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GREENING THE OPERATION OF THE ARLEIGH BURKE-CLASS (DDG-51) VESSEL UNDER CLIMATE CHANGE SCENARIOS: A COST AND EMISSIONS PERSPECTIVE

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Abstract: Since its inception in 1991, the DDG-51 naval class vessel continues to be a workhorse for the US Navy. In the coming three decades, naval performance is expected to be influenced by climate change. We would like to investigate whether the current marine diesel run vessel will benefit from retrofitting any other technology to tackle climate change impact and contribute to a greener operation. We argue that substituting diesel with methane gas while retrofitting with air lubrication can indeed lend help to this effort. More technically, drawing inspiration from maritime logistics, we arrive at our conclusion that the conventional diesel run DDG-51 naval vessel with air lubrication will offer similar CO_2 per ton nautical mile emissions and related costs per ton nautical mile like the environmentally better methane gas fuel run without air lubrication. We thus conclude that the methane gas run vessel with air lubrication is better than diesel run vessel with air lubrication. This conclusion is shown to be valid via a climate scenario projection for three decades into the future.

Key words: Air lubrication, Arleigh Burke-class (DDG-51), cost and emissions per ton-nautical mile, retrofitting**.**

1. INTRODUCTION

In commercial shipping, LNG powered ships are being encouraged as a means to provide reduced carbon footprint of maritime vessel operations [13]. This process is termed as "Greening". From a naval perspective, greening operation has recently been given serious thought. The US navy plans to achieve net zero carbon emissions by 2050 [14]. The Arleigh Burke-class (DDG-51) has appeared to be representative of the wider fleet of conventional fuel driven vessels of the US Navy [7]. The present work of ours investigates greening operation on the same. More precisely, in this article we study impact of climate change on its operation with regards to emissions and costs for three decades starting from the year 2025. We then recommend technologies for its greening objective. For this analysis, we choose a strategically important travel path for the vessel. Hence the vessel is assumed to travel from Florida to Chagos island with a distance of around 7000 nautical mile (nm). It traverses though Atlantic, Southern and the Indian ocean. Distance traversed one way from Florida to Chagos island is divided into following three sections (Table 1):

Table 1. Ocean routes

Ocean route	Distance (nm)
Florida to North of Southern Ocean	6000
North of Southern Ocean to Madagascar	200
Madagascar to Chagos island	1400

Like any other oceans, these oceans have been thought to be impacted adversely by the climate change. The IPCC report [8] leads us to the following conclusion on the sea states with regards to sea surface temperature, salinity and wave heights (Table 2):

Table 2. Projections of climate variables

Ocean	Salinity	Sea Surface temperature	Wave height
North Atlantic	↑↔	↖↑	↓↑
South Atlantic	↑↔	↖↑	Null

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Southern	↓↔	↑↑	↑↑
Indian	Null	Null	Null

We read the table in the following way: the IPCC concludes that for the South Atlantic Ocean, it has high confidence (up arrow) that the sea surface temperature will be increasing in a non-decreasing way (north west arrow). For the Southern Ocean, one has medium confidence (left right arrow) that the salinity will decrease (down arrow). For Indian ocean there is no discussion on salinity. We can similarly read the other entries of the above table. We translate these projections into numbers for various sea states drawn from the IPCC reports [9] which we now describe.

South Atlantic Ocean is assumed to have the following projected growth in temperature, density and viscosity of ocean water (Table 3).

Table 3. South Atlantic climate projections

Climate variables	2025-2035	2036-2045	2046-2056
Temperature(F)	75.15	75.28	75.42
Viscosity $(ft^2/s)\times10^5$	1.0392	1.033	1.030
Density $(lb\text{-}s/ft^4)$	1.986	1.9859	1.9858

Southern Ocean is assumed to have the following projected growth in temperature, density and viscosity of ocean water (Table 4):

Table 4. South Ocean climate projections

Climate variables	2025-2035	2036-2045	2046-2056
Temperature(F)	69.86	69.72	69.58
Viscosity $(ft^2/s)\times10^5$	1.0519	1.055	1.060
Density $(lb\text{-}s/ft^4)$	1.986	1.9859	1.9858

Indian ocean is assumed to have the following projected growth in temperature, density and viscosity of ocean water.

Table 5. Indian Ocean climate projections

Climate variables	2025-2035	2036-2045	2046-2056
Temperature(F)	75.50	75.80	76.10
Viscosity $(ft^2/s)\times10^5$	1.030	1.028	1.020
Density $(lb\text{-}s/ft^4)$	1.986	1.9859	1.9858

To understand the comparative futuristic values of the wave height we investigate the literature on the same and synopsize it in the Table 9 in appendix.

