Decarbonizing maritime transport: a Ro-Pax case study

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ABSTRACT

In an effort to reduce carbon emissions from international shipping, the International Maritime Organization (IMO) developed its initial strategy in April 2018 setting ambitious targets for the sector. According to the initial strategy, greenhouse gas (GHG) emissions from international shipping need to be reduced by at least 50% by 2050, and the CO_2 emissions intensity by 40% by the year 2030, both compared to the 2008 levels. In order to achieve these goals, a combination of operational measures, investments in emissions abatement technology, and market-based measures will be necessary. The goals currently do not differentiate among different shipping sectors, and each sector faces different challenges. In this paper, we focus on short sea shipping (SSS), and on Ro-Pax services in particular that in general have not been examined thoroughly in the literature. We examine the emissions reduction potential of several measures, and we assess their efficacy compared with the targets set by the IMO initial strategy. The paper shows that the examined measures are not sufficient on their own to achieve the desired levels of reductions, and that a combination will be necessary, while technological solutions will need to be made more competitive through market based instruments.

Keywords: short sea shipping, Ro-Pax shipping, decarbonization, maritime transport, energy saving devices

1 Introduction

Climate change is arguably one of the greatest challenges of our time. Decarbonization of our activities or the reduction of greenhouse gas (GHG) emissions and CO_2 in particular is necessary in order to achieve the long-term goal of the COP21 climate change agreement in Paris, that is, to keep the increase of the global average temperature to 1.5°C maximum compared to pre-industrial levels by the end of the century. With regards to transportation, the EU adopted the new Transport White Paper back in 2011 where an aggregate emissions reduction of 60% was sought after for all modes of transport by 2050 compared to 1990s levels. The respective targets for maritime transport were set on a 40% reduction compared to the 1990 levels, and if possible 50% by 2050 (EU, 2011).

Maritime shipping moves about 80% of the total worldwide cargo by volume (UNCTAD, 2019) and contributes to less than 3% to the total global anthropogenic CO_2 emissions (IMO, 2014). It is therefore widely considered the most fuel-efficient mode of transportation due to the economies of scale it allows for. Despite its good performance when compared to other transportation modes, GHG emissions from shipping are expected to grow between 50 and 250% by 2050 due to the continuous growth of the sector (IMO, 2014). While at the time international shipping was not included within the mandate of the Paris agreement (Psaraftis, 2019a), the IMO decided to set its own targets for the decarbonization of shipping. During April 2018, the Marine Environment Protection Committee (MEPC) of the IMO adopted the initial IMO strategy on reduction of GHG emissions from ships (Resolution MEPC.304 (72)). The strategy has set some very ambitious targets where the objective is that GHG emissions peak as soon as possible and are to be reduced in absolute terms by at least 50% by 2050 taking 2008 as the comparison point. In addition, the CO_2 emissions intensity (per transport work) should be reduced by 40% by 2030 and by 70% by 2050 always compared to the 2008 levels. We have to note that at this stage the IMO has not specified how the emissions intensity is to be quantified. We therefore consider the emissions intensity as grams of CO_2 emissions per transport work. Transport work typically is measured as tonne-kilometres in most transportation modes. Our paper examines SSS and we define transport work as lane-meters-nautical miles (lm-NM). The initial IMO strategy includes a list of short-term, medium-term, and long-term candidate measures. A substantial part of discussions has revolved around potential speed reduction or speed optimization short-term measures, all of which concern the cruise leg of a voyage. Currently the only mandatory measure concerning decarbonization has been the adoption of the Energy Efficiency Design Index (EEDI) in 2011. The EEDI is essentially a ratio of the total CO_2 emissions produced by a vessel over the product of the ship's capacity and reference speed, expressed in grams of CO_2 per tonne mile. This has to be compared with the EEDI reference line that is a function of ship type and DWT. There has been some criticism of the measure, as compliance can be secured through the construction of underpowered ships, and particularly for the case of Ro-Ro and Ro-Pax vessels, the reference lines have been agreed to after a long discussion; for details of EEDI see Polakis et al. (2019). However, what is clear from the case of the EEDI is that the various ship types have significant differences in their environmental performance. As such, a universal reduction of emissions per transport work by 40% across all shipping types may not be feasible. In addition, there has been some criticism as EEDI currently does not consider the effects of waves and as such, vessels the design of which has been optimized to perform better at realistic sea conditions are penalized (Lindstad et al., 2019).

In the context of the global decarbonization target, analyses of specific shipping sectors may be of interest. SSS is very important as a means to reduce GHG emissions and other externalities from road transport, and at least in Europe it has been considered an important instrument towards this goal (EU (2011), Psaraftis and Zis (2020)). Ro-Pax and Ro-Ro vessels differ as the former carry passengers, their cars, and cargo, while the latter are considered as cargo only carrying ships. Ro-Pax vessels have been an important element of the SSS fleet, carrying a mix of cargo and passengers and, as such, are a critical alternative to road transport in many cases. In this paper, we focus on the potential of GHG emissions reduction for short sea shipping (SSS), using an indicative case study. We note that there are also Ro-Ro vessels deployed on deep-sea shipping services, and there can be feeder containerships on SSS links as well, but these are beyond the focus of our work, the case study we examine is an SSS Ro-Pax service. We have chosen to focus on a service connecting Gothenburg and Kiel with a deployment of Ro-Pax vessels. This service is very interesting as a case study, as it competes with both landbased and maritime transportation modes, and it is an important link between the two ports. The fact that these ships also carry passengers has important repercussions on the emissions intensity per transport work. The route is within the Baltic Sea Emission Control Area and as a result, the deployed ships have already faced pressure to improve their environmental performance. The port of Gothenburg is one of the first terminals to offer shorepower, and the first ship to use methanol for propulsion is serving these two ports.

This paper attempts to address several pertinent questions in the context of decarbonization of shipping. What are the prospects of GHG reduction in the SSS sector? What may be the role of GHG reduction technologies and can these be applied in SSS ships. How can a potential change of sailing speed affect both GHG emissions and result in modal shifts to other modes. Is it possible to reach these targets using alternative fuels or emissions reduction technologies in ports such as cold ironing? We examine these issues in a specific geographical case study in Europe, examining a Ro-Pax service due to its unique challenges.

The rest of this paper is organized as follows: section 2 presents a brief literature review on the issue of decarbonization of the maritime sector, highlighting research that has focused on the SSS sector. Section 3 presents a list of logistical, technological, and policy measures that are relevant for the SSS sector. In section 4, we present a quantitative framework for the estimation of the potential in emissions reduction and their associated costs. Section 5 applies the methodology for a Ro-Pax vessel sailing between Germany and Sweden, and Section 6 concludes with some comments on the aspirations of the IMO targets, as well as with recommendations for future work in this line of research.

2 Literature Review

2.1 Decarbonization of maritime transport

Academic research in maritime shipping has traditionally focused more on liner shipping as well as dry and liquid bulk shipping. This can be in part attributed to the world fleet breakdown that is dominated by containerships, dry bulkers, and tankers whereas Ro-Ro and Ro-Pax ships only form a very small portion of the world fleet. According to data from Clarkson's in the World Fleet Register database, as of December 2019 all types of Ro-Ro vessels grouped together (passenger-only ships, pure car carriers, cruiseships, Ro-Ro's and Ro-Pax) constitute only 7.7% of the world fleet whereas containerships amount to 15.6%, bulkers to 42.7%, and tankers to 23.2% in absolute numbers of ships. The sector is particularly important as it competes with land-based transportation options, and can help relieve roads from freight transport. In fact, the promotion of Ro-Ro shipping has been a priority of the European Union as a means to move cargoes from the road to the sea, in a bid to not only improve air quality, but also to stimulate economic growth in coastal areas (Psaraftis and Zis, 2019). The Ro-Ro sector comprises of typically older vessels with an average age of 21 years (based on data from the World Fleet Register). These ships sail faster than most other types, with an average service speed of 18.7 knots. Woxenius (2011) notes that most ferries have a speed capacity of 20 knots, with lower speeds during night sailings. Despite the relatively high design sailing speeds, Ro-Ro shipping is a slower mode than land-based alternatives, even more so when taking into account the waiting times at ports. For example in Europe high goods vehicles (HGVs) tend to travel at average speeds of 80-100 km/h in highways while high speed rail cargo services can reach 180 km/h. Despite its lower speed, Ro-Ro shipping is highly competitive as it can offer lower transportation costs, as well as shorter travel distances due to geographical advantages it may offer for specific shipments. It can be particularly competitive when it serves routes between ports that form part of the Motorways of the Sea in Europe (Morales-Fusco et al., 2013). It is widely considered more environmentally friendly than land-based options in terms of carbon intensity. This may not always be true considering certain electric rail services powered by renewable energy sources (RES) as for example in Sweden. SSS has also faced some criticism on its environmental performance (Cullinane and Cullinane, 2013) when other emission species are taken into consideration. Sulphur and nitrogen oxides, as well as particulate matter emissions are higher due to the lower quality of fuel used in shipping (Halff et al., 2019) compared to other transport modes with lower emission factors (Mousavi et al., 2018). In addition, the actual emissions intensity of SSS may fall further due to the potentially low utilization rates of the capacity of the ship, combined with a potential low utilization capacity of the transported unitized cargoes themselves. The latter can be better understood as a half-empty trailed loaded on a vessel that itself is not fully loaded with trailers would result in a very poor performance in emissions intensity. Hjelle (2011) describes this as the double load factor problem and shows that there are cases where Ro-Ro shipping is less environment friendly than land-based alternatives. This has also been confirmed in other studies. For instance Panagakos et al. (2014) concluded that the reverse shift of cargoes from sea to road in case the Mediterranean was designated as a SECA (sulphur emissions control area) would also result in less CO_2 overall. This implied that the Ro-Pax ships that would lose traffic due to this development were less environment friendly than the trucks to which traffic would shift.

