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Potential power setups, fuels and hull designs capable of satisfying future EEDI requirements

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ABSTRACT

Maritime emission regulations set limits for SOx and NOx emissions for health and environmental reasons, and for CO_2, through the Energy Efficiency Design Index (EEDI), with the general aim of mitigating global warming. EEDI verification is performed at the vessel's design speed and design loads, under calm-water conditions. This, although calm seas are the exception in shipping, and that even with calm-water conditions, ships usually operate at lower speeds than their design speed. A major challenge, if greenhouse gases (GHG) reduction targets are to be met through the EEDI, will be to identify EEDI-compliant solutions that reduce energy consumption and GHG emissions under realistic operational conditions, from lying idle at berth in port to when full power is required in critical situations at sea. In view of all the above, we use the Aframax tanker class to illustrate how such an assessment can be performed, and to display the differences in costs and benefits of options, all of which meet the requirements of the EEDI.

1. Introduction

The EEDI limits will demand a reduction of 30% in CO_2 emissions per ton nautical mile (nm) by 2025, compared to those permitted for vessels built in 2013–2014, and 20% reduction compared to vessels built in 2015–2019. The options available to meet these forthcoming EEDI requirements are first, to reduce hull resistance to achieve the desired speed with less power; second to switch to fuels with lower carbon content; third to reduce the design speed through installing less power; and fourth, various combinations of these measures.

First; reducing hull resistance. Ships are designed to operate at their boundary speeds (Faltinsen et al., 1980). For any given hull form, the boundary speed can be defined as the range of speeds within which the resistance coefficient goes from virtually constant to rising rapidly and making further increases costly (Silverleaf and Dawson, 1966). Kristensen (2010), Stott and Wright (2011), Lindstad et al. (2013) and Lindstad (2015) have studied how hull forms can be made more efficient by modifying the main ratios between beam, draught and length to reduce block coefficients while keeping the cargo-carrying capacity unchanged. The results show that these novel hull designs, which we term *slender designs*, are less full-bodied, which reduces drag and significantly lower power requirements and fuel consumption. Measures, such as light-weighting, improved hull coatings and better lubrication can contribute to upgrading hull performance (Buhaug et al., 2009; Hertzberg, 2009; Wang et al., 2010; Faber et al., 2011; Wang and Lutsey, 2013; Tillig et al., 2015).

Secondly, switching to fuels with lower carbon content reduces CO_2 emissions directly from combustion (Bengtsson, 2011; Chryssakis et al., 2014; Gilbert, 2014; Taljegard et al., 2014; Thomson et al., 2015; Psaraftis, 2016). Liquid Natural Gas (LNG), is

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favourable due to its hydrogen to carbon ratio, which reduces the emitted carbon per kW h by approximately 25% compared to diesel. However, when LNG is burnt in ships' engines, un-combusted methane CH_4, a GHG with an impact 28–34 times as great as that of CO_2 in a one hundred-year perspective (IPCC, 2013), offers a GHG challenge (Verbeek et al., 2011; Verbeek and Verbeek, 2015; Stenersen and Thonstad, 2017). For biofuels, the CO_2 emitted at combustion is per definition zero (IPCC), since it is first extracted from the atmosphere and absorbed by the crops used to produce the biofuel. The carbon-neutrality assumption of biofuels is highly dependent on the rotation periods of the source crop, its geographical location, and direct and indirect albedo changes due to harvesting, all of which have effects on climate (Cherubini et al., 2013). Hydrogen is attracting growing attention (Bouman et al., 2017) since it emits no CO_2 at combustion, and so are renewable energy sources such as wind (Perkins et al., 2004; Clauss et al., 2007; Traut et al., 2014; Teeter and Cleary, 2014; Tillig et al., 2015; Psaraftis, 2016) and solar power (Sjöbom and Magnus, 2014).

