Economic and Environmental Impacts of Scrubbers Investments in Shipping: A Multi-sectoral Analysis

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Abstract

The International Maritime Organization (IMO) has implemented a series of increasingly stricter regulations to reduce sulphur emissions from international shipping. As of January 2020, the global sulphur cap requires the use of fuel containing a maximum of 0.5% sulphur content, or the use of technology achieving a similar reduction in sulphur emissions. Deciding between fuel switching or investing in abatement technologies has been a recurring topic for research in the last decade, with a focus on shipping activities within Emission Control Areas (ECAs). The quest for the desulphurization of shipping results in higher operating costs as well as CO_2 emissions. We estimate the economic and environmental impacts of compliance with sulphur limits for a variety of representative ship types. This paper quantitatively assesses case studies across the most important shipping sectors highlighting their different challenges. The results confirm that scrubber investments are more profitable at times of higher fuel prices, and for ships that spend relatively more time sailing. We show that the potential for speed differentiation inside and outside ECAs has been diminished. This framework can be a useful decision support system for selecting the best response amongst different compliance options to environmental regulations.

Keywords: Maritime transport, Sulphur emissions, Scrubbers, transport policy, payback period

1. Introduction

1.1 Background

Over the past 15 years, there has been a significant focus on reducing the sulphur emissions of the shipping sector. Through MARPOL Annex VI, the International Maritime Organisation (IMO) has introduced progressively more stringent regulations on the maximum allowed sulphur content in fuel used in shipping and designated Emission Control Areas (ECAs) with even stricter limits. The first ECA was the Baltic Sea, followed by the North Sea and the English Channel, where only sulphur emissions were regulated. Later on, North American coasts within 200 NM of the shore and the US Caribbean were designated as ECAs, with limits on nitrogen and sulphur emissions.

Two critical points in time were the 1st of January 2015 and the 1st of January 2020 when, respectively, limits within (1% to 0.1%) and outside ECAs (3.5% to 0.5%) were significantly lowered. To abide by these limits, ship operators can use very low-sulphur fuel oils (including Marine Gas Oil – MGO, Marine Diesel Oil – MDO, Ultra-low sulphur Heavy Fuel Oil – ULSHFO, blends) or install scrubbers that permit the use of regular HFO by treating the exhaust gases to capture SO_x emissions. This decision is a recurring subject of academic research, with several works performing techno-economic analyses and comparisons of the different abatement options. Jiang et al. (2014) focused on what price differential is required to justify investing in scrubbers for a containership of 5000 TEU capacity. Panasiuk and Turkina (2015) showed that scrubbers would always be profitable in their case study of a ferry service sailing fully inside an ECA. Zis et al. (2016) focused on the very low fuel prices during 2015-2016 that effectively doubled the scrubber's payback period for three small containerships on hypothetical services, spending different percentages of their time within ECAs (full, 53%, and 57%). The previous studies focused on simpler services of only one type of ship, that spent considerable parts of their sea time within ECAs on a different era (3.5% and 0.1% limits outside and inside ECAs respectively). Abadie et al. (2017) used stochastic modelling on Brent prices, to compare scrubbers with low-sulphur fuels for hypothetical ships spending different proportions of their time within ECAs, and noted the several uncertainties that affect which decision is preferable for the operator. Li et al. (2020) constructed a multinomial regression model to compare low-sulphur fuels, scrubbers, and LNG as compliance alternatives. They conclude that low-sulphur fuels should be used primarily by older vessels. Other fuel types secure compliance, for example LNG or methanol, which have practically zero sulphur content. Their retrofits are also more costly compared to a scrubber. For instance, a typical LNG retrofit cost for a 15,000 TEU ship is reported at around

25 to 30 million USD. A methanol retrofit is estimated to be cheaper due to its similarities with HFO. So far, there has been only one known conversion of a Ro-Pax vessel that required €13 million. Nikopoulou (2017) examined LNG as an emissions reduction option and found that it is not the most economic alternative, with expected recovery of investment between 5 and 7 years depending on ship type and fuel prices. LNG and methanol are not considered further in this paper since these cost far more than scrubbers, and there are not many vessels using these fuels. The World Fleet Register as of March 2021 shows that 1043 ships are capable of using LNG, the vast majority of which are LNG carriers. In contrast, there are currently 4655 vessels of various types that are equipped with scrubbers.

1.2 Effects on fuel prices

The main concerns following January 1st 2015 related to the increased freight rates that were expected to emerge and, as a result, the potential modal shifts to unaffected services or land-based alternatives, particularly in terms of the effects on short sea shipping (SSS) services. Either through the workings of the freight market or the imposition of explicit premia on freight rates in the form of a Bunker Adjustment Factor (BAF), it was feared that freight rates would increase as a direct result of more stringent sulphur regulations and the need to take into account the price differential between regular and low-sulphur fuels. As it transpired, due to the unexpectedly low fuel prices during the period 2015-2017, the anticipated modal shifts in SSS in Northern Europe were not realized (Zis and Psaraftis, 2019). In anticipation of the global sulphur cap that would affect all shipping operations, the same fears re-emerged. In the final few months of 2019, several shipowners started investing in scrubber systems, to the extent that there was a significant backlog of orders reaching 5 months from order to retrofit. In February 2019 there were 1754 vessels globally equipped with scrubbers, a number that more than doubled within 2 years.

Fuel prices vary from port to port, and so does the price differential between regular and ultra-low sulphur blends. Figure 1 shows the fuel prices for the four main bunker oils from 2010 to 2020 for the port of Rotterdam. In the period between 2010 and 2015, the prices of HFO (with 3.5% sulphur content) and MGO (0.1%) are shown, while in the middle of 2015 another fuel type was commercially available (ultra-low sulphur HFO – ULSFO) that allowed compliance with the 0.1% limit. Price data for very low-sulphur fuel oil (VLSFO – 0.5%) has only become available since January 2020. However, since it is possible to blend regular HFO and ULSFO, we have also simulated what the price of VLSFO would have been through blending, for some years prior to 2020. During 2020, the simulated price generally follows the actual VLSO price, although the actual price is slightly cheaper in the later months of 2020.

Figure 1: Fuel prices for different bunker oils

Low-sulphur fuel prices generally follow the trends of HFO and, for the majority of the period examined, the price differential was relatively stable. In some ports, the price is almost identical (0.5% and 0.1%), while elsewhere the differential varied from as low as $30 to as high as $150 per ton. In Rotterdam, the average price differential was $38. The pandemic outbreak of Covid-19 led to a sharp decline in demand for oil and historically low fuel prices. From a ship operator’s perspective, the very low fuel prices may lead to increased sailing speeds for certain sectors (particularly liner shipping), while product and crude tankers may wait things out until fuel prices increase again. However, fuel prices started recovering during the last months of 2020.