2.2 Research on short sea shipping

There is a wide belief that containerships are the highest GHG polluters as documented by Psaraftis and Kontovas (2009), due to their higher sailing speeds at the time, and their large size. At the time, the authors constructed an emissions inventory for CO_2, broken-down by ship type. The 1999 Ro-Ro ships produced a transport work of 1624 billion-tonne-kilometers and emitted 42.87 million tonnes when the global fleet (36538 ships) was estimated at 943.44 million tonnes with a total transport activity of 104,144 billion-tonne-kilometers. This translates to 4.54% of the total international shipping CO_2 emissions, attributed to 5.47% of the fleet (by number), or 1.56% of the transport activity. These numbers were based on the global fleet and transport activity in 2007. The authors noted the difficulty in allocating emissions in the case of Ro-Pax vessels (cargo and passengers), and opted to exclude these ships from the calculation. Similar concerns on allocating emissions in Ro-Pax services have been raised and three main types have been proposed: weight, volume, or economic value (Zhu et al., 2014). Twelve years after the analysis of Psaraftis and Kontovas (2009), the fleet has increased but sailing speeds for major shipping types (containerships, bulk carriers, tankers) have been reduced. This resurgence of slow steaming can be attributed to the offered overcapacity and the volatility of the markets in recent years. At the same time, technological progress has resulted in better fuel efficiency in engines, and improvements in fuel quality. Emissions abatement technologies have also been developed and improved in that period.

In all types of shipping, a critical decision is the selection of the optimal sailing speed. The optimality may consist of finding a fuel consumption minimizing speed, or a profit maximizing one. Particularly in times of high fuel prices, the practice of slow steaming resurfaces in academic research as well as in industrial practice. The issue of speed optimization is a recurring theme in transportation research with the majority of applications in liner shipping as seen in the reviews of Wang et al. (2012) and the taxonomy of Psaraftis and Kontovas (2013). There are also many studies looking into the optimal sailing speed in the spot market sectors, with significant differences seen between ballast and laden legs (Norstad et al., 2011; Gkonis and Psaraftis, 2012). When it comes to SSS, the issue of sailing speed is not the main focus of research. Andersson et al. (2014) note that most fleet deployment papers stem from container shipping, and stress that this problem is harder in the case of Ro-Ro shipping due to the increased flexibility of the sector and its services, and the far less homogeneous fleet. Historically the sailing speed of Ro-Ro and Ro-Pax vessels has not changed significantly and service speeds typically are in the range of 15 to 20 knots. While increased fuel prices could lead to reduced sailing speeds in most sectors, the SSS sector appears to be more inelastic in that regard. For example, on the aftermath of the new 0.1% sulphur limit within sulphur emission control areas (SECA), Raza et al. (2019) interviewed several affected ship operators and reported that speed reduction was not considered as a response to the new sulphur limits.

On the technology side, several papers have considered cost benefit analyses of different emissions reduction technologies, with applications in all types of shipping. A recurring theme in the literature is the evaluation of scrubber systems as a sulphur oxides and PM emissions reduction technology (Jiang et al., 2014; Zis et al., 2015; Lindstad and Eskeland, 2016). On a more technical paper, Livanos et al. (2014) consider the economics of alternative propulsion plants for ferries and Ro-Ro ships and show that dual-fuel engines (using LNG) with waste heat recovery systems to generate eclectic power onboard can provide a cost-effective solution with low EEDI values. Ammar and Seddiek (2017) compare the use of seawater scrubbers with LNG, MGO, and selective catalytic reduction for a medium speed Ro-Ro vessel of a service speed of 17 knots. They also conclude that economically an LNG dual-fuel engine system is more cost effective, and stress that LNG conversion viable for new built ships or existing ships with an age below 16 years.

2.3 Competition with land-based modes and externalities

Less attention has been paid on the SSS and Ro-Ro sectors in academic research. However, the Ro-Ro sector is particularly important as it competes with land-based transportation options, and can help relieve roads from freight transport. In fact, the promotion of Ro-Ro shipping has been a priority of the European Union as a means to move cargoes from the road to the sea, in a bid to not only improve air quality, but also to stimulate economic growth in coastal areas.

Most papers considering SSS have focused on the environmental benefits of Ro-Ro shipping vs land-based options, or on optimization aspects within the sector. Mulligan and Lombardo (2006) argued that in order to promote the environmentally friendlier SSS it is vital that public subsidies are provided to SSS operators. The literature review of Medda and Trujilo (2010) presents a thorough list of mechanisms to promote SSS, which they find to have a lower CO_2 footprint. Styhre (2009) considers the importance of the capacity utilization of SSS vessels and identifies a range between 75 and 88% as the optimal following interviews with ship operators. Hjelle and Fridell (2012) attempt to quantify when SSS is environmentally preferable to land-based options and note that a Ro-Ro vessel was marginally better than a truck/trailer combination concerning carbon emissions under realistic load factor assumptions. In their case studies, the maritime options are far worse when it comes to nitrogen and sulphur oxide emissions; however, this was before the stricter limits of 0.1% within SECAs that are effective since 1st January 2015. Following the designation of SECA in the North and Baltic Sea, several studies tried to address the implications these would have on the SSS sector. The lower sulphur limit (0.1% as of January 2015) was expected to increase significantly the operating costs of Ro-Ro and Ro-Pax services, and there were fears that this could lead to a loss of market share towards land-based alternatives (Odgaard et al., 2013). Higher freight rates were expected in several studies due to the anticipated increase in fuel prices (Lemper et al., 2009). Notteboom (2011) expected an increase in shipping costs between 29 and 40% for faster Ro-Pax services, and between 8 and 20% for traditional cargo services. However, Zis and Psaraftis (2017) showed that due to the unexpectedly low fuel prices in the 2015-2017 period the SSS sector actually achieved record-breaking profits. De Boer et al. (2016) argued that Ro-Ro shipping had lost part of its competitive advantage over road transport due to the lower sulphur limits. Svindland (2018) examined the environmental effects of ECA regulations on SSS, using case studies of feeder containerships in Northern Europe Zis and Cullinane (2020) provide a thorough review of the wider impacts of desulphurization of shipping and literature that focused on ECAs.