A third option is to reduce the design speed through installing less power. Because the power needed for propulsion increases with the speed by the 3rd power and beyond (Silverleaf and Dawson, 1966), fuel consumption per nautical mile also drops by approximately the quadratic of the speed (Corbett et al., 2009; Lindstad et al., 2011). With today's higher fuel prices compared to those in the 1990 s and early 2000s combined with overcapacity in shipping markets, vessels now typically operate at around 50% or less of their available power (Smith et al., 2014). As far as EEDI is concerned, reducing operational speed is irrelevant, while reducing the installed power is one way to remain within the permitted limits of the EEDI. The explanation is that if we reduce installed power by around 30%, both the speed and distance traveled will be reduced by around 10%, resulting in a 20% reduction in emissions per ton nautical mile (nm). On the other hand, the EEDI scheme punishes higher maximum speeds, since an 10% speed increase CO_2 emission per ton nm by 20%.

Combination of policies, regulations, and legislation such as the EEDI can reduce GHG emissions from the shipping sector, but successful implementation need to be supported by studies that address multiple effects and measures simultaneously, to avoid affects that counteract one another. There are multiple studies which discuss the EEDI (Devanney, 2011; Kruger, 2011; Armstrong and Banks, 2015; Lindstad and Eskeland, 2015; Lindstad et al., 2015c; Ančić et al., 2018; Psaraftis, 2018; Vladimir et al., 2018). IMO have also an additional voluntarily regulation called Energy Efficiency Operational Index (EEOI). EEOI is an index which can be used by operators to evaluate the energy efficiency of the vessels operation (in contrast to EEDI which evaluate the design).

Our motivation for this study has been to identify and rank EEDI-compliant solutions that would reduce energy consumption and GHG emissions under realistic operational conditions, ranging from lying idle in port to when peak power is required in critical situations at sea. As discussed earlier, there are many studies which presents abatement technologies and discuss the EEDI, but by the knowledge of the authors the novelty of this study is to investigate cost increases and GHG reductions as a function of alternative EEDI compliant options for ships employed in typical trading pattern. For this purpose, we use the Aframax tanker class as a typical representative of bulkers and tankers

2. Description of the model

The model provides for a full evaluation of fuel consumption, costs and emissions as functions of vessel operation, abatement options and fuel prices; see Lindstad et al. (2011, 2015a, 2017).

A vessel's fuel consumption for a given trip is given by Eq. (1).

$$F = \sum_{i=1}^{n} t_i p_i spfc(p_i) \tag{1}$$

During a voyage, the sea conditions will vary and the model deals with this by dividing each voyage into sections, with a time duration t_i, power P_i, and specific fuel consumption *spfc* as a function of power. The time duration is either the time spent in port or the time duration of traveling a certain distance D_i, such that $t_i = D_i/v_i$. The power is calculated from the power curve later presented in Fig. 2. The specific fuel consumption curve is later presented in Fig. 4.

The cost per freight unit transported, i.e. per ton-mile is given by Eq. (2):

$$C = \frac{1}{D \cdot M} \cdot (F \cdot C_{Fuel} + \text{CAPEX} \cdot T/365 + \text{OPEX} \cdot T/365) \tag{2}$$

The first factor converts total costs to cost per ton-mile, where M is the mean weight of the paying cargo carried on the roundtrip voyage and D is distance sailed. While large bulkers and tankers typically sail one way fully loaded and return or are repositioned empty in ballast, container vessels tend to carry more cargo in one direction than the other, and are usually neither empty nor completely full. Inside the main bracket, the first term refers to the cost of fuel, where C_{Fuel} is the cost of fuel per ton. The second term includes the cost of capital for the vessel, CAPEX is the yearly capital cost of the vessel and is set to 8% of the investment cost, T is the time duration per trip measured in days and 365 are days per year. The third terms give the operational cost and is set to 4% of the investment cost.

Emissions, ε per pollutant, comprises fuel and freight work as expressed by Eq. (3):

$$\varepsilon = \left(\frac{F}{D_c \cdot M \cdot N_c}\right) \cdot K_{ep} \tag{3}$$

K_{ep} is the emission factor for each exhaust gas as a function of power and fuel. D_c is the distance of the cargo voyage, M is the weight of the cargo and N_c is the annual number of cargo voyages. SOx and CO_2 are always strictly proportional to fuel consumption by fuel