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The influence of the waterjet propulsion system on the ships' energy consumption and emissions inventories

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HIGHLIGHTS

- Ship's energy and emission inventories are subjected to high uncertainties.
- New equation to calculate the ship's energetic and emission inventory have been proposed.
- The propulsion system efficiency value should be introduced in this type of inventory.

GRAPHICAL ABSTRACT

Own source: Ship mooring to the port of Algeciras (Strait of Gibraltar). May 2016.

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ABSTRACT

In this study we consider the problems associated with calculating ships' energy and emission inventories. Various related uncertainties are described in many similar studies published in the last decade, and applying to

Abbreviations: $(\frac{D}{V})$, activity time (hours); AE, auxiliary engine; AIS, automatic identification system; ARB, Air Resources Board; Bottom-up, inventory methodology type; Bulk Carriers, ships designed for transporting large volumes of dry cargo; CARB, California Air Resources Board; Container ships, ships designed for transporting large numbers of ISO containers; Cruise mode, the cruise mode emissions in the near ports analysis extend 25 nautical miles beyond the end of the RSZ lanes; D (miles), distance that a ship travels within the study area; EEA, European Environment Agency; EF, emission factor; EF_{AE}(g[kWh]$^{-1}$), emission factor for an auxiliary engine, for the pollutant of interest.; EF_{ME} (g[kWh]$^{-1}$), emission factor for the main engine, for the pollutant of interest (varies by engine type and fuel consumed rather than by activity mode).; ENTEC, Environmental Engineering Consultancy; EPA, Environmental Protection Agency; FERRY, ship used to carry passengers, and sometimes vehicles and cargo; GHG, Green House Gas; HFO, heavy fuel oil; HOTELLING, operations that take place while the vessel is docked or anchored near a dock; IHSF, IHS fairplay maritime journal; IMO, International Maritime Organization; LF, load factor; LF_{AE}(%), load factor for an auxiliary engine as a fraction of the MCR; LF_{ME}(%), load factor for a main engine as a fraction of the MCR; MANOEUVRING, ship operations that take place close to the dock; MCR, maximum continuous rating (kW); MDO, marine diesel oil; MEPC, Marine Environment Protection Committee (IMO); ME, main engine; MSD, medium speed diesel (engine type); nm, nautical mile; PASSENGER, passenger cruise service vessels; PM, particulate matter; $P_{transient}$, instantaneous power (kW) at time t; $P_{installed}$, total installed power (kW) of the main engine(s); $P_{reference}$, power (kW) at 100% MCR, from the Lloyd's database (IHSF); RO, residual oil; RoRo, roll-on roll-off ships for transporting vehicles, e.g. automobile carriers; RoPax, ships built for freight vehicle transport along with passenger accommodation; SECA, sulphur emission control area; SFOC, specific fuel oil consumption; Short sea shipping, the movement of freight by water over short distances; STEAM, ship traffic emission assessment model; STEEM, Ship Traffic, Energy, and Environmental Model (Waterway Network); TANKER, ship for transporting liquid cargo in bulk, esp. crude oil and chemicals; Top-down, inventory methodology type; $t_{transient}$ (m), draught at time t (from onboard data) (Eqs. (5) and (7)); $t_{reference}$ (m), draught (taken from onboard data) (Eqs. (5) and (7)); ton, metric system unit of mass equal to 1000 kg, also known as a metric ton; V_{design}(m/s), ship speed at 100% MCR from the Lloyd's database (IHSF) (Eq. (4)); $V_{transient}$(m/s), instantaneous at time t from AIS system. (Eq. (4)); V_{safety}(m/s), safety margin speed. (Eq. (4)); $V_{reference}$(m/s), reference speed (taken from IHSF) (Eq. (4)); ε_p, coefficient applied to the total installed main engine power (Eq. (4)); n, coefficient that represents the relationship between speed and power (Eqs. (3) and (5)); η_f, modification of propulsion efficiency due to fouling. (Eq. (5)); η_j, propulsion system efficiency; η_w, modification of propulsion efficiency due to weather $\mu = \frac{V_s}{V_j}$ (Eq. (11)); V_s (m/s), ship speed (Eq. (12)); V_j(m/s), jet velocity (Eq. (12)); η_j, jet efficiency (Eq. (12)); w, effective Taylor wake factor at station (Eq. (12)); $h_j(m)$, height of centreline above sea level (Eq. (12)); ζ, loss factor (Eq. (12)); ψ, (1-η_j). (Eq. (12)).

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Europe, the USA and Canada. However, none of them have taken into account the performance of ships' propulsion systems. On the one hand, when a ship uses its propellers, there is no unanimous agreement on the equations used to calculate the main engines load factor and, on the other, the performance of waterjet propulsion systems (for which this variable depends on the speed of the ship) has not been taken into account in any previous studies. This paper proposes that the efficiency of the propulsion system should be included as a new parameter in the equation that defines the actual power delivered by a ship's main engines, as applied to calculate energy consumption and emissions in maritime transport.
To highlight the influence of the propulsion system on calculated energy consumption and emissions, the bottom-up method has been applied using data from eight fast ferries operating across the Strait of Gibraltar over the course of one year. This study shows that the uncertainty about the efficiency of the propulsion system should be added as one more uncertainty in the energy and emission inventories for maritime transport as currently prepared. After comparing four methods for this calculation, the authors propose a new method for eight cases. For the calculation of the Main Engine's fuel oil consumption, differences up to 22% between some methods were obtained at low loads.