On the issue of modal shifts, Douet and Cappuccilli (2011) reviewed a series of EU policies that aimed to move cargoes from land-based options to SSS, and argued that there needs to be significant improvements. Focusing on the Marco Polo initiatives, Suarez-Alemán et al. (2015) show that these measures were not as successful and better policies are required. Wilmsmeier et al. (2014) note the need for deeper integration between ports and inland nodes to increase modal shifts towards maritime modes. Other papers have considered applied case studies on mode choice between an SSS option and landbased alternative. For a more detailed review of modal shift studies, we refer to Raza et al. (2020). Monios et al. (2018) consider the port of Gothenburg, and how it may face additional competition due to new infrastructure (for example the tunnel linking Denmark and Germany to be completed by 2028), or simply the increasing capacities of competing ports. The main narrative of studies focusing on SSS is on the comparison of the mode in economic and environmental terms with their land-based competition. As such, the issue of external costs is also a recurring one in the literature. Vanherle and Delhaye (2010) provide a thorough comparison of emissions and external costs between road and SSS for several case studies in Europe. They provide a cost of €0.032/tonne-km for Ro-Ro vessels. Brons and Christidis (2012) developed an external cost calculator for the Marco Polo project and provide estimates between €0.00055/tonne-km to €0.01963/tonne-km for high-speed Ro-Ro vessels, considering the higher sulphur fuel content allowable at the time. Morales-Fusco et al. (2012) consider the benefits for cargo carriers when using Ro-Pax services, and find economies of scale are emerging. However, they stress high investment costs when sending unaccompanied trailers through SSS services. Zis et al. (2019) provide a summary of external cost estimates for road and sea transport in different areas of Europe. For example, emissions at berth (or near the port) have a higher external cost than emissions in the high seas, due to the detrimental effect of PM emissions on human health. Vierth et al. (2018) compare the external costs of transporting trailers via ship-only and ship-and-road options and find a discrepancy between the EU and Swedish guidelines. A lower cost for the direct shipping mode when the Swedish guidelines are followed and a higher one with the EU guidelines. However, when all taxes and fees are included the combined mode is favoured. The issue of emissions at berth from SSS has not been discussed extensively in the literature. De Meyer et al. (2008) conduct an interesting analysis of emissions in the Belgian part of the North Sea, and the Belgian seaports. They provide emissions per type of ship and conclude that Ro-Ro and container vessels are the main contributors in the emission in the sea, while Ro-Pax and Ro-Ro vessels are by far the main contributors at the port. However, this paper will focus on the issue of decarbonizing maritime transport and therefore will not examine the emissions and external costs of other pollutant species. The next section presents a summary of potential CO_2 emissions reduction measures that can be utilized in the case of SSS, with an example application based on a Ro-Pax service.

3 Relevant Reduction Measures

In this paper, we examine different measures that can be used to reduce the absolute GHG emissions and the emissions intensity for SSS. Emissions reduction measures with a focus on GHG emissions typically fall into three categories: logistics-based measures, technological solutions, and market-based measures (Psaraftis, 2012). There have been several examples of the deployment of these measures, and the efficiency of each measure varies significantly depending on the application area (shipping sector, specific ship, voyage, current market conditions). In this section, we present a subset of these measures that we examine as candidate measures for the Ro-Pax service under examination. These have been selected following discussions with relevant stakeholders, and based on a principle of modularity that would allow the simultaneous deployment of these measures.

3.1 Logistics-based measures

Logistics-based measures or operational include speed optimization, weather routing, improved fleet deployment and management, as well as other measures that seek to increase the capacity utilization of a vessel. In the context of SSS, Zis and Psaraftis (2018) examined how Ro-Ro and Ro-Pax ship operators could cope with the competition with land-based alternatives should they face a potential increase in fuel prices. The authors note that these services are relatively fast and offer a high sailing frequency, and due to the nature of the sector, there are constraints on how slow the voyages could be. They propose that new sailing speeds should ensure that the voyages last an integer number of hours or half-hours in order to facilitate the planning of cut-off times for the embarkation of goods and passengers. Other measures examined include the addition or removal of weekly sailings, and changing the fleet deployment of vessels to harmonize the load factor of the vessels. Such decisions will affect the attractiveness of the service, as a slower sailing service may result in some market share losses towards the unaffected land-based options. Another operational measure that can be used to reduce fuel consumption is the use of weather routing. Weather routing can be defined as the decision-making process of selecting the optimal route in a given voyage taking into account the expected weather and sea conditions. Due to the improved weather forecasts and available data, weather routing has seen increased attention in recent years. The potential for fuel savings is significant, particularly for longer voyages where the vessel is exposed to streams and more extreme weather effects. Fewer academic works have been considering SSS, but Coraddu et al. (2013) examine the impact of weather for a Ro-Pax vessel sailing in the Mediterranean Sea, and report that fuel consumption can increase by as much as 10% compared to the calm water conditions. In this paper, we will examine the impact of different sailing speeds in the examined route for a series of voyages with different prevailing weather conditions.

3.2 Technological measures

Several technologies are being developed that seek to reduce the fuel consumption of a ship. Gilbert et al. (2015) attempt to construct a roadmap for the use of technologies in shipping that could assist in meeting the climate change goals of holding the increase in global temperature blow $2°C$. They consider Flettner rotors, energy storage devices, fuel cells, cold ironing, alternative fuels such as biogas and biofuel, and carbon capture technologies. In their case studies, they examine three vessels, including a SSS vessel, which they consider that by year 2050 could see a reduction between 67 and 97% if all measures (including operational measures) are adopted.

Flettner rotors are vertical cylinders that spin around their axis and generate a propulsive force in a perpendicular direction to that of the wind hitting the rotor. These rotors are driven by an electrical motor to take advantage of the Magnus effect and can act as a propulsion supplement for the vessel (De Kat and Mouawad, 2019). Another technology is the ejection of air-bubbles from the hull of the ship as a means to reduce the frictional resistance of the hull (Kato et al., 2001). In these types of solutions, it is imperative that the fuel consumption savings exceed the energy consumption to run these technologies. Other technological measures can include the use of dual-fuel engines as discussed in section 2, or the use of LNG as fuel due to its lower CO_2 emission factor as a fuel, and the improved energy efficiency of the engine. LNG powered vessels are not the norm in SSS, although there are some Ro-Pax LNG powered vessels developed (Unseki, 2013). Other alternative fuels of interest include methanol which has been deployed on one of the two vessels serving the route under examination, which was the first ever methanol powered ship in the world. If methanol is produced from biomass then it can have a significant potential in reducing CO_2 emissions compared to HFO and MGO. Winnes et al. (2015) consider several emissions reduction scenarios for the port of Gothenburg including the use of methanol as fuel for some ships. They note the high emissions reduction potential of bio-methanol but consider it not a viable solution for full implementation until 2030 due to its high price premium over fossil based LNG and methanol. Svanberg et al. (2018) examine the potential of methanol as a fuel for international shipping, and show that it is a viable option with few economic barriers that could be overcome if regular fuel prices revert to previous higher levels. Finally, Psaraftis and Zachariadis (2019) note that while methanol offers negligible SO_x emissions not all is positive for this alternative fuel. Its NO_x output is above the Tier-III levels, and unless produced from biomass using RES, it has higher GHG well-to-propeller emissions than HFO and MDO.

Concerning voyage fuel consumption, the use of antifouling coating can be used to reduce biological fouling at the hull and propeller, and subsequently fuel consumption. In cases of significant fouling there have been reports that for a high-speed (24 knots) vessel there could be an increase in the effective power by up to 38% (Demirel et al., 2017). However, there are some environmental concerns on its potentially toxic effects on marine life. Finally, it should be stressed that in order to decarbonize maritime transport the emissions at berth should not be neglected. Particularly for SSS vessels, the fuel consumption during port stays is far from negligible. Ro-Ro vessels have significant energy demands at the port to provide sufficient ventilation during loading/unloading operations. One option to reduce emissions at port is through cold ironing, otherwise known as alternative marine power (AMP). Zis (2019) discusses the prospects of cold ironing as an emissions reduction option, and presents its status worldwide; within Europe there are several ferry terminals that can provide shorepower, and from 2025, all EU ports will be required to have some capacity for AMP provision. In terms of electrification, the use of batteries to power demands at the port and assist in propulsion has also been examined for Ro-Pax vessels (Kavli et al., 2017). In this paper, we will be considering the use of Flettner rotors, cold ironing, and the impact of fouling at the hull to examine the potential emissions reduction of each option.

3.3 Impact of market based measures on the sector

Market-based measures (MBM) include emissions trading schemes (ETS), imposing a bunker levy, or hybrid schemes. MBMs at the IMO belong to the roster of medium-term measures, to be agreed on and implemented by 2030; however, it would seem that the need to do so is more urgent. Psaraftis (2012) reviews the IMO activity on reducing GHG based on the MBM proposals that were under consideration. An ETS would revolve around setting a cap on emissions, and providing permits to be auctioned at a market price. If these permits were to be exhausted, the ships would not be able to legally emit more CO_2. However the main criticism on ETS is the uncertainty on what should be the cap, and what would the price per tonne of CO_2. If too many permits were issued the carbon prices could drop significantly (as in the EU ETS case in recent years). However, setting a cap on emissions could lead to reductions in sailing speed, and investments in emissions reduction technologies. A bunker levy (or fuel tax) has also been considered in several research studies as regards its potential to result in emissions reduction. Devanney (2010) examines the effects of a bunker levy, and estimates that a $50 per ton of fuel levy on a base bunker price of $465 would lead to a 6% reduction in VLCC emissions over their life cycle, whereas a $150 levy could result to 11.5% CO_2 reduction. Kosmas and Acciaro (2017) compare two forms of a levy, one that is a unit-tax per ton of fuel, and one that is a percentage of the current fuel prices. The authors stress that added operating costs would be passed on to shippers. Psaraftis (2019b) compares speed limits with bunker levies and concludes that the former presents a number of deficiencies compared to the latter. For speed limits it is not clear what each limit should be for each shipping sector, given the great differences in design speeds for different ship types. There is also the risk that a speed limit would actually benefit the ship owners of inefficient vessels, as it would require their competitors to sail at the same sailing speeds. Considering the impact of a bunker levy on Ro-Pax vessels is an interesting problem but is outside the scope of this paper. For more details on the possible role of MBMs and a more recent review of relevant work see Lagouvardou et al. (2020).