1.3 Objectives and contribution of this paper

The literature has paid less attention to the environmental benefits of sulphur regulations and on how the different compliance options compare in carbon emissions. Zis and Psaraftis (2019) identified a slight increase in CO_2 emissions following the introduction of the 0.1% limit in SECAs, while Lindstad and Eskeland (2016) suggested that the environmental benefits of sulphur regulations will come at the cost of a significant increase in CO_2 emissions. Zis and Cullinane (2020) reviewed the literature on the desulphurization of maritime transport and predicted an impending new wave of research focusing on the implications of the global sulphur cap on carbon emissions, in anticipation of the IMO initial strategy on the decarbonization of shipping. This paper seeks to plug this research gap by estimating the emissions for a variety of shipping sectors through illustrative case studies. The next section presents the model used to estimate fuel consumption and associated emissions. Section 3 presents the six case studies and the rationale behind their selection. Sections 4 and 5 apply the methodology for an environmental and economic analysis of the different abatement options respectively, discussing key differences between various sectors. Section 6 illustrates that the potential of speed differentiation has been diminished due to the global sulphur cap, and discusses the views of shipowner vs ship operator in the sulphur abatement decision. The paper concludes with a discussion of the main findings, and suggestions for further research.

2. Methodology

2.1 Fuel consumption

In the absence of a comprehensive, systematic and reliable source of open data on shipping emissions, models are required to translate estimated fuel consumption into emissions. There are various approaches used in the literature, for example Le et al. (2020) note that bottom-up approaches are useful when there are ship-specific data (fuel consumption rates for main and auxiliary engines), and in their absence they provide fuel consumption per containership class using a regression model to do so. We use an activity based methodology where fuel consumption and associated emissions of individual ships are estimated based on their complete transport activity and technical specifications. A voyage is broken down into four distinct activities: sailing (*S*), anchorage (*N*), manoeuvring (*M*) and at-berth (*B*). Fuel consumed during each activity is the summation of all active engines on-board.

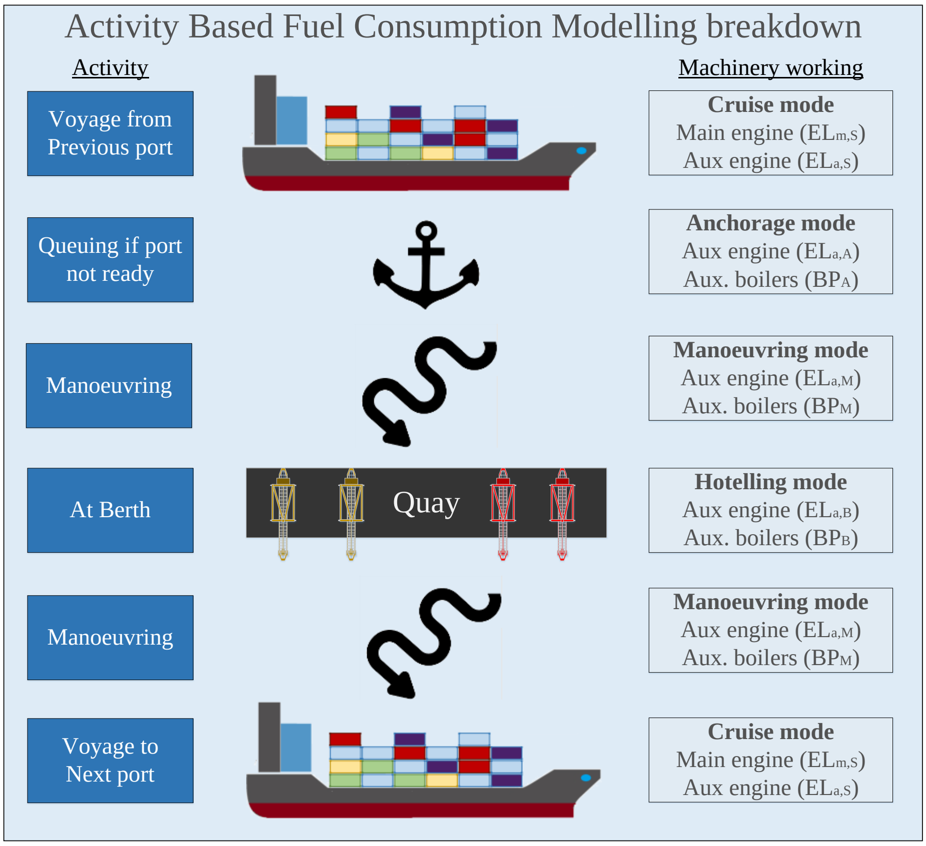

Figure 2: The different activity phases during a voyage and the machinery operating during each activity

These include the main engines (*m*) that propel the ship, the auxiliary engines (*a*) covering electricity, ventilation and hoteling energy demands for the vessel, and lastly, the boilers (*b*) that operate when the main engines are not working to maintain fuel and engine cylinder temperatures. The fuel consumption $FC_{e,A}$ (kg of fuel) of any marine engine $e \in \{m, a, b\}$ during activity phase $A \in S, N, M, B$ is calculated by equation 1:

$$FC_{e,A} = 10^{-3} \cdot SFOC_{e,A} \cdot EL_{e,A} \cdot EP_e \cdot t_A \tag{1}$$

SFOC denotes the Specific Fuel Oil Consumption (g/kWh) of the engine, *EL* (%) is dimensionless and expresses the percentage output of the engine compared to its maximum continuous rating (MCR), *EP*(kW) is the nominal installed power of the engine, and t_A represents the time (hours) of activity *A*. The *SFOC* is a measure of efficiency of the engine and is a function of *EL*. The fuel consumption of the main engines propelling the vessel is governed by the sailing speed. The resistance of a ship during sailing is roughly proportional to the square of the ship's speed (Bernoulli's law) and, as a result, the power (speed times resistance) requirement follows the cube of speed. This so-called "propeller law" has been used widely in research to model the effects of slow steaming on emissions or costs (Cariou, 2011). It is shown in equation 2 for two sailing speeds V_{S1} and V_{S2}, and their respective engine loads.

$$\frac{EL_{m1}}{EL_{m2}} = \left(\frac{V_{S1}}{V_{S2}}\right)^n \tag{2}$$

In calm water and for low sailing speeds, the exponent *n* is approximately 3. Often, a higher value for *n* is used to account also for the effects of weather. The boilers are operating with constant loads *BP* (kW), during manoeuvring and at berth.

