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Operational profiles of ships in Norwegian waters: An activity-based approach to assess the benefits of hybrid and electric propulsion

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ABSTRACT

Various regulations are imposed on shipping to increase energy efficiency and reduce environmental impacts. Alternative fuels and power systems are among the solutions for compliance with these regulations. The power system of a ship may not operate optimally because of the diversity of the operational profile during its lifetime. This article uses an activity-based approach and big data from the Automatic Identification System (AIS) to study the operational profiles of eight ship types operating in Norwegian waters around mainland Norway in 2016. The aim is to identify ship types that can benefit from electric and hybrid propulsion through analysis of their operational profiles. Close to shore, the operational profiles of various ship types are similar, and all ships spend a great proportion of their time with lower loads. As the distance from shore increases, the operational profiles of various ship types follow distinct trends. Among the considered ship types, reefers spend more operational time close to the diesel engine design condition. On the other hand, offshore and passenger ships show the most dynamic operational profiles and spend a large percentage of their operational time with a partial load, away from diesel engine design conditions. Such ships can benefit from hybridisation, diesel-electric propulsion, and other electric concepts, such as batteries and fuel cells. Another option is to downsize diesel engines for better operation while fuel cells and batteries supply peak and partial loads. Operational profiles are plotted and details of the approach are presented in the article.

1. Introduction

In the period 2007–2012, shipping accounted for nearly 2.8% of the annual anthropogenic greenhouse gas (GHG) emissions on a CO_2-equivalent basis (Smith et al., 2014). In the same period, maritime transport was responsible for approximately 15% and 13% of nitrogen oxide (NOx) and sulphur oxide (SOx) emissions from anthropogenic sources (Smith et al., 2014). Approximately 70% of ship emissions occur within 400 km of land, which contributes to pollution in coastal communities (Corbett et al., 2007). GHGs lead to climate change, which affects human health and biodiversity (Goedkoop et al., 2009). NOx and SOx can cause photochemical smog, acid rain and consequent health problems (Goedkoop et al., 2009).

Various international and national regulations are imposed on shipping to control these emissions and their adverse health and environmental impacts. Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) aims at a progressive reduction of emissions of GHGs, NOx and SOx. To reduce GHG emissions, MARPOL Annex VI focuses on improving

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energy efficiency through the adoption of various technical and operational measures. These regulations set NOx caps on the basis of the ship construction date, diesel engine speed and operation area. To reduce SOx emissions, MARPOL Annex VI imposes limits on the sulphur content of marine fuels. For instance, the North Sea is a Sulphur Emission Control Area (SECA), where stringent limits are imposed (IMO, 2013a, 2013b). In April 2018, International Maritime Organisation (IMO) set a goal to reduce GHG emissions from shipping. Taking 2008 as a baseline year, IMO aims to reduce GHG emissions by at least 50% by 2050. The IMO's vision is to phase out such emissions as soon as possible within the century (DNV GL, 2018).

Some countries have introduced additional regulations to further control these emissions. For instance, Norway introduced a NOx tax in 2007 that applies to various sectors, including domestic shipping and fishing. A year later, the Norwegian state and some business organisations, including the Norwegian Shipowners' Association, reached a NOx agreement. The involved parties cofounded a NOx fund and pay a lesser amount to the fund instead of paying the tax when emission-reducing measures are implemented. The fund supports NOx-reducing measures (Jafarzadeh, 2016). For example, an offshore ship can receive 5 million Norwegian Krones (NOK) (one NOK ≈ 0.11 EUR in 2017) to retrofit its battery systems. In addition, the NOx fund can provide 4 NOK/kWh charged shore power to offshore ships, measured over one year (NHO, 2017; Norges Bank, 2017). To receive this support, offshore ships must meet several conditions. For instance, their batteries must have a capacity that enables reduced emissions from the diesel machinery (NHO, 2017).

