Operational profiles of ships in Norwegian waters: A tool for analysis of the potential for hybrid and electric propulsion

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Abstract

Various regulations are imposed on shipping to limit its adverse health and environmental impacts. Alternative fuels and power systems are among solutions for compliance with these regulations. Power system of many vessels do not operate optimally due to diversity of operational profiles or slow steaming. Vessels may slow steam to save fuel; however, these savings are closely tied to design specifications of engine. This paper uses an activity-based approach and big data from the Automatic Identification System (AIS) to study the operational profiles of eight vessel types operating in Norwegian waters around mainland Norway in 2016. The aim is to identify vessel types that can benefit from electric and hybrid propulsion through the analysis of their operational profiles. Close to shore, the operational profiles of various vessel types are relatively similar, and all spend a great share of their time in lower loads. As the distance from shore increases, the operational profiles of various vessel types follow distinct trends. Among the considered vessel types, reefers spend more operational time close to engine design condition to reduce carriage time of perishable cargo. On the other hand, offshore and passenger ships show the most dynamic operational profiles and spend a large percentage of their operational time in part load, away from engine design condition. Such vessels can benefit from hybridisation, diesel-electric propulsion and other electric concepts,

such as batteries and fuel cells. Another option is to downsize engines for more optimal operation while fuel cells and batteries supply peak and part loads.

Keywords: Electric propulsion; Hybrid propulsion; Ship operational profiles; Energy efficiency; Emissions; Automatic Identification System

1 Introduction

In the period 2007–2012, on yearly average, shipping accounted for nearly 3% of annual global greenhouse gas (GHG) emissions. In the same period, maritime transport was responsible for approximately 15% and 13% of nitrogen oxides (NOx) and sulphur oxides (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. NOx and SOx can cause photochemical smog, acid rain and consecutive 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. The Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) aims at a progressive reduction of GHGs, NOx and SOx. To reduce GHG emissions, MARPOL Annex VI focuses on improving energy efficiency through the adoption of various technical and operational measures. To reduce SOx emissions, these regulations impose limits on sulphur content of marine fuels. For instance, the North Sea is among Sulphur Emission Control Areas

(SECAs) where stringent limits are imposed. Based on ship construction date, engine speed and operation area, MARPOL Annex VI sets NOx caps (IMO, 2013a, b).

Some countries introduce additional regulations to control these emissions further. For instance, Norway introduced a NOx tax in 2007, which applies to various sectors including domestic shipping and fishing. A year later, the Norwegian state and some business organisations, including Norwegian Shipowners' Association, reached a NOx agreement. The involved parties cofounded a NOx fund, and they pay a lesser amount to the fund instead of the tax when emission-reducing measures are implemented. The fund supports NOx-reducing measures (Jafarzadeh, 2016). For example, a platform supply vessel can receive 5 million Norwegian Krones (NOK) (one NOK ≈ 0.11 EUR in 2017) in support for retrofit of battery systems. There is also an additional support of 4 NOK/kWh charged shore power, measured over one year (NHO, 2017; Norges Bank, 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). At this range, specific fuel oil consumption (SFOC [g/kWh]) is at its minimum. However, operational profile of vessels may include diverse operations with different power demands (e.g. offshore vessels), or vessels may slow steam to reduce power and fuel consumption (e.g. container ships). Power system of many vessels do not operate optimally, where the fuel consumption is in line with the power demand (Skjong et al., 2017). During operations outside the optimum load range, SFOC and, consequently, emissions per kWh increase. In the case of slow steaming, the environmental benefits and corresponding fuel savings diminish as the vessel operates further away from the engine design condition (Smith et al., 2013). Diversity of operational profiles together with the increased pressure for environmental friendly operations call for alternative fuel and power systems.

Several studies estimate emissions of air pollutants 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 fuel consumption. Their difference is in the way they estimate fuel consumption: 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. sailing speed) from, for instance, Automatic Identification System (AIS) and technical data (e.g. service speed) from other sources, such as IHS Markit (IHS Markit, 2017) to estimate operational profile of vessels and consequently their fuel consumption and emissions. Nunes et al. (2017) reviews recent articles that use activity-based approach to estimate emissions from shipping. Although these studies investigate the operational profiles, their final goal is to estimate emissions. As a result, they may not elaborate on the difference of vessels regarding operational profiles, and they may not focus on evaluating the need for alternative propulsion systems to improve efficiency and reduce emissions.

This paper uses the activity-based approach to study the operational profile of various vessel types operating in Norwegian waters around mainland Norway in 2016. This study covers the following vessel 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 supply vessels and (viii) passenger ships. This paper investigates whether the studied vessels use their installed power optimally. This is to suggest improvements by integrating electric or hybrid propulsion on board the most appropriate types of vessels. Electric/hybrid propulsion, among others, refers to diesel-electric systems, fuel cells and batteries, which could be used for full or partial propulsion. For instance, if a vessel type uses engines in a suboptimal manner, one may argue the possibility of downsizing the main engines to operate them at an optimum point, while fuel cells together with batteries provide part 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 total installed power. Instead, the focus is on switching to diesel-electric or combining engines with fuel cells and batteries to improve efficiency.

The remainder of this study is organised as follows: Section 2~~2~~ gives an overview of marine power 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~~6~~ and conclusions in Section 7~~7~~.

2 Marine propulsion systems

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

Figure 2 illustrates the composition of propulsion systems adopted in Norwegian waters in 2013. A large group of larger cargo ships are equipped with slow-speed direct-driven engines that mainly operate on heavy oil variants. For other ship types, a large group of vessels use medium and high-speed engines with reduction gear. A large proportion of offshore vessels, passenger ships and other vessels have different oil/diesel-electric propulsion configurations. It is relatively easy to integrate hybrid configurations and install batteries on board these vessels. It is considerably more costly to integrate batteries on board mechanically driven vessels, with or without gear. In general, ships with direct-driven power systems are larger and operate more in international traffic, while the group with reduction gear and electric transmission mainly operate in domestic traffic. The exception is the major cruise ships and offshore supply vessels that also operate internationally (DNV GL, 2014).

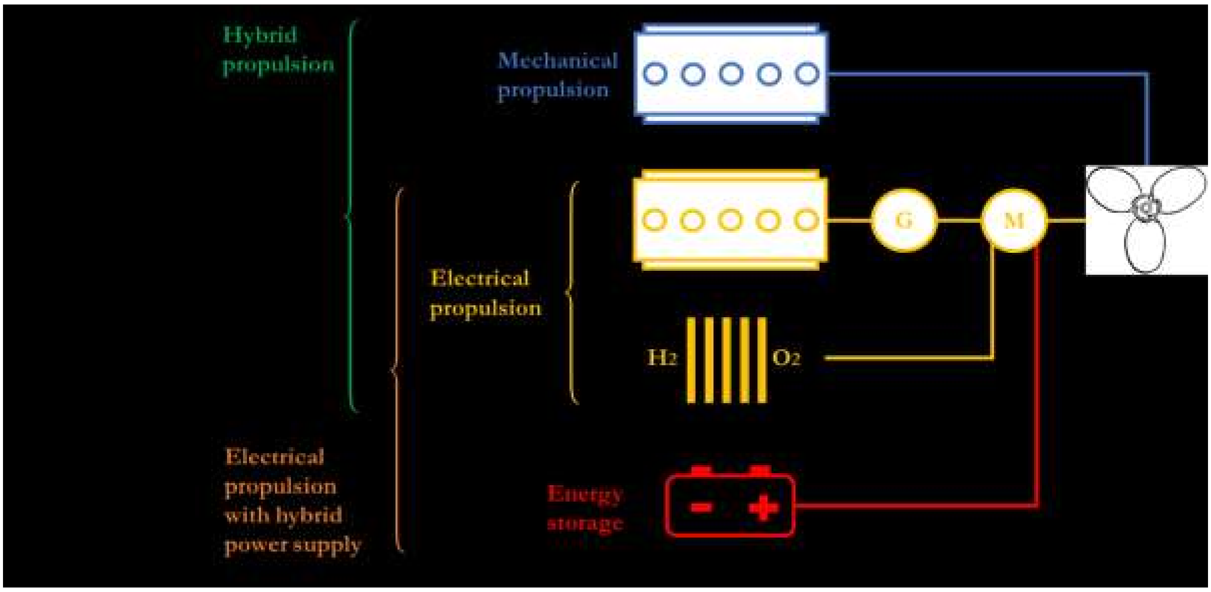

Figure 1. Propulsion systems based on Geertsma et al. (2017)

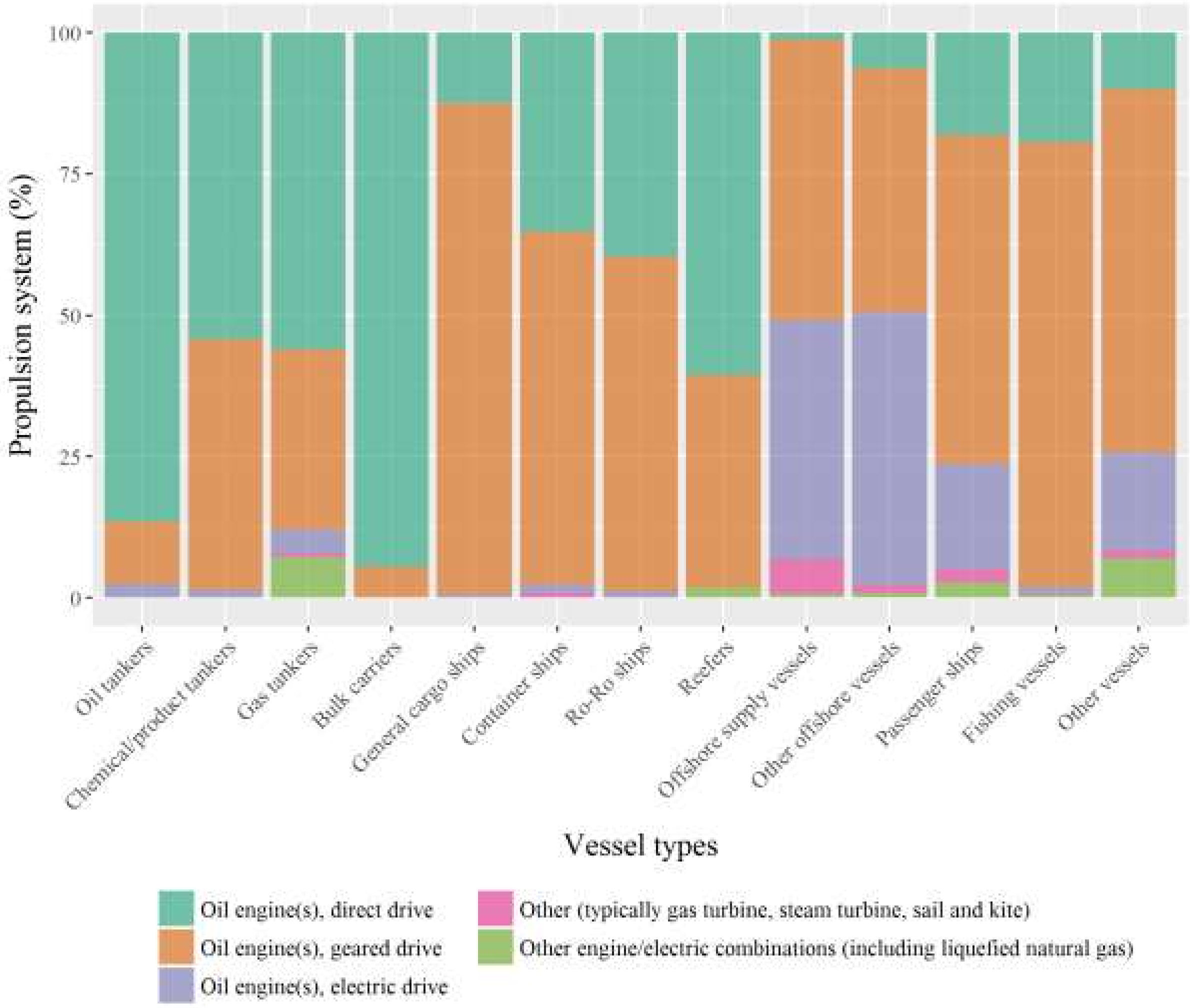

Figure 2. Propulsion systems used in Norwegian waters in 2013 (based on DNV GL (2014))

3 Materials

3.1 Data sources

The Norwegian Coastal Administration (NCA; Kystverket in Norwegian) is responsible for services related to maritime safety and transport planning and efficiency, among others (NCA, 2017a). The NCA established AIS Norway in 2005, which currently consists of approximately 50 base stations that receive information from all vessels over 300 gross tons in international traffic. AIS Norway covers, with some exceptions, the area within 40–60 nautical miles (nm;

one nm ≈ 1.852 km) from the Norwegian baseline[1] (NCA, 2016a). In addition, the NCA receives AIS data from AIS satellites. Data from the satellites is used for civil traffic monitoring in the ocean areas that are not covered by the land-based AIS stations (Moen, 2017; NCA, 2016b).