2.2 Scrubber power demands and additional costs

There are different types of scrubbers: dry scrubbers that do not require the use of water to treat exhaust gases, but are rarely used in marine operations and wet scrubbers that are further classified into open-loop, closed-loop and hybrid. Open-loop scrubbers use seawater that needs to be alkaline to succeed in removing SO_x. These are bound by the geographical territories where the ship operates. Closed-loop scrubbers do not have such restrictions, as they use water that has been treated with sodium hydroxide. This needs to be stored in tanks and subsequently discharged in appropriate shore reception facilities. Capital investment costs vary depending on the technology, ship type, and engine size. Den Boer and Hoen (2015) reported installation costs of 200-400€ per kW of installed power (equivalent to 235-470$ per kW). As the technology matures the costs will become lower, and for larger installations, economies of scale can be expected. DNV GL (2018) reported that the additional cost to install a scrubber for a new 19,000 TEU containership would be around $10 million. Retrofits on an existing ship would be more costly. Operating a scrubber requires energy and this increases fuel consumption during voyage. Hansen (2012) conducted a technical analysis of one of the first (and at the time, largest) hybrid scrubbers installed on a Ro-Ro ship. The author estimated that the scrubber with seawater would increase fuel consumption by 1.4%, while when using fresh water an additional 2% should be attributed to the energy required for the production of sodium hydroxide.

2.3 Emission factors

Emissions are estimated by multiplying the fuel consumption of each engine with appropriate emission factors. We focus solely on CO_2 and SO_x emissions. The respective emission factors depend on the carbon and sulphur content of the fuel. Table 1 presents the factors we use for CO_2 and SO_x in the ensuing analysis. These are based on the third and fourth IMO GHG studies (Smith et al., 2014).

Table 1: Fuel specific emission factors for the different fuel types

Fuel	**Emission Factor (g/g fuel)**	
	CO_2	***SO_x***
HFO (3.5%)	3.114	0.07
MGO (0.1%)	3.206	0.002
ULSFO (0.1%)	3.151	0.002
Blended HFO (0.5%)	3.195	0.01

3. Case studies

In this section, illustrative case studies from various shipping sectors are developed. We briefly present key aspects of each service, before analysing their environmental and economic performances. The objective is to understand how the compliance option decided upon by ship operators affects their economic performance, and what are the environmental ramifications for each. CO_2 and SO_x emissions for the various key stages of the sulphur limits are compared on an absolute level. For each ship, the use of compliant fuel is compared with a scrubber on this basis and the economic value of the scrubber investment is estimated. We use the following assumptions:

- When a scrubber is used, it only treats exhaust gases from main engines.
- The additional fuel consumption due to the scrubber is assumed to be 3%
- When low-sulphur fuel is used, all ships are using the maximum allowed content fuel
- Auxiliary engines and boilers always use 0.1% sulphur content fuel (MGO)
- Each year the vessels are operated for up to 345 days, to allow some time off for maintenance.
- The impacts of weather and other environmental factors are not considered.
- CO_2 emissions due to further refining in low-sulphur fuel production are not considered
- Other emissions are not considered (e.g. PM emissions would be lower with scrubbers or MGO).

We have selected six representative ships and services. These include two containerships in important trade routes (Far East – EU, transpacific), two short-sea shipping Ro-Ro services (one fully inside a SECA, one fully outside), a cruise ship, and a tanker in the spot market. All data are from real routes and ships, based on schedules during 2019. The selection criteria for the case studies included a good geographical balance, representative ship types and sizes, and data availability on the technical specifications and service plans. Table 2 presents their key technical specifications.

Table 2: Technical specifications of the examined ships. Data source: Clarkson's Research

Ship	**Service**	**Capacity**	**Year**	**Design Speed**	**Main Engine Power (kW)**	**SFOC at 85%MCR (g/kWh)**	**Aux. Engine Power (kW)**	**SFOC Aux. (g/kWh)**	**EL Aux (cruise)**	**EL Aux port**
ULCV	**EU-Far East**	**15500 TEU**	**2007**	**25**	**80000**	**173**	**20800**	**177**	**15%**	**13%**
Post-Panamax	**Transpacific**	**10000 TEU**	**2016**	**23**	**72198**	**166**	**13500**	**210**	**17%**	**11%**
Ro-Ro	**North/Baltic Sea**	**3800 lm**	**2003**	**22.5**	**20070**	**192**	**6520**	**220**	**13%**	**18%**
Ro-Ro	**Mediterranean**	**4600 lm**	**2008**	**21.5**	**16200**	**181**	**3600**	**220**	**10%**	**27%**
Cruiseship	**Mixture**	**3500 passengers**	**2007**	**22.9**	**50400**	**173**	**12600**	**185**	**65%**	**65%**
Tanker	**Transatlantic**	**250000 dwt**	**2000**	**14**	**27160**	**197**	**4500**	**220**	**20%**	**70%**

3.1 Containerships

Before 2020, containerships would typically switch fuel when entering SECAs and, in an effort to further minimize their fuel costs, would choose where to enter the SECA and at what speed. Anticipating the global cap, containership owners started investing in scrubbers, as the 0.5% limit would affect all international voyages (Baker, 2019). Scrubber-equipped vessels could speed up on their longer legs (e.g. transoceanic) and complete the roundtrip in a shorter time. This could result in a potentially smaller fleet deployment as the faster vessels could perform the same transport work over a set period time (more trips per year). The first vessel we examine is the Ultra Large Container Vessel (ULCV) from Table 2. Table 3 provides data on the full rotation lasting 83 days. Speeds are based on the published schedule and port to port distances. We assume a manoeuvring time of 30 minutes during arrival and departure; although there may be deviations across ports.

Table 3: The full rotation schedule of the ULCV on the Europe – Far East service

Origin	Destination	Sea Distance (NM)	Average speed (Knots)	Berth hours at Destination
Tangier	Suez Canal	2015	19.5	NA
Suez Canal	Suez Canal	120	14.4	NA
Suez Canal	Salalah	1908	17.2	19.45
Salalah	Abu Dhabi	1030	11.8	30.28
Abu Dhabi	Jebel Ali	64	12.5	36.42
Jebel Ali	Ningbo	5547	15.1	44.92
Ningbo	Shanghai	54	1.4	25.25
Shanghai	Nansha	739	15.9	17.00
Nansha	Yantian	54	3.4	19.78
Yantian	Tanjung Pelepas	1475	19.5	20.60
Tanjung Pelepas	Suez Canal	4915	16.6	0.02
Suez Canal	Suez Canal	120	14.6	0.33
Suez Canal	Tangier	2024	16.8	26.27
Tangier	Rotterdam	1397	17.6	20.08
Rotterdam	Hamburg	305	12.0	50.53
Hamburg	Antwerp	397	8.5	46.70
Antwerp	London	190	8.6	25.82
London	Le Havre	220	9.7	14.32
Le Havre	Tangier	1215	16.9	16.15
Full Rotation	**Sailing hours: 1569.2**	**23751**	**15.3**	**413.95**

Table 3 reveals a wide variation in sailing speeds between each leg of the rotation. This may be attributed to commercial reasons (freight rates or utilisation are higher in some legs), ocean currents, or merely to the network design. Sailing speed within SECAs is generally lower, although this may not only be due to the fuel price differential. The legs Ningbo-Shanghai and Nansha-Yantian are very short, and we anticipate that there must be some anchorage time taking place during these legs. The full rotation takes place within SECAs for 7.37% of the total sailing distance.

