The study of an innovative propulsion plant for a High-Speed Catamaran Ferry for decarbonisation in the marine industry

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Abstract. This paper supports decarbonisation in the marine industry by demostrating that a proper design methodology and state of the art technologies can significantly reduce greenhouse gas emissions. The paper demonstrates the possibility of reducing the environmental footprint of Marine High-Speed passenger transportation with innovative propulsion plant designs. The challenging solutions to designing a high-speed hybrid catamaran ferry, that satisfy design criteria and requirements, are presented and applied to a realistic case study. The design process investigated the potential electrification of the vessel to reduce its carbon footprint without compromising function and performance and a quantitative comparison to a conventional propulsion plant was carried out and presented.

Keywords: Hybrid, electric, high-speed, catamaran, ferry.

1. INTRODUCTION

The incentives and international pressures to reduce emissions from waterborne transport are constantly growing, and with the emission targets getting more stringent, technological solutions are becoming more challenging. New regulations have motivated the industry to catalyse the evolution process and seek/explore long-term solutions with *the industry prepared to invest $5billion in R&D* aimed at identifying the pathways to zero-carbon shipping [1]. Large ships that travel long distances are relying on a fuel revolution [2] while it has been demonstrated that short-range vessels can be successfully fitted with fully electric propulsion plants [3]. With smaller vessels, the number of challanges increases. Barriers to the adoption of electrification in the ferry market are generally linked to technical, operational as well as regulatory issues [4]; overcoming these barriers becomes an even greater challenge when the design in question is a high-speed boat. The significant power demand of such vessels generally requires a large battery pack due to the low energy density of batteries, therefore storage/space allocation and weight limitation often present a bottleneck. High-speed ferries are mainly used for the transportation of passengers, generally operating a very tight schedule with back-to-back trips and very limited stationary time: this minimises the time available to charge batteries thus requiring specific electric infrastructure facilities [5] as well as thorough planning of the logistics. Given the complex design criteria that have been described, the shipbuilding industry has yet to venture into the sector of low-emission, high-speed crafts.

This paper investigates various scenarios and power generation configurations for electrifying a high-speed catamaran ferry to reduce emissions and maximise energy efficiency. It presents the optimal solution based on a real-life case study application.

2. BACKGROUND

With the increasing demand for shorter travel times, there is a continuous need for high-speed passenger ferry services [6]. This market will continue to increase in size [7] as the ferry services become more efficient, cost-effective, and reliably consistent. Most passenger ferries operate in coastal and urban areas, and their environmental impact on public welfare is a matter of concern. It is highlighted in [8] that *vessels operating at high speeds raise concerns with issues of safety, environmental impact, comfort, and powering*, and as Cooper [6] indicates, harbour emissions during berthing manoeuvres and stoppages are of special interest. Although fast ferries have been operating for decades, very few sources can be found in the literature regarding the impact that the high-speed regime may have on the environment. [9] debates this topic and analyses two case studies where the implementation of fast ferry service into the existing fleet had a negative outcome due to the environmental threats such as high local emissions, coastline erosion and destruction of marine wildlife. The continuous development in technologies is now providing feasible solutions to the market: smaller and more efficient engines, lighter construction materials, and the adoption of technologies such as the electric propulsion plant, are paving way for the next generation of high-speed passenger craft.

Diesel-electric hybrid propulsion is a configuration that allows the vessel to be propelled by coupling, or alternating, electric motors with the main internal combustion engines. Such a system gives the option of operating a direct diesel-driven engine when the power demand is high and switching to electric propulsion for lower speeds and power requirements. Diesel engines are most efficient when operating around 65% - 85% MCR, with the losses increasing outside this range [10], while electric motors have a quite constant efficiency over the whole working range. Vessels that spend a significant amount of time operating at lower speeds can benefit from such a hybrid system [11]. Dynamic loads on the hull, such as manoeuvring operations, change of course or speed, cause irregular power demand from the engines. By integrating an Energy Management System, one can transfer power between the mechanical drive and the electrical network to cater for load fluctuations so the engines continuously operate at their efficient range leading to reduced fuel consumption.

Table 1. Advantages & Drawbacks of Hybrid Systems

Advantages	Drawbacks
Improved vessel performance	More batteries
Reduced Emissions	Added Weight
Safety	Reduced cargo space
Lower operating costs	High Initial Investment
EM requires lower maintenance than ICE	System is more complex
Reduced vibrations and noise levels	

Hybrid systems can be set up and installed with different configurations:

Figure 1 reports the parallel arrangement, which was used for this study.