The NCA provided 12 monthly datasets during 2016 for various vessel types operating in Norwegian waters around mainland Norway (Aamot, 2017). Each dataset contains processed AIS data and includes operational information on (i) the International Maritime Organisation (IMO) number, (ii) vessel type, (iii) vessel size (shown within a range), (iv) date and time, (v) distance to next data point, (vi) time to next data point and (vii) position (in the format of well-known binary geometry representation). The data covers thirteen vessel types: (i) chemical/product tankers, (ii) gas tankers, (iii) oil tankers, (iv) bulk carriers, (v) general cargo ships, (vi) container ships, (vii) Ro-Ro ships, (viii) reefers, (ix) offshore supply vessels, (x) other offshore service vessels, (xi) passenger ships, (xii) fishing vessels, and (xiii) others. The available data is big AIS data with more than 240 million records.

The IMO numbers of the vessels are used as cross-references for deriving their technical information (i.e. service speed, main engine power, fuel type and propulsion type) from IHS Markit, commonly known as Sea-web. To enable this cross-reference and activity-based analysis, only vessels with valid IMO numbers and information on their service speed, main engine power, fuel type and propulsion type are considered.

The Norwegian Mapping Authority (Kartverket in Norwegian) collates, systemises, manages and communicates public geographical information (The Norwegian Mapping Authority, 2017). This Authority provided geographical information of Norway (Tolpinrud Jøntvedt,

[1] A baseline, as defined by the United Nations Convention on the Law of the Sea, is the line along the coast from which the seaward limits of a state's territorial sea and certain other maritime zones of jurisdiction are measured (United Nations, 1982).

2017), which among others includes maritime zones and data on land bordering Sweden, Finland and Russia as well as coastal islands, islets and skerries (i.e. isolated rocks or reefs in the sea).

3.2 Geographical boundaries

Figure 3 illustrates geographical boundary of the data provided by the NCA. To clarify the boundary, Figure 4. (a) illustrates the internal waters, territorial sea, contiguous zone and Exclusive Economic Zone (EEZ) around mainland Norway. The internal waters consist of fjords, bays and small marine areas between the coastline and baseline, which is the reference point for calculating other jurisdictional areas. The territorial sea extends 12 nm from the baseline. The contiguous zone extends 12 nm seaward from the outer limit of the territorial sea. The EEZ extends 200 nm from the baseline, unless the EEZs of neighbouring countries, such as Denmark overlap (Norwegian Ministry of Foreign Affairs, 2017).

In Figure 4. (b), the data points received from the NCA for April 2016 (more than 29 million records) are overlaid on the maritime zones (i.e. Figure 4. (a)). The data points for other months have a similar boundary. Regarding Figure 4. (b), the data used in this study covers the internal waters, territorial waters, contiguous zone and some parts of the EEZ around mainland Norway. The only exceptions are in the northeast and southeast of the mainland: in the northeast, some parts of international waters are also covered, whereas in the southeast, some parts of the internal waters, territorial waters and contiguous zone are left out.

Figure 3. Geographical boundary of data provided by the Norwegian Coastal Administration (Aamot, 2017)

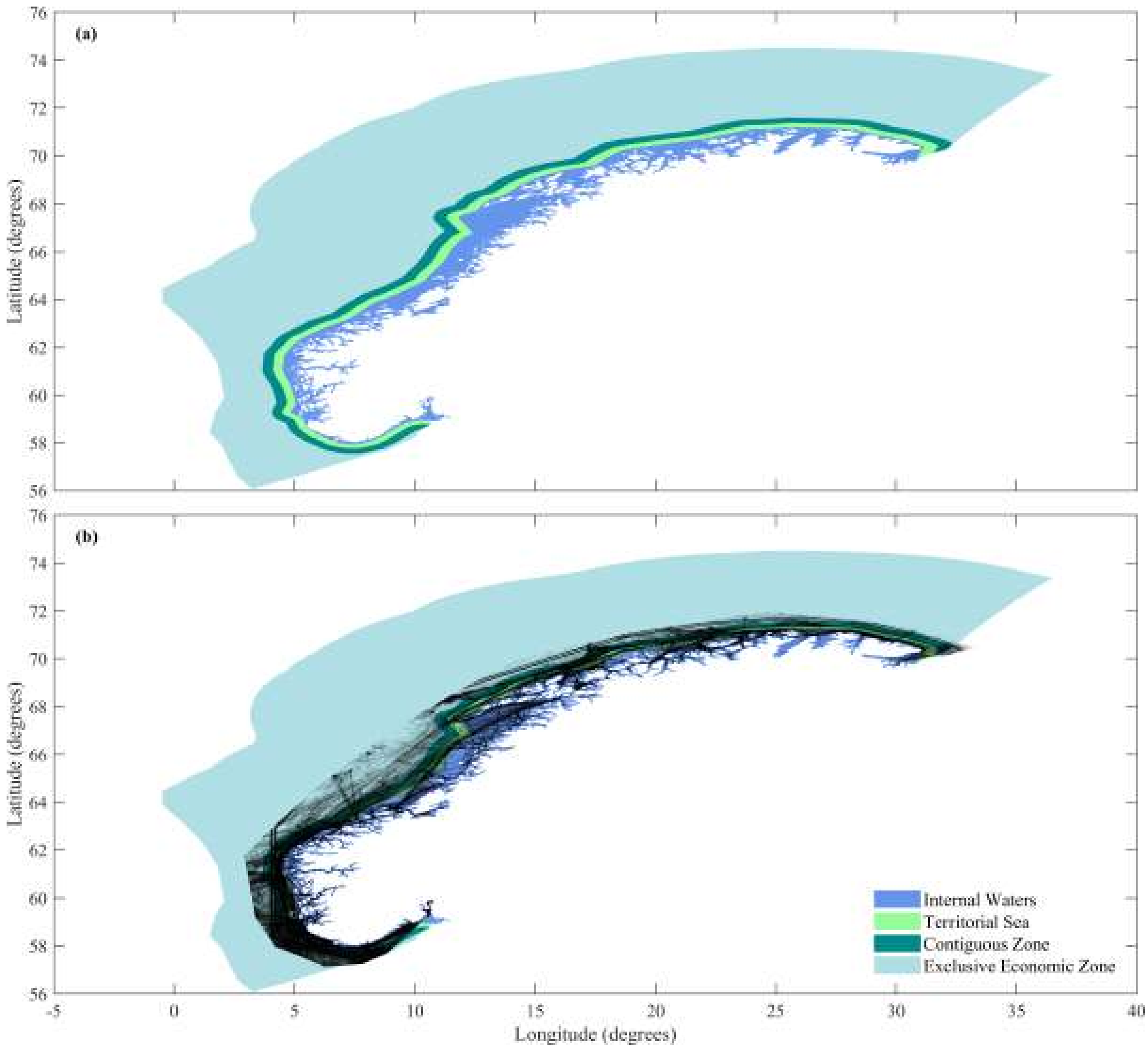

Figure 4. (a) Maritime zones around mainland Norway, (b) The black shadow represents the data points received from the Norwegian Coastal Administration for April 2016, which are overlaid on the maritime zones around mainland Norway (based on data from Aamot (2017); Tolpinrud Jøntvedt (2017)).

4 Method

Activity-based or bottom-up approach uses shipping activity to estimate operational profile of vessels and their fuel consumption and emissions. This method is data intensive and requires operational data (e.g. sailing speed) and technical specifications (e.g. service speed) of each vessel (Jafarzadeh, 2016).

AIS is an automatic tracking system primarily used for collision avoidance of ships. Through signal transmission, AIS allows ships to view marine traffic in their area and to be seen by that traffic to avoid accidents. In addition to serving this purpose, the transmitted signals contain valuable information for estimating operational profile of vessels. The AIS signals provide information on ship name, ship type, ship speed over ground and position, among others, in specific time intervals (Goldsworthy and Goldsworthy, 2015). Until 2009, only AIS data from shore-based stations were available. Since 2009, a greater geographical coverage via satellite technology has improved the quality of data available for the activity-based approach (Smith et al., 2014). Other sources, such as IHS Markit provide detailed information on vessel characteristics, such as service speed and installed power. In activity-based approach, one can use AIS data, vessel characteristics and empirical formulas to estimate operational profile of vessels. The third IMO GHG Study applied this approach for estimating emissions from shipping (Smith et al., 2014). The current study follows this approach.

AIS datasets include high-volume and high-variety information (i.e. big data), which makes processing and storage with conventional methods highly challenging. In this study, the available data contains more than 240 million records, which are processed to provide insight into the operational profile of various vessel types. The process of extracting insights from big data can be divided into two sub-processes: (i) data management and (ii) analytics. Data management involves processes and technologies to acquire and store data and to prepare and retrieve it for analysis. Analytics refers to techniques used to analyse and acquire intelligence from big data (Gandomi and Haider, 2015). Figure 5 and the rest of this section explain the steps taken to prepare and analyse the AIS datasets.

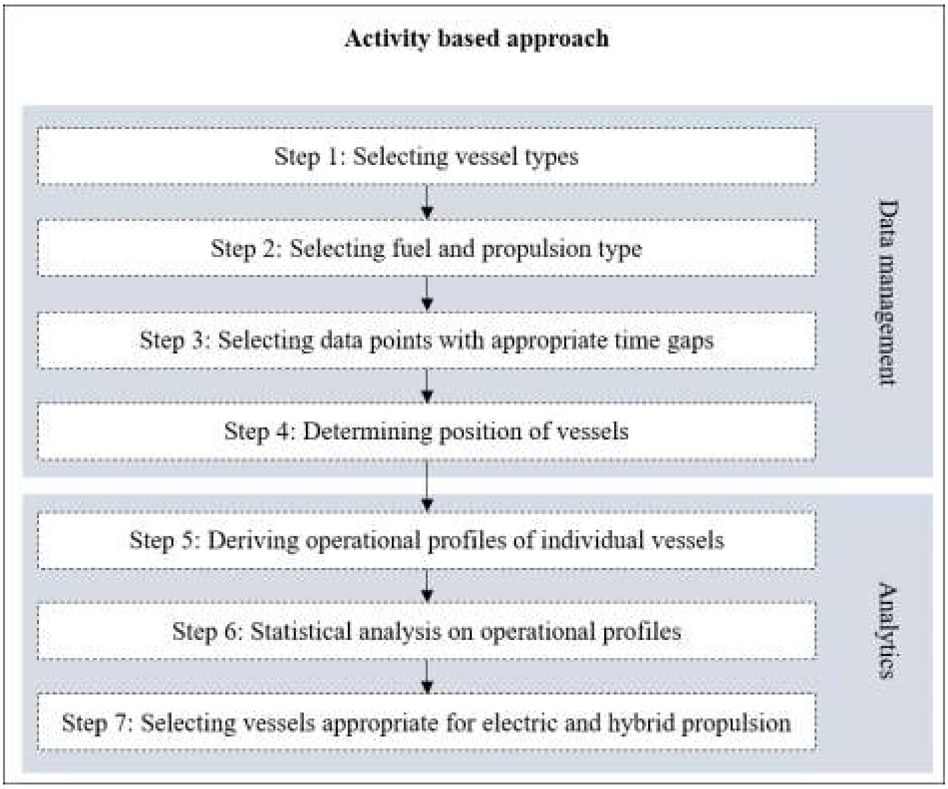

Figure 5. Method used in this study

4.1 Step 1: Selecting vessel types

Two of the thirteen vessel types (see Section 3.1) were excluded from the analysis: (i) fishing vessels and (ii) others. Fishing vessels, such as trawlers tow fishing gears, which results in high engine loads at relatively low speeds (Coello et al., 2015). Therefore, low speeds do not necessarily translate into low engine power for these vessels. In addition, energy efficiency of fishing vessels depends on the fishing gear or method used. Jafarzadeh et al. (2016) studied the energy efficiency of ten segments of the Norwegian fishing fleet during 2003–2012. While coastal seiners below the 21.36 m quota length[2] had a mean fuel use coefficient[3] of 0.054 kg fuel/kg fish, factory trawlers had a mean fuel use coefficient of 0.354 kg fuel/kg fish. Their study excluded shrimp trawlers, which may be even more fuel intensive. Various factors, such as fish quotas and total fish stock biomass also affect the energy efficiency of fishing vessels (Jafarzadeh et al., 2016). In addition, AIS covers larger vessels, and coverage of smaller vessels in databases used in activity-based approach is uncertain. For instance, in 2013, roughly 1000 Norwegian fishing vessels had AIS-transmitters. As a result, AIS did not cover around 5000 Norwegian fishing vessels. Although the excluded vessels were relatively small, they contributed to approximately 20% of fuel consumption from the Norwegian fishing fleet (DNV GL, 2015). Moreover, to estimate fuel consumption of vessels, they should appear in the IHS Markit database (or a similar database) and have an IMO number. While this should include all ships involved in international shipping, many domestic vessels may not be covered (Jafarzadeh, 2016; Smith et al., 2014). As a result, this study does not cover fishing vessels. The "Others" category, among others, includes well-boats, tugboats and coast guard vessels (DNV GL, 2015). Since "Others" category is broad and may include several vessel types, they are also excluded from this study.