The second case study concerns a Post-Panamax with a carrying capacity of just over 10,000 TEU. The vessel is deployed on a weekly service that connects the Far East with South America, operating entirely outside SECAs. The full rotation shown in Table 4, requires 77 days with 14 port calls.

Table 4: The full rotation schedule of the transpacific service

Origin	Destination	Sea Distance (NM)	Average speed (Knots)	Berth hours at Destination
Keelung	Yantian	469	9.9	9.90
Yantian	Hong Kong	54	2.6	16.05
Hong Kong	Shanghai	841	9.6	10.85
Shanghai	Ningbo	152	15.5	15.25
Ningbo	Busan	505	14.8	7.92
Busan	Manzanillo	6385	17.9	35.93
Manzanillo	Lazaro Cardenas	140	5.9	23.23
Lazaro Cardenas	Callao	2329	13.1	16.93
Callao	Iquique	660	15.0	23.75
Iquique	Antofagasta	226	5.5	29.87
Antofagasta	Valparaiso	577	17.1	34.30
Valparaiso	Coronel	275	11.7	18.78
Coronel	Valparaiso	275	16.5	35.00
Valparaiso	Keelung	10018	16.3	24.03
Full Rotation	**Sailing hours: 1547.9**	**22906**	**15.5**	**301.8**

Significant variation is seen in the sailing speeds across different legs that relates to the length of the leg. For the transpacific legs, speeds are higher. The speed on the Busan to Manzanillo leg is 17.9 knots, while on the Valparaiso to Taiwan leg it is 16.3 knots.

3.2 Short Sea Shipping Routes

Two relatively fast services are examined; one fully within a SECA, and one non-SECA. The first Ro-Ro vessel connects Belgium and Sweden, with two return trips each week. The service deploys three vessels in order to offer six sailings each week in each direction with a sailing speed of 18 knots. The route is completely within the Baltic and North Sea SECA. Therefore, the global cap has no direct effect on this service, and may only indirectly affect it through its impact on low-sulphur fuel prices. The second Ro-Ro vessel connects Turkey and Italy, with one return trip each week. The service offers six sailings per week, and six vessels are deployed on the route sailing with an average speed of 19 knots. The route is entirely outside SECAs.

3.3 Cruise ship

SECA limits had primarily affected cruise ships that spent part of their time calling at North American, US Caribbean and Baltic ports, and especially itineraries visiting the Hawaiian Islands. Following the global cap, all cruises are affected by the stricter sulphur requirement. Cruise ships operate throughout the year, taking advantage of the different seasons, spending different parts of the year in different areas. Sailing speed is dictated by their itinerary and, typically, cruise ships arrive at a port early in the morning and depart late in the afternoon, to allow passengers to visit tourist attractions. As such, sailing speeds vary significantly in different legs. Considering SECAs, cruise ships that are fuel switching could theoretically have a minor benefit from speed optimization (faster outside, slower inside), but this is unlikely in practice with passengers aboard.

We focus on a cruise ship spending part of its time serving the Hawaiian islands and the West Coast of North America (November to April). Then, the ship moves through the Panama Canal, with additional stops in Colombia, before traversing the Atlantic Ocean for calls in the Azores, Canary Islands and Morocco. The ship spends May to October in the Mediterranean Sea, before moving back to the Pacific Ocean via the Panama Canal. It is within SECAs for 12.4% of its annual sailing distance. Table 5 presents key data for a full year of operation.

Table 5: The main areas of operation of the cruise ship in a calendar year (based on 2019 schedules)

Period	Main Geography Area	Port Calls	Cruise hours	Sea Distance (NM)	SECA (NM)	Average speed (knots)	Berth hours
January - March	California, Baja California, Hawaii	35	1686.25	29832	10001	18.1	377.25
April	British Columbia, California, Baja California, Nicaragua Costa Rica Panama Colombia Florida	14	868.25	8730	1487	10.2	146.25
May	Azores, Canary islands Morocco, Gibraltar	7	209	3075	0	15.2	81
May - October	Spain, France, Italy, Montenegro, Croatia, Greece	127	2512	40145	532	16.8	1499
November	Morocco, Canary islands, Azores, Florida	6	314	5669	91	18.4	60
November - December	Florida, Panama, Costa Rica, Nicaragua, Colombia, Baja California	23	773	12626	338	16.8	243
Full Year Operation		**212**	**6362.5**	**100077**	**12449**	**16.3**	**2406.5**

Sailing speeds when on an active cruise period are usually around 16 to 18 knots. Speeds are lower when the ship is crossing the Atlantic Ocean to change season. It may be increased up to 21 knots (for example, legs that need to be completed during one night) while in other legs speed can be as low as 10 knots. This wide variation in speeds has an important impact on the total fuel consumption.

3.4 Tanker ship in the spot market

In stark contrast to all the previous cases, bulk carriers tend to operate in the spot market with no predetermined schedules. These ships tend to increase their sailing speeds when cargo freight rates are high or when fuel costs are very low (or combinations thereof). Frequently, these ships are chartered in and are not owned by the operators. Theoretically, the charterer/operator should use the ship as much as possible during the charter period (by sailing at high speeds) and, if given the option, is likely to prefer to charter a vessel equipped with a scrubber to reduce fuel costs. That means that the charterer/operator would pay a higher charter rate, but could sail faster complete more trips, and increase their revenue during the charter period. Significant distortions in the charter market appeared during the first half of 2020 as a combined result of the global cap, the outbreak of the COVID-19 pandemic, and the severe drop in fuel prices. In January 2020 a Very Large Crude Carrier (VLCC) charter rate was reported to attract a premium of $4000 to $5000 per day where a scrubber is installed[1]. However, this unprecedented situation has several additional complexities. For example, several VLCCs were used as storage for fuel due to the negative oil prices which led to extreme increases in charter rates. In our case study, we focus on the impacts of the global cap on these ships without considering the effects of the pandemic. We examine a VLCC operating between Russia and Venezuela throughout its time charter. We consider a ballast speed of 13 knots and a laden speed of 13.5 knots for a 40 day duration roundtrip, the ship is within a SECA for 25.3% of its sailing distance.