4 Methodology

This section presents the methodological framework used in this paper to calculate the emissions generation from shipping activity given ship, voyage, cargo, and weather conditions. Constructing a baseline is vital in order to assess the emissions reduction potential of the measures described in section 3, both in absolute (total emissions) and in intensity terms.

4.1 Fuel consumption modeling

In this work we are interested in the fuel consumption during each activity phase of a voyage, focusing mainly on the sailing (denoted as S) and at-berth (denoted as B) energy demands and associated emissions. In this section, we present a comparison of the use of simple activity-based models, with a more analytical microscopic model tailored on a specific ship, and with the actual fuel consumption data provided by a ship operator. The first type of models have been widely used in studies concerned with the construction of emissions inventories of either a fleet, a port, or the world merchant fleet, and are typically taking as input each vessel's installed power, and activity information (hours at a port, hours sailing, sailing speed), often disregarding environmental factors. Such models use a non-linear relationship between the sailing speed and the fuel consumption, using the so-called propeller law typically assuming a cubic relationship. Let m denote the main (or propulsion) engines that operate during sailing, α the auxiliary engines that power the vessel's electricity demands and operate at all phases, and b the boilers that are used whenever the main engines are switched off. The associated fuel consumption (kg of fuel) of an engine i (which can be m, α, or b) onboard a vessel during activity A (either S or B) can then be estimated by equation 1:

$$FC_{i,A} = 10^{-3} \cdot SFOC_{i,A} \cdot EL_{i,A} \cdot EP_i \cdot t_A \qquad with\ i \in (m, a, b), A \in (S, B) \tag{1}$$

where $SFOC$ (g/kWh) is the specific fuel oil consumption of the engine, EP (kW) is the installed engine power, EL is the fractional (%) load of the maximum continuous rating of the engine, and t_A (hours) is the time duration of activity A. As stated earlier, during sailing the $EL_{m,A}$ (%) depends on the sailing speed, the weather conditions, and the amount of cargo loaded. An exponential relationship known as the propeller law is used to estimate the changes of engine load at different sailing speeds (let them be V_S^1 and V_S^2, with respective $EL_{m,S}^1$ and $EL_{m,S}^2$ as in equation 2 with exponent n.

$$\frac{EL_{m,S}^1}{EL_{m,S}^2} = \left(\frac{V_S^1}{V_S^2}\right)^n \tag{2}$$

Typically, a cubic relationship (n = 3) is used in most studies in the literature (Cariou, 2011; Corbett et al., 2009) but for vessels sailing at faster speeds or at harsh weather higher exponents need to be used. For Ro-Ro ships, values between 3.2 and 3.5 have been advised (Psaraftis and Kontovas, 2013). Most papers in transportation science dealing with shipping emissions consider only the sailing speed in the fuel consumption estimation. The weight of the ship (and thus the weight of the cargo on-board) can also affect the total fuel consumption. There are several empirical approximation models, where for a given speed, the fuel consumption is proportional to the total weight raised to the power of $\frac{2}{3}$ as in equation 3:

$$FC_{m,S} \propto (cw + ew)^{\frac{2}{3}} \tag{3}$$

where *cw* is the cargo weight (including fuel on-board and consumables) and *ew* is the weight of the ship if empty. For auxiliary engines, the value of $EL_{a,S,k}$ varies depending on the time of operation (for lighting requirements) and the cargo carried (more power is required for additional reefer containers in the case of liner shipping).

The previous models perform well when it comes to studies concerning several vessels, but such models do not explicitly consider environmental factors (waves, wind) and therefore are less accurate. In this paper, we will be performing a comparison on the fuel consumption during sailing with a more analytical model named ShipCLEAN. This is essentially a simulation model that can be considered as a virtual ship that mimics the behavior of a specified commercial ship type. This model is divided into two parts: a static part for calm water power prediction that uses empirical methods for the estimation of power prediction, and a dynamic part that considers realistic operational conditions including environmental factors (wind, wave, currents, temperature differences, fouling, and shallow water effects). More detailed information on the ShipCLEAN model can be found in the paper of Tilling and Ringsberg (2018).

4.2 Transport modelling / modelling transport activity and transport demand

We consider the total transport work carried out by the ships in the examined service, and we also consider the transport work of any viable alternatives. By shipping activity, we consider the number of voyages between the two ports, and the total transport work is expressed in lane-meters of cargo multiplied by nautical miles. For the case of Ro-Pax, the transport work is calculated in lane-meters carried at each voyage. A lane-meter is unit that measures how much space on-board the decks of the vessel the cargo is occupying. Ro-Pax operators charge shippers in monetary units per lane-meter transported unlike other shipping markets. In order to understand the effects of the examined measures from section 3 on the transport activity, we will use a modal split model to estimate the transportation demand for the examined ship operator and the land-based or maritime alternatives. According to most modal split model methodologies, the shipper is perceived as a rational decision maker on which mode to use, taking into account the available information, based on its expected utility. On freight transport, typically this is translated into minimizing the disutility of generalized cost of transport. The latter is a function of total transportation cost, travel time, value of cargo, and other attributes such as the reliability of a service, convenience, number of mode changes and others. In most studies the generalized cost for freight only takes into account the time and cost, linking the two variables with information on the value of cargo and its depreciation. We use the model developed by Zis and Psaraftis (2017) that was applied in similar case studies in the North and Baltic Sea. In that model, the generalized cost is given by equation 4:

$$GC_j = TC_j + \alpha \cdot TT_j \tag{4}$$

where TC_j (€/lm) represents the total monetary cost that the shipper is paying if mode j is chosen. Parameter α (€/lm/hour) is the value of time and finally TT_j is the total transit time if mode j is chosen including all waiting times and time lost due to intermodal changes. The shipper decides which option (*M for maritime or L for land-based)* to choose. The logit model can be calibrated if information on the market share of each option is known, as well as if the generalized cost of transport for each option is retrieved. Calculating the generalized cost is simple if the cargo value, the total transportation time, and the freight rate for each transport mode is known. It is then possible to estimate the probability of choosing a mode using equation

5, where λ is a scale parameter that acts as a weight on the modeled disutility. Higher values for λ can be interpreted as a higher sensitivity on mode choice of shippers.

$$P_j = \frac{e^{-\lambda \cdot GC_j}}{\sum_{j=M,L} e^{-\lambda \cdot GC_j}} \quad (5)$$

Each change at the generalized cost of an option through any of the measures described in section 3, will result in a change in the total transport demand for the service under examination. Finally, changes in the fuel prices (by for example a bunker levy) are linked with the transportation cost of the service. Ship operators can pass on changes in fuel price on their freight rates via the bunker adjustment factor (BAF). Each operator is required by law to devise its own BAF method, and in this paper we use a generic relationship between the two based on observations on freight rates and fuel prices in the examined services in recent years.

4.3 Reaching the emission targets and associated costs

As stated in section 1, the IMO has set some very ambitious targets in the effort to decarbonize maritime transport. At the same time, the IMO already has in place regulation that seeks to minimize sulphur and nitrogen emissions from shipping. It has been shown in the literature that such regulations are very successful in targeting these specific pollutant species, but occasionally at a cost of increased carbon emissions. Particularly for the case of sulphur regulation, compliance can be achieved through either use of ultra-low sulphur fuel, which has a higher CO_2 emissions factor, or with scrubber systems, that require additional energy (between 1 and 3%) and as a result increase fuel consumption associated CO_2 emissions. It has to be noted that the use of LNG as fuel is also securing compliance to the sulphur limits, and LNG actually has a much lower CO_2 emissions factor, although there are some concerns due to the potential increase of CH_4 emissions via the methane slip (Attah and Bucknall, 2015). In this paper, we compare the baseline case of the Ro-Pax service, with the potential savings in fuel and associated emissions through the examined measures. Concerning emissions intensity in terms of transport work, we note the importance of increasing the capacity utilization of the vessel. To simplify our analysis, we attribute all emissions to cargo units when comparing the emissions intensity, as we consider that the examined measures would not have an impact on the passenger transportation demand.