This study evaluates eight vessel types: (i) tankers (including chemical/product tankers, gas tankers and oil tankers), (ii) bulk carriers, (iii) general cargo ships, (iv) container ships, (v) Ro-Ro ships, (vi) reefers, (vii) offshore vessels (including offshore supply vessels and other offshore service vessels) and (viii) passenger ships.

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[2] In Norway, traditionally, vessel length was the basis for quota allocation among coastal fishing vessels. However, it is not desirable to extend a vessel or replace it with a larger one to claim a larger quota. Therefore, the vessel length on a specific date is the basis for quota allocation, called the quota length. The vessel owners can still change to larger or smaller vessels; however, this will not affect the quota. Therefore, quota length might differ from actual vessel length (Jafarzadeh et al., 2016).

[3] In fisheries, it is normal practice to use a coefficient, such as the fuel use coefficient (kg fuel/kg fish) to indicate energy efficiency. High fuel use coefficients indicate low energy efficiency and vice versa (Jafarzadeh et al., 2016).

4.2 Step 2: Selecting fuel and propulsion type

Vessels using liquefied natural gas (LNG) fuel are filtered out due to their lower emissions compared to vessels with conventional fuels, such as marine gas oil (Jafarzadeh et al., 2017). Vessels using coal or vessels for which fuel is not applicable (e.g. battery driven vessels) are also excluded. This study covers vessels using distillate or residual fuel. Several vessels use fuel, but their fuel type is not known. Assuming that these vessels use conventional fuels, they were covered in this study.

Despite having diesel-electric systems, power systems of many vessels do not operate optimally. For instance, due to dynamic power demands, operators may run more diesel engine generators (gensets) than needed. This may lead to partial loading of gensets and lower energy efficiency (Skjong et al., 2017). However, considering the available data, this study can only estimate total power of vessels at each data point. Therefore, power distribution among engines and efficient operation of diesel-electric ships are unclear. As a result, only vessels with engines and direct/gear drives are considered and diesel-electric vessels are excluded. Vessels with steam/gas turbines, sail and kite are also filtered out.

4.3 Step 3: Selecting data points with appropriate time gaps

Time gaps might occur if the AIS signal is temporarily lost due to, for instance, a vessel going out of range or a vessel going international and returning (Goldsworthy and Goldsworthy, 2015). In the available data, time steps range from one second to approximately 54 hours. However, in each monthly dataset, 97–99% of data points have time steps below 10–13 minutes. As a result, this study excludes data points with time gaps above 13 minutes.

4.4 Step 4: Determining position of vessels

Norway has several fjords and islands, close to which vessels may spend a great share of their time manoeuvring. As a result, it is considered beneficial to distinguish vessels close to coast from the rest of vessels for data analysis. In Norway, speed limits at sea vary among municipalities, and each municipality may enforce different limits in different areas. The NCA provides guidelines on speed limits at sea, which may be followed by municipalities (NCA, 2017b). For instance, the NCA recommends a speed limit of 5 knots in short sea shipping of 100–500 meters from land, where there can be recreational activities and aquaculture facilities, among others (NCA, 2009). This study uses 500 meters (≈ 0.27 nm) distance from coast as a baseline for distinguishing vessels close to coast from the rest of vessels.

As mentioned in Section 3.1, the Norwegian Mapping Authority provided geographical information of Norway. In addition, the NCA provided position of vessels in each data point in the format of well-known binary geometry representation. After converting the position data to coordinates (i.e. latitude and longitude), the minimum distance of vessels from coastline of Norway at each data point was found. More specifically, land bordering Sweden, Finland and Russia as well as coastal islands, islets and skerries where considered while finding the distance of vessels from coastline of Norway.

4.5 Step 5: Deriving operational profiles of individual vessels

Distance and time between consecutive data points 1 and 2 (see Section 3.1) are used to calculate the average vessel speed between these points (u_{12}). Therefore, it is assumed that vessels follow a straight trajectory between consecutive data points. The IMO number of the vessels is used to derive their main engine power (P_{max}) and vessel service speed (u_s) from IHS Markit database (see Section 3.1). Some other databases may provide vessel speed at maximum engine power (u_{max}). Propulsive power (*P*) and load factor (*LF*) at each data point are generally estimated based on the cubic law (Equation (1)) (Goldsworthy and Goldsworthy, 2015):

$$LF = \frac{P}{P_{max}} = \left(\frac{u_{12}}{u_{max}}\right)^3 = f\left(\frac{u_{12}}{u_s}\right)^3 \tag{1}$$

Typical values for the fraction *f* in the literature are 0.8–1.0 (Goldsworthy and Goldsworthy, 2015; Mjelde et al., 2014). This study uses the value 0.83, which is suggested by the US Environmental Protection Agency (ICF International, 2009). This approach for *LF* estimation is similar to the approach used in some other AIS analyses, such as Coello et al. (2015); Goldsworthy and Goldsworthy (2015); Mjelde et al. (2014).

Ships often cycle their propulsion engine on and off during manoeuvring to reduce speeds below the dead slow setting. For instance, container ships have their engines stopped 25–50% of their manoeuvring time. Therefore, *LF*s as low as 0.02 are possible (ICF International, 2009), and this study considers this minimum limit for *LF*s while ships are under way. Lower *LF*s are excluded from this study and are considered representative of no motion.

Neither IHS Markit nor other data sources provide auxiliary engine or auxiliary boiler utilization data (Smith et al., 2014). Some studies, such as Smith et al. (2014) assume the auxiliary power based on various factors, such as vessel capacity and operational mode (e.g. manoeuvring). This study only focuses on power of main engines and excludes auxiliary power consumption.

4.6 Step 6: Statistical analysis on operational profiles

To represent operational profile of vessels, the distribution of active/operational time spent in each load (i.e. *LF*; see Section 4.5) range by individual vessels within various ship categories are studied. To illustrate this distribution, Tukey's boxplots are used. The boxes represent the lower quartile (Q_1), median and upper quartile (Q_3) of values. The whiskers represent the lowest data within a 1.5 interquartile range (i.e. 1.5 (Q_3 - Q_1)) of Q_1 and the highest data within a 1.5 interquartile range of Q_3 (Krzywinski and Altman, 2014). Blue lines, dots and triangles in the graphs respectively represent median, outliers and mean values. Outliers may overlap. In other words, an outlier may represent one or more vessels.

4.7 Step 7: Selecting vessels appropriate for electric and hybrid propulsion

To achieve full potential efficiency and environmental gains, vessels must be considered as engineering systems within their operational profiles (Trovão et al., 2016). Electric propulsion is a fuel-efficient option for ships with large auxiliary loads compared to their propulsion power, ships with diverse operational profiles, and ships that are operated in partial loads for a significant portion of their time (Breucker et al., 2009; Geertsma et al., 2017). When the auxiliary load is only a fraction of the propulsion power, the losses associated with the electrical conversion reduce efficiency of electric propulsion systems. Therefore, ships with low hotel load that frequently operate at low speed can benefit from hybrid propulsion systems (Geertsma et al., 2017). Ships with short-term peaks or long periods of very low load benefit the most from hybrid power systems (Grimmelius et al., 2011). However, other types of vessels can also benefit from optimal loading of their prime movers and load levelling through hybridisation (Dedes, 2013).

After deriving the operational profiles of various vessel types, this study identifies the vessels that can benefit the least and most from switching to electric and hybrid propulsion.

5 Results

This section includes two operational profiles for each vessel type: one for vessels with 0.27 nm or less distance from the coastline of Norway (hereinafter coastal vessels; see Section 4.4) and one for vessels further than 0.27 nm from the coastline of Norway (hereinafter ocean-going vessels). Each operational profile shows the active time spent by vessels in various load ranges (see Section 4.5). Tukey's boxplots show data distribution (see Section 4.6). Figure 6 shows the number of coastal and ocean-going vessels covered in this study after the data filtering explained in Sections 4.1–4.3.

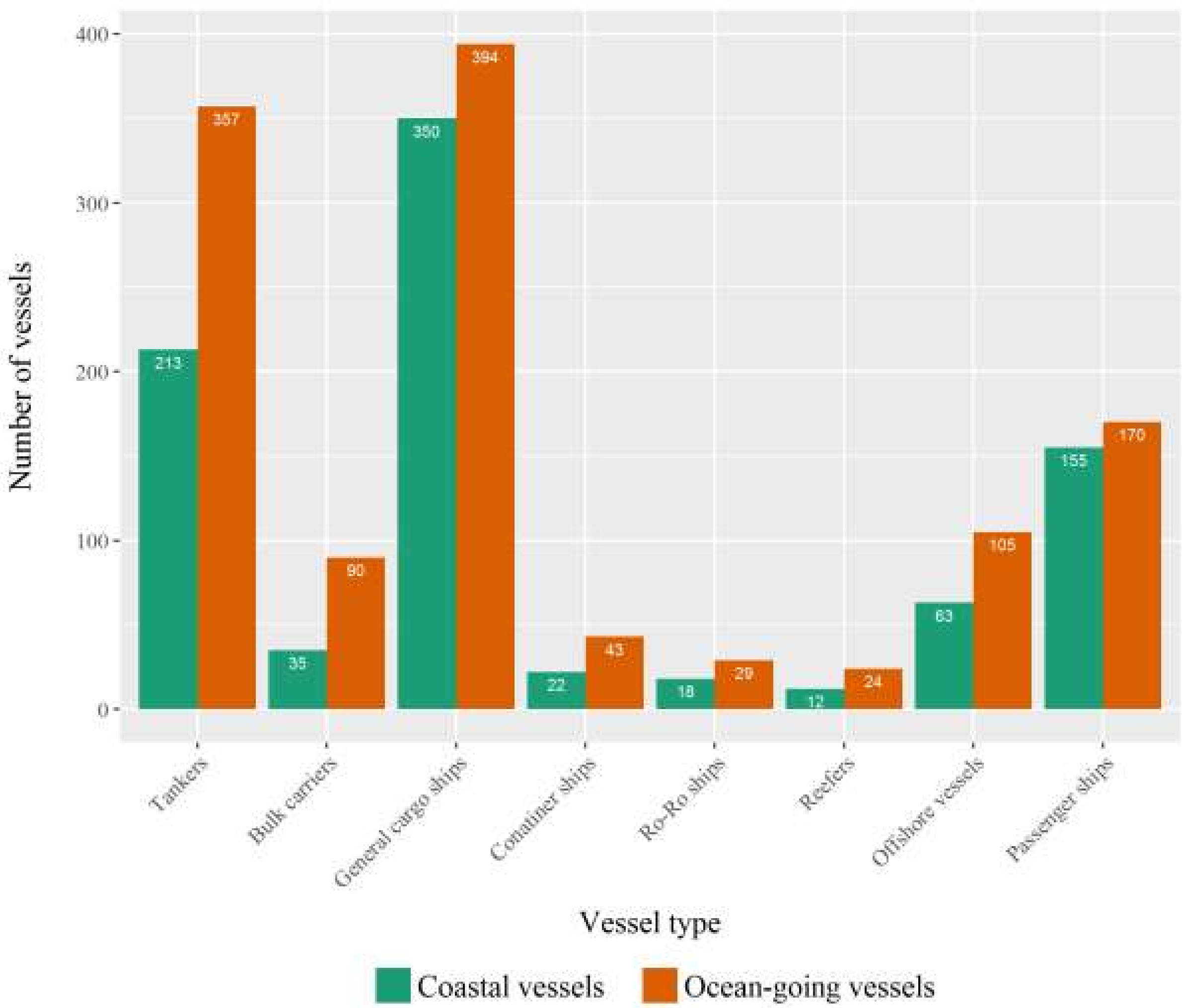

Figure 6. Number of coastal and ocean-going vessels in this study. Coastal and ocean-going vessels operate in Norwegian waters within and beyond 0.27 nautical miles from shore during 2016, respectively.

5.1 Tankers

Figures 7 illustrates the operational time spent by coastal and ocean-going tankers in various load ranges in 2016. While the median coastal tanker spends all its time in loads below 0.4, the median ocean-going tanker spends a substantial share of its time in higher loads, with a peak at 0.5–0.6 load. More specifically, while a median coastal tanker spends approximately 40% of its time in loads as low as 0.02–0.2, the corresponding value for a median ocean-going tanker is less than 10%.

There is a considerable difference in operational profile of vessels within the same category (i.e. coastal and ocean-going). For instance, coastal tankers spend 0–50% of their time at load range 0.3–0.4, except for four outlier vessels (overlapped in Figures 7), which spend all their time in this load range. The median value is approximately 6%: half of the coastal tankers spend less than 6% of their time in this load range. The mean value of the time spent in load range 0.3–0.4 is approximately 14%.