In the bulk trades, there is typically a speed difference between the ballast and laden legs of a voyage, the extent of which depends on the prevailing fuel price and freight market conditions. The optimal sailing speed in ballast and laden is affected by both the prevailing fuel prices and freight rates. It is beyond the scope of this paper to optimize speed for profit maximization, but we will make some observations. Lindstad and Eskeland (2015) noted that operators tend to sail as fast as possible

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[1]

without regard to speed optimization at very low fuel prices. They estimate that the cost minimizing speeds would be 1.5 to 2 knots lower for laden legs compared to ballast, due to the lesser resistance in the latter. The World Fleet Register provides sea trial data for several vessels, suggesting that the laden speed is typically 1 knot lower than the ballast speed. In reality, ships do not regularly sail on calm waters (as in sea trials), so the 1.5 to 2 knots estimate from Lindstad and Eskeland (2015) seems appropriate. However, there are occasions when the opposite relationship (i.e. higher laden speed) maximizes profit (Gkonis and Psaraftis, 2012; Adland and Jia, 2016).

4. Environmental analysis

We estimate the annual emissions assuming that the ships are deployed for one year on their respective services from section 3. Figure 3 presents the annual CO_2 and SO_x emissions for the examined six ships, to facilitate comparisons across the different ship types. The emissions are calculated for different abatement options (scrubber vs low-sulphur fuel) and regulation requirements (no limits, SECA only at 0.1%, global cap at 0.5% outside SECAs). The first observation is that the cruise ship has the highest emissions per year, followed by the tanker and ULCV that are at a similar level. This can be explained by the respective ship sizes, and the fact that the cruise ship and ULCV show an important variation of sailing speeds across different legs. The least emissions come from the much smaller Ro-Ro vessels. We compare the individual ships, and not the associated services that may require a higher number of vessels.

We do not focus on which abatement option is better in terms of sulphur reduction, although it is obvious that the stricter sulphur limits have led to significant reductions in SO_x emissions. The lowest SOx emissions are occurring when a scrubber is installed, but significant reductions are observed in non-retrofitted vessels. The global cap had a major impact on ships that were sailing mostly outside SECAs before. This is depicted by the relative difference of the dashed and the dark-red barcharts. It is bigger for the ULCV (which spent relatively less time within SECAs) and lower for the tanker

What is more interesting is the environmental penalty in terms of additional GHG (in this case CO_2) emissions, given the commitment of the IMO to reduce GHG emissions. For all ships and all sulphur restrictions, CO_2 emissions are slightly higher as a result of using low-sulphur fuel, or from the additional energy required to operate the scrubber. The highest CO_2 emissions are observed when a scrubber is working throughout the rotation.

The global cap had no additional effect on the first Ro-Ro vessel (3c) that was already affected by the strictest possible limit of 0.1%. The other Ro-Ro vessel (3d) is compared when using a scrubber or relying on VLSFO with 0.5% sulphur content. It has slightly higher CO_2 emissions as it sails slightly faster and SOx emissions when fuel switching are higher due to the different limit. The cruise ship (3e) sees a small increase in CO_2 emissions for both compliance methods. This is smaller than in the case of other ship types, which can be attributed to the larger share of the auxiliary engines' and boilers' fuel consumption (running on low-sulphur fuel) for this shipping sector. We can also see that the global cap had a bigger impact on SO_x emissions for the ULCV compared to the other ships, as only 7.37% of the total year was spent within SECAs.

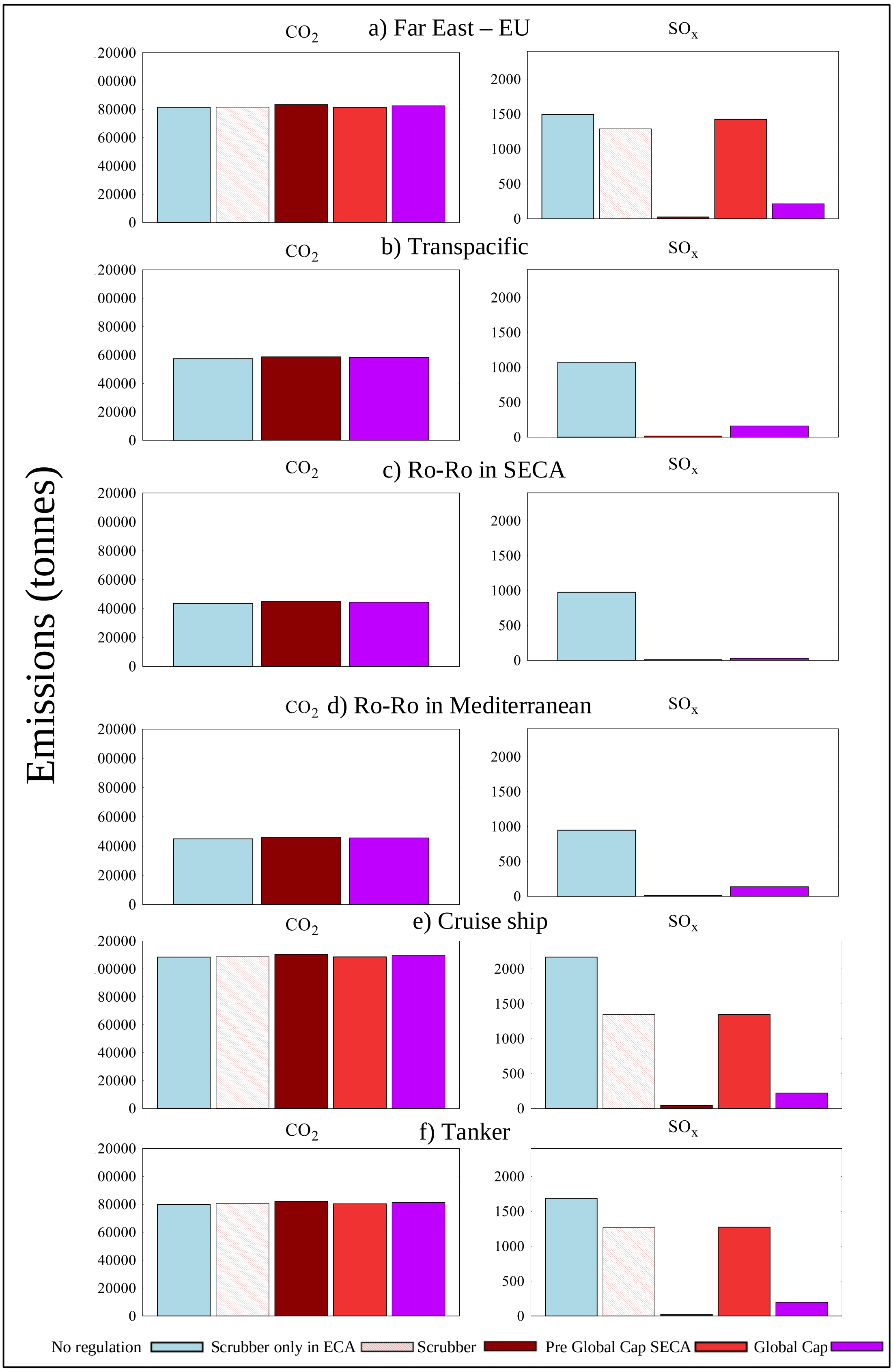

Figure 3: Annual CO_2 and SO_x emissions for the examined ships for different sulphur requirements and abatement options

5. Economic analysis

Capital investment costs of scrubbers and the fuel price differential between regular and low-sulphur fuels dictates which abatement option is economically superior. In this section, we compare the effects of sulphur regulations on the annual fuel costs for the six ships. We use three different fuel price scenarios (low, medium, and high) that represent the quartiles of the last ten years of prices.