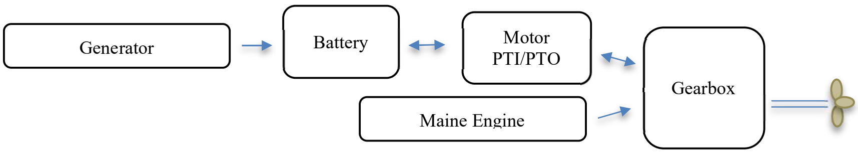

Figure 1. Parallel Hybrid System Configuration

4. CASE STUDY

Figure 2. Case Study Catamaran Ferry (NAS Ltd. Concept Design)

The case study vessel, an NAS Ltd. in-house concept design shown in Figure 2, is a 37m high speed catamaran designed with an optimal hybrid configuration to operate a realistic schedule structured to satisfy the demand for local transportation by a community of approx. 100 thousand users. The vessel is intended for all-year-round operation in conditions of significant wave height of up to 1.5 metres and a schedule anticipated to engage back-to-back trips every day. This hybrid vessel is designed to run at a maximum speed of 30 knots using internal combustion diesel engines and a speed of 7 knots in near/approaching waters using electric propulsion. This combined with optimised hull design ensures low impact of the wave pattern on the shoreline and lower CO_2 production.

Table 2. Case Study Vessel Characteristics

Vessel Particulars			
Length Overall	LOA	~ 38.00	*m*
Length of Waterline	LwL	~ 35.00	*m*
Depth	D	~ 3.50	*m*
Beam	B	~11.00	*m*
Draught	T	~1.5	*m*

Gross Tonnage	GT	495	*T*
Passengers	Pax.	450	-

The operational speed range of the case study vessel is between 20 knots and 30 knots. This is a grey area for the selection of the optimal propulsive configuration with propellers generally having higher efficiency below speeds of 20 knots and waterjets best performing at speeds of over 30 knots. The determining factor for the selection of a waterjet over a propeller was, in this case, given by the shallow waters that characterize some landing areas that the ferry would have to approach. Installing a waterjet with its inlet flush to the hull bottom would maintain the overall draught of the vessel within the 1,7 m boundary, allowing berthing operations in waters as shallow as 2,5 m. Matching waterjet propulsion to a diesel-electric hybrid system means combining two constantly evolving technologies. Literature on the subject is limited and very few designs are currently sailing with this propulsion configuration.

3. DESIGN METHODOLOGY

3.1 Resistance Estimation

The main dimensions of the vessel were defined through a statistical study of reference vessels combined with the operational criteria. A good prediction of the resistance experienced by the vessel in calm water was then computed for the estimation of power requirements: the software DelftShip was used for the modelling of the hull form, which was then tested for resistance with analytical, empirical, and numerical methods. In the high-speed range, the hull's geometric ratios allowed for the use of the systematic series developed by Insel and Molland [12] and then revised in 1994 by Molland and associates [13], which offered a term of comparison above 0.4 Fn (approx. 15kts). A CFD analysis was at the same time performed to achieve more accuracy for the critical speeds of 30 knots and 7 knots: Commercial flow solver, Star- CCM+ was used to compute the multiphase flow using Unsteady Reynolds Averaged Navier-Stokes (URANS) equations to simulate a three-dimensional environment and predict the performance of the vessel in the aforementioned conditions at full scale. The results of the latest were deemed to be the most accurate of all the methods adopted, particularly at slow speed, but the information obtained was limited to the two critical speeds. A resistance curve that could describe the vessel's behaviour in the whole speed range was required for the selection of the waterjet: the analytical slender body method was used for this purpose. Based on the Michell [14] approach, this resistance prediction method computes the wave resistance of a port/starboard symmetrical monohull, to which the viscous resistance component is calculated using the ITTC'57 friction coefficient method [15], and the specified form factor, are then added to obtain the total resistance. Eventually, the results obtained with this method were used for power estimation purposes and a correction factor, based on the values obtained with CFD, was applied to the resistance curve, as reported in Figure 3.