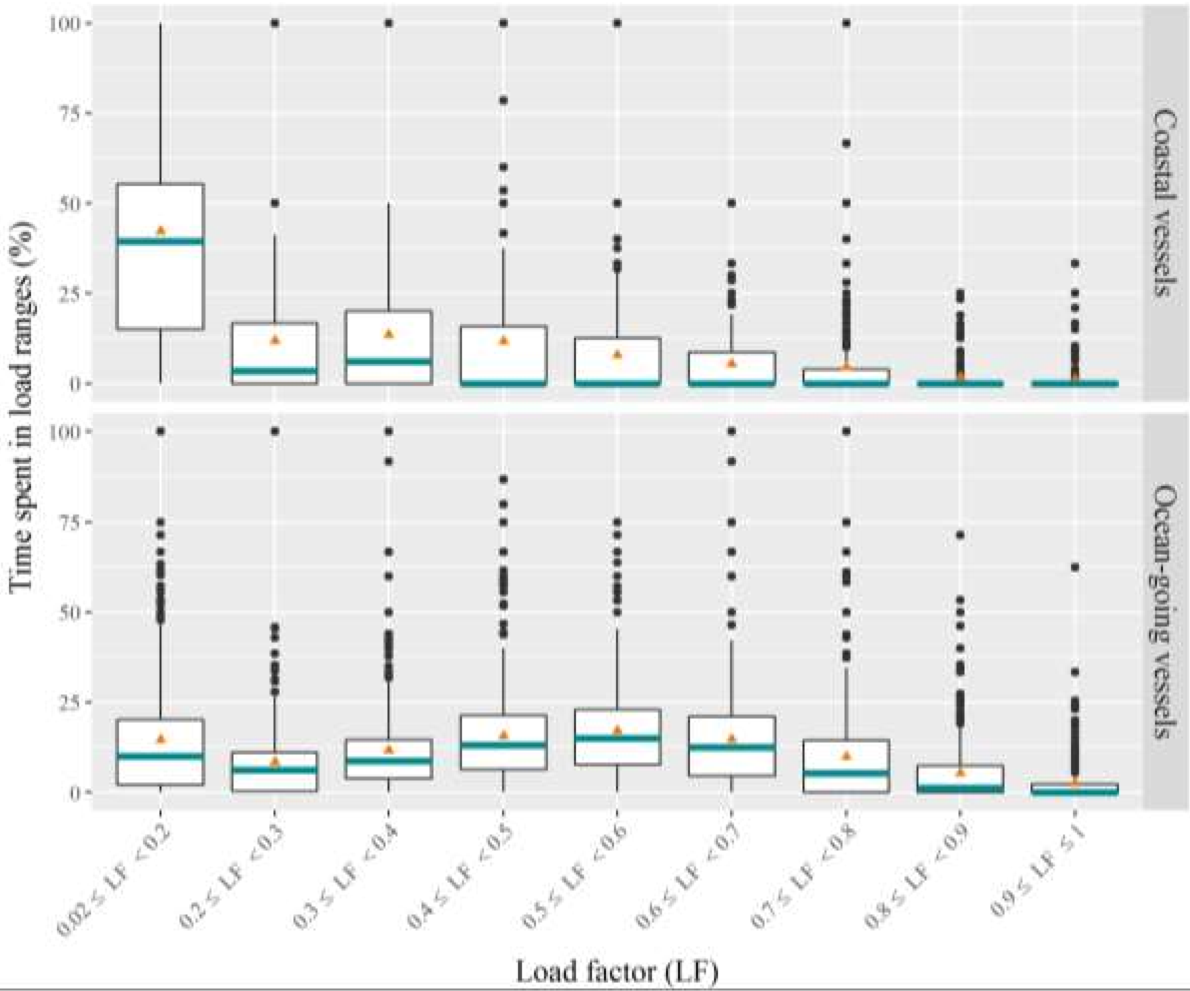

Figure 7. Operational time spent by tankers in various load factor ranges while operating in Norwegian waters within and beyond 0.27 nautical miles from shore during 2016 (i.e. coastal and ocean-going vessels, respectively). The boxes represent the 1st and 3rd quartiles, with the median (blue line). The whiskers follow Tukey's method. The dots are outliers. The triangles show mean values.

5.2 Bulk carriers

Figures 8 illustrates the time spent by coastal and ocean-going bulk carriers in various load ranges in 2016. While the median coastal bulk carrier spends approximately 23% of its time in load range of 0.02–0.2, the corresponding value for the ocean-going counterpart is as low as 4%. The median ocean-going bulk carrier has the peak at load range of 0.4–0.5 and spends approximately 16% of its time in this range. While the load factor of the median coastal bulk carrier never reaches 0.6–0.7, the ocean-going vessel spends approximately 7% of its time in this load range. Similar to tankers (see Section 5.1), there is a considerable difference in operational profile of vessels within the same category (i.e. coastal and ocean-going) and the time they spend in each load range.

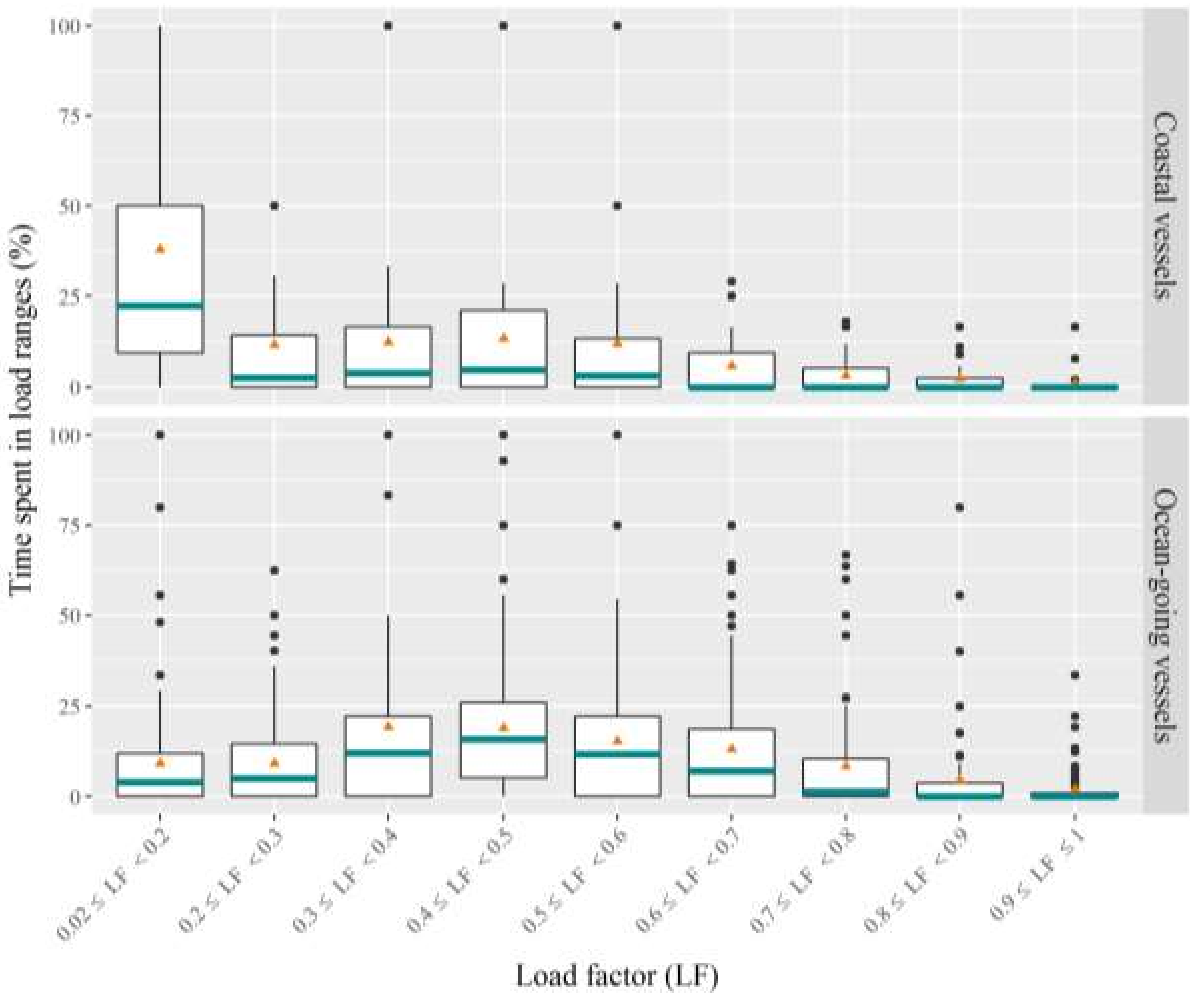

Figure 8. Operational time spent by bulk carriers in various load factor ranges while operating in Norwegian waters within and beyond 0.27 nautical miles from shore during 2016 (i.e. coastal and ocean-going vessels, respectively). The boxes represent the 1st and 3rd quartiles, with the median (blue line). The whiskers follow Tukey's method. The dots are outliers. The triangles show mean values.

5.3 General cargo ships

Figures 9 illustrates the time spent by coastal and ocean-going general cargo ships in various load ranges in 2016. The median coastal general cargo ship has the peak in load range of 0.02–0.2 with approximately 24% of its active time spent in this range. The corresponding value for the ocean-going counterpart is approximately 10%. The median ocean-going general cargo ship has the peak at load range 0.4–0.5 and spends approximately 17% of its time in this range. In addition, there is a considerable difference in operational profile of vessels within the same category (i.e. coastal and ocean-going) and the time they spend in each load range.

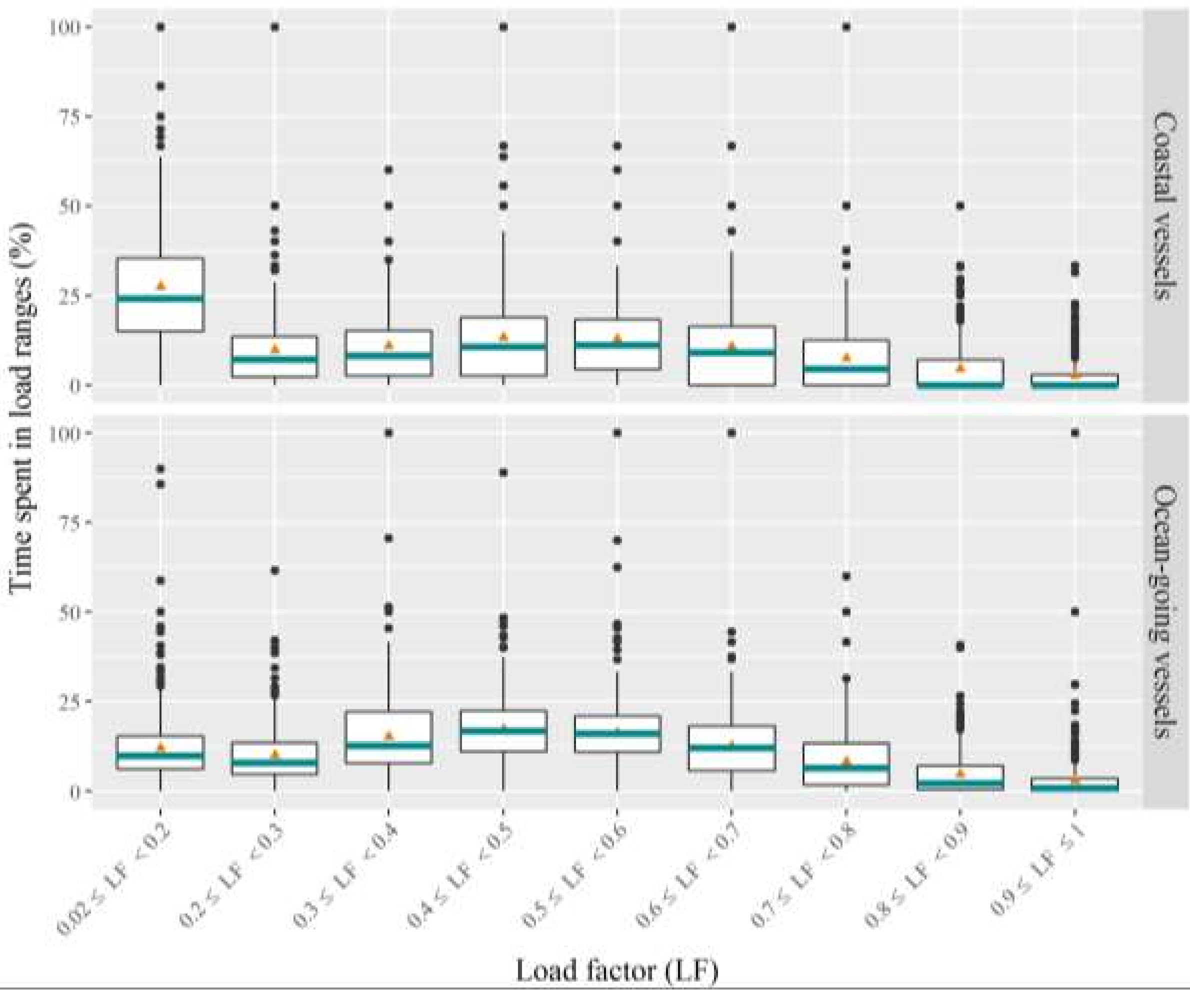

Figure 9. Operational time spent by general cargo ships in various load factor ranges while operating in Norwegian waters within and beyond 0.27 nautical miles from shore during 2016 (i.e. coastal and ocean-going vessels,

respectively). The boxes represent the 1st and 3rd quartiles, with the median (blue line). The whiskers follow Tukey's method. The dots are outliers. The triangles show mean values.