5.1 Impacts of sulphur regulations on fuel costs

Figure 4 presents the annual fuel costs for the examined ships in their respective services, for the different abatement options and fuel prices. We compare with a baseline case with no sulphur limits.

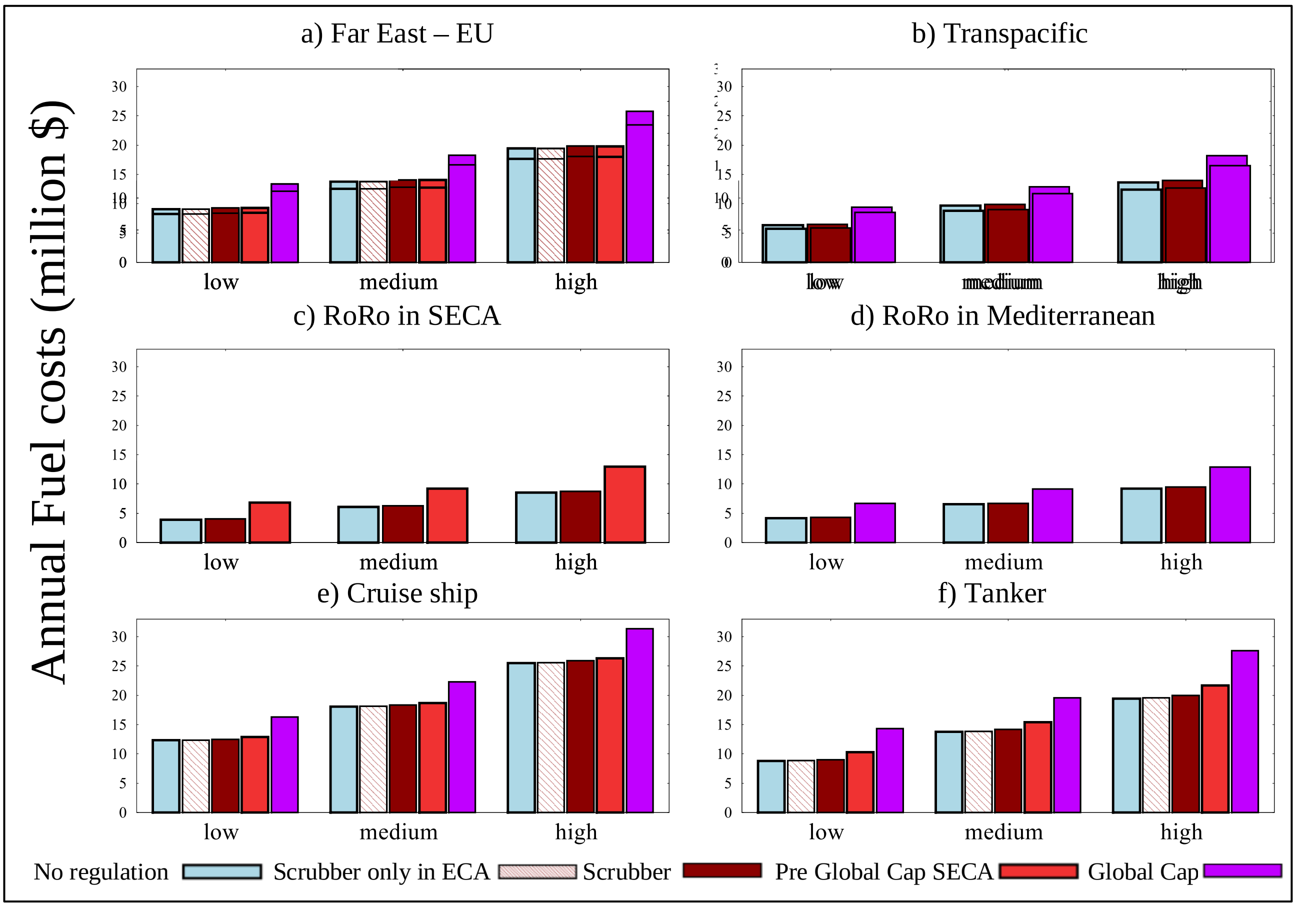

Figure 4: Comparison of annual fuel costs for examined ships for different abatement options and fuel prices

The relative difference between the purple bars (fuel switching under a global cap) and the dark-red bars (scrubbers) changes significantly with different fuel prices. Scrubbers are a better option when this difference is growing (this is the case for high fuel prices, and for ships spending a larger part of their time at-sea than at-port). For the containerships (Figure 4a, 4b), the difference in fuel costs is significant following the introduction of the global sulphur cap. The previous era (0.1% in SECAs, 3.5% outside) would have an almost negligible impact on the fuel costs compared to the hypothetical absence of any sulphur limits. For the EU-Far East service the fuel savings from using a scrubber would be very small and fuel switching would be preferable before the global cap, as only a very small fraction of the service was within ECAs.

For the SSS services, (4c-d) operating costs increased substantially with fuel switching. The SECA service was severely affected since 2015, whereas the Mediterranean service was unaffected until 2020. This leveled the playing field in comparison with other SSS operators already operating with very low-sulphur fuel within SECAs. The cost of fuel switching is lower for operators outside SECAs and, therefore, the scrubber investment would be slightly less attractive compared to vessels operating fully within a SECA. For the cruiseship (4e) we can observe that fuel costs increased substantially with the introduction of the global cap (20% for the low and high fuel price scenarios, 26.7% for the medium). The previous era led to a much smaller increase in the fuel costs for cruise ship operators.

5.2 Payback period analysis for scrubbers

This section summarizes the economic implications of a scrubber investment for each ship type, by calculating their payback period. This is defined as the necessary time to reach the break-even point when the net present value (NPV) of the investment is zero. Therefore, the scrubber is profitable when the payback period is smaller than its expected lifetime. The NPV represents the summation of all cash flows over a period of time, discounted back to the present. The NPV^i of investment i is:

$$NPV^i = CAPEX^i + \sum_{t=0}^{N} \frac{B_t^i - OPEX_t^i}{(1+r)^t} \tag{3}$$

where $CAPEX^i$ is the capital investment costs of the investment, $OPEX_t^i$ are the operating and maintenance expenses in period t, and r is the discount rate. B_t^i indicates the annual benefits of option i, that may involve social costs and benefits as a result of differences in emissions generated. We assume that vessels sailing on transoceanic legs and operating in different geographical areas, are equipped with more expensive hybrid scrubbers, while the SSS vessels use a lower-cost technology.