Based on those, we assume the following values of sea states with regard to the wave height for the following oceans (Table 6):

Table 6. Wave heights

Oceans	2025-2035 (m)	2036-2045 (m)	2046-2055 (m)
S. Atlantic	10	8	7
Southern	7	8	10
Indian	8	8	8

Having the above climate data in mind, we set further to analyze its impact. The article is organized as follows. In the next section, we tabulate the key characteristics of the DDG-51 class destroyer. The statistics of the cost per ton mile and emissions as a function of total hull resistance that the vessel will encounter while at sea will be described. In the third section, we present the output. In the fourth section, we present the deductions from the output. In section 5, the appendix refreshes vessel performance preliminaries useful for understanding naval performance modeling. As expected, this material is fairly standard, and we have borrowed it from the lecture notes on Ship performance taught at US Naval Post Graduate School [11]. An algorithm to calculate the total hull resistance is mentioned at the end.

2. THE DDG-51 CLASS DESTROYER

The Arleigh Burke class destroyer (DDG-51) put into operations on 4th July 1991, is a representative of US navy fleet [7]. Its dimension is below

Table 7. The DDG-51 characteristics

Characteristics	Dimensions
Waterline length (L_s)	142 m
Beam (B_s)	18 ft
Draft, T_s	6.4 m
Wetted Hull Area ,(S_s)	3001 m^2
Displacement, Δ_s	8768 metric tons
DWT	8373 tons
Propeller diameter (D_0)	18 m
Fuel	F-76 diesel fuel
Fuel carbon factor (K_F)	12.2 g CO_2e/MJ

The DDG-51 is powered by four General Electric LM2500 gas-turbine engines which can produce 80000

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kW in shaft power. For cruising speed of 15 knots only, single engine powers a single shaft while other engines are idle. In full power mode, all engines are operational and can steam a ship at 30 knots.

The LM2500 is assumed to run on marine diesel. A methane gas run dual engine is also available. Characteristics of these fuels viz. carbon factor (C_F), specific fuel consumption (SFC) and assumed costs are (Table 8)

Table 8. Fuel characteristics

Fuel	C_F	SFC(g/kwh)	Cost in USD per ton
Marine diesel	3.206	200	700
Methane	2.750	200	781

The cost of fuel is assumed to be constant throughout the three decades. We make this assumption to understand the cost runs solely as a function of climate variables rather than via inflationary adjustment on fuel cost.

2.1 Assumptions

1. We ignore the impact of fouling. This is in fact known to significantly corrode the hull leading to frequent maintenance. However, for our focus on operational cost and emissions, this may be ignored.
2. We nullify the impact of slow steaming by assuming constant velocity throughout the journey of the vessel.
3. Turbo sails, Flettner rotor, Towing kite and Ship lengthening aren't feasible carbon reduction strategies for the DDG-51 owing to the latter's military application.

Thus, we are left to focus on the air-lubrication technology and it impact on carbon emission and cost to run. Similarly, fuel-wise, we are limited to the current available feasible engines that run either on marine diesel and methane gas. Hence, we can rule out other possible fuels even though they may be creating low carbon foot print.

A modified formula from [4] of CO_2 emitted per ton nautical mile
(e_{V_i}) is given by

$$e_{V_i} = \frac{1}{DM}\sum_{i=0}^{n}\frac{D_i}{V_i} * SFC * P_i * K_F \qquad (1)$$

where the factor $\frac{1}{DM}$ transforms the cost per voyage to a cost per ton nautical mile for which D which is the voyage distance and M is ``light displacement,'' and has a assumed value of 2000 ton. The sectoral factor $\frac{D_i}{V_i}$ gives the hours in each ocean section of the voyage for velocity V_i. P_i=R_T for section i is the total hull resistance and K_F is the carbon factor in (t- CO_2/t-Fuel). Here we have n=3 sections.The cost of fuel burnt in this voyage is likewise calculated by

$$c_{V_i} = \frac{1}{DM}\sum_{i=0}^{n}\frac{D_i}{V_i} * SFC * P_i * C_{Fuel} \qquad (2)$$

An algorithm to calculate the Total hull resistance P_i has been described in the appendix. From the SFC values in the Table 8 and equations (1), it is apparent that the emissions from Marine diesel will be about $\frac{3.206\text{-}2.75}{2.75}*100 \approx 17\%$ higher than that of methane. If air lubrication is involved, it is expected that the total hull resistance will be reduced by about 10-20% [5][6]. Hence if climate change does not grossly impact operability of the DDG-51 for coming three decades, then diesel run engines retrofitted with air lubrication will result in a performance similar to the expensive Methane gas run operation. Further, if we were to substitute fully the diesel operation with methane and air lubrication; though expensive than diesel, we achieve approximately twice the reduction in emission than the conventional diesel run without air lubrication. This is in line with the US State department's initiative to invest in upgrading technology to battle greenhouse gas emissions [1]. Hence, it is imperative to understand the performance of the vessel with respect to cost and emissions under climate change for various vessel speeds. If these don't vary much for each speed, then our observation that conventional diesel run vessel with air lubrication will provide similar performance to costly methane gas-run vessel without air lubrication will get validated.

