatively smaller size and cargo-carrying capacity (Schramm, 2020).

- The RoPax ship is a maritime vessel that enables the conveyance of both passengers and motor vehicles. It can be compared to a ferry in terms of its operational characteristics and intended use (Antão & Guedes Soares, 2006).

Car carriers do not require the use of specialist equipment for the loading and unloading procedure, unlike other types of vessels that rely on cranes or pumps for cargo handling activities. The ship is equipped with ramps, often located at the stern or stem (sometimes on the side, although less commonly), which facilitate the transportation of wheeled vehicles to their designated areas on board. Following the procedure in reverse, the unloading of cargo is then carried out at the designated port

(Tuswan et al., 2021). Cargo ships and container ships have different criteria for measuring load capacity. Cargo ships commonly adopt the Deadweight Tonnage (DWT) measure, whilst container ships typically utilize the Twenty Foot Equivalent Units (TEU) meter. In contrast, Ro-Ro vessels quantify their cargo-carrying capability by assessing the aggregate loading length in lanes or the overall count of vehicles conveyed (Sun et al., 2022).

The Höegh Target, a famous Pure Car Carrier, exhibits an impressive capability to transport up to 8500 autos throughout its fourteen distinct decks. The design of this ship has been purposefully optimized in order to improve and simplify commercial operations between the East Asian and European regions (Nieuwenhuis, 2017). Despite its impressive payload capacity, this particular vessel does not qualify as the longest vehicle carrier, as its dimensions measure approximately 200 meters in length and 36 meters in width.

Car carriers can be readily identified based on their external features, as they are equipped with noticeably elevated sideboards (Simopoulos et al., 2008). According to Thies and Ringsberg (2023), the lateral sides of ships, characterized by their expansive surface area, are susceptible to straying from their intended orientation when exposed to high winds. The increase in the vehicle's transport capacity is achieved by vertically arranging multiple decks. To address the issue of less cargo space, the configuration of tween decks is strategically adjusted to maximize loading capacity (Skoupas et al., 2009). Moreover, the ship utilizes two ramps located at the front and back ends, respectively, to enhance the efficient execution of loading and unloading procedures (Sun et al., 2022).

According to the International Energy Agency (IEA), the projected quantity of electric vehicles in circulation during the year 2021 is around 16.5 million. Additionally, the IEA anticipates an additional 10 million EVs to be sold in the subsequent year of 2022 (IEA, 2023). In the year 2022, inside the European Union (EU), the proportion of newly registered vehicles that were powered by petrol accounted for 36.4%, and diesel-fueled cars constituted 16.4% of the total registrations. The data reveals that electrically chargeable vehicles account for 21.6% of recently registered passenger cars in the European Union. In September 2019, a maritime incident transpired with a cargo vessel carrying a substantial load of 4200 autos, which encountered a disastrous occurrence leading to its overturning. The occurrence pertaining to the capsizing of the cargo vessel known as the "Golden Ray," which possessed a deadweight tonnage (DWT) of 20995, in the vicinity of the Georgia coastline, resulted in significant monetary damages over $200 million (Mok et al., 2023). The primary cause of this terrible incident can be largely traced to inaccurate stability calculations related to the vessel. According to Riess and Gray (2021), a significant sum of $142 million was reported as damages directly associated with the carried cargo. Considerable attention is devoted to the matter of stability for this particular type of vessel, both in its intact state and when subjected to damage (Ruggiero, 2015). Additionally, the ship's stability is examined in connection to its operational profile, considering the specific climatic conditions it is expected to encounter along its intended sailing path. The objective of this study is to evaluate the feasibility of utilizing a PCC for the transportation of electric vehicles as a viable alternative to traditional fossil fuel-powered vehicles. The primary emphasis was placed on examining the ability of electric vehicles to contribute towards the reduction of greenhouse gas emissions. The primary objective of this study is to investigate the effects of transporting electric vehicles, in comparison to conventional automobiles, on the stability of ships. Moreover, comparative data was obtained by conducting transportation scenarios that involved both conventional automobiles and electric vehicles. The scenarios included an equal number of vehicles and a similar total cargo weight.