1. Introduction

Shipping is the most energy-efficient way to transport large volumes of cargo over long distances, yet ships emit nitrogen oxides (NO*x*), sulphur oxides (SO*x*), carbon dioxide (CO_2) and particulate matter (PM) into the atmosphere. Worldwide from 2007 to 2012, shipping accounted for 15% of the annual NOx emissions from anthropogenic sources, 13% of SOx and 3% of CO_2. In Europe, in 2013, Maritime Transport contributed 18% of total NOx emissions, 18% of SOx and 11% of emissions of particles of less than 2.5 μm in size ($PM_{2.5}$). For comparison, Road Transport accounted for 33%, 0% and 12% of these emissions, respectively, whereas Aviation accounted for only 6%, 1% and 1%, respectively, and Rail just 1%, 0% and 0% (Smith et al., 2014).

Exposure to toxic emissions from shipping is reported to cause cardiovascular and respiratory diseases, especially in densely populated areas (Mueller et al., 2015). Concentrations of these emissions were found to increase by up to 4–5 times on coastlines where ships pass by regularly (Lu et al., 2006).

A continued increase in international marine transport without any significant gains in energy efficiency may result in shipping being responsible for 6% of the world's Green House Gases (GHG) emissions by 2020 and 15% by 2050 (Lu et al., 2006). In this regard, the European Commission has approved the 2030 Framework for Climate and Energy, and it has committed to achieving a target of reducing GHG emissions by at least 40% compared with 1990 levels. This commitment added momentum for both the European Council and Parliament to agree, at the end of 2014, to create the legislation for a Monitoring, Reporting and Verification (MRV) system for large ships (over 5000 gross tons) from 1 January 2018 (European Commission, n.d.).

The statistics above are based on the energy consumption and emission inventories (bottom-up and/or top-down approach) prepared and published in many European countries, the USA and Canada.

However, the issue of ships' emission inventories is still highly debated and several contradicting papers have been published on the topic.

For example, papers published by Endresen et al. (2007) and Dalsøren et al. (2009), Wang et al. (2008), Jalkanen et al. (2009), Olesen et al. (2009a), Miola et al. (2010), Eyring et al. (2005), Paxian et al. (2010), and Corbett (2002) have not been universally accepted. Endresen et al. (2007) applied a bottom-up approach similar to those applied previously and they declared that an improvement with respect to the previous work is the estimation of the time that each ship individually spends at sea.

Results obtained are in a similar range of uncertainty as those reported in Corbett and Koehler (Corbett, 2002) and Eyring et al. (2005). Results published by Dalsøren et al. (2009), confirm that the estimation problem is still a topic that is worth investigating. Results from all the other studies seem to fall within the same range of uncertainty.

In addition, to add an even greater degree of uncertainty, some but not all of these inventories claim to take into account the efficiency of the propulsion system, as we propose in this paper for estimating the emissions of a Fast Ferry propelled by waterjet.

The bottom-up method combines activity data obtained from Automatic Identification Systems (AIS) (n.d.) and technical data obtained from Lloyd's Register of Ships (IHSF) (Lloyd's register - Fairplay, n.d.). The AIS data includes, among other things, a ship's identity, position, speed and draught at a given time-stamp. Calculations usually are carried out for every individual commercial ship identified as in-service in the IHSF database (military vessels are not included).

To calculate the energy consumption and emissions in this type of inventory, the most important factors are the actual power delivered by both the main and auxiliary engines. To calculate these factors, the load factor (LF) values for both engines need to be determined.

However, for the calculation of the LF, none of the existing publications addressing this topic take into account the performance of the propulsion system.

Currently, not much is known about the effects that differing operating conditions and propulsion systems have on ships' emissions. This information is needed to evaluate and design current and future emissions inventories, in order to quantify as accurately as possible energy consumption and emissions. This requires knowledge of how propulsion systems influence the final results, but the methodologies are based on the general assumption that propulsion system performance is constant. Even though recent modifications have been implemented in order to reduce the uncertainties surrounding ships' energy use, emissions and the corresponding inventories, none of these refer to the propulsion system.

Regulating engine speed may be beneficial to the environment. Speed is determined by the engine setup, either through the direct propeller drive or indirect drive via an electrical generator. In any case, the efficiency of the propeller is considered to be constant, independently of the ship's speed.

The issue of speed, however, is even more complex for the RoPax vessels (a case studied in this paper) than other segments. It is also evident that slow steaming in the RoRo/RoPax segment has received little attention from researchers, compared to other segments of the shipping industry. The contextual characteristics of the RoRo/RoPax segment, with conditions varying between geographical markets, routes and seasons, make it hard to generalize results (Finnsgard et al., 2017). A detailed analysis of vessel speeds when approaching or exiting ports, on a port by port basis, would be required in order to be able to apply robust assumptions (Finnsgard et al., 2017).

In order to reduce the level of uncertainties from the AIS and ISHF, this paper presents a detailed analysis of vessel speed for each situation and navigation mode, from onboard data. The authors propose a new method for eight cases studied, after comparing four existing methods applied to all the cases. As can be seen in the four methods analysed in this paper, when changes in speed are applied to fast ferries propelled by a waterjet system, the efficiency of the propulsion system is not