The results are shown in Table 6. Here we present what the payback period would be, if the decision maker opts to invest in a scrubber considering only the sulphur limit (before and after the global cap), and the average fuel price in any given year from 2010 to 2020. We used the highest possible investment costs for scrubbers in order to produce a more conservative estimate. The payback period for different policy tiers (before and after the global cap) are also shown. We do not consider weather effects which increase the fuel consumption and operating costs. Similarly, our assumption that each vessel operates 345 days (including port time) may not necessarily be true for other ships, which can have shorter sailing times over the year. For a lower period of operation, the payback period of the scrubber investment would increase. Additional sensitivity analyses on the effects of weather and active time can be performed. In order to conduct this in detail, weather data, real voyage fuel consumption data, and full itineraries for a longer period of time would be necessary.

Table 6 presents a significant variation in the payback period that depends on the prevailing fuel prices at the time. The payback period is reduced as the regulation becomes stricter with the global cap. Across the different ships examined, it is lower for the smaller Ro-Ro vessels as the capital cost is lower for these ships. We can also observe that the lowest payback period (across each column) is for the fuel prices of 2014, when fuel prices were very high, and the price differential was also relatively higher. With the exception of the Ro-Ro services that were operating fully in SECAs, scrubbers in the pre-global cap era would not return their capital investment. We mark this by writing "Not possible" in Table 6. In reality, a payback period that exceeds the remaining lifetime of the vessel, is also an indication that the investment in a scrubber is not worthwhile. Table 6 explains why containership owners would invest in scrubbers in anticipation of the global sulphur cap. For most prices, the payback period would be less than 10 years and this would make the scrubber investment sensible. However, in 2020 with the very low fuel prices in conjunction with the COVID-19 impacts on trade and crude oil prices, the payback period has been significantly increased to almost 20 years. Therefore, a scrubber investment is not advised if fuel prices remain at these low levels.

During the ongoing pandemic, several cruises were cancelled, which was worse for ship operators that invested in scrubbers in preparation for the global cap. Regarding the tanker case, this will actually depend on the premium on the charter rate. In Table 6, a low premium of $3000 per day and a high premium of $6000 were used. In reality, these premiums will change depending on the fuel price differentials. For newbuilds, the cost of installing a scrubber is smaller than for retrofits and, therefore, in most cases it would make sense to install a scrubber. A scrubber installation would require some space on the ship that would slightly reduce the carrying capacity of the vessel and the revenue per voyage, which can be perceived as a cost. This, as well as the vessel lay-up time for the installation (minimum of 2 weeks), has not been included in the calculation.

Table 6: Payback period of a scrubber retrofit for the examined ships

Payback period (years)								
Ship	ULCV (Europe - Far East)		Post-Panamax (transpacific)	Ro-Ro (SECA)	Ro-Ro Mediterranean	Tanker (Spot Market, owner's perspective)	Cruiseship	
Fuel prices	Only SECA	Global Cap	Global Cap	SECA	Global Cap	Global Cap	Only SECA	Global Cap
2010	Not possible	7.6	7.5	2.8	2.5	4.3-8 years depending on premium and not the fuel prices	79	4.4
2011		5.6	5.5	1.2	1.0		24	3.4
2012		5.4	5.3	1.2	2.9		25	3.3
2013		5.4	5.3	1.2	2.9		26	3.3
2014		5.1	6.7	1.1	2.8		29	3.1
2015		7.2	7.2	2.7	2.5		45	4.2
2016		10.5	10.5	2.3	2.1		98	6.7
2017		10.5	10.3	2.3	2.0		Not possible	6.6
2018		10.1	11.3	2.2	3.7			6.3
2019		13.2	14.1	3.6	3.3			8.5
2020		19.3	20.2	4.7	4.4			10.2

6. Speed optimization, and roles of charterer vs shipowner

In the early 2010s, certain shipping sectors (most notably liner shipping and tankers) started significantly lowering sailing speeds due to the high fuel prices. Notteboom and Vernimmen (2009) examined the impacts of high fuel costs on liner shipping, considering ships sailing at 24 knots. In 2011 Maersk announced its order of the so-called triple-E class ships, which had increased capacities (up to 18,000 TEUs) and a design speed of only 19 knots. Reduced sailing speeds were also evidenced by the reduction in estimated CO_2 emissions from maritime shipping between the second and third IMO GHG studies (Smith et al., 2014). One impact of sulphur limits on shipping was the resurfacing of speed optimization for voyages with legs that have different sulphur requirements (Patricksson and Erikstad, 2017), while also the optimal point of entry into a SECA was investigated (Fagerholt and Psaraftis, 2015). This differentiation in speed would only be possible for services with legs partially within ECAs. It is apparent that with higher fuel price differentials, the difference in sailing speeds inside and outside SECAs increases as well as the environmental penalty in CO_2 emissions. With the global cap, the potential for fuel savings through speed differentiation is diminished. We will show this for two of the previous case studies (EU – Far East, tanker) that have legs requiring fuel switching (entering/exiting a SECA). Two scenarios are considered; one prior and one after the global cap.

6.1 The potential of speed differentiation

When fuel switching is implemented on the same leg, sailing speed can be different in the portion of the leg outside (faster) and inside (slower) the ECA to minimize fuel costs. Table 7 summarizes the optimal speeds, the resulting fuel cost savings and the additional emissions for different fuel price combinations, and for 3.5% and 0.5% sulphur limits outside the ECA (pre and post global cap).

Table 7: Economic and environmental impacts of speed optimization in legs with segments in and out of SECAs

Ship and Leg	Fuel Price Scenario	Sailing Speed (knots)					Trade-offs from Speed Differentiation					
		Original	Pre Global Cap		Post Global Cap		Pre Global Cap			Post Global Cap		
			Inside ECA	Outside ECA	Inside ECA	Outside ECA	Fuel Savings	Extra CO_2	Extra SO_x	Fuel Savings	Extra CO_2	Extra SO_x
ULCV Morocco – Rotterdam	Low	17.61	16.3	18.23	17.38	17.7	2365	7.24	1.19	31	0.20	0.02
	Medium		16.45	18.16	17.45	17.68	1988	5.58	1.05	25	0.11	0.02
	High		16.32	18.22	17.44	17.68	2913	7	1.18	36	0.11	0.02
ULCV Le Havre – Morocco	Low	16.85	15.42	17.23	16.62	16.91	1378	4.15	0.69	18.5	0.11	0.01
	Medium		15.56	17.19	16.67	16.9	1167	3.28	0.62	14.9	0.07	0.01
	High		15.43	17.23	16.67	16.9	1706	4.08	0.69	20.9	0.07	0.01
Tanker (ballast) Venezuela – Russia	Low	13.5	11.73	14.23	13.33	13.56	9292	73.33	7.08	102	0.59	0.07
	Medium		12.19	14	13.36	13.55	7010	36.66	4.88	82	0.36	0.05
	High		12.2	14	13.36	13.55	9855	36.43	4.87	115	0.37	-0.05
Tanker (laden) Russia – Venezuela	Low	13	11.3	13.7	13.06	12.83	11144	87.63	8.48	123	0.76	0.08
	Medium		11.75	13.49	13.05	12.87	8407	43.73	5.84	98	0.45	0.06
	High		11.75	13.48	13.04	12.87	11819	43.52	5.82	138	0.42	0.06