2 Ship Stability Parameters and Regulations

The existence of several stability control factors in the equilibrium of forces acting on floating bodies, such as ships, has been demonstrated by Im and Choe (2021). The idea of "metacenter height," which is employed to assess initial stability, is considered the most fundamental among these concepts (Ibrahim & Grace, 2010). The calculation of this variable term is contingent upon factors such as displacement, hull shape, and trim angle. In order to attain a state of equilibrium, it is necessary for the total sum of forces and moments acting on an item to be equal to zero. In the absence of any inclination, it may be observed that the center of buoyancy and the center of gravity of a ship align in the same orientation. According to Shakeel et al. (2022), in the event of a change that results in a non-zero distance between these centers, the motion of the ship's heel is noted until the alignment of the ship's center of buoyancy and center of gravity is restored. The point denoted as "M" in Figure 1, which lies on the ship's center line and crosses the new buoyancy center of the ship perpendicularly to the "B" waterline, is commonly referred to as the metacenter point in the state of equilibrium. The ship's "GM" value is determined by the distance between the ship's center of gravity "G" and the point "M" on the center line. The parameter in question is a value that is assessed according to the intact stability regulations of the IMO. The concept of stability is referenced specifically when this value exceeds zero, as noted by Marlantes et al. (2022). If this requirement is not met, the ship will be unable to maintain buoyancy.

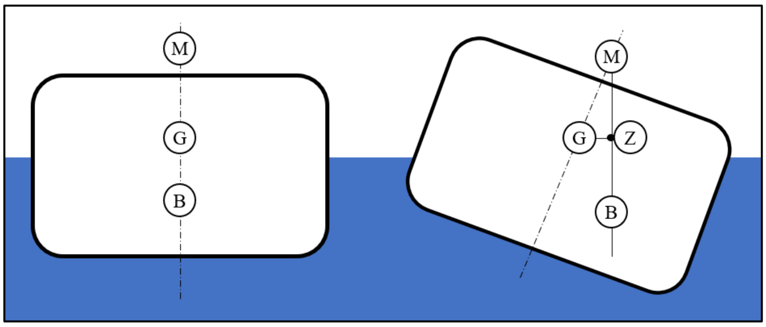

Figure 1: The representation of the initial ship stability condition

The concept of "righting arm - (GZ)" is also employed in the assessment of ship stability (Perrault, 2016). The determination of the moment arm, denoted as the "Z" point, which crosses the line passing through points B and M, and is measured from the ship's center of gravity, is contingent upon the ship's heel angle. The ships revert to their original positions and maintain the initial configuration due to the presence of a moment arm generated at this location.

The current regulations pertaining to Intact Stability (IS) predominantly rely on statistical and semi-empirical methodologies, which fail to sufficiently account for specific perilous dynamic phenomena that may arise in wave conditions. One of the observed occurrences is Parametric Roll (PR), which refers to the occurrence of resonance-induced rolling due to periodic fluctuations in the righting lever caused by longitudinal waves. Another occurrence that can occur is known as Pure Loss of Stability (PLS). This phenomenon is characterized by substantial heel angles or capsizing caused by a decrease in transverse stability when encountering following or stern quartering waves, especially when the wave crest is in close proximity to the midship region. Surf-riding/broaching (SF) is a perilous occurrence that is distinguished by significant heel angles or capsizing, which occurs due to a diminished ability to maintain course in surf-riding conditions. The phenomenon known as Excessive Acceleration (EA) is commonly linked to the roll motion of a ship. On the other hand, the Dead Ship Condition pertains to a ship that lacks power while encountering beam waves and wind.

During the 8th meeting of the International Maritime Organization (IMO) sub-committee on Ship Design and Construction (SDC) in 2022, the final draft of the Explanatory notes to the interim guidelines on the Second-Generation Intact Stability criterion (SGISc) was approved (IMO, 2022). The paper in question was formally endorsed by the Maritime Safety Committee (MSC) during its subsequent meeting in 2022, with the endorsement being sent by an MSC Circular. This event is the completion of a lengthy developmental process that began around twenty years ago. The authoritative document containing the text of the SGISc can be located in the MSC.1/Circular 1627, as published by the International Maritime Organization in 2020. Currently, the utilization of the application is not mandatory according to the IMO; nonetheless, the organization strongly advocates for its adoption in order to improve the gathering of feedback and experiences, hence facilitating future improvements. The SGISc represents notable progress in the implementation of a probabilistic and performance-based approach in the field of ship safety. The aforementioned criteria pertain to the ship's stability performance, specifically considering the dynamic influences resulting from wind and waves.

The formulation of the SGISc has taken into account the operating parameters of the ship. This development represents a notable progression as compared to the first set of standards, particularly the IS code (IMO, 2008). The recently implemented standards include a collection of Operational Measures (OM), including two elements: Operational Limitation (OL) and Operational Guidance (OG). The significance of implementing this measure has been acknowledged as a result of the understanding that, in order to improve the safety of ship operations, it is crucial to take into account various operational elements (Liwång, 2019; Rudaković & Bačkalov, 2019). The operational measure can be considered as an additional tool for effectively addressing the safety performance of a vessel.