Marine diesel engines are optimised for operation at a specific load range, which is typically 70–100% of their maximum continuous rating (MCR) (Cariou, 2011; Smith et al., 2014). Within this range, specific fuel oil consumption (SFOC [g/kWh]) is at its minimum. However, the operational profiles of ships may include diverse operations with different power demands (e.g., offshore ships), or ships may reduce speed to reduce power and fuel consumption (e.g., container ships). The power systems of many ships do not operate optimally, when the fuel consumption is in line with the power demand (Skjong et al., 2017). During operations outside the optimum load range, the SFOC and, consequently, emissions per kWh increase. When ships reduce speed, the environmental benefits and corresponding fuel savings diminish as the ship operations deviate more from the diesel engine design condition (Smith et al., 2013). The diversity of operational profiles together with the increased pressure for environmentally friendly operations call for alternative fuel and power systems.

Several studies estimate pollutant emissions from shipping (Buhaug et al., 2009; Coello et al., 2015; Goldsworthy and Goldsworthy, 2015; Skjølsvik et al., 2000; Smith et al., 2014; Winther et al., 2014). These studies follow either one or a combination of two approaches, both of which rely on estimating the fuel consumption. The difference between these approaches is in the way fuel consumption is estimated: the top-down or fuel-based approach bases the estimation on bunker sales, while the bottom-up or activity-based approach considers ship activity (Jafarzadeh, 2016). In other words, the latter uses operational data (e.g., speed over ground) from, for instance, the Automatic Identification System (AIS) and technical data (e.g., design speed) from other sources, such as IHS Markit (IHS Markit, 2017) to estimate the operational profile of ships and consequently their fuel consumption and emissions. Nunes et al. (2017) reviews recent articles that use an activity-based approach to estimate emissions from shipping. Although these studies investigate the operational profiles, their ultimate goal is to estimate emissions. As a result, they may not elaborate on the differences in ships related to operational profiles and may not focus on evaluating the need for alternative propulsion systems to improve efficiency and reduce emissions.

This article uses the activity-based approach to study the operational profiles of various ship types, irrespective of their flag, operating in Norwegian waters around mainland Norway in 2016. This study covers the following ship types: (i) tankers, (ii) bulk carriers, (iii) general cargo ships, (iv) container ships, (v) roll-on/roll-off (Ro-Ro) ships, (vi) reefers (refrigerator/freezer), (vii) offshore ships and (viii) passenger ships. This article investigates whether the studied ships use their installed power for propulsion optimally in order to suggest improvements by integrating electric or hybrid propulsion on board the most appropriate types of ships. Electric/hybrid propulsion refers to propulsion by sources, such as diesel-electric systems, fuel cells and batteries, which could be used for full or partial propulsion. For instance, if a ship uses diesel engines in a suboptimal manner, the main diesel engines could be downsized such that they operate at an optimum point, while fuel cells together with batteries could provide partial and peak loads. It is normal practice in shipping to install excess power in case of emergency. However, this study does not focus on reducing the total installed power. Instead, the focus is on studying the possibilities for switching to diesel-electric or combining diesel engines with fuel cells and batteries to improve efficiency.

Although this study investigates the operational profiles of ships in Norwegian waters, the method can be applied to international shipping. This study focuses on the operation of existing ships. However, the findings can also be used for retrofits and new-buildings.

The remainder of this study is organised as follows: Section 2 gives an overview of marine propulsion systems. Section 3 explains the materials used. Section 4 elaborates on the method. Section 5 presents the results, followed by a discussion in Section 6 and conclusions in Section 7.

2. Marine propulsion systems

In searching for fuel efficiency, reduced cost, adaptability to diverse operational profiles, comfort and reliability, various propulsion systems have emerged (Geertsma et al., 2017). Fig. 1 illustrates some of the propulsion systems in practice today. The high efficiency of mechanical propulsion at the design point makes it the preferred choice for ships with a single cruising speed, such as cargo ships. Other ships, such as tugs, spend a substantial amount of their operational time well below their design speed and/or maximum diesel engine power. During transit, tugs only require 20% of the power required for towing, and their diesel engine efficiency drops significantly. Such ships can improve their efficiency by adopting electric or hybrid propulsion. However, most tugs still use mechanical propulsion (Geertsma et al., 2017).