To evaluate the costs of each of the examined emissions reduction options we use a simple cost benefit approach. For the case of technological investments (for example the installation of a Flettner rotor), we estimate the fuel consumption savings for the remaining lifetime of the project, and we compare it with the installation costs at the current year, including operating and maintenance costs this might have in the future. For more generic measures (for example a reduction in sailing speed), we compare the fuel savings with the new revenue assuming it might lead to a drop in transport demand. The next section examines the efficacy of representative measures described in section 3, with the methodology presented here.

5 Analysis

In the ensuing analysis, we consider the case of a Ro-Pax service between the Swedish port of Gothenburg and the German port of Kiel. We construct a baseline using information provided from the ship operator, and we attempt to quantify the emissions reduction potential of the following measures: use of alternative fuels (methanol or bio-methanol), installation of one or more Flettner rotors, new sailing speed, impact of weather routing, impact of hull fouling, and provision of shorepower at the port. We compare the reduction in absolute emissions per trip and per year for the service through the selected available abatement options. We consider each measure on its own to assess its effectiveness in reducing both absolute emission levels, and emissions intensity.

5.1 The examined route: Gothenburg – Kiel

The route is served daily with two vessels deployed (one sailing southbound and the other northbound each day). The specifications of the vessels are shown in Table 1 below in terms of cargo and passenger capacity, machinery on-board, age, and other relevant information. Also shown in the table is the option of sending cargo by road, via the Øresund bridge.

Table 1: The available transport options. Data source: down compilation and adaptation from Zis and Psaraftis (2017).

Transport option	Vehicle type	Capacity (lm)	Service speed (knots)	Maritime distance (NM)	Freight rate	Road distance (km)	Total time (hr)	Market share (%)
Gothenburg - Kiel	Ro-Pax	4,000	15.5	236	40€/lm	200	20	29.7
Gothenburg - Ghent	Ro-Ro	3,000	18	577	50€/lm	100	38	44.7
Road via Øresund bridge	HGV	14	70 km/h (37.8 knots)	NA	0.63€/km	1300	23	25.6

We consider that the route competes for cargo mainly with another Ro-Ro service serving Gothenburg and Ghent, and with a fully land-based route as shown in Figure 1. The three alternatives are based on the case study of Zis and Psaraftis (2017).

Figure 1: The competing alternative modes in the case study.

In terms of fuel consumption during the voyage we compare the actual fuel consumption as provided by the ship operator (that includes the effects of currents and weather), with the ShipCLEAN model, and with a generic activity-based model as the one described in section 4.1. For the latter, we are using the engine specifications for the ships and assuming an exponential relationship (n = 3.2, based on the exponent that best fit our data) between engine load and speed. In contrast, the ShipCLEAN model is using more comprehensive data and incorporates the effects of metocean data (waves, winds and ocean currents) in the voyage. We provide the mean fuel consumption and standard deviation as retrieved from the model.

Table 2: Comparison of actual fuel consumption with generic activity-based methodologies and the ShipCLEAN model.

Fuel consumption (FC) (tonnes)	Machinery	Generic activity-based	ShipCLEAN model	Actual fuel consumption as provided by operator
FC voyage Kiel Gothenburg	Main engines	26.26	29.94	31.23 (HFO and methanol)
	Aux. engines	4.89	-	5.03 (MGO)
FC voyage Gothenburg Kiel	Main engines	26.26	30.51	34.42 (HFO and methanol)
	Aux. engines	4.89	-	5.02 (MGO)
FC at port (aux. engines)	Aux. engines	2.33 Assumed EL_{aux} 23%	NA	2.12 (MGO at Kiel) or cold ironing (Gothenburg)
FC at port (aux. boilers)	Boilers	0.60	NA	0.54 MGO

We can observe that a generic activity based model would underestimate the fuel consumption as it does not consider weather impacts. The more refined ShipCLEAN model is closer to the actual fuel consumption of this trip. Based on Table 2, it is possible to construct the baseline CO_2 emissions footprint of this route. We are interested in the emissions reduction potential of several measures compared to the 2008 levels as in the strategy adopted by the IMO. For this reason, we roll back the current technological improvements of the service, and we estimate what the emissions would have been in 2008 based on the following assumptions and facts[1]:

- We base the calculations on the average actual fuel consumption of the vessels as provided by the operator for years 2014-2019.
- In reality different vessels might had been deployed at the time for this service but to facilitate comparisons we assume a similar service.

[1] It is interesting that the 2008 carbon intensity levels are not yet officially estimated by the IMO, this being one of the objects of the 4th IMO GHG study.

- The ships did not have scrubbers equipped in 2008, so the fuel consumption would have been slightly lower during sailing.
- Cold ironing was not used at the port of Gothenburg in 2008.
- The service speed and sailing frequency (and voyages per year) would be the same as now.
- Both ships would be using HFO fuel with 1.5% sulphur content as at the time required during voyage, but 0.1% MGO at the port as required by EC Directive 2005/33/EC.
- We assume an average cargo capacity utilization of 70%
- We consider that the number of passengers is not changing, and we do not allocate emissions to passengers due to lack of data.
- We allocate all emissions to cargoes.
- We define emissions intensity as grams of CO_2 per lm-NM as in Zis and Psaraftis (2017)

Under these assumptions, the annual CO_2 emissions broken down by activity phase (sailing, maneuvering, at-berth) are shown in Table 3. We also show the emissions reduction goals as suggested by the IMO, without considering possible differentiation of targets amongst different shipping sectors (which may well make sense).

Table 3: Reduction goals vs a baseline case with no emissions reduction actions.

Emissions	Baseline (2008)	Emissions intensity target (2030)	Absolute emissions target (2050)
CO_2 during cruise (tonnes/year)	78,233.5	NA	NA
CO_2 at ports (tonnes/year)	5,696.1		
Total CO_2 (tonnes/year)	83,929.6	NA	41,964.8
CO_2 intensity (g/lm-NM)	93	57.8	NA

5.2 Alternative fuels (methanol)

The use of alternative fuels has been considered as a long-term measure from the IMO in reaching the goals of the strategy. Alternative fuels could consider the use of nuclear energy, LNG, or biofuels. In this example, we consider the use of methanol, which in fact is already used in one of the two vessels deployed in the Gothenburg – Kiel service. Methanol can be produced from fossil fuels or from biogas in which case it is considered bio-methanol and essentially is a biofuel. The combustion of methanol generates 1.375 kg of CO_2 per kg of fuel burned (Cheng et al., 2008). Brynolf et al. (2014) compare various marine fuels in environmental terms including LNG, liquefied biogas, methanol, and bio-methanol. For the latter two, they suggest the use of a similar lifecycle emission factor (expressed in 69 g of CO_2 per MJ of fuel).

Table 4: Comparison of CO_2 emission factors of different fuel types.

	Methanol	**HFO**	**MGO**	**LNG**
Heat value (MJ/kg)	22.7	41.8	45.9	55.2
CO_2 emissions (tank to propeller) (g/MJ)	69	77	75	54
Attained CO_2 Emission factor in this study (g/g)	1.566	3.219	3.443	2.981
Emission factor in literature	1.375 (Cheng et al., 2008)	3.021 (IMO, 2008) 3.114 (IMO, 2014)	3.082 (IMO, 2008) 3.206 (IMO, 2014)	2.6-2.8 (IMO, 2008) 2.75 (IMO, 2014)

Brynolf et al. (2014) note that there are no measurements from use of methanol in marine engines so far, and for this reason we will simply use the 1.566 factor. In the only real world application of using methanol as fuel, the ship operators have started using the fuel since 2015 for propulsion, gradually replacing HFO with this fuel. In this case study, we consider the emissions reduction potential through the use of methanol for propulsion for several different blend scenarios, taking as baseline the 2008 case (with no methanol used at the time). Methanol has a significantly lower heat value than the other fuels, so we assume that more methanol is necessary to replace HFO in the next scenarios. The ratio we are using is 1.84 kg of methanol for each kg of HFO to be replaced based on the calorific content of the fuel. It has to be noted that this is a very simplified approximation due to the limited information available regarding methanol as a marine fuel. Using this approximation, methanol produces 10.46% less CO_2

emissions than HFO. Methanol has been marketed as a better fuel environmentally due to its much lower SO_x and PM emissions. Although as stated in section 3.2 it is not as good in terms of NO_x emissions. However, the focus of this paper is strictly on CO_2 and on comparing different decarbonisation options to reach the IMO targets. Figure 2 presents the potential emissions savings per year using methanol in one or two ships, for different levels of participation in the fuel use of the main engines. We can observe that the absolute emissions target from Table 3 can only be attained if using a significant percentage of bio-methanol in the fuel mix for both deployed ships. Currently this would not be economically viable.