3 General Characteristics of the Concept Vessel

The ship used in this study was designed by the author, and the geometric features of similar ship types in current use were taken into consideration. The initial design calculations for a PCC-type Ro-Ro vessel encompass the creation of a model representing the proposed design and the identification of crucial aspects, such as loading conditions. The determinations are derived from rough calculations of the overall weight categories, hydrostatic properties, and stability measurements. When assessing the stability characteristics, it is postulated that the vessel maintains buoyancy at two discrete drafts, specifically 10.50 m and 11.11 m. A water depth of 10.50 meters is required to facilitate the transportation of an entire fleet of 7700 conventional-engine cars or 5775 electric vehicles (EVs). A water depth requirement of 11.11 meters is deemed necessary when the cargo consists only of 7700 new-generation electric vehicles. Consequently, the calculated level of stability encompasses three distinct combinations. Table 1 presents a detailed summary of the fundamental data pertaining to the vessel.

The PCC Ro-Ro vessel, which has been designed specifically to facilitate the movement of vehicles, incorporates a total of 14 decks that are exclusively allocated for the purpose of containing cars. The present design facilitates the effective loading and transportation of a maximum capacity of 7700 automobiles. The schematic depiction of the ship's design, as examined in this investigation, is presented in Figure 2. The design comprises a conventional propulsion system, consisting of a singular internal combustion main engine and a propeller.

Table 1: *Details about the ship*

Specifications	**Values**	
Length overall (LOA) [m]	230.0	230.0
Draft amidships (T) [m]	10.50	11.11
Displacement [t]	53050	56900
Waterline (WL) length [m]	219.99	220.25
Beam max extents on WL [m]	32.00	32.00
Wetted area [m^2]	8991.1	9300.9
Waterplane area [m^2]	6189.9	6268.9
Prismatic coefficient (C_p)	0.748	0.755
Block coefficient (C_b)	0.700	0.707
Max Section area coefficient (C_m)	0.945	0.948
Waterplane area coefficient (C_{wp})	0.879	0.890

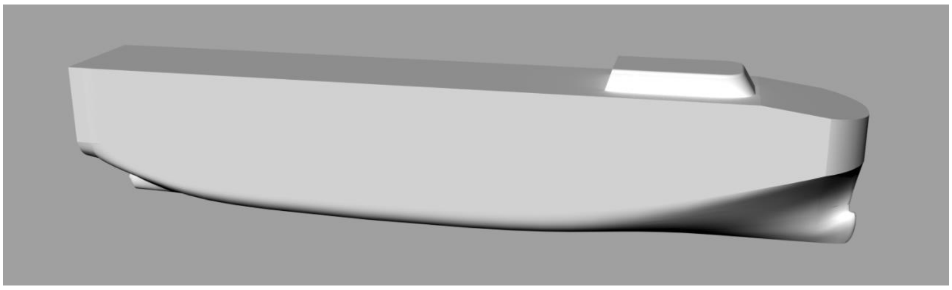

Figure 2: An overall perspective of the concept vessel

The process of assigning weight categories to the ship was carried out by employing empirical calculations derived from relevant literature sources. The utilization of empirical formulas for estimating values is a prevalent technique in the early phases of ship construction, particularly for the purpose of preliminary design. Table 2 provides a thorough compilation of weight categories, along with empirical weight estimation methodologies and their corresponding values.

Table 2: *Properties of the weight categories*

Weight group	**Calculation method**	**Weight [t]**	
		T=10.50m	**T=11.11m**
Construction	Kafalı (1988)	20000	
Main machinery	Barrass (2004)	1800	
Auxiliary machinery	Kupras (1981)	1000	
Outfitting	Kafalı (1988)	4500	
Engine car cargo load	Jia (2007)	11550	-
Electrical car cargo load	Kane (2023)	-	15400
Service requirements	Sun et al. (2022)	14200	
Displacement		25750	29600
Total displacement		53050	56900

The total displacement of a ship is determined by its general characteristics, weight groups, and distributions. The consideration of ship stability maintains significant importance within the realm of ship design.

4 Results and Discussion

Ships are subjected to a wide range of fluctuating conditions during the course of their trips. Despite a lack of understanding of how these variables affected ships before that period, adherence to stability requirements set by international conventions and recognized by classification societies in ship designs ensures safety. The sinking or damage to ships can occur due to the presence of inappropriate cargo or a failure to adhere to adjustments in ship equilibrium throughout the course of the journey. Maritime incidents result in various adverse consequences, including casualties, material damage, and substantial harm to marine ecosystems and the environment. Irrespective of the specific characteristics and size of the vessel under consideration, it is imperative to get the hydrostatic values table as an initial phase in the ship design process. Table 3 displays the pertinent parameters utilized in the hydrostatic calculations of the PCC Ro-Ro vessel concept under examination.