5.4 Container ships

Figures 10 illustrates the time spent by coastal and ocean-going container ships in various load ranges in 2016. Fifty percent of coastal container ships spend more than approximately 39% and 27% of their time in load ranges of 0.02–0.2 and 0.2–0.3, respectively. The corresponding values for ocean-going container ships drop to approximately 18% and 12%, respectively. While the load factor of the median coastal vessel never reaches 0.5 and above, the ocean-going vessel spends approximately 8% and 2% of its time in load ranges 0.5–0.6 and 0.6–0.7, respectively. Similar to previous vessel types, there is a considerable difference in operational profile of vessels within the same category (i.e. coastal and ocean-going) and the time they spend in each load range.

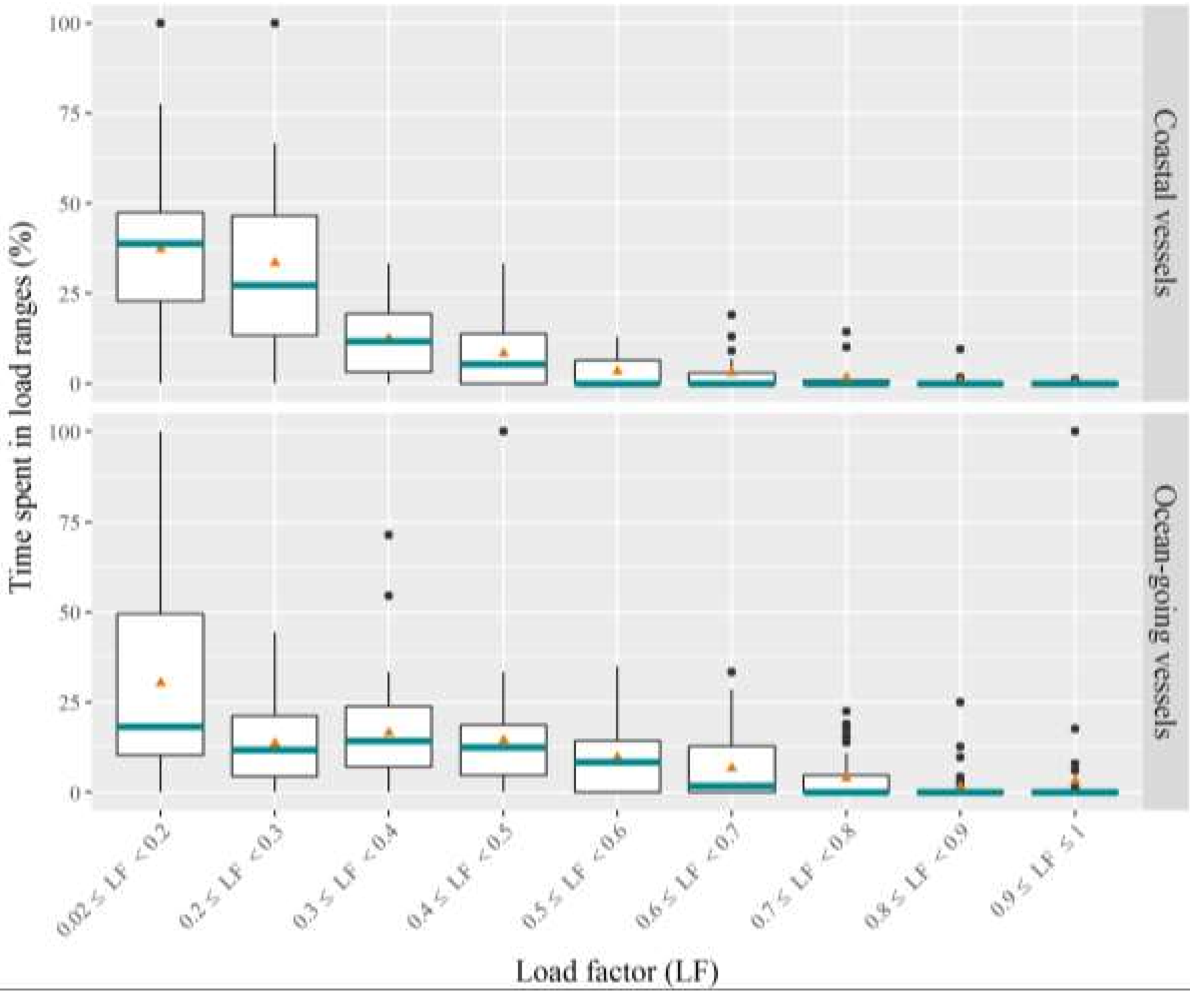

Figure 10. Operational time spent by container ships in various load factor ranges while operating in Norwegian waters within and beyond 0.27 nautical miles from shore during 2016 (i.e. coastal and ocean-going vessels, respectively). The boxes represent the 1st and 3rd quartiles, with the median (blue line). The whiskers follow Tukey's method. The dots are outliers. The triangles show mean values.

5.5 Ro-Ro ships

Figures 11 illustrates the time spent by coastal and ocean-going Ro-Ro ships in various load ranges in 2016. Fifty percent of coastal Ro-Ro ships spend more than 50% of their time in loads as low as 0.02–0.2. The median ocean-going Ro-Ro ship also has its peak at the lowest load range, although it spends less time in this range (20%). While the median coastal vessel barely spends any time above 0.5 load, the ocean-going counterpart spends approximately 10% of its time in load range 0.5–0.6.

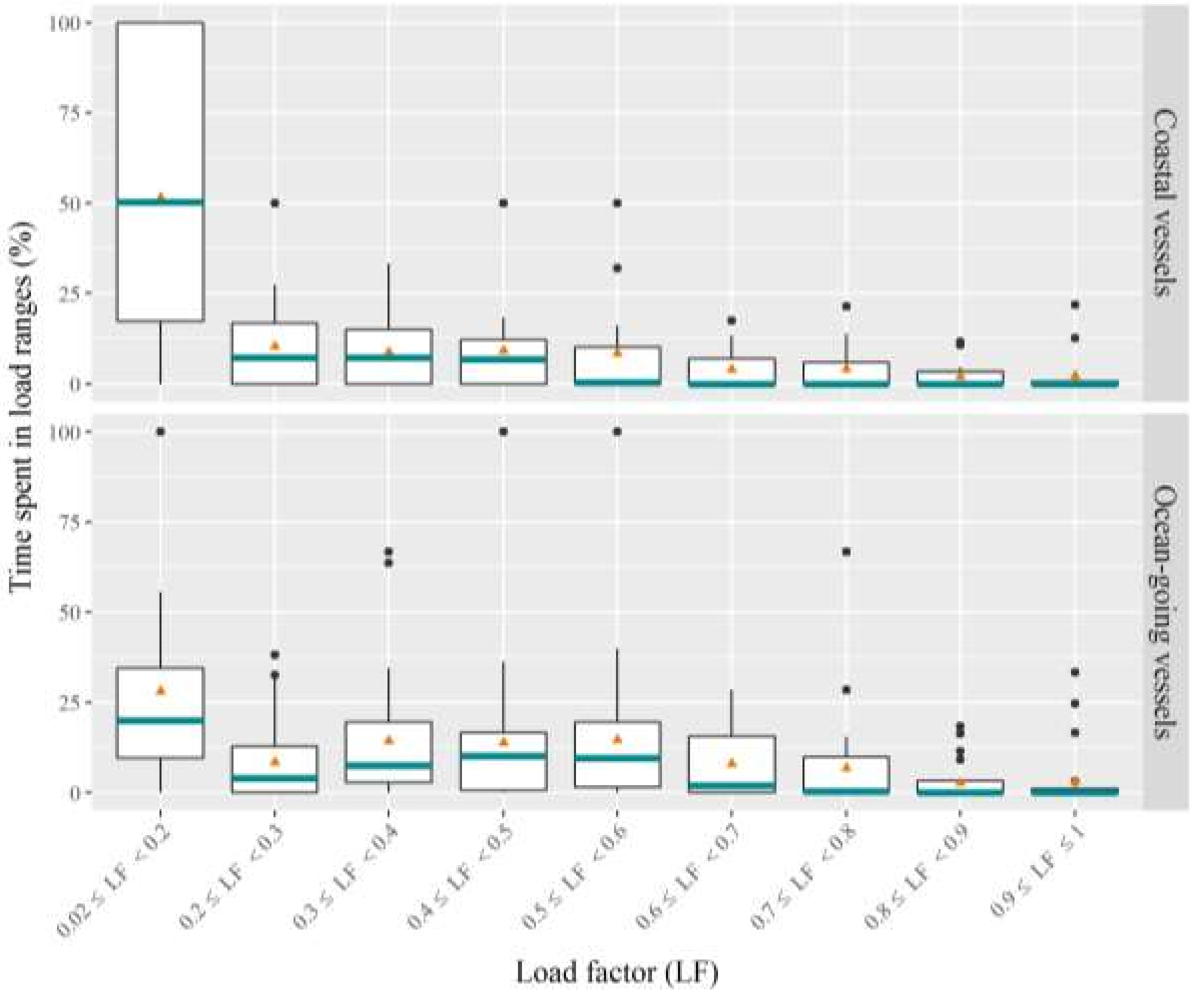

Figure 11. Operational time spent by Ro-Ro ships in various load factor ranges while operating in Norwegian waters within and beyond 0.27 nautical miles from shore during 2016 (i.e. coastal and ocean-going vessels, respectively). The boxes represent the 1st and 3rd quartiles, with the median (blue line). The whiskers follow Tukey's method. The dots are outliers. The triangles show mean values.

5.6 Reefers

Figures 12 illustrates the time spent by coastal and ocean-going reefers in various load ranges in 2016. Fifty percent of coastal reefers spend more than 23% of their time in load range 0.02–0.2. Coastal reefers also spend substantial time in higher loads: fifty percent of them spend approximately 8%, 8%, 11% and 9% of their time in load ranges 0.4–0.5, 0.5–0.6, 0.6–0.7 and 0.7–0.8, respectively. The median ocean-going reefer has the peak in load range 0.6–0.7, with approximately 15% of its time spent at this range.

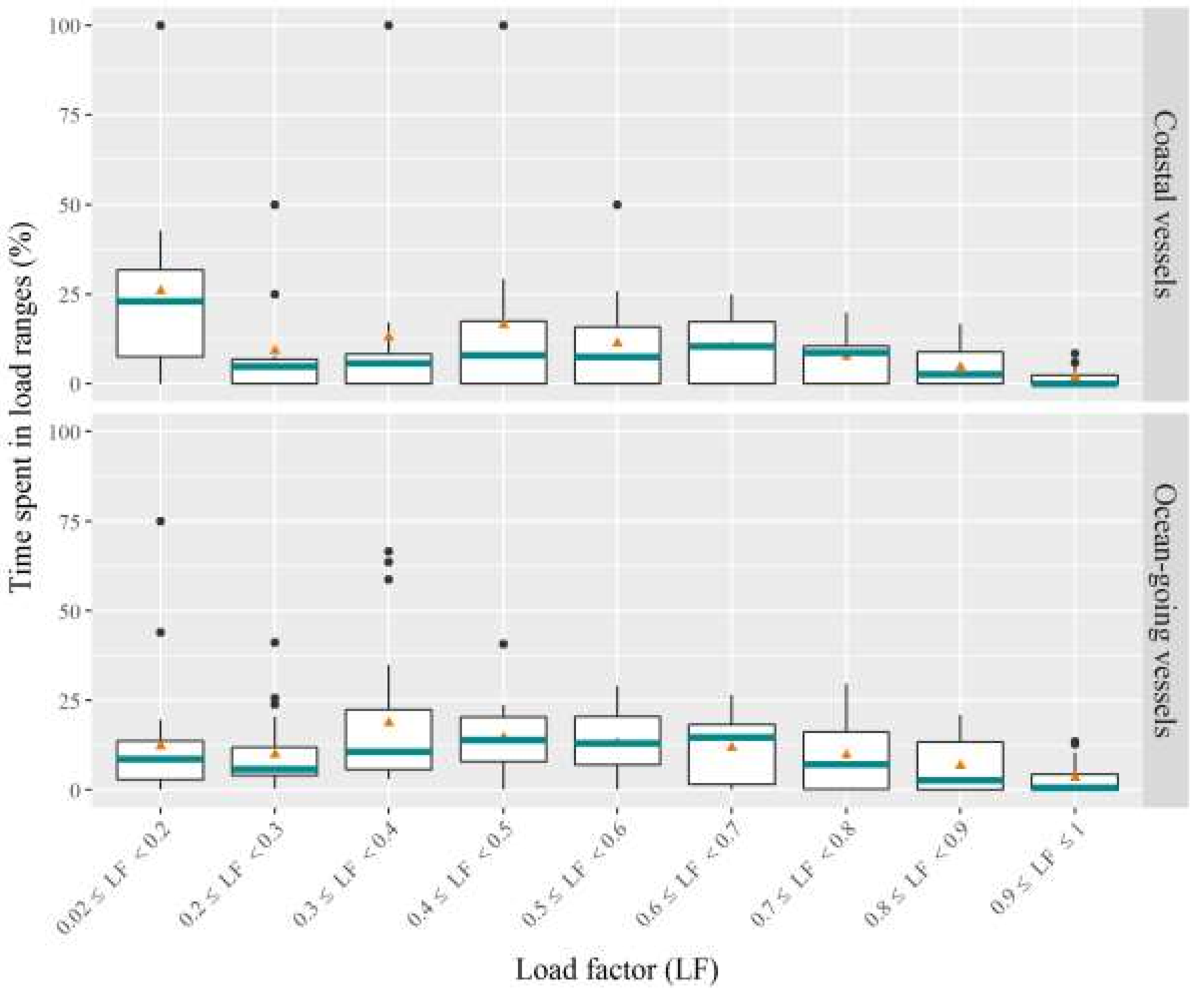

Figure 12. Operational time spent by reefers in various load factor ranges while operating in Norwegian waters within and beyond 0.27 nautical miles from shore during 2016 (i.e. coastal and ocean-going vessels, respectively). The boxes represent the 1st and 3rd quartiles, with the median (blue line). The whiskers follow Tukey's method. The dots are outliers. The triangles show mean values.