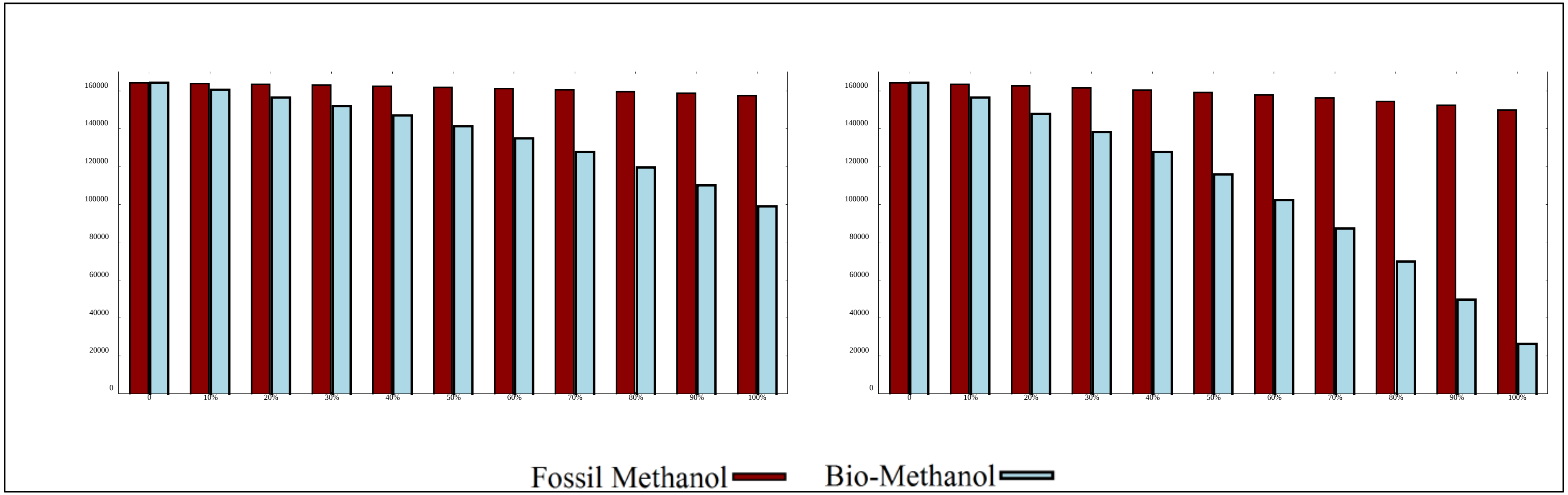

Figure 2: Emissions savings through the use of methanol (or bio-methanol) in one or both ships.

5.3 Flettner rotors

The installation of one or more Flettner rotors can reduce the fuel consumption during the cruise phase of a voyage. This technology has been considered as one viable option for the decarbonization of the shipping sector, with a wide range of potential savings from 2 to 24% in some examples (Traut et al., 2014). Using the ShipCLEAN model and the measured wind speed and wind angle, the fuel savings from the installation of one and two Flettner rotors with a diameter of 5 m and a height of 30 m are estimated. Results show a total fuel saving of 3.9% for the case of one rotor and 6.4% for the case of two rotors. We assume that the installation of the rotor would not have an effect on the transportation demand of the service, as we are not changing the speed of the service, nor the freight rate. Table 5 summarizes the effects of the installation of one or two Flettner rotors in trying to reach the emissions targets as set by the IMO, considering the aforementioned savings as average across a year.

Table 5: Emissions savings from the installation of 1 or 2 Flettner Rotors.

Emissions	**Baseline**	**1 Flettner rotor**	**2 Flettner rotors**	**IMO goal**
CO_2 during cruise (tonnes/year)	78,233	75,182	73,227	NA
CO_2 at ports (tonnes/year)	5,696	No change	No change	NA
Total CO_2 (tonnes/year)	83,930	80,879	78,923	41,965 (2050 target)
CO_2 intensity (g/lm-NM)	93	89.62	87.45	57.8 (2030 target)

We can see that the installation of the Flettner rotors can improve the fuel efficiency of the vessel, but that this technological measure it is not sufficient on its own to reach the IMO targets. We can also note that the additional fuel consumption savings from the second rotor are slightly lower than the first. In terms of costs, a Flettner rotor of these dimensions would require approximately €750,000 as a capital cost of investment, and a maintenance cost of 2% of capital costs per year. In both cases, the payback period of the investment would be less than

2 years (assuming the current fuel prices for HFO, and the fuel savings from the ShipCLEAN model).

5.4 New speed from operator, impact on transport demand and new emissions

With this option, we simply consider the potential in reducing emissions from slight changes in the total sailing time of the service. We do note that already the vessels are sailing at relatively slow speeds (15.5 knots average versus a design speed in the range of 20 to 22 knots). Changes in the total travel time would also influence the generalized cost of transport, and as a result, a change in the total transportation demand for the service would be expected. We assume that the competing maritime mode does not change the total duration of its voyages. Finally, a change in the crossing time would result in a change in the total number of hours at each port, and there is therefore a limit on how slow the service could be to allow sufficient time for the at-port operations. We consider as baseline the crossing time of 15 hours, and we examine the impacts of crossing times of 13, 14, 16, 17, and 18 hours. To facilitate comparisons we assume that the hoteling demands at the port are proportional to the time spent at the port, although in reality that is not always the case for Ro-Ro's (Zis et al., 2019). Table 6 summarizes the impacts of changing sailing speed in terms of CO_2 emissions, and the impact on trade.

Table 6: Impacts of new sailing speed on transport demand and emissions.

Crossing time (hours)	**Service speed (knots)**	**Market share (%)**	**Vessel utilization rate (%)**	**CO_2 at ports (AMP at Gothenburg, fuel at Kiel) (tonnes)**	**CO_2 during voyage (tonnes)**	**Emissions intensity (g/lm-NM)**
13	18.08	45.3	76.08	4,465	126,679	143.26
14	16.79	45.0	75.51	4,059	103,068	119.61
15 (Current crossing time)	15.50	44.7	75.00	3,588	78,562	91.03
16	14.69	44.3	74.38	3,248	63,237	74.80
17	13.82	44.0	73.81	2,841	47,851	56.61
18	13.06	43.7	73.25	2,436	35,710	42.60

It is evident that as the sailing speed is reduced, some cargoes are lost (hence the reduction in the vessel utilization rate), but the emissions are significantly reduced both in absolute and in intensity terms. Vessels are already sailing at low speeds compared to their design speeds, and it is not certain that commercially a crossing time of 18 hours would be viable taking into account the expectations of passengers in this Ro-Pax service.

5.5 Impact of hull biofouling in the fuel consumption of a vessel

Biofouling on ship hulls and propellers is increasing the frictional resistance during propulsion and as a result increases the fuel consumption during cruise. Antifouling coatings are used to address this issue. These coatings contain biocides that are toxic to marine organisms that form the biofouling. The impact on the fuel consumption varies and depends on the extent of the accumulation of the biofouling on the hull, and the geographical area of the voyage. For example back in 1952, the British Navy proposed a 0.25% per day increase in the frictional resistance for ships in temperate waters, raising that number to 0.5% for ships in tropical waters (WHOI, 1952). According to SSPA (2019) the frictional resistance increases by about 30% if the hull has biofouling with some barnacles. Schultz et al. (2011) consider three levels of cleaning; full (removal of fouling from the entire hull, propeller, shaft, and all openings), interim (shafts, struts, propellers), and partial (specific sections of the hull). They document an average frequency of full hull cleanings of 0.21 per year, and 2.4 interim cleanings per year. Therefore, an important decision for the shipowner is how often to perform a cleaning of the hull and propeller. This decision would depend on the expectation of fuel savings, fuel price, and the actual cost per cleaning. Schultz et al. (2011) note that the costs vary across different ports, and provided representative estimations of approximately $27,000 and $19,000 for a full and interim cleanings respectively in 2010. Using the ShipCLEAN model, a re-evaluation of the fuel consumptions using an increased frictional resistance shows an increase of the average fuel consumption by 16.5%. This could be detrimental in the quest to reduce the CO_2 emissions as per the IMO goals. The fuel consumption provided in Table 2 was provided by the ship operators as an average over one year of voyages for the two ships. There was no information provided on the frequency of cleanings, but the literature and the ShipCLEAN model results indicate that increasing the frequency of cleaning can be useful to reduce the CO_2 emissions of the service.

5.6 Cold ironing savings at the port, for a year of operation. One or two ports.

Both of the deployed vessels are equipped with technology that allows the use of AMP at berth. However, only the port of Gothenburg currently provides shorepower and thus the vessels are only using this there. At the Swedish port, the only fuel consumption during berth is that of the auxiliary boilers that are still powered to maintain fuel temperatures. The total emissions savings through cold ironing can be estimated if the emissions at the source of power are known. Sweden is powered predominantly by RES, and has very low grid emissions factors as shown in the paper of Zis (2019). Taking into account some energy transmission and transportation losses, Table 5 compares the emissions at berth in the current situation, with two hypothetical cases where in the first cold ironing was not used in Gothenburg, and in the second cold ironing was also used in Kiel.