Table 3: *The ship's hydrostatic values*

Draft amidships [m]	**9.50**	**10.00**	**10.50**	**11.00**	**11.50**
Displacement [t]	46763	49877	53050	56221	59442
Heel [deg]	0.00	0.00	0.00	0.00	0.00
Draft at FP [m]	9.50	10.00	10.50	11.00	11.50
Draft at AP [m]	9.50	10.00	10.50	11.00	11.50
Draft at LCF [m]	9.50	10.00	10.50	11.00	11.50
Trim (+by stern) [m]	0.00	0.00	0.00	0.00	0.00
WL length [m]	219.39	218.96	219.99	220.23	220.25
Beam max extents on WL [m]	32.00	32.00	32.00	32.00	32.00
Wetted area [m^2]	8486.68	8731.17	8991.05	9247.34	9497.87
Waterplane area [m^2]	6046.66	6116.79	6189.96	6256.76	6312.67
Prismatic coefficient (C_p)	0.737	0.745	0.748	0.754	0.760
Block coefficient (C_b)	0.684	0.695	0.700	0.708	0.716
Max section area coefficient (C_m)	0.939	0.942	0.945	0.948	0.950
Waterplane area coefficient (C_{wp})	0.861	0.873	0.879	0.888	0.896

In order to determine the equilibrium and stability characteristics of a constructed ship model, it is imperative to conduct a series of computational analyses. To conduct these calculations, it is essential to first determine the weight of the ship's hull, machinery, and equipment, together with the cargo carried on both the decks and holds. Furthermore, it is necessary to ascertain the required load for the service as well as identify the placement of comparable specialized equipment on the vessel's hull. By employing data acquired via stability calculations and the accompanying equilibrium conditions, it becomes possible to predict the motions of a vessel in its buoyant condition. Table 4 displays the cargo statistics for every loading combination of the conceptual vessel. The utilization of these computations also presents several benefits in the realm of hull design.

Based on the data provided in Figure 3, it is important to possess the GZ-φ graph in order to evaluate the ship's ability to sustain its buoyant state after undergoing modifications caused by internal and external forces acting upon it. In the absence of these forces, the ship has the ability to return to its initial state of balance. In the present study, it is important to analyse the data obtained for the three different loading conditions.

The stability curve of the loading scenarios demonstrates that the minor disparity in stability values between conventional and electric vehicles can be ascribed to the negligible fluctuation in weight on the vehicle decks, assuming a consistent total load weight. The projected maximum limit for the moment arm of the righting capability in the 7700 conventional vehicles and 5775 electric vehicles is approximately 3.20 meters. The aforementioned measurement is attained when the angle of the heel reaches 44.5 degrees. However, if all the cargo compartments of the ship are occupied with 7700 electric vehicles (EVs), there is a 15% reduction in the value of the righting moment arm, leading to a decrease of 2.689 meters. The mentioned reduction is equivalent to a heel angle of 42.7 degrees. Hence, it is evident that the transportation of an equal quantity of conventional and electric cars results in an increase in the ship's draft and a decrease in the stability needed.

Table 4: *Loading conditions*

Item Name	**Longitudinal Arm [m]**	**Vertical Arm [m]**	**Total Mass (7700 Conv.)[t]**	**Total Mass (5775 EVs) [t]**	**Total Mass (7700 EVs) [t]**
Construction	110.00	10.00	20000	20000	20000
Machinery	28.00	3.00	2800	2800	2800
Outfitting	110.00	8.00	4500	4500	4500
Car deck 1	110.00	2.70	450	450	600
Car deck 2	110.00	5.00	450	450	600
Car deck 3	110.00	7.30	525	540	700
Car deck 4	110.00	9.60	825	830	1100
Car deck 5	110.00	11.90	825	830	1100
Car deck 6	110.00	14.20	825	830	1100
Car deck 7	110.00	16.50	825	830	1100
Car deck 8	110.00	18.80	975	970	1300
Car deck 9	110.00	21.10	975	970	1300
Car deck 10	110.00	23.40	975	970	1300
Car deck 11	110.00	25.70	975	970	1300
Car deck 12	110.00	28.00	975	970	1300
Car deck 13	110.00	30.30	975	970	1300
Car deck 14	110.00	32.60	975	970	1300
Service req.	115.00	8.00	14200	14200	14200
Total tonnage			53050	53050	56900

* "Conv." is for carrying conventional engine cars; "EVs" is for carrying electric vehicles.