3. RESULTS

Throughout this section, speeds range from 5 knots to 20 knots with increment of 5 knots on Y axis. For marine diesel run engines we have, emissions $e_5, e_{10}, \ldots, e_{20}$ in CO_2 emitted per ton nautical mile and cost $c_5, \ldots, c_{20}$ in USD for corresponding vessel speeds on X axes of the below two charts respectively (Figure 1, Figure 2).

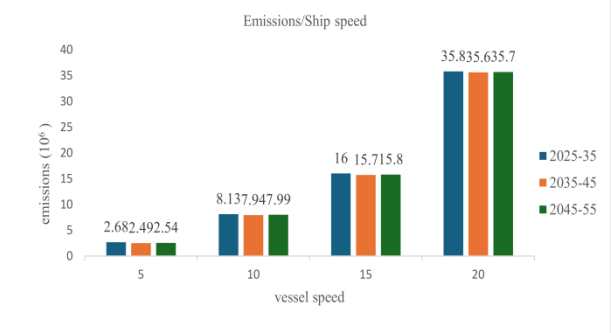

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Figure 1 Emissions/speed

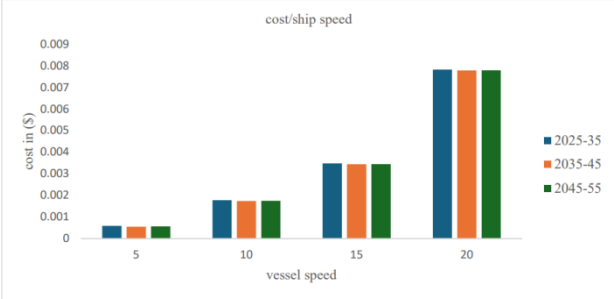

Figure 2 Costs/speed

3.1 Observations

1. The total hull resistance has a very large value in contrast to the energy added by the term describing the square of the wave heights in equation (7).
2. From the Figure 1 and 2 on cost and emissions for DDG 51 respectively, we observe that there is only slight variation between emissions and costs over three decades for a fixed speed ranging from 5 knots till 20 knots even under climate change. In fact, there is a slight decreasing trend. Though it may seem surprising at first, we can deduct from the total hull resistance equation (7) being quadratic in ship speed when inputted in to the cost and the emissions formula (1-2), which upon division by ship speed V_i in section i; results in an expression consisting of being weighted linear in ship speed. Since over time, climate change impacts for worse, the vessel expectedly will travel at a similar or lesser than assumed speed with non-increasing weight multiplier like here thus producing similar or close to decreasing emissions and costs. However, this observation does not preclude the fact that from the perspective of naval operations, the vessel will take a hit in the form of disruptions as climate change worsens [3].
3. As speed increases, costs and emissions increase. The difference is rather large. For example, emissions and costs rise by 1400% between speeds of 5 knots and 25 knots. However, for military applications, slow steaming is not always feasible. Hence, we need to focus on retrofitting the vessel with green technology.

4. CONCLUSIONS

1. We conclude that the DDG-51 operation is spectacularly green if it performs slow steaming. However, strategically speaking, slow steaming is not expected. On the other hand, effective air lubrication is known to reduce the power consumption by around 10-20%. Since no other green technology like Towing kite, solar panels, wind energy harnessing, ship lengthening is feasible in a retrofit, we can conclude that air lubrication is a feasible green technology for the DDG-51.
2. The projected climate change does not impact the cost or emission per ton-nm performance of DDG-51. Hence the diesel run engines with the vessel retrofitted with air lubrication will result in a performance similar to the expensive Methane gas run operation without air lubrication. Methane gas run vessel with effective air lubrication of course leads to green and cost comparative running vis a vis the diesel run engine.

5. APPENDIX

5.1 Vessel performance preliminaries

Ships performance is solely impacted by the resistance it faces to its hull. The total hull resistance is written as

$$R_T=R_v+R_w+R_a \tag{3}$$

where R_v is viscous (friction) resistance, R_w is wave making resistance and R_a is air resistance caused by ship moving in calm air. We rewrite this equation in terms of dimensionless constants as $C_T=C_v+C_w$ where C_T is total hull resistance, C_v is viscous (friction resistance and C_w is wave making resistance. We note here that here there is no air making resistance in dimensionless form. Since the total hull resistance is a function of hull form, ship speed, and the water properties, the coefficients of total hull resistance is also a function of these and given by

$$C_T=\frac{R_T}{\frac{1}{2}\rho S V^2} \tag{4}$$

where ρ is density of water in (lb-s^2/ft^4), S is wetted surface area of the underwater hull (ft^2) , V is velocity (ft/s). We elaborate on the various dimensionless coefficients further.