5.7 Offshore vessels

Figures 13 illustrates the time spent by coastal and ocean-going offshore vessels in various load ranges in 2016. Fifty percent of coastal offshore vessels spend at least 50% of their time in load range 0.02–0.2. The power of the median coastal vessel never reaches or passes 0.4. Ocean-going offshore vessels also spend the majority of their time in lower loads: fifty percent of these vessels spend approximately at least 38%, 11% and 7% of their time in load ranges 0.02–0.2, 0.2–0.3 and 0.3–0.4, respectively. However, the ocean-going vessels also spend more time in higher ranges: half of them spend at least approximately 6% and 4% of their time in load ranges 0.4–0.5 and 0.5–0.6, respectively.

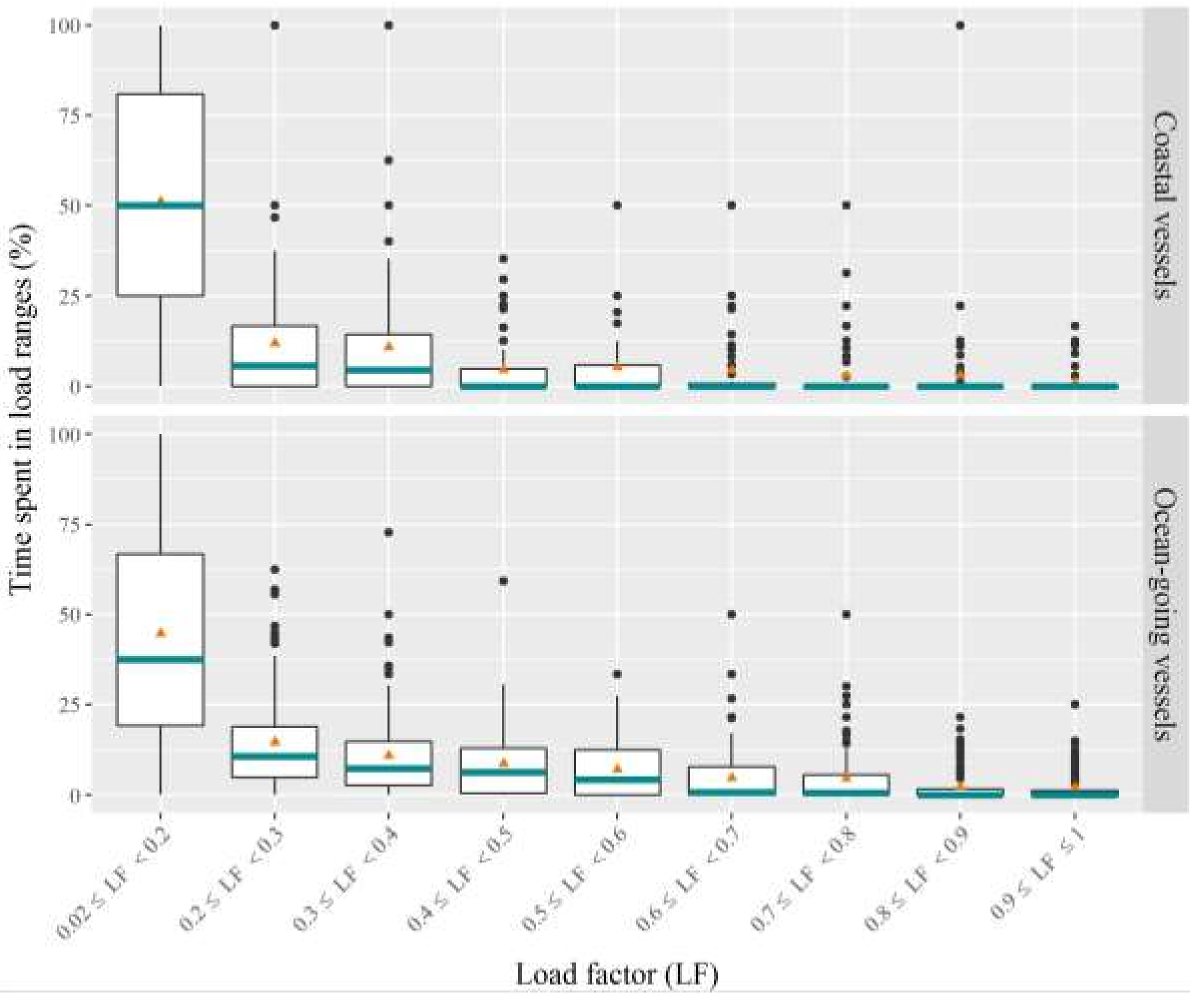

Figure 13. Operational time spent by offshore vessels in various load factor ranges while operating in Norwegian waters within and beyond 0.27 nautical miles from shore during 2016 (i.e. coastal and ocean-going vessels, respectively). The boxes represent the 1st and 3rd quartiles, with the median (blue line). The whiskers follow Tukey's method. The dots are outliers. The triangles show mean values.

5.8 Passenger ships

Figures 14 illustrates the time spent by coastal and ocean-going passenger ships in various load ranges in 2016. Coastal passenger ships spend the majority of their time in lower loads: half of these vessels spend approximately at least 57% and 9% of their time at load ranges 0.02–0.2 and 0.2–0.3, respectively. Ocean-going passenger ships also spend substantial share of their time in lower loads: half of them spend approximately at least 23%, 17% and 16% of their time in load ranges 0.02–0.2, 0.2–0.3 and 0.3–0.4, respectively.

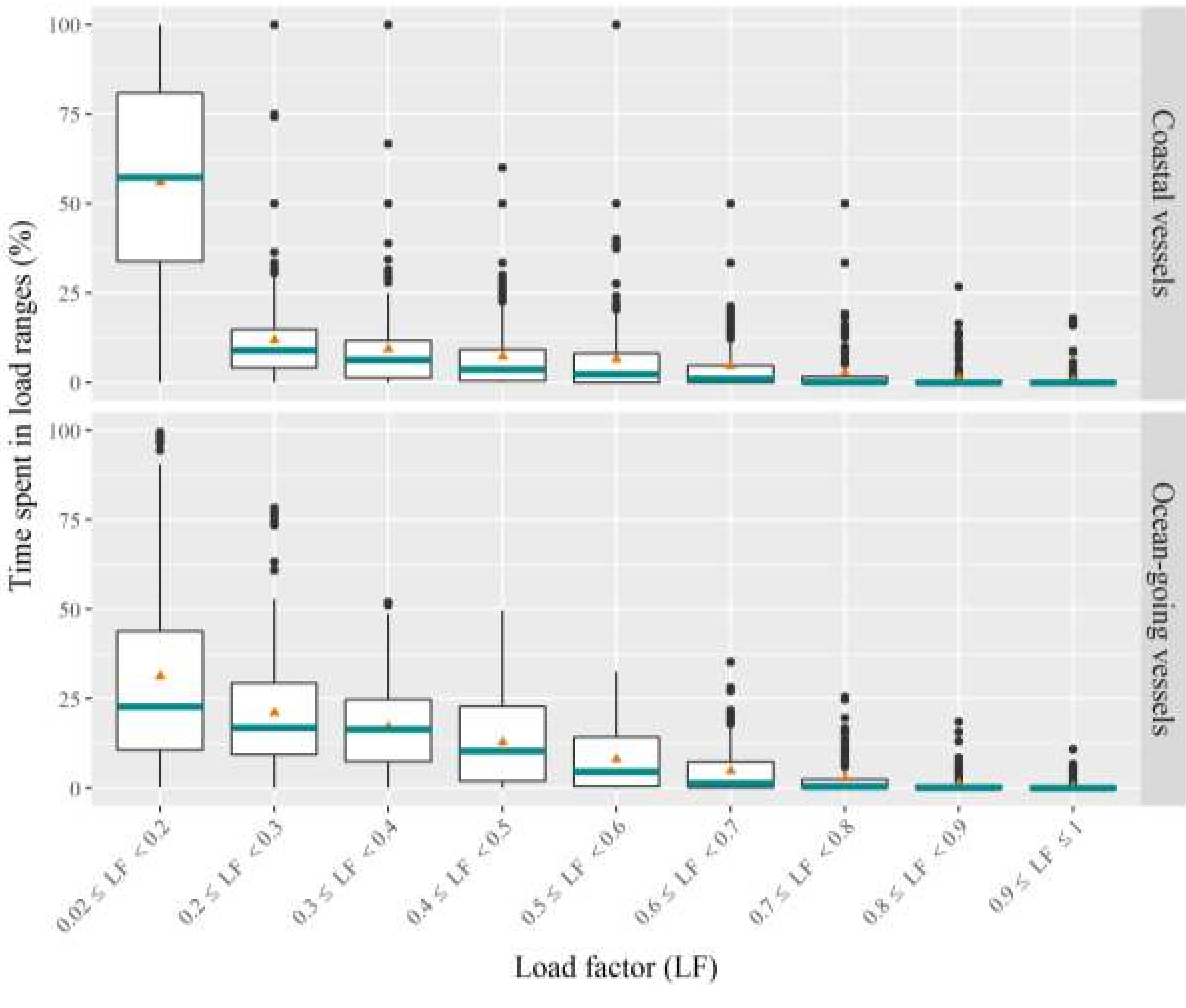

Figure 14. Operational time spent by passenger ships in various load factor ranges while operating in Norwegian waters within and beyond 0.27 nautical miles from shore during 2016 (i.e. coastal and ocean-going vessels, respectively). The boxes represent the 1st and 3rd quartiles, with the median (blue line). The whiskers follow Tukey's method. The dots are outliers. The triangles show mean values.

6 Discussion

6.1 Coastal vessels versus ocean-going vessels

Figure 15 compares the operational profile of the median coastal vessel in each vessel category with its ocean-going counterpart. In all vessel categories, median coastal vessels spend more time than their ocean-going counterparts in the lowest load range (i.e. 0.02–0.2). This may be due to the manoeuvring and speed limits close to coast. Median coastal and ocean-going vessels in all categories spend negligible time in loads above 0.8. The load range 0.8–1 may be reserved for emergencies.

In all vessel categories, operational profile of median coastal vessels have the peak in the lowest load range. Operational profiles of median ocean-going tankers, bulk carriers, general cargo ships and reefers have their peaks at load range 0.4–0.7. Operational profiles of median ocean-going container ships, Ro-Ro ships, offshore vessels and passenger ships have their peak at the lowest load range.