Table 7: Comparison of hoteling emissions between auxiliary engines and cold ironing.

Case	**AMP at Gothenburg, fuel at Kiel**	**Fuel at Gothenburg fuel at Kiel**	**AMP at Gothenburg, AMP at Kiel**
Gothenburg Fuel Consumption of aux. engines (tonnes per call)	NA	2.14	NA
Kiel Fuel consumption of aux. engines (tonnes per call)	2.14	2.14	NA
Energy demand at grid (kWh)	10,790	NA	10,790
Fuel consumption of aux. boilers (tonnes per call)	0.65	0.65	0.65
CO_2 emissions per year at Gothenburg (tonnes)	738.2	2,849.90	738.20
Gothenburg CO_2 emissions per year at Kiel (tonnes)	2,849.9	2,849.90	738.20
CO_2 emissions per year grid Sweden (tonnes)	36.30	NA	36.30
CO_2 emissions per year grid Germany (tonnes)	NA	NA	1,467.1
Total CO_2 emissions (tonnes) (port, grid, and voyage)	82,186	84,261	81,541

CO_2 emissions intensity (g/NM-lm)	91.08	93.38	90.36
Deviation from baseline intensity	-2.08%	+0.4%	-2.85

It is evident that the current set up makes a lot of sense environmentally as Sweden is powered by a superior grid in environmental terms, and as result globally there are great reductions of 75.5% in CO_2 (due to the use of AMP). If the port of Kiel would also provide AMP, there would still be global benefits, but in a much lesser extent at 23.4% due to the energy mixture powering Germany. However, when comparing the total emissions intensity of the service (considering the full voyage), the improvement is small. If we consider as a baseline case the use of fuel at both ports, the emissions intensity would be 93 grams of CO_2 per NM-lm, which can be improved by 2.08% through AMP in Gothenburg, or 2.85% through AMP in both ports.

6 Conclusions and decarbonization policy implications

All of the previous measures would be successful in reducing the CO_2 emissions of this service. In terms of the technological measures, the use of Flettner rotors or shorepower would not be sufficient on its own to reach the ambitious targets of the IMO initial GHG strategy. Alternative fuels (bio-methanol) could lead to the required emissions reductions, but it has to be noted that currently bio-methanol is extremely expensive compared to fossil fuels, and the costs of retrofitting a vessel with an engine that can burn methanol is also very high. According to DNV GL, the total costs including engine costs, other equipment and shipyard costs would reach $10.5 million (DNV GL, 2016). A combination of these measures would be sufficient to reach the IMO levels for this particular service, but it may not be feasible financially to deploy all of these measures. At the same time, operational measures (speed reduction) can guarantee the reduction of CO_2 emissions to the desired levels. However, due to the nature of the sector and the fact that in these voyages passengers are also transported there are limits to the extent of slow steaming for the service. It has been shown, that for small speed reductions the loss of cargo demand would be almost negligible, but that may not be the case for other services. In addition, in the future a service that deploys greener vessels may have a competitive advantage and manage to offer a faster service while still reaching the IMO targets. The presented methodology is transferable and can be readily applied to other SSS services provided that the same type of data (vessel specifications, service schedules, techno-economic data, and market shares of competing modes) are available. This would allow affected ship operators to make informed decisions on the best way to reach the CO2 reductions required by the IMO in the near future, as we can expect that different services will have different emissions reduction potential.

At the same time, we believe that the above analysis has also shown that the potential reduction of CO_2 emissions associated with the measures that were examined, even though they surely do have some promise, are not enough to fully satisfy the IMO reduction targets, in and of themselves. To achieve these targets, something more radical will have to be implemented, for instance fuels that have a much lower carbon coefficient than those examined in this paper, or even a zero carbon coefficient. These fuels may include hydrogen, ammonia, bio-fuels and others. The path toward eventually using such fuels, or other groundbreaking energy saving technologies, is in our opinion worth pursuing, however it is currently full of a number of obstacles that will have to be circumvented if one is to see such fuels and technologies being implemented. Some major obstacles are of economic nature, that is, one has to develop a credible business case for the production, deployment and use of such fuels and technologies. To that effect, a discussion that is certainly relevant is the discussion on possible Market Based Measures (MBMs), which would incentivize the development of such fuels and technologies, and would provide the necessary push to make these viable from a commercial perspective. For instance, a substantial bunker levy would induce technological changes in the long run and logistical measures (such as slow steaming) in the short run. In the long run, it would lead to changes in the global fleet toward vessels and technologies that are more energy efficient, more economically viable, and less dependent on fossil fuels than those today. A levy would also raise monies that could be used for "out-of-sector" GHG emission reductions, aid to least developed countries (LDCs) and Small Island Developing States (SIDS), and other purposes. For more details on the spectrum of decarbonization options, see Bouman et al. (2017), DNV GL (2018) and OECD (2018).

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References

Ammar, N. R., & Seddiek, I. S. (2017). Eco-environmental analysis of ship emission control methods: Case study Ro-Ro cargo vessel. *Ocean Engineering*, *137*, 166-173.

Attah, E. E., & Bucknall, R. (2015). An analysis of the energy efficiency of LNG ships powering options using the EEDI. *Ocean Engineering*, *110*, 62-74.
Bouman, E. I., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review. *Transportation Research Part D, 52*, 408–421.
Brons, M., & Christidis, P. (2012). External cost calculator for Marco Polo freight transport project proposals. *Publications Office of the European Union: Luxembourg*.

Brynolf, S., Fridell, E., & Andersson, K. (2014). Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. *Journal of cleaner production, 74*, 86-95.

Cariou, P. (2011). Is slow steaming a sustainable means of reducing CO2 emissions from container shipping?. *Transportation Research Part D: Transport and Environment*, *16*(3), 260-264.

Cheng, C. H., Cheung, C. S., Chan, T. L., Lee, S. C., & Yao, C. D. (2008). Experimental investigation on the performance, gaseous and particulate emissions of a methanol fumigated diesel engine. *Science of the total environment*, *389*(1), 115-124.

Coraddu, A., Figari, M., Savio, S., Villa, D., & Orlandi, A. (2013). Integration of seakeeping and powering computational techniques with meteo-marine forecasting data for in-service ship energy assessment. *Developments in Maritime Transportation and Exploitation of Sea Resources: IMAM 2013*, 93.

Corbett, J. J., Wang, H., & Winebrake, J. J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment*, *14*(8), 593-598.

Cullinane, K., & Cullinane, S. (2013). Atmospheric emissions from shipping: The need for regulation and approaches to compliance. Transport Reviews, 33(4), 1-25.

De Kat, J. O., & Mouawad, J. (2019). Green Ship Technologies. In *Sustainable Shipping* (pp. 33-92). Springer, Cham.

De Meyer, P., Maes, F., & Volckaert, A. (2008). Emissions from international shipping in the Belgian part of the North Sea and the Belgian seaports. *Atmospheric Environment*, *42*(1), 196-206.

Demirel, Y. K., Turan, O., & Incecik, A. (2017). Predicting the effect of biofouling on ship resistance using CFD. *Applied Ocean Research*, *62*, 100-118.

Devanney, J. W. (2010). The impact of EEDI on VLCC design and CO2 emissions. *Center for Tankship Excellence, USA. Retrieved from www. c4tx. org*.

DNV GL. (2018). Assessment of selected alternative fuels and technologies. Guidance paper 2018-
05.

EU, 2011, European Commission: WHITE PAPER. Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. *COM(2011) 144*, Brussels, 28.3.2011.
Douet, M., & Cappuccilli, J. F. (2011). A review of Short Sea Shipping policy in the European Union. *Journal of Transport Geography*, *19*(4), 968-976.

Gilbert, P., Bows-Larkin, A., Mander, S., & Walsh, C. (2014). Technologies for the high seas: meeting the climate challenge. *Carbon Management*, *5*(4), 447-461.

Gkonis, K. G., & Psaraftis, H. N. (2012). Modeling tankers' optimal speed and emissions. *Society of Naval Architects and Marine Engineers. Transactions*, *120*, 90-115.

Halff, A., Younes, L., & Boersma, T. (2019). The likely implications of the new IMO standards on the shipping industry. *Energy policy*, *126*, 277-286.

Hjelle, H. M. (2011). The double load factor problem of Ro-Ro shipping. *Maritime Policy & Management*, *38*(3), 235-249.