5.2 Wave making resistance

As Ships traverse, they create waves which in turn ``drag" the ship by its resistance. As ship speed increases, the height of the waves produced increases and therefore the energy required to produce these waves increases. From the wave theory, the length of a free wave on the surface is related to velocity as follows:

$$L_w=\frac{2\pi V_s^2}{g} \tag{5}$$

where L_w is wave length (ft), V_s is ship velocity (ft/s) and g is acceleration due to gravity ft/s^2.
We have $V_s\approx 1.212\sqrt{L_w}$. The speed where wavelength equals ship length can be solved for in the above equations and is given by

$$V_s=1.34\sqrt{L_s}\left(kt/\sqrt{ft}\right) \tag{6}$$

where V_s is ship speed in knots and
L_s is ship length (ft). This is called as hull speed rule of thumb. Hence, we have $L_w\approx 1.22\,L_s$. When wavelength L_w is close to L_s the hull speed is the least efficient speed

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for displacement of ship. Likewise, if $L_w=1.5L_s$, hull speed is the worst speed to operate at. From above equations it is obvious that increase in ship speed increases R_T. From wave theory, energy in a wave is proportional to the wave height. This if wave height increases wave making resistance becomes dominant. Hence $R_w=L_s+H^2$. Since L_s is given constant, we can assume that $R_w \approx H^2$.

5.2 Air resistance (R_a)

Air resistance is the resistance caused by the flow of air over the ship with no wind present. This component of resistance is affected by the shape of the ship above the waterline, the area of the ship exposed to the air, and the ships speed through the water. Resistance due to air typically are 4-8% of total ship resistance but may be as high as 10% for aircraft carriers. Hence, we can safely assume that $R_a=0.1R_T$. Hence

$$R_T=R_v+R_w+R_a$$
$$=R_v+H^2+0.1R_T$$
$$=\frac{C_v*\frac{1}{2}\rho V_s^2*S+H^2}{0.9} \quad (7)$$

Here C_v is affected by hull form, speed and water properties as before. C_v takes into account the friction of the water on the ship as well as the influence of hull form on the viscous pressure drag $C_v=C_F+KC_F$ where C_F is tangential component of viscous resistance; KC_F is normal viscous pressure drag component of viscous resistance. The skin friction coefficient given below is based on the assumption that the hull is a flat plate moving through the water and is a function of Reynolds number (ship speed, its length and kinematic viscosity). The form factor K accounts for the effect of hull form on viscous resistance. Both the skin friction coefficient and the form factor equation are empirically derived from many tests on the flat plates and ships.

$$C_F=\frac{0.075}{[\log_{10}(L_S V_S/v)^{-2}]} \quad (8)$$

$$K\approx 19\times\left(\frac{\nabla}{L_s^2\times T}\right)^2 \quad (9)$$

We further complete our discussion on power shaft calculation by defining the thrust T as

$$T=\frac{1}{2}\rho A_0 V_A^2 * A_F \quad (10)$$

where A_0 is propeller disc area, V_A is speed of advance given by $V_A=V_S-V_W$ i.e. ship speed minus the wave speed. A_F is the axial flow factor given by $2b+b^2$. Below is the algorithm to calculate the total hull resistance.

Algorithm:

1. From ideal propulsion efficiency η_I calculate b via $\eta_I=\frac{2}{(1+(1+b))}$
2. Decide the wave velocity V_W . $V_A=V_S-V_W$
3. A_0 is obtained via the propeller diameter.
4. $\nabla=\frac{Displacement}{(waterdensity*g)}$
5. $K\approx 19\times\left(\frac{\nabla}{L_s^2\times T}\right)^2$
6. $C_v=C_F+KC_F$.
7. $S=\nabla^{2/3}\times\left(3.4+\frac{L_s}{2\times\nabla^{1/3}}\right)$ is wetted surface area.
8. Hence calculate R_T.

Table 9. Wave height predictions

Ocean	Unit	Values till 2100 References
Southern	Annual Mean wave height (AMWH)	5-10% (5-8%) rise Ref. [10], [12], [2]
South Pacific	AMWH[Annual Extreme wave height (AEWH)]	5-10% (5-8%) rise Ref. [10], [12], [2]
N. Atlantic/ Mediterranean	AMWH	Up to 10% decrease Ref. [10],[2]
N. Pacific	AMWH	Up to 10% decrease Ref. [10],[2]
S. Atlantic	AMWH[AEWH]	0-20% [5-8%] rise Ref. [12],[2]
Indian	AMWH[AEWH]	Upto 10% [5-8%] rise Ref. [12],[2]

6. CREdit authors statement

Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing:. A. D.

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