

External costs of maritime shipping: A voyage-based methodology

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Abstract

This paper estimates the external costs of maritime shipping for individual voyages. A voyage-based model has been proposed, which geographically reflects the origin, destination and sea areas, technically reveals the voyage details and ship conditions, and economically distinguishes the external costs in various operation modes. The model enables a precise measurement of external costs and is applied for a case study with a container vessel travelling between Rotterdam and Gothenburg. Then the model application is extended to explore the costs and benefits of investing emission reduction technologies. The external cost model applied here will facilitate the decision-making in cost internalization, transport pricing and technology investment.

Keywords

External costs; Maritime transport; Shipping voyages; Cost-benefit analysis

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1. Introduction

Shipping carries almost 90% of world cargo annually and plays a vital role in the international trade and world economy (UNCTAD, 2011). Along with its significant contribution, shipping activities can and have already had harmful effects on society and the global environment. For instance, ship emissions contain a variety of air pollutants that may present a health hazard. With increased freight volumes being transported over longer distance, there is a growing awareness of environmental impacts caused by shipping (Vanherle and Delhaye, 2010). As a result, a number of international maritime regulations have been made to reduce ship emissions and to improve the environmental performance of new and existing ships (IMO, 2008).

From a welfare point of view, shipping has significant externalities, where environmental damages associated with the ship emission are borne not by the shipping companies but by the society (Pindyck and Rubinfeld, 2008). When these harmful emissions are not priced, the shipping price fails to properly account for the total social costs. It would lead to a failure in the shipping market. Similarly, if the emissions are not priced, there will be no incentive for shipping firms to deploy emission reduction technologies or mitigate the environmental externalities.

In order to correct this market failure and promote effective solutions, external costs of shipping need to be estimated. Such estimation could offer a precise insight for the environmental impacts of shipping. More importantly, it is a prerequisite to internalize external costs by developing instruments and transport policies (Essen et al., 2007). The next step is to identify the costs for achieving emission reductions. Once these numbers are generated, the cost-benefit analysis of reduction technologies, operational and market-based measures can be made prior to their implementation.

Although there is a burgeoning literature on ship emissions, external costs of shipping have not been adequately evaluated for their economic and policy importance. This paper aims to evaluate the environmental external costs of air pollutants and greenhouse gas from shipping. The evaluation is based on a bottom-up approach and followed by the cost-benefit analysis of scrubber technology. Most of the previous work focused on external cost estimation at global, national or regional scales, but little research has actually addressed the issue for shipping voyages. The current paper makes a contribution by proposing a voyage-based model for external

cost estimation, with a focus on Europe. It is based on a bottom-up approach and can reflect voyage details and ship specific parameters. The voyage is divided into three operational stages and external costs are estimated respectively. In this way, the model provides a voyage-specific estimation, which would facilitate the voyage choice and intermodal comparison in terms of green shipping and logistics. Given the range of measures available for reducing emissions from ships, there is a need for a consistent and rational framework for decision-making and selection of measures. Therefore, the Sea Water Scrubbing technology is illustrated and assessed from a cost-benefit perspective. The presented framework can be applied by individual ship owners, policymakers and regulators for decision-making.

The paper is organized as follows. Section 2 presents an intensive literature review, which covers the approaches for estimating external costs of transport and their maritime applications. Section 3 develops the voyage-based model of maritime external costs. The model is then applied for a typical container vessel traveling between Rotterdam and Gothenburg in Section 4. Costs and benefits of Sea Water Scrubbing technology are analyzed in Section 5. Conclusions are offered in Section 6.

2. Literature review

2.1. Approaches for estimating external costs of transport

Generally, there are two ways of estimating external costs of transport, i.e. bottom-up and top-down approaches. Bottom-up approach starts at the micro-level, where basic elements are first specified in details and then linked together to form a complete system. Hence, this approach is more precise with a potential for differentiation and is superior to derive marginal external costs¹ (Friedrich and Bickel, 2001; Miola et al., 2008). However, due to its complexity and completeness, bottom-up approach may be costly and difficult to implement. On the contrary, a top-down approach works with the macro-level. For instance, external costs of a country can be calculated and divided by the national transport volume, leading to the average external costs. This method is easier to manipulate, but fails to incorporate specific details (Bickel and Friedrich, 2005).

¹ The marginal external costs here refer to the costs caused by one additional pollutant unit to an already existing system.