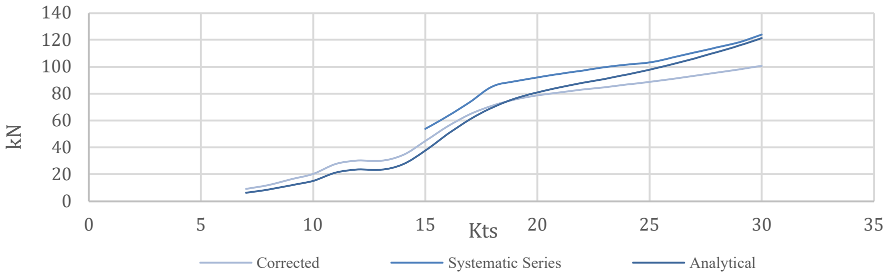

Figure 3. Resistance Curve

3.2 Waterjet Selection

While there is extensive literature and data, that a designer can use to estimate the power losses of a conventional propeller-driven vessel, there is limited information available on waterjet systems. A designer-friendly analytical method proposed in [16], was used for this purpose. The paper also suggests the criterion to estimate the optimal jet size and offers a preliminary prediction of thrust, required torque and propulsive efficiency. Contacts with a manufacturer of waterjets proved, at a later stage of the project, the accuracy and reliability of this method. The main engines could then be selected, as well as the electric motors for the slow speed operations. The motor is fitted on the gearbox through a PTI/PTO clutch that allows for mechanical or electrical engagement/disengagement to the shaft line. Solutions such as a *parallel hybrid* with the electric motor aligned on the shaft, or a "hybrid ready" waterjet were also investigated, both discarded because currently, systems of this type that are available on the market do not meet the powering needs of the case study vessel.

3.3 Battery Charge Analyses

A battery pack is considered in each demihull, its state of charge is maintained above the minimum level by the generators and/or by the fast-charging stations, depending on the number of modules considered for the pack. The hotel load of the vessel was calculated and considered in the comparison of different scenarios where charging and discharging times are differently alternated. Both the number of daily trips and the duration of the eco-mode sailing time were kept as fixed parameters, the variables were limited to the running time of the generators, the number of battery modules and the location of the fast-charging stations.

5. RESULTS

5.1 Power Estimation

The selected waterjet unit revealed a value of 63% overall propulsive efficiency for the speed of 30 kts. With this information available, it was possible to calculate the brake power (Pb) requirement. The selected engines "2 x M72-2000-16V" can deliver 1440kW each at 100% MCR and run at 85%MCR for the operational speed of 30kts. The same study was used to estimate the power requirement at slow speed and evaluate the correct sizing of the electric motors: a propulsion configuration of 2 x 100 kW E-motors was defined as a suitable arrangement considering that the vessel may have to manoeuvre in adverse weather conditions and that no bow-thrusters will be installed.

4.1 Propulsion configuration

In view of the operational nature of the vessel, which would not allow any PTO from the engines during high-speed cruising, the highest impact on the reduction of emissions was deemed achievable by having the electric motors stand in for the main engines during the time spent approaching and leaving each jetty at slow speed. Five configurations (A, B, C, D, E) were investigated by looking into the different combinations of battery modules (7.8kWh each), generator modes and the number of fast-charging points.

Configuration A indicates that 68 battery modules are required to have one of the generators running constantly and at all times. For B and C, it was ensured that the weights of the battery packs did not exceed 1.3 tonnes in total, considered a crucial limit for the influence on vessel performance. For the second solution, B, both generators are switched on when underway and are both switched off during eco-mode operations. The third configuration, C, discusses the option of having two generators running during transition time but then having one of them switched off when approaching moorings in the metropolitan area and both generators switched off when reaching more natural environments, the number of battery modules is then reduced to 10. The other two options include the possibility of connecting to a fast charger during the 3 minutes of docking that allow for passengers to disembark and board the vessel; option D sees the installation of a charger in one single stop, while option E considers a fast charger in 3 different stops. The running time of the generators is also different between the two solutions, in the first case (D) one generator is kept running during transition time, while in option E, the only need for generators on board is to have redundancy of powering solutions in case of failure of both main engines. These two solutions feature a battery pack respectively made of 19 and 23 modules. A summary of the results is reported in Table 3.

Table 3. Battery Configurations

Configuration	No. Modules	Pack Weight	Battery Pack Cost	Cost of charging station
		Kg	$€ \cdot 10^3$	$€ \cdot 10^3$
A	68	4000	86	--
B	18	1300	29	--
C	10	600	13	--
D	19	1126	24	650
E	23	1351	29	1950

5.2 Optimal configuration – Costs, Weight, Battery Lifespan, Emissions

When compared to the full diesel configuration, the first three systems offer a return of investment within one year from the beginning of operations, thanks to fuel savings. Option A considers the installation of 60 batteries, the associated costs are considerable, but the high capacity of the battery pack allows for a reduced number of full discharge cycles per day, increasing the lifespan of the batteries and extending the time between their replacement; the main drawback of this system is its weight of four tonnes, which would harm the performance of the vessel. On the other side of the spectrum, Option C offers the lowest initial investment, but the reduction in fuel consumption is minimal and the replacement of the batteries would have to take place almost every year, following a maintenance schedule that is not suitable for the operations of this kind of vessel. From the configurations that do not consider the installation of fast chargers, Option B was found to offer the best compromise; the initial investment of 70 thousand Euro for the hybrid system would be recovered within three months of operations, and the operator would benefit from fuel-saving for two years before having to replace the battery pack. With an acceptable battery pack weight of 1.2 tonnes, this system reduces CO_2 emissions by 735 tonnes per year.