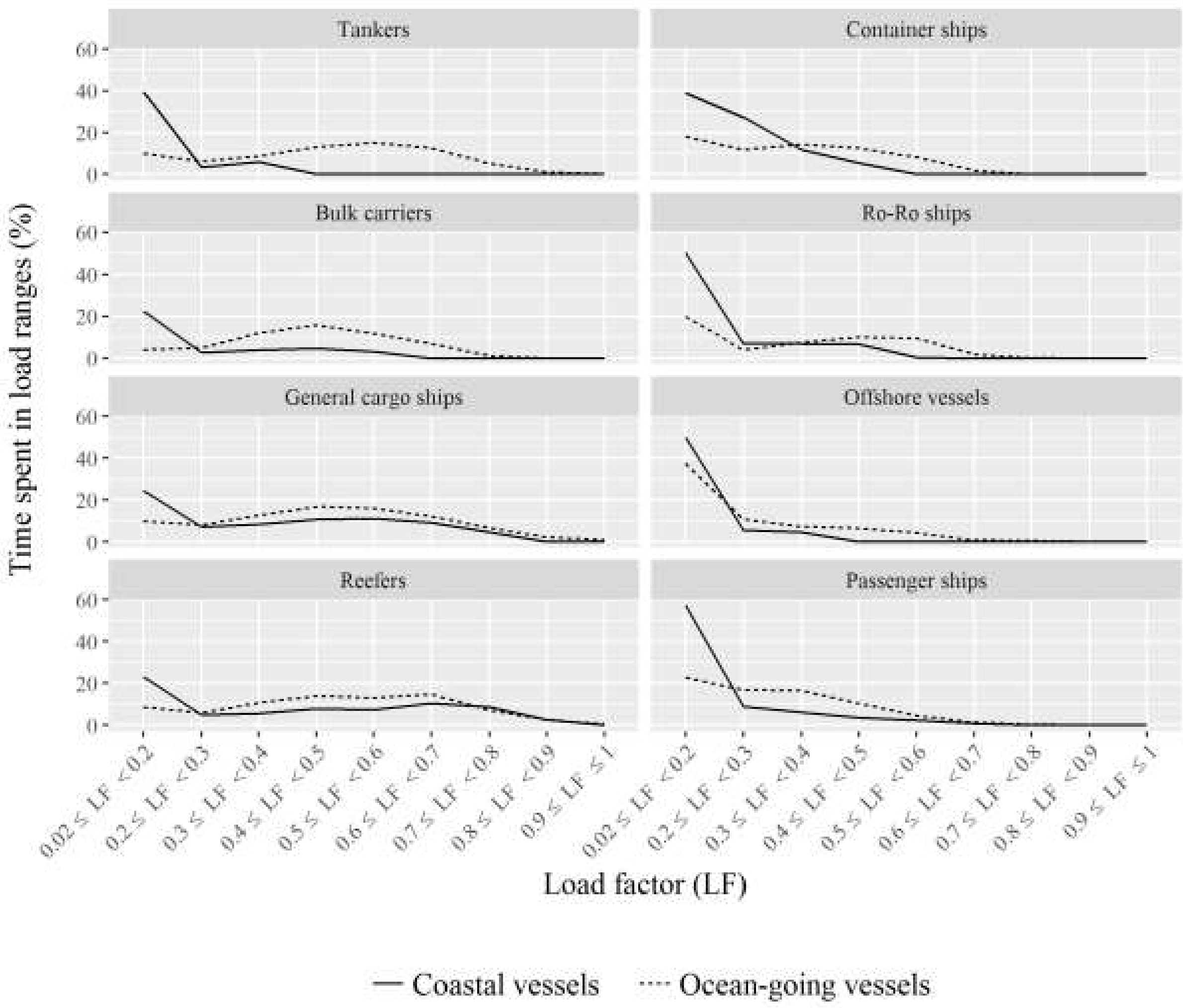

Figure 15. Operational profiles of median coastal vessels versus median ocean-going vessels in various vessel categories (i.e. vessels operating in Norwegian waters within and beyond 0.27 nautical miles from shore during 2016, respectively).

6.2 Operational profile of vessels

To compare operational profile of various vessel types in coastal waters (Figures 7–14 in Section 5), Figure 16 illustrates the time spent by median coastal vessels in various load factor ranges.

Median coastal vessels spend a great share of their time in load range 0.02–0.2. The median coastal passenger ship and bulk carrier spend the most and least amount of time in this load range (i.e. approximately 57% and 23%), respectively. As mentioned in Section 4.4, close to coast, vessel speed is regulated, and as a result, vessels slow steam. In addition, due to the presence of fjords and islands, vessels spend a great share of their time manoeuvring.

Although the median container ship spends less time than median passenger ship, offshore vessel and Ro-Ro ship in load range 0.02–0.2, it spends more time than all other vessel categories in load range 0.2–0.4. The median reefer and general cargo ship spend more time than other median vessels in load range 0.4–0.9 and 0.4–0.8, respectively. The load of the coastal median tanker and offshore vessel never reaches 0.4 and above.

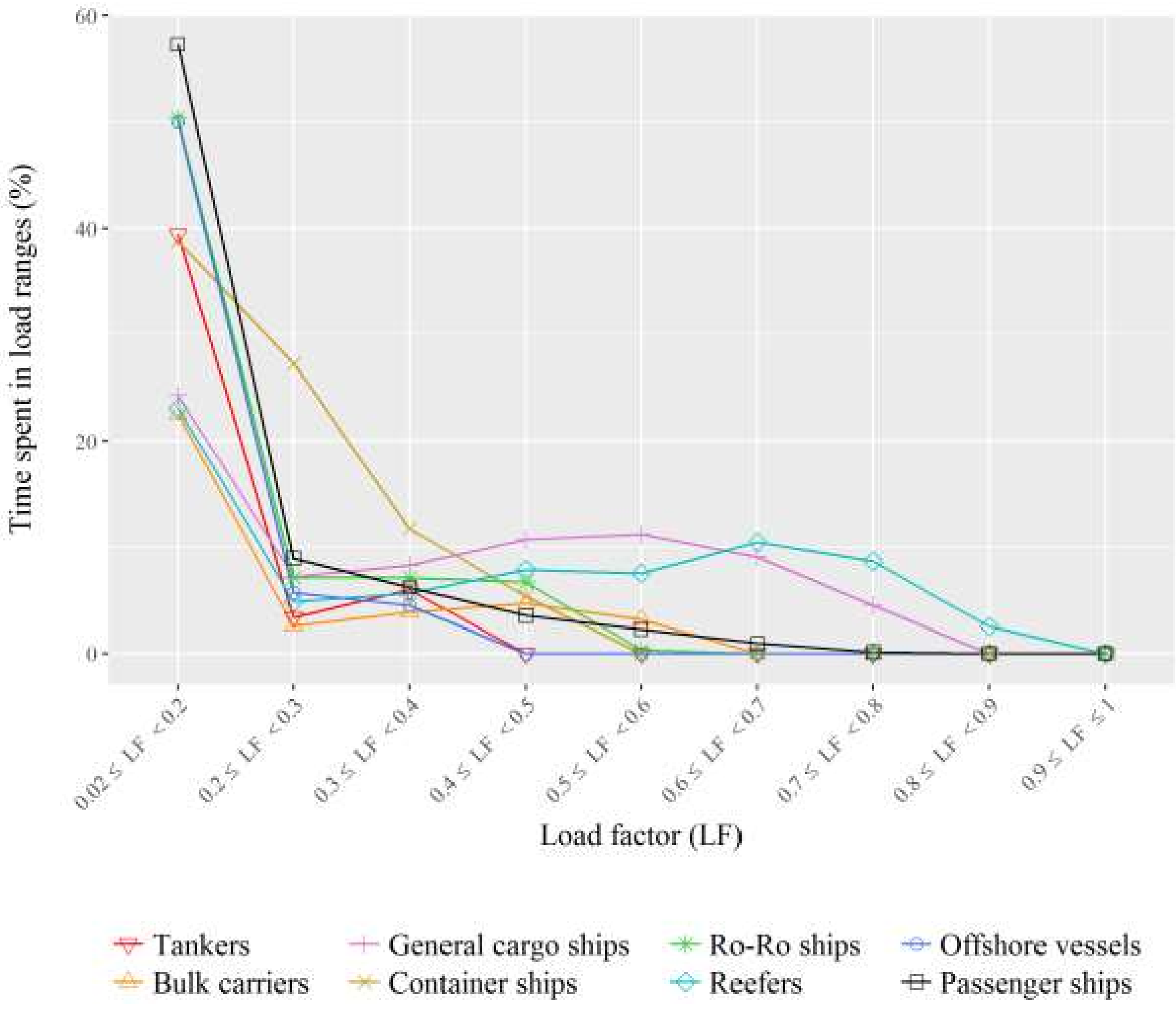

Figure 16. Operational time spent by median vessels in various load factor ranges while operating in Norwegian waters within 0.27 nautical miles from shore during 2016 (i.e. coastal vessels).

To compare the operational profile of various vessel types in distant waters (Figures 7–14 in Section 5), Figure 17 illustrates the time spent by median ocean-going vessels in various load factor ranges.

Among the ocean-going vessels, offshore vessels and passenger ships show a distinctive operational profile: they spend the highest amount of time in lower loads and vice versa. In higher load ranges (i.e. 0.5–0.9), tankers, general cargo ships and reefers spend a substantial share of their time. Among coastal vessels, reefers and general cargo ships also spend the highest percentage of time in 0.4–0.9 and 0.4–0.8, respectively (Figure 16).

While ocean-going median reefers, tankers and general cargo ships have their peak at 0.4–0.7 load range, where they spend approximately 15–17% of their active time, ocean-going median container ships, Ro-Ro ships, offshore vessels and passenger ships have their peak at the lowest load range. While the median coastal passenger vessel (Figure 16) spends the largest amount of time in this load range (approximately 57%), the median offshore vessel spends the highest corresponding value among ocean-going vessels (approximately 38%). Offshore vessels perform various operations close to offshore platforms, which among others involves standby functions. As a result, these vessels may spend a great share of their time in low loads. The median ocean-going container ships, Ro-Ro ships and passenger ships spend approximately 18–23% of their time in this range. In any case, these values are substantially lower than the corresponding values for coastal vessels (Figure 16). Although data records very close to shore (at 0.27 nm distance) are filtered out, still the ocean-going passenger and Ro-Ro ships (including ferries) may reduce their speed as they may have several stops on their trip. In order to save fuel, some ship types, such as container ships may slow steam. However, the fuel savings are closely tied to the design specifications of engines among others, which should be taken into account (see Section 1). As mentioned in Section 4.5, container ships have their engines stopped 25–50% of their manoeuvring time (ICF International, 2009), which may also explain the time spent in low load ranges. In addition, major carriers use trans-shipment hubs. Trans-shipment occurs where export cargo is taken by feeder vessels from a feeder port to a hub port, usually on the same continent, for onward shipment to other vessels, which carry the cargo to a third port usually on another continent. Import cargo follows the reverse process (Lun and Browne, 2009). As a result, the container fleet contains smaller feeder vessels and larger vessels. While feeder vessels may operate mainly between Norwegian ports, the larger vessels carry large consignment of goods destined for the continent. The feeder vessels may spend larger share of their time in part load, whereas larger vessels may operate in higher loads, which affects the operational profile of the container fleet.

Other median ocean-going vessel types spend less than 10% of their time at 0.02–0.2 loads. Smith et al. (2013) studied the energy efficiency of global tankers, bulk carriers, container ships and pure car carriers in 2011. Regarding their findings, these ships operated at an average of 15% below their design speed. Container ships operated at lower relative speeds (i.e. 23% below their design speed), whereas tankers operated at higher relative speeds (i.e., approximately 10% below design speed). Therefore, containers had the lowest average relative speed. Following a similar pattern, container ships spend more time in lower loads compared to tankers and bulk carriers (Figure 17).

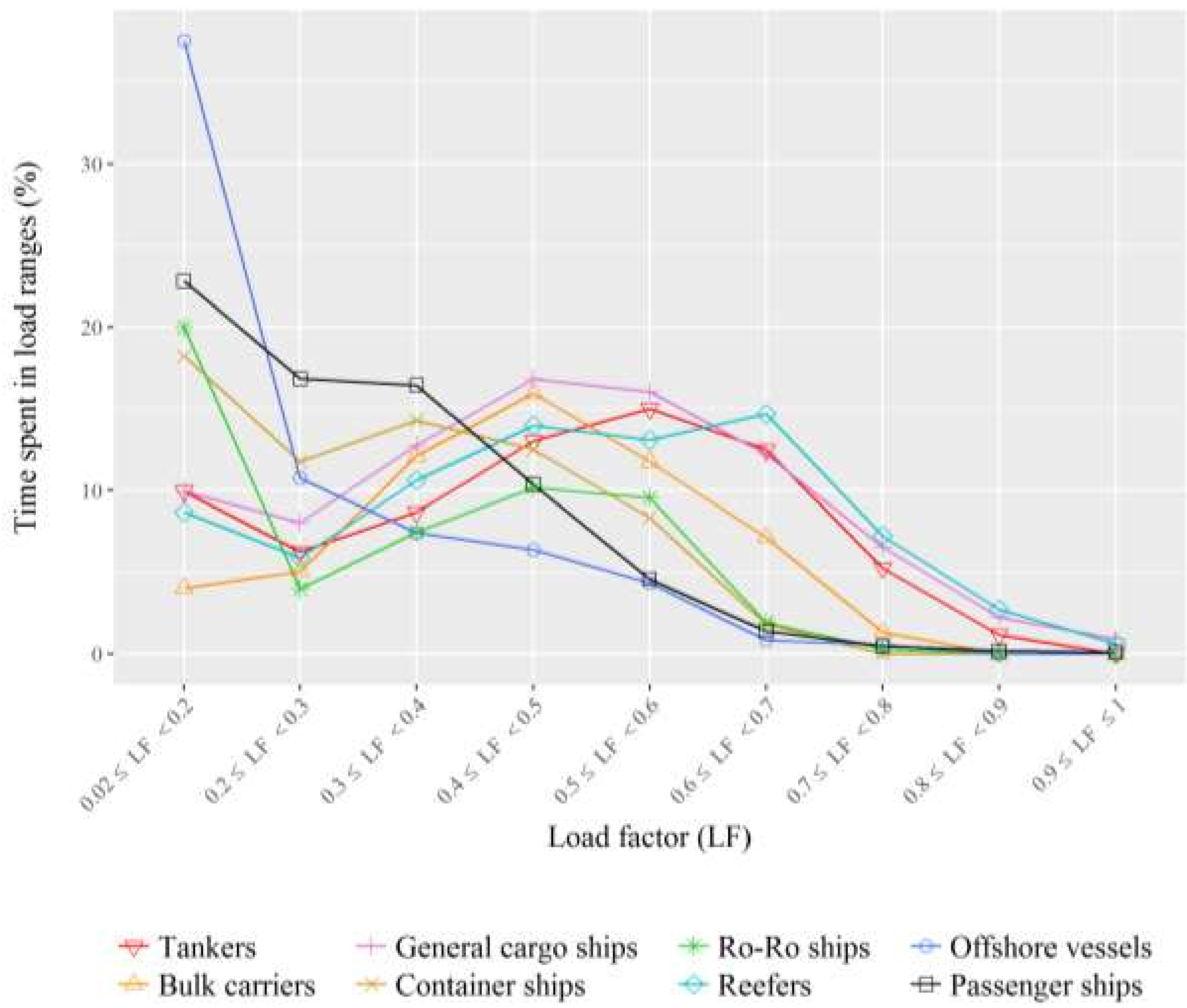

Figure 17. Operational time spent by median vessels in various load factor ranges while operating in Norwegian waters beyond 0.27 nautical miles from shore during 2016 (i.e. ocean-going vessels).