The above approaches have been widely used in a number of studies, for instance ExternE, UNITE, CAFE, HEATCO, RECODIT, and GRACE (Bickel and Friedrich, 2005; Tervonen, et al., 2002; Nash, 2003; Holland et al., 2005; Bickel et al., 2006; Black et al., 2003; Nash et al., 2008). Despite their variations in model assumption, cost category, emission factor and input value, there is a wide consensus on the choice of methodology. For external costs of air pollution, Impact Pathway Analysis² (IPA, a bottom-up approach) is broadly acknowledged as the preferred approach. For external costs of climate change, the avoidance cost approach is regarded as the best practice in the short term (Maibach et al., 2008).

2.2 Applications of external cost approach in shipping

Maritime studies in general focus on the external costs of air pollution at global, national and regional levels (Endresen et al., 2003; Corbett and Fischbeck, 2000; Saxe and Larsen, 2004; Jalkanen et al., 2009; among others). There are two main steps involved. The first step is to compute the amount of ship emissions, which relies on either fleet activity-based or fuel-based methodologies³ (Tzannatos, 2010a). The second step is to calculate the total external costs by multiplying the amount of emission and the marginal external costs. Following such method, maritime applications can be roughly classified into three categories:

- External cost estimation for maritime cases
- External cost comparison between shipping and road transport
- Cost-benefit analysis of ship emission reduction technologies

The first category is mainly derived from the dense ship traffic and large population in the study areas. For example, Tzannatos (2010b) analyses the external costs for the passenger port of Piraeus (Greece), which is the largest and busiest cruise port in the Mediterranean. The results indicate that summer emissions from coastal passenger ships and cruise ships and their associated externalities are much more profound. Similarly, Berechman and Tseng (2012) investigate the issue for the port of Kaohsiung (Taiwan). It is found that tankers have the largest negative externalities, followed by container ships and bulk carriers. Kalli & Tapaninen (2008)

² Details of the method can be found at Friedrich and Bickel (2001) and Schmid et al. (2001).

³ Fleet activity-based methodology utilizes detailed information on ship movements (e.g. location and sailing distance) and ship categories (ship type, size and age, engine type, fuel type) in conjunction with corresponding fuel consumption figures and emission factors. The fuel-based approach combines data on marine fuel sales (fuel quantities and types) with fuel related emission factors (Tzannatos, 2010b).

calculate the air emission from ships in the Gulf of Finland until the year 2015. They predict the effects of international maritime regulation and increasing ship traffic on environmental externalities. This is a new perspective for research, as extant studies mostly focus on the current emissions and their impacts. However, the accuracy of these estimates is questionable when the emission amounts of other pollutants are based on the volume prediction of NO_x (Nitrogen Oxides). A more comprehensive analysis of maritime transport externalities has been made by Vanherle and Delhaye (2010). They not only consider three environmental impacts of shipping, namely marine pollution into the sea, air quality and climate change, but also make cost comparisons among various ships types. It shows that remarkable differences of external costs exist between bulk transport (0.3 Euro cent/t-km), container transport (0.5 Euro cent/t-km) and the Ro-Ro transport (3.2 Euro cent/t-km). Another detailed analysis made by Holland and Watkiss (2002) differentiates the ship emissions and their external costs based on the sailing distance from the port, i.e. port, close to shore and offshore areas.

The second research direction focus on comparing the short sea shipping (SSS) and road transport in terms of environmental external costs. Lee et al. (2010) provides a comparison between truck transport and SSS in Taiwan and find that SSS is a relatively environmental friendly mode. The paper also presents obstacles and policy instruments to promote the SSS in Taiwan. Denisis (2009) also justifies the superiority of intermodal short sea shipping in terms of lower external costs compared to the all-truck transportation. In addition, he argues that traditional top-down or bottom-up methodologies reveal the vagueness, imprecision, and subjectivity in estimation, because surveys and questionnaires are described with linguistic variables and words. Thus the fuzzy logic model is suggested to solve the problem, which can be handled in a rigorous but also simply way. This study contributes to the literature by providing a precise and site-specific estimation.

Thirdly, it is the cost-benefit analysis of emission reduction technologies, which is highly relevant for policy-making and investment decisions. Wang and Corbett (2007) provide a cost-benefit analysis for the sulphur emission control in the US west coast. The cost-benefit ratio varies between 1.8 and 3.36, depending on the size of the control area and the sulphur content limit. Sieber (2008) makes a similar calculation for a number of technical measures. All scenarios show that environmental benefits are at least double of costs, ranging between 2.3 and 5.4. Given that Humid Air Motor

technology is not widely used at that time, the author suggests that the low sulphur fuels combined with a Humid Air Motor is an appropriate solution. Its ratio is more than four and will reduce 70-80% of NO_x and SO₂ (Sulphur Dioxide) emissions.