Option D and E are extremely interesting in terms of emissions; although investors would have to wait from 2 (option D) to 4 (option E) years before being able to benefit from any profits. These options would respectively reduce the emission of CO2 by approx. 950 and 1100 tonnes per year.

Table 4. Costs and ROI

Scenario	Daily Fuel	Annual Fuel Savings	Additional System Cost	RoI
	$L \cdot 10^3$	$€ \cdot 10^6$	$€ \cdot 10^3$	months
A	8.05	0.36	216	8
B	8.15	0.32	72	3
C	8.27	0.27	32	2
D	7.9	0.41	725	21
E	7.7	0.51	2041	48

The charge/discharge cycles of the battery packs in configurations B and E are shown respectively in Figure 4 and Figure 5.

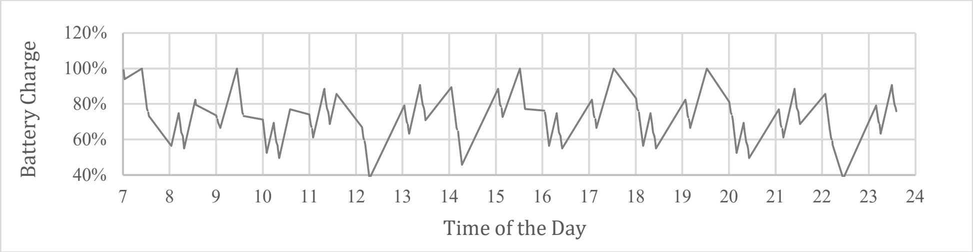

Figure 4. Battery Daily Charge- Configuration B

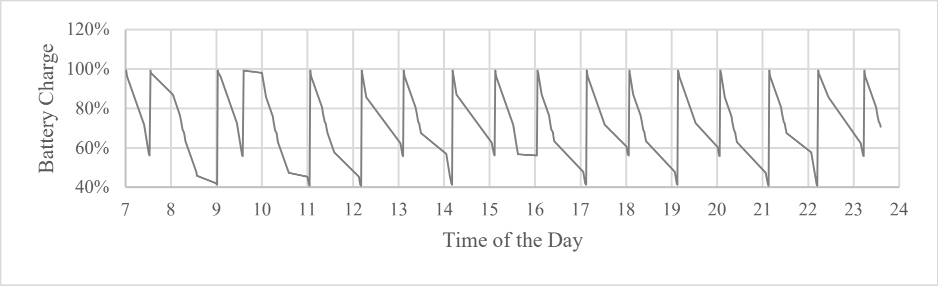

Figure 5. Battery Daily Charge- Configuration E

5.3 Environmental Impact

Table 5. Hybrid System Environmental Impact

		Hybrid	**Conventional**
Distance Covered (day)	*nm*	423	423
Distance Covered (Total)	*nm*	2284200	2284200
Eco Time (Total)	*hrs*	35190	0
Transit Time (Total)	*hrs*	67950	103140
Fuel Consumption (Total)	*L*	44037000	48006000
CO2 Emissions	*tonnes*	122423	133457
% Diff CO2		**8.3**	

The environmental impact of this hybrid configuration, B, was then assessed over a 15-year period operational profile of the vessel and the benefits clearly identified. The respective values are reported in Table *5* above. The table indicates that over the 15-year period, 9000 tonnes of CO_2 are saved when compared to the conventional propulsion system indicating an 8% overall improvement.

6. CONCLUSION

The innovative powering technologies that are being developed thanks to the great effort of the research community are mostly applicable on slow speed crafts or on vessels that operate discontinuous daily schedules. The demand for faster and readily available means of public transportation can find a meeting point with emerging technologies only in the form of a hybrid solution that features both the standard internal combustion engine and also a secondary propulsive system that can be used for slow speed operations. This study demonstrates the economical and environmental benefits of such a solution, finding an optimal configuration that reduces fuel consumption by 8% over 15 years of operations and a return of investment of 3 months in battery replacement cycles of 2.5 years.

A significant design constraint was set by the density of trips per day and an optimisation of the daily schedule would certainly lead to much higher performance achievements. High-speed crafts should deserve greater attention from the research community since they present very challenging parameters. Moreover, policy-makers should decide to apply also to these kind of vessels the regulations that are coming into force to reduce the environmental impact of the world fleet.

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