6.3 Potential for electric and hybrid propulsion systems

In close distance to coast, operational profiles of the various vessel types are relatively similar, and all vessels spend a great share of their time using lower loads due to manoeuvring and speed limits. However, as the distance from shore increases, the operational profile of various vessel categories follow distinct trends.

Table 1 shows the potential for hybrid and electric propulsion for the eight vessel types considered. The potential is shown on the scale of 1–4, where 1 and 4 represent the lowest and highest potential, respectively. These conclusions are based on the analysis of the operational profiles. As a result, Table 1 only reflects on propulsion power and does not include the effect of auxiliary loads.

Table 1. Potential for hybrid and electric propulsion of various vessel types. LF_{max} stands for the load factor (LF) at which the median vessel spends the highest share of its operational time (T_{max}). The potential is shown on the scale of 1–4, where 1 and 4 represent the lowest and highest potential, respectively.

Vessel type	LF_{max} and T_{max} (%) for the coastal median vessel	LF_{max} and T_{max} (%) for the ocean-going median vessel	Potential for hybrid and electric propulsion
Tankers	0.02–0.2, 39.45	0.5–0.6, 15.00	2
Bulk carriers	0.02–0.2, 22.55	0.4–0.5, 15.95	2
General cargo ships	0.02–0.2, 24.24	0.4–0.5, 16.83	2
Container ships	0.02–0.2, 38.79	0.02–0.2, 18.23	3
Ro-Ro ships	0.02–0.2, 50.34	0.02–0.2, 20.00	3
Reefers	0.02–0.2, 23.06	0.6–0.7, 14.68	1
Offshore vessels	0.02–0.2, 50.00	0.02–0.2, 37.50	4
Passenger ships	0.02–0.2, 57.29	0.02–0.2, 22.81	4

Among the vessel types, the median coastal and ocean-going reefer spends more time in higher loads and close to engine design condition, where energy efficiency is optimal. Operational profile of the median ocean-going reefer has its peak at load range 0.6–0.7, while for other vessel types the peak is at lower loads. Reefers operate at high speeds, primarily to reduce carriage time of perishable cargo (e.g. fruit and meat). Therefore, reefers have the lowest potential for adopting alternative power systems.

Offshore vessels and passenger ships show the most dynamic operational profiles and spend a large percentage of their active time in lower loads, where energy efficiency reduces substantially. Regarding Figure 2, although many offshore vessels and passenger ships use diesel-electric or LNG fuel, still the majority uses conventional propulsion systems. These vessels have the highest potential for adopting hybrid and electric propulsion systems. Such vessels can benefit from diesel-electric propulsion or downsizing engines to operate them in optimal point, while fuel cells and/or batteries supply peak and part loads. Another possibility, is the all-electric ship concept, which can be applicable to short-sea shipping, where the possibility for more frequent charging of batteries or fuelling hydrogen (or other hydrogen-rich fuels) reduces battery and fuel tank size and corresponding costs. In addition, if the operational speed of the vessel is generally lower than the one originally optimised for, it may be beneficial to consider de-rating of the main engine and propeller. De-rating as a retrofit reduces the maximum speed at MCR by 10–15%. Consequently, the operational speed better matches the optimisation speed, which enables fuel consumption savings (MAN Diesel & Turbo, 2013). It is not clear, whether the studied vessels have implemented de-rating.

Among the possible solutions, there is a growing interest in the use of hydrogens and fuel cells in shipping (Bassam, 2017; Choi et al., 2016; de-Troya et al., 2016; Jafarzadeh and Schjølberg, 2017; Klebanoff et al., 2017; LR and UMAS, 2017; Raucci, 2017; Tronstad et al., 2017; van Biert et al., 2016). From an environmental perspective, partial or full propulsion of vessels by fuel cell hybrid systems is a promising option (van Biert et al., 2016).

Similar to batteries, fuel cells convert chemical energy of reactants into electrical energy. Fuel cells convert the chemical energy of hydrogen or hydrogen-rich fuels, such as methane into electricity. However, while batteries stop functioning upon the depletion of their internal reactants, fuel cells function as long as fuel and oxidant are supplied from an external source (Jafarzadeh and Schjølberg, 2017).

Among the available fuel cell types, the following have been mainly studied for marine application: (i) low temperature polymer electrolyte membrane fuel cell (LT-PEMFC), (ii) high temperature polymer electrolyte membrane fuel cell (HT-PEMFC), (iii) molten carbonate fuel cell (MCFC) and (iv) solid oxide fuel cell (SOFC). High temperature fuel cells have longer start-up times and permit slow load transients. Consequently, high temperature fuel cells, such as SOFC are more suitable for auxiliaries, while low temperature fuel cells, such as LT-PEMFC are appropriate for propulsion (van Biert et al., 2016).

Fuel cells can provide power for full/partial propulsion, auxiliary power units and hot water/vapour generation using cogeneration (Díaz-de-Baldasano et al., 2014). Compared to diesel engines, fuel cells have higher energy efficiency, especially at part-load. As a result, fuel cells reduce emissions, especially when using hydrogen fuel generated from renewables. In addition, fuel cells reduce vibration and noise, which can benefit crew, passengers, harbour communities and marine life (Jafarzadeh and Schjølberg, 2017).

Tronstad et al. (2017) gives an overview of various research projects (e.g. FellowSHIP and SF-BREEZE), which have investigated the possibilities of using fuel cells on ships. Despite the aforementioned benefits of hydrogen and fuel cells, their application in shipping has been limited to few demonstration projects at power range of 12–320 kW (Tronstad et al., 2017). However, power systems of ships range from few hundred kilowatts to more than one hundred megawatts. Conceptual designs have investigated higher powers. For instance, SF-BREEZE, which is a high-speed hydrogen fuel-cell ferry designed for commercial use on the San Francisco Bay, has a 4.92 MW fuel cell system (Klebanoff et al., 2017). The higher cost of this solution, lack of adequate fuel supply infrastructure, regulatory gaps, safety concerns, limited operational experience and short lifetime of fuel cells, among others, may hinder its adoption in shipping (Jafarzadeh and Schjølberg, 2017). Future research addressing such knowledge gaps and issues may facilitate the adoption of hydrogen and fuel cells in shipping.

6.4 Limitations

This study has some limitations, which are due to the conscious definition of research scope and resource constraints.

As mentioned in Section 4.1, the coverage of smaller vessels in databases used in the activity-based approach is uncertain. AIS covers larger vessels. In addition, vessels should appear in the IHS Markit database (or a similar database) and have an IMO number. While this should include all ships involved in international shipping, many domestic vessels may have been excluded.

The activity-based approach is data intensive and requires operational profile (e.g. sailing speed) and technical specifications (e.g. service speed) of each vessel. Therefore, emission estimations based on this approach contain modeling assumptions and uncertainties (Jafarzadeh, 2016). For instance, AIS reports speed over ground instead of speed through water, which could be either higher or lower than the former depending on whether the ship is travelling against or with the assistance of a current. For trans-oceanic voyages, the effect of currents should be negligible; however, for smaller ships operating in coastal, tidal waters, the AIS data could be misrepresentative (Smith et al., 2013).

This study uses Equation (1) in Section 4.5 for estimating load factors. Although this relationship is widely applied in ship emissions inventories, it has some limitations. The greatest deviations would occur for higher speed vessels, such as container ships, where wave-making drag becomes more significant near their service speed. The effect of deviations from the relationship would be significant only at speeds significantly different from the service speed. Numerous other factors, such as the fraction f used in Equation (1), straight trajectory assumption between consecutive data points, wave, wind, hull fouling and engine condition affect the accuracy of load factor prediction (Goldsworthy and Goldsworthy, 2015). However, due to lack of data, simplifications are made in this study.

Due to the poor coverage of fishing vessels by AIS data and IHS Markit, lack of data on fishing vessel gears and the effect of factors, such as fish quota and fish stock biomass on fuel consumption, fishing vessels are excluded from this study. However, in 2013, fishing vessels were the third largest fuel consuming shipping segment in Norwegian waters after passenger ships and offshore vessels (DNV GL, 2015). As a result, a future study on operational profile of fishing vessels in Norwegian waters may be beneficial.

This study only focuses on the environmental aspects while evaluating the possibilities for integrating alternative power systems, such as fuel cells and batteries. However, as mentioned in Section 6.3, such power systems may impose additional costs and safety concerns. In addition, fuel supply infrastructure and durability of fuel cells need further improvement to facilitate their adoption in shipping.

Usually propulsion is not the main power consumer of passenger ships. Instead, auxiliaries, such as hotel loads are the main consumers. Ro-Ro ships and reefers may also have large auxiliary energy demand relative to their propulsion energy demand. This study only focuses on propulsion power due to lack of data on auxiliaries.

The operational profiles shown in Figure 16 and 17 and the potential for the adoption of hybrid and electric propulsion shown in Table 1 are based on the median vessel. Although the median values provide an insight into the “typical” operational time of vessels within various load ranges, individual vessels may have different operational profiles.

As mentioned in Section 3.1, IMO numbers of the vessels are used as cross-references for deriving technical information on the vessels. The AIS datasets included some vessels with invalid IMO numbers, and these were excluded. Some other vessels lacked service speed, main engine power, fuel type and/or propulsion type and were also excluded. In addition, neither IHS Markit nor other data sources provide auxiliary engine or auxiliary boiler utilization data. Smaller vessels are also not covered. Gathering data for the purpose of studying energy efficiency and operational profiles may solve some of these problems.

7 Conclusions

This study investigates the operational profile of eight vessel types operating in Norwegian waters in 2016 using big data from AIS. The aim has been to identify vessel types that can benefit from electric and hybrid solutions through the analysis of their operational profile.

To take the effect of manoeuvring and speed limits close to shore into account, vessels close to land are distinguished from those operating in distant waters. Close to coast, the operational profile of various vessel types are relatively similar, and all vessels spend a great share of their time in lower loads due to manoeuvring and speed limits close to shore. As the distance from shore increases, the operational profiles of various vessel types follow distinct trends.

Among the vessel types, reefers spend more time in higher loads and close to engine design condition, where energy efficiency is optimal. Operational profile of the median ocean-going reefer has its peak at load range 0.6–0.7, while for other vessel types the peak is at lower loads. Therefore, reefers have the lowest potential for hybrid and electric propulsion systems. The median ocean-going tankers, bulk carriers and general cargo ships spend a great share of their time at higher loads and have their operational profile peak at 0.4–0.6 load range. These vessels can benefit from alternative power systems, although to a low extent. Container ships and Ro-Ro ships have their peak at the lowest load range (0.02–0.2) and spend relatively lower time than reefers, tankers, bulk carriers and general cargo ships in higher loads. As a result, they have a higher potential for hybridisation and electrification. Among the vessel types, offshore vessels and passenger ships show the most dynamic operational profiles and spend a large share of their operational time in lower loads, where energy efficiency reduces significantly. Such vessels can benefit the most from hybridisation, diesel-electric propulsion and other electric concepts, such as downsizing engines to operate them in optimal point, while fuel cells and/or batteries supply peak and part loads.

Future research may investigate case study offshore vessels and passenger ships to investigate the effect of adopting hybrid or electric propulsion systems on their energy efficiency.

8 Acknowledgements

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