3 Voyage-based model for maritime external costs

3.1 Model specification

This paper focuses on the external costs of air pollution and climate change, which are the most relevant environmental impacts of shipping. Generally, external costs are situation-specific and may vary from voyage to voyage and from ship to ship. We propose a voyage-based model, which reflects the detailed information of a round trip, such as ship type, operation condition, sailing distance and manoeuvring and berthing time at port. The model can be presented as below:

$$C_{ij} = E_{ij} \times MC_i \quad (1)$$

where i represents four types of ship emissions, including NO_x, SO₂, PM_{2.5} (Particulate Matter 2.5) and CO₂ (Carbon Dioxide). C_{ij} represents the external costs (Euro) of emission i from ship j ; E_{ij} represents the total amount (kg) of emission i from ship j ; MC_i represents the marginal external costs (Euro per kg) of emission i . The amount of ship emission and marginal external costs are introduced in the following content.

3.2 Amount of ship emission

The level of ship emission depends on such factors as the fuel consumption and the design, operation and maintenance of engines. When specifying the ship and fuel, the emission amount would rely on the operation of engines (Entec, 2005a). Therefore, a single voyage is divided into three stages according to vessel operation modes, namely free sailing, manoeuvring and berthing⁴. This differentiation will enable an accurate calculation of the total amount of ship emission. Although port emissions (during manoeuvring and berthing) are not significantly contributing to the overall picture of ship emissions, it is important to note its direct effects on the population

⁴ Manoeuvring refers to the slow speed movement of the ship between the port's breakwater (entry/exit) and point of berth, whereas berthing refers to the dockside mooring of the ship (Berechman and Tseng, 2012).

and environment of port cities. On the contrary, emissions during free sailing would cause less damaging effects on human health due to the sparse population. For the free sailing stage, the total amount of air emission i from ship j is:

$$E_{ij} = EF_{ij} \times D_j \quad (2)$$

where EF_{ij} is the emission factor (kg/nautical mile) under specific ship conditions; D_j is the sailing distance between origin and destination (nautical miles) of ship j . For the manoeuvring and berthing stages, ship still produces air emissions but sailing very limited distance. So, their emission amounts are expressed as follows:

$$E_{ij} = EF_{ij} \times T_j \quad (3)$$

where emission factor EF_{ij} is expressed in kg /hour and multiplied by the hours spent manoeuvring and berthing. Manoeuvring time is calculated as the distance between port entry/exit and berth point divided by vessel's average in-port speed plus an average docking/undocking time. Berthing time begins when a ship ties-up at a berth and ends when it leaves that berth, and this will differ by port and ship type (Tzannatos, 2010b). Ship emission factors is obtained from the technical model developed by Kristensen (2012), which is the most up to date and comprehensive study on emission of marine engines.

3.3 Marginal external costs

In this paper, the marginal external costs of air pollution are adopted from CAFE and HEATCO projects, which are based on the Impact Pathway Analysis and considered as the best practice values (Holland et al., 2005; Bickel et al., 2006; Maibach et al., 2008).

In CAFE, the marginal external costs are evaluated for 29 European countries based on four sensitivity combinations and thus are robust. Moreover, costs are also provided for four European regional seas, namely the Baltic Sea, Mediterranean Sea, North East Atlantic and North Sea. In contrast, the HEATCO project has no sensitivity test. However, it develops more detailed marginal external costs of $PM_{2.5}$

for urban, metropolitan and outside built-up regions ⁵. It is claimed that PM_{2.5} exposure is highly associated with the site of release, where other pollutants have less local effects and national values would be adequate (Maibach et al., 2008). To combine the advantage of these two projects, this paper adopts the marginal external costs of PM_{2.5} from HEATCO, and the costs of NO_x and SO₂ from CAFE (Table 1). In this way, the damaging effects of PM_{2.5} in the port area can also be highlighted in term of costs. The costs in year 2000 prices are converted to the 2010 costs.

Table 1
Marginal external costs of air pollutants for a shipping voyage.

	NO _x	SO ₂	PM _{2.5}
Manoeuvring	National value	National value	Urban/Metropolitan/Outside built-up area value
Berthing	National value	National value	Urban/Metropolitan/ Outside built-up area value
Free sailing	Sea value	Sea value	Sea value
Data source	CAFE	CAFE	HEATCO

Source: authors' self-summary

As climate change has a global-scale impact, it does not matter where the emission of CO₂ takes place (Maibach et al., 2008). The climate change costs vary significantly with the emission reduction target, application year, discount rate and equity weights. For this reason, the central values for external costs of climate change (25 Euro/ton CO₂, 2010 costs) have been taken from the report by Maibach et al. (2008) and applied for all countries.

