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Maritime shipping and emissions: A three-layered, damage-based approach

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ABSTRACT

Policy emphasis in ship design must be shifted away from global and idealized towards regional based and realistic vessel operating conditions. The present approach to reducing shipping emissions through technical standards tends to neglect how damages and abatement opportunities vary according to location and operational conditions. Since environmental policy originates in damages relating to ecosystems and jurisdictions, a three-layered approach to vessel emissions is intuitive and practical. Here, we suggest associating damages and policies with ports, coastal areas possibly defined as Emission Control Areas (ECA) as in the North Sea and the Baltic, and open seas globally. This approach offers important practical opportunities: in ports, clean fuels or even electrification is possible; in ECAs, cleaner fuels and penalties for damaging fuels are important, but so is vessel handling, such as speeds and utilization. Globally we argue that it may be desirable to allow burning very dirty fuels at high seas, due to the cost advantages, the climate cooling benefits, and the limited ecosystem impacts. We quantify the benefits and cost savings from reforming current IMO and other approaches towards environmental management with a three-layered approach, and argue it is feasible and worth considering.

1. Introduction

The main source of emissions from sea-going vessels is the exhaust gas from burning fuel in the ship's combustion engines. Upon ignition in the engine, a mix of air and fuel releases mechanical energy which is harnessed for propulsion, and produces hot exhaust gases as a byproduct. Of these exhaust gases, carbon dioxide (CO_2) has only climate effects, while carbon monoxide (CO), sulphur oxides (SO_x), nitrogen oxides (NO_x), methane (CH_4), black carbon (BC) and organic carbon (OC) have both climate and adverse local and regional environmental impacts, e.g. on human health.

Climate impact assessments for marine transport have traditionally been based on amounts of CO_2 emitted from fuel combustion (Corbett et al., 2009; Lindstad and Mørkve, 2009; Psaraftis and Kontovas, 2010; Faber et al., 2009; Lindstad et al., 2011), while other trace emissions in the exhaust gas have been ignored (Lindstad and Sandaas, 2014). Current regulations provide emission limits for CO_2 for its climate change effects and for NO_x and SO_x for their health and environmental effects (Eide et al., 2013). This represents a conflict, since the NO_x and SO_x emissions that are regulated for environmental reasons tend to mitigate global warming (Lauer et al., 2007; Eyring et al., 2010), while the unregulated emissions, i.e., BC and CH_4, contribute to global warming (Jacobson, 2010; Bond et al., 2013; Myhre and Shindell, 2013; Fuglestvedt et al., 2014; Lindstad and Sandaas, 2014). Complicating matters, emissions in one region may lead to a direct climate forcing that differs in magnitude to the same quantity emitted in another region. This is due to regional differences in sea ice extent, solar radiation, and atmospheric optical conditions (Myhre and Shindell, 2013). For example, the deposition of black carbon over highly reflective surfaces such as snow and sea ice reduces the albedo of these surfaces, thereby increasing their surface temperature. This in turn leads to increased melting and additional reductions in snow/sea ice extent and consequently further reductions in the surface albedo, i.e., it is a significant positive feedback loop (Hansen and Nazarenko, 2004; Zender, 2012; Sand et al., 2013; Jacobson, 2010; Bond et al., 2013). Region-specific global warming potential (GWP) characterizations are therefore needed to more accurately quantify the climate

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impact of each emission species. Emission metrics such as GWP, or "*CO_2-equivalent emissions*," have become the common means to quantify and compare the relative and absolute climate change contributions of different emissions species (Shine, 2009). The GWP integrates radiative forcing from a pulse emission over the chosen time horizon, (Borken-Kleefeld et al., 2013). GWP is usually integrated over 20, 100 or 500 years, consistent with Houghton et al. (1990). Longer time horizons place greater weight on compounds with persistent warming (or, in the case of negative values, cooling) effect.

In response to regional and global impacts of emissions, the International Maritime Organization (IMO) is tightening the emission limits for NO_x, SO_x and CO_2 (Lindstad and Sandaas, 2014). First, IMO has defined the coastlines of North America and the North Sea and the Baltic as Emission Control Areas (ECAs). From 2015, the fuel used within these ECAs has a sulphur content restricted to a maximum of 0.1%. From 2020, the limit for fuel Sulphur content outside of ECAs will be 0.5%, down from the current limit of 3.5%. Second, the IMO requires that vessels built from 2016 onwards which operate fully or parts of their time in the North American ECA shall reduce their NO_x emissions by 75% compared to the Tier 2 present global standard for vessels built after 2011 (MARPOL Convention). Third, the energy efficiency design index (EEDI) uses a formula to evaluate the CO_2 emitted per unit of transport, with EEDI limits agreed upon for major vessel types. It is expected that these thresholds stepwise will become 30–35% stricter within the next 15–20 years (Lindstad et al., 2014).