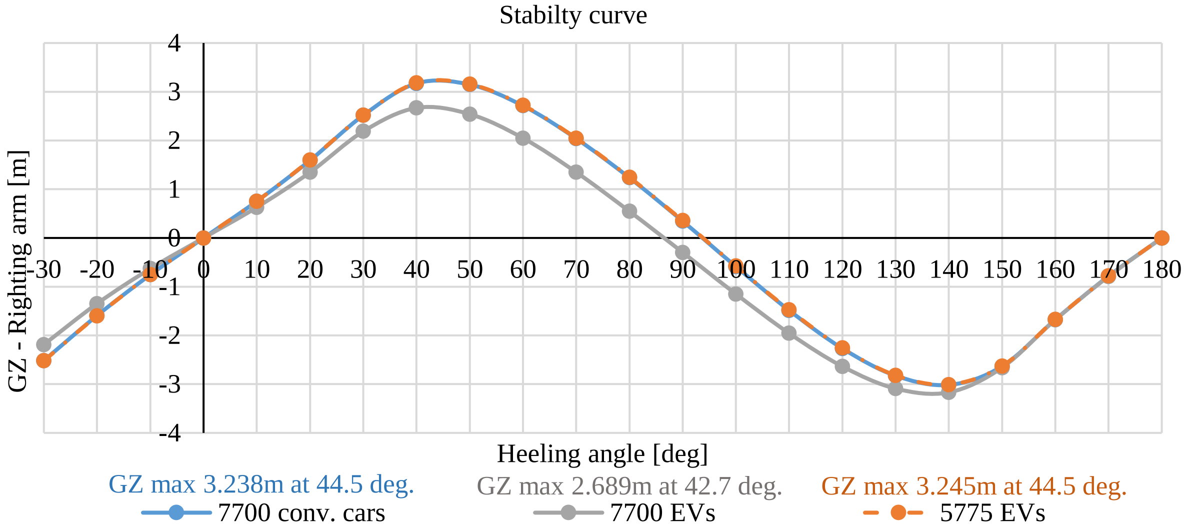

Figure 3: Calculated stability values

5 Conclusions

The objective of this research is to examine the effects of shipping a specific number of electric vehicles, respectively 5775 and 7700, on the stability of a Ro-Ro vessel. This investigation focuses on a scenario where the Ro-Ro ship is already loaded with 7700 cars that are powered by internal combustion engines. Additionally, it is important to acknowledge that electric vehicles (EVs) possess a greater unit weight in comparison to traditional vehicles. This prompts inquiry into the potential equilibrium condition that might ensue if the entirety of the ship were to be exclusively occupied by electric cars. Furthermore, it is crucial to consider the hydrostatic values while examining the state of balance.

The findings indicate that, when considering standard operational circumstances and a consistent ship draft, the transportation capacity of traditional cars is 7700, while electric vehicles have a capacity of 5775. This finding suggests a decrease of 25% in the vehicle's carrying capacity for products. In this particular case, it can be inferred that the cost of transportation per automobile will have a direct correlation with the rise in quantity.

When the quantity of vehicles being transported remains constant, the presence of 7700 electric vehicles within the cargo compartments leads to a rise in the ship's draft of 61 cm. This suggests that the vessel requires supplementary engine power due to the increased wet surface area, even when accounting for the situation when the ship is exclusively engaged in displacement-type motion. If the installed engine power is enough, a larger quantity of fuel is required to sustain the same operational velocity. From an alternative perspective, it denotes the choice to decrease the rate of service without incurring any additional operational costs. Therefore, the identification of supplementary operating costs incurred due to a delayed arrival at the intended location underscores the need for optimization.

In the upcoming study, an examination will be conducted on the disparities in operational expenditures related to the conveyance of 7700 and 5775 electric cars (EVs), with a specific emphasis on fuel expenditures. Furthermore, it will be investigated situations in which an increase of fuel and engine power is unattainable and proceed to examine the consequences of diminished velocity on various ancillary expenditures. In addition, there is a chance to evaluate the components that might be modified in order to avoid these changes in costs.

6 Declarations

6.1 Study Limitations

This study considers two draft values of the Ro-Ro ship, and the stability criterion mentioned only includes static stability. In addition, the configurations of the vehicle transportation service only include the separate transportation of electric or internal combustion engine vehicles, and the combined transportation of the two vehicle types is not considered.

6.2 Acknowledgements

This study is an expanded version of the proceeding presented at the I. International Maritime and Logistics Congress.

6.3 Competing Interests

There is no conflict of interest in this study.

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