The fuel price scenarios are as follows ($/ton):
Low – (HFO 263, MGO 471, 0.5% VLSFO 447), Medium – (HFO 421, MGO 639, 0.5% VLSFO 613), High – (HFO 595, MGO 900, 0.5% VLSFO 864)

We can observe that the speed differential depends more on the relative fuel price differential between low-sulphur and regular fuel; the higher the relative differential, the greater the potential for speed differentiation. Before the global cap and for high fuel prices, the speed difference between sailing in the SECA and outside was substantial at around 2 knots. For the tanker case, as expected, the speed differential was larger for the laden leg. Considering the full return voyage, speed optimization would result in some savings, with a maximum value of $21700 per rotation. The environmental penalty would at maximum be around 170 tons of CO_2, and a small increase in global SO_x emissions as well. It is apparent that with the global sulphur cap, the potential of speed optimization is negligible, due to the very small price differential between fuel with 0.1% and 0.5% sulphur content.

6.2 The perspectives of the shipowner and the charterer

A ship that has a scrubber has a competitive advantage and the charterer benefits from the lower fuel costs to sail faster. We examine the trade-off between spot charter rates and fuel cost savings in this section. The decision on whether to retrofit a ship with a scrubber is up to the shipowner, but influenced by the attitudes and actions of players in the charter market. An operator under a time charter is responsible for the fuel costs and decides the sailing speed on each voyage. The investment in a scrubber will make sense to the shipowner if the charter rate is higher. The operator then decides whether the additional premium for the retrofitted vessel is lower than the fuel savings, or the additional revenue from completing more voyages in the same period. For the reported premiums of $4-5,000, the payback period for the owner would vary between 5 and 6 years and would be independent of fuel prices. In reality, the value of the premium will depend on the fuel price differential and would be adjusted accordingly, but this mechanism is beyond the scope of this paper. Table 8 shows the results of this analysis.

Table 8: Ship operator benefit from chartering a retrofitted vessel to either sail faster, or reduce operating costs.

	Sail at same speed, save operating costs		Sail faster, same operating costs	
Fuel Prices	Annual savings from scrubber (million $)	Additional cost of chartering (million $)	Voyage duration (baseline 39.7 days)	Trips per year (baseline 8.56)
2010	4.7	1.36-1.7	35.6	9.54
2011	6.54		35.2	9.67
2012	6.23		35.5	9.57
2013	6.18		35.3	9.63
2014	5.73		35.3	9.64
2015	4.44		34	10.01
2016	3.43		34.7	9.81
2017	3.37		36	9.43
2018	3.11		36.9	9.22
2019	2.53		37.5	9.07
2020	2		37.9	8.98

Two cases are considered. In the first, the ship operator does not increase speed with the retrofitted vessel and enjoys the financial benefit of greater fuel economy. In the second, the operator sails faster to perform more trips. For all fuel price combinations, the level of premium is very low and the ship operator would benefit from hiring a retrofitted vessel. If the operator opts to sail faster at the same operating costs (including the charter rate) then more trips are completed. A time charter of one year is assumed and for higher fuel price differentials between 0.1% and 0.5% sulphur content fuel, the ship operator could generate revenue from an increased number of voyages. If this revenue is higher than the charter premium, the operator would benefit from selecting this ship. Additional analyses for different bulk cargoes, trade routes (different ratios of legs inside/outside SECAs), and ship sizes would be interesting. Several optimization problems on the charter rate premium can be envisioned.

7. Conclusions

This paper analysed several representative case studies across the main shipping sectors to show the economic and environmental repercussions of sulphur regulation on each ship type. The results confirmed the significant increase in operating costs, for the examined abatement options. In environmental terms, the regulations have been successful in reducing sulphur emissions, particularly within SECAs since 2015, but the global cap will also result in further significant reductions. The environmental penalty for this reduction comes at a cost of additional CO_2 emissions, considering that low-sulphur fuel has a higher carbon content, and that scrubber systems require additional energy for their operation. Furthermore, the additional CO_2 emissions at the refineries for the production of low-sulphur fuel (Schuller et al. (2019) estimate 2-10% additional CO_2 emissions at refineries compared to regular HFO) or the additional energy (and costs) required for the treatment of scrubber residues at each port have not been considered in the calculations. Sulphur emissions have a climate cooling effect, which will be reduced following the global cap. Compliance options are likely to have an impact on other emissions to air or water. These are additional environmental trade-offs that are important, but lie beyond the scope of this paper. The decision on the most appropriate emissions reduction option depends on the fuel price differential between low-sulphur fuel, and the total operating time each year for every ship. For several ships, the payback period may be as low as 4 or 5 years. However, it needs to be borne in mind that the operator may have multiple ships in the same service and, therefore, capital investment costs to fully retrofit the fleet quickly grow. Future research could look further into the effects of using a scrubber on the optimal sailing speed for a voyage, as this paper has shown that, at least for the spot market and some containership services, the scope exists to reap potential benefits. As the technology of scrubbers matures, capital costs will be reduced, and reduce market demand for low-sulphur fuels, which can affect fuel price differentials.

We showed quantitatively that because of the global cap and the currently very low fuel price differential between fuel with 0.5% and 0.1% sulphur content, the practice of speed differentiation inside and outside SECAs currently does not have significant economic benefits. The paper has also shown the importance of distinguishing between ship owner and operator, particularly for tramp services, and further research could look into how ship owners that have invested in green technologies can earn a premium on spot rates. Modal shifts due to ECAs were an important concern, particularly for SSS. Modal shifts in newly affected SSS due to the global cap, as well as shifts from deep sea shipping to alternative modes (e.g. through One Belt One Road) are worthy of investigation.

While similar conclusions can be drawn from ships in different sectors, the stakeholders need to better understand what ships should be prioritized for each abatement option. Based on our findings and considering the increasing backlog of orders for scrubbers, we suggest that these should be prioritized for new-builds. Retrofits should target younger vessels that ideally spend relatively more time sailing than at port, and have a wider variation in sailing speeds. We propose the creation of new decision support systems to contrast and compare environmental solutions from the perspective of all stakeholders (ship owner, operator, and society), tailored to the unique characteristics of each market. These can be used to compare emissions reduction options to address the Initial IMO strategy goals.

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