Power generation systems for cargo vessels have generally been designed to ensure that vessels have the power necessary to be seaworthy in rough weather and also in calm water to achieve their design speed by utilizing 75–85% of the installed main engine power (Lindstad, 2013). Historically, fuel costs have been low compared to the total cost of operating the vessel. As these other costs are mostly fixed, i.e., are independent of power output and therefore sailing speed, high speed operation has generally minimized total costs per unit transport, and thus maximized profit. More recently, higher fuel prices and low freight markets have made it profitable to instead reduce fuel consumption through speed reductions (Lindstad, 2013). Since the power output required for propulsion is a function of the speed to the power of three, when a ship reduces its speed, the power required and therefore the fuel consumed per freight work unit is considerably reduced (Corbett et al., 2009; Sea at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010; Lindstad et al., 2011; Psaraftis and Kontovas, 2013). Accordingly, average operational speeds have been reduced in the later years (Smith et al., 2014) when oil prices have remained around USD 100 per barrel compared to 10–20 USD per barrel in the 1990s and early 2000s.

Since speed reduction drastically reduces power requirements, it has become common to operate from 15% to 40% of the installed power at calm to moderate sea conditions. Although low power output saves energy through the hull's resistance-to-speed relation, fuel consumption per kWh produced increases (Duran et al., 2012) due in part to incomplete combustion. In contrast, at medium to high power production, the combustion engine achieves greatest fuel efficiency and therefore has the lowest emissions per kWh. Relative to total operational costs, the increase in specific fuel consumption per kWh at lower loads makes a small impact on costs. Nevertheless, the emissions of exhaust gases such as NO_x (Duran et al., 2012; Hennie et al., 2012; Ehleskog, 2012; Lindstad and Sandaas, 2014), aerosols such as BC (Ristimaki et al., 2010; Kasper et al., 2007; Lack and Corbett, 2012), and un-combusted CH_4 (Stenersen and Nielsen, 2010; Ehleskog, 2012) increase substantially, due to less favourable combustion conditions.

From an environmental viewpoint, one of the challenges with the current IMO legislation (MARPOL Convention) is that it assumes engine performance at '*ideal lab-conditions*' at medium to high loads and calm water. In reality, vessels today operate more commonly at low to medium power, and only at high power loads in rough seas or other special conditions. As a consequence of the IMO legislation, engine manufacturers tune their engines to meet the IMO emissions standards for NO_x at high power loads, since these high loads are weighted highly in the test cycle. Such tuning generally results in higher NO_x emissions at low loads and also raises fuel consumption at low to medium loads (Hennie et al., 2012; Ehleskog, 2012). The test cycle thus places excessive emphasis on an idealized operational scenario, which results in less efficient combustion and hence higher emissions of all exhaust gases under normal operation.

An important idea is to shift the emphasis from idealized to realistic vessel operating conditions (Lindstad and Sandaas, 2014). This shift leads to a realization that vessel and engine configurations are generally environmentally inefficient in part by having insufficient flexibility. Typically, vessel engines have sub-optimal conversion of fuel to propulsion at very high or low loads and thus have excessive emissions when operating in these states. The engine load 'sweet spot', or range, will for these reasons vary somewhat depending not only on commercial and navigational aspects, but also on how various emissions species are valued and addressed in the regulatory framework. While some of these dependencies will be further developed in subsequent research motivated by this study, a perspective of multi-pollutant control and internalization of environmental externalities forms the basis of our approach (Eskeland, 1994, 1997; Eskeland and Xie, 1998).

While there is no question that SO_x and NO_x emissions must be reduced when the vessel is close to land, sensitive ecosystems and densely populated areas, the main objective of this paper is to investigate if it is possible to fulfil the requirements for reducing harmful emissions in ports and coastal areas without giving away the overall cooling effect of maritime transport. The employed model is described in Section 2, its application and data are presented in Section 3, the analysis and results in Section 4 and the results obtained are discussed in the final section with respect to their implications for policy development.

2. Methodology

We need assessment of costs, fuel consumption and emissions (see Lindstad et al., 2014) limiting our attention to the vessels and their use, excluding activities while in port. The model consists of four main equations, of which the power element describing fuel consumption is the most important. The power function (Eq. (1)) (Lewis, 1988; Lloyd, 1988; Lindstad et al., 2013) considers the power needed for still water conditions, P_s, the power required for waves, P_w, the power needed for wind, P_a, the required auxiliary power, P_{aux}, and propulsion efficiency, η. This setup is established practice (Lewis, 1988; Lloyd, 1988; Lindstad et al., 2013).

$$P_i = \frac{P_s + P_w + P_a}{\eta} + P_{aux} \tag{1}$$

Eq. (2) calculates voyage cost as a function of required power, voyage length, and vessel characteristics.

$$C = \sum_{i=0}^{n} \left(\frac{D_i}{v_i} \cdot \left((K_{fp} \cdot P_i \cdot C_{Fuel}) + \frac{TCE}{24} \right) \right) + \left(D_{lwd} \cdot \left((K_{fp} \cdot P_{aux} \cdot C_{Fuel}) + \frac{TCE}{24} \right) \right) \tag{2}$$

The first term represents cost at sea while the second term determines cost at port. During a voyage, the sea conditions will vary and this is handled by dividing each voyage into sailing sections, with a distance D_i for each sea condition influencing the vessels speed v_i and the required power P_i. The hourly fuel cost per section is given by $(K_{fp} \cdot P_i \cdot C_{Fuel})$, where K_{fp} is the fuel

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