Hjelle, H. M., & Fridell, E. (2012). When is short sea shipping environmentally competitive?. *Environmental health—emerging issues and practice*.

IMO (2014). Third IMO Greenhouse Gas Study 2014. International Maritime Organization (IMO), London.

Kato, H., Takahashi, Y., Yoshida, Y., Masuko, A., & Watanabe, O. (2001). *U.S. Patent No. 6,186,085*. Washington, DC: U.S. Patent and Trademark Office.

Kavli, H. P., Oguz, E., & Tezdogan, T. (2017). A comparative study on the design of an environmentally friendly RoPax ferry using CFD. *Ocean Engineering*, *137*, 22-37.

Lagouvardou, S., Psaraftis, H. N., & Zis, T. (2020). A Literature Survey on Market-Based Measures for the Decarbonization of Shipping. *Sustainability*, *12*(10), 3953.

Lindstad, E., Borgen, H., Eskeland, G. S., Paalson, C., Psaraftis, H., & Turan, O. (2019). The need to amend IMO's EEDI to include a threshold for performance in waves (realistic sea conditions) to achieve the desired GHG reductions. *Sustainability*, *11*(13), 3668.

Lindstad, H. E., & Eskeland, G. S. (2016). Environmental regulations in shipping: Policies leaning towards globalization of scrubbers deserve scrutiny. *Transportation Research Part D: Transport and Environment*, *47*, 67-76.

Livanos, G. A., Theotokatos, G., & Pagonis, D. N. (2014). Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships. *Energy Conversion and Management*, *79*, 640-651.

Monios, J., Bergqvist, R., & Woxenius, J. (2018). Port-centric cities: The role of freight distribution in defining the port-city relationship. *Journal of Transport Geography*, *66*, 53-64.
Morales-Fusco, P., Saurí, S., & De Melo, G. (2013). Short sea shipping in supply chains. A strategic assessment. *Transport Reviews*, *33*(4), 476-496.

Morales-Fusco, P., Saurí, S., & Lago, A. (2012). Potential freight distribution improvements using motorways of the sea. *Journal of Transport Geography*, *24*, 1-11.

Mousavi, A., Sowlat, M. H., Hasheminassab, S., Pikelnaya, O., Polidori, A., Ban-Weiss, G., & Sioutas, C. (2018). Impact of particulate matter (PM) emissions from ships, locomotives, and freeways in the communities near the ports of Los Angeles (POLA) and Long Beach (POLB) on the air quality in the Los Angeles county. *Atmospheric Environment*, *195*, 159-169.

Norstad, I., Fagerholt, K., & Laporte, G. (2011). Tramp ship routing and scheduling with speed optimization. *Transportation Research Part C: Emerging Technologies*, *19*(5), 853-865.

Notteboom, T. (2011). The impact of low sulphur fuel requirements in shipping on the competitiveness of roro shipping in Northern Europe. *WMU Journal of Maritime Affairs*, *10*(1), 63-95.

Odgaard, T., Frank, C., Henriques, M., & Bøge, M. (2015). The Impact on Short Sea Shipping and the Risk of Modal Shift from the Establishment of an NOx Emission Control Area. *North Sea Consultation Group. Accessed June*.

OECD. (2018). Decarbonising maritime transport. Pathways to zero-carbon shipping by 2035.
Report of the Organisation for Economic Cooperation and Development, International Transport
Forum, Paris, France, March.

Panagakos, G. P., Stamatopoulou, E. V., & Psaraftis, H. N. (2014). The possible designation of the Mediterranean Sea as a SECA: A case study. *Transportation Research Part D: Transport and Environment*, *28*, 74-90.

Polakis, M., Zachariadis, P., & de Kat, J. O. (2019). The energy efficiency design index (EEDI). In *Sustainable Shipping* (pp. 93-135). Springer, Cham.

Psaraftis, H. N., & Zachariadis, P. (2019). The way ahead. In *Sustainable Shipping* (pp. 433-463). Springer, Cham.

Psaraftis, H. N., & Zis, T. (2019). European Policies for Short Sea Shipping and Intermodality. In *Short Sea Shipping in the Age of Sustainable Development and Information Technology*.

Psaraftis, H. N. (2012). Market-based measures for greenhouse gas emissions from ships: a review. *WMU Journal of Maritime Affairs*, *11*(2), 211-232.

Psaraftis, H. N. (2019a). Decarbonization of maritime transport: to be or not to be?. *Maritime Economics & Logistics*, *21*(3), 353-371.

Psaraftis, H. N. (2019b). Speed Optimization vs Speed Reduction: the Choice between Speed Limits and a Bunker Levy. *Sustainability*, *11*(8), 2249.

Raza, Z., Svanberg, M., Wiegmans, B., 2020. Modal shift from road haulage to short sea shipping: A systematic literature review and research directions. Transport Reviews, 40(3), 382-406

Raza, Z., Woxenius, J., & Finnsgård, C. (2019). Slow Steaming as Part of SECA Compliance Strategies among RoRo and RoPax Shipping Companies. *Sustainability*, *11*(5), 1435.

Schultz, M. P., Bendick, J. A., Holm, E. R., & Hertel, W. M. (2011). Economic impact of biofouling on a naval surface ship. *Biofouling*, *27*(1), 87-98.

SSPA (2019). Skin Friction Database. [Online]. Available at: https://www.sspa.se/tools-and-methods/skin-friction-database. [Accessed: 01 10 2019].

Styhre, L. (2009). Strategies for capacity utilisation in short sea shipping. *Maritime Economics & Logistics*, *11*(4), 418-437.

Svanberg, M., Ellis, J., Lundgren, J., & Landälv, I. (2018). Renewable methanol as a fuel for the shipping industry. *Renewable and Sustainable Energy Reviews*, *94*, 1217-1228.

Svindland, M. (2018). The environmental effects of emission control area regulations on short sea shipping in Northern Europe: The case of container feeder vessels. Transportation Research Part D: Transport and Environment, 61, 423-430.

Tillig, F., & Ringsberg, J. W. (2018). A 4 DOF simulation model developed for fuel consumption prediction of ships at sea. *Ships and Offshore Structures*, *14*(sup1), 112-120.
Traut, M., Gilbert, P., Walsh, C., Bows, A., Filippone, A., Stansby, P., & Wood, R. (2014). Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. *Applied Energy*, *113*, 362-372.

United Nations Conference on Trade and Development - UNCTAD, 2019. Review of Maritime Transport. UNCTAD/RMT/2019. United Nations Publication. http://unctad.org/en/PublicationsLibrary/rmt2019_en.pdf. accessed April 2020.

Unseki, T. (2013). Environmentally superior LNG-Fueled vessels. *Mitsubishi Heavy Industries Technical Review*, *50*(2), 37-43.

Vierth, I., Sowa, V., & Cullinane, K. (2018). Evaluating the external costs of trailer transport: acomparison of sea and road. Maritime Economics & Logistics, 21(1), 61-78.

Wilmsmeier, G., Monios, J., & Lambert, B. (2011). The directional development of intermodal freight corridors in relation to inland terminals. *Journal of Transport Geography*, *19*(6), 1379-1386.

Winnes, H., Styhre, L., & Fridell, E. (2015). Reducing GHG emissions from ships in port areas. *Research in Transportation Business & Management*, *17*, 73-82.

Woods Hole Oceanographic Institution (1952). Marine fouling and its prevention. Annapolis, MD:
United States Naval Institute.

Woxenius, J. (2012). Flexibility vs. specialisation in ro-ro shipping in the South Baltic Sea. Transport, 27(3), 250-262

Zhu, W., Erikstad, S. O., & Nowark, M. P. (2014). Emission allocation problems in the maritime logistics chain. *EURO Journal on Transportation and Logistics*, *3*(1), 35-54.

Zis, T. P., & Cullinane, K. (2020). The desulphurisation of shipping: Past, present and the future under a global cap. *Transportation Research Part D: Transport and Environment*, *82*, 102316.

Zis, T., & Psaraftis, H. N. (2017). The implications of the new sulphur limits on the European Ro-Ro sector. *Transportation Research Part D: Transport and Environment*, *52*, 185-201.

Zis, T., & Psaraftis, H. N. (2019). Operational measures to mitigate and reverse the potential modal shifts due to environmental legislation. *Maritime Policy & Management*, *46*(1), 117-132.

Zis, T. P., Psaraftis, H. N., Panagakos, G., & Kronbak, J. (2019). Policy measures to avert possible modal shifts caused by sulphur regulation in the European Ro-Ro sector. *Transportation Research Part D: Transport and Environment*, *70*, 1-17.

Zis, T. P. (2019). Prospects of cold ironing as an emissions reduction option. *Transportation Research Part A: Policy and Practice*, *119*, 82-95.