4 Case study

It is now possible to apply the external cost model in a case study. A 5000 Twenty-foot Equivalent Units (TEU) container ship sailing between Rotterdam and Gothenburg has been selected (through North Sea, see Fig. 1). The round trip is approximately 1000 nautical miles (nm). The vessel does not adopt any emission

⁵ Urban is defined as smaller and mid-sized cities with up to 0.5 million inhabitants. Cities with more than 0.5 million inhabitants are regarded as Metropolitan. Others are rural areas.

reduction technology yet and the capacity utilization is assumed to be 70%. The speed is set at 24.9 knots for free sailing. Generally, hours spent on manoeuvring and berthing is subject to numerous factors, such as weather condition, harbour efficiency, port schedule and access to cranes. Based on discussion with experts, it is assumed that berthing takes 12 hours at both ports and manoeuvring takes 2 hours at port of Rotterdam and 3 hours at port of Gothenburg. The figures for calculating the amount of ship emissions and total external costs are summarized in Table 2.

With regard to the amount, CO₂ emission is overwhelming and accounts for more than 97 per cent of the total emission throughout the trip, followed by NO_x, SO₂ and PM_{2.5} in decreasing order. As expected, emission amount at the free sailing stage is far greater than the levels at the manoeuvring and the berthing stages. This imbalance will become even greater with the increase of sailing distance. In this case study, the vessel has to perform manoeuvring twice (inbound and outbound) in each port, but the sum of their emission amounts are approximately half the amount of berthing emission.

The overall externalities are valued at 423,116 Euro including 399,498 Euro of air pollution costs and 23,618 Euro of climate change costs. More specifically, the individual contribution of air emissions is around 169,460 Euro for NO_x, 147,422 Euro for SO₂, 82,616 Euro for PM_{2.5} and 23,618 Euro for CO₂. Fig. 1 shows the total external costs of the round trip and the size of the pie charts indicates the level of external costs. It can be seen that the free sailing stage accounts for the largest external costs, followed by the external costs at the berthing and the manoeuvring stages. Furthermore, the external costs of PM_{2.5} are dominating in the port areas despite its low level of emission. This is because PM_{2.5} has the highest marginal external costs due to its serious threats to the human health. However, currently there is no specific regulation for restricting the particulate emissions in ports and it is an issue that needs attention and improvement. The external costs of NO_x and SO₂ becomes more influential in the open sea, where there is a sparse population and therefor low exposure.

Table 2

External cost estimation for the Rotterdam-Gothenburg voyage (2010 price).

Voyage Externality	Headhaul				Backhaul			
	Rotterdam	North Sea	Gothenburg		North Sea	Rotterdam		
	Manoeuvring	Free sailing	Manoeuvring	Berthing	Manoeuvring	Free sailing	Manoeuvring	Berthing
Voyage data (unit: hours for manoeuvring and berthing, nm for free sailing)								
	2	500	3	12	3	500	2	12
Emission factor (unit: kg/hour for manoeuvring and berthing, kg/nm for free sailing)								
<i>NO_x</i>	26.88	27.08	26.88	18.17	26.88	27.08	26.88	18.17
<i>SO₂</i>	8.81	17.62	8.81	3.02	8.81	17.62	8.81	3.02
<i>PM_{2.5}</i>	1.23	2.24	1.23	0.49	1.23	2.24	1.23	0.49
<i>CO₂</i>	1211.12	910.39	1211.12	922.12	1211.12	910.39	1211.12	922.12
Emission amount (kg)								
<i>NO_x</i>	54	13,538	81	218	81	13,538	54	218
<i>SO₂</i>	18	8,811	26	36	26	8,811	18	36
<i>PM_{2.5}</i>	2	1,118	4	6	4	1,118	2	6
<i>CO₂</i>	2,422	455,194	3,633	11,066	3,633	455,194	2,422	11,066
Marginal external costs (Euro/kg)								
<i>NO_x</i>	8.25	6.12	2.62	2.62	2.62	6.12	8.25	8.25
<i>SO₂</i>	16.25	8.28	3.34	3.34	3.34	8.28	16.25	16.25
<i>PM_{2.5}</i>	170.50	33.61	135.24	420.50	135.24	33.61	170.50	528.11
<i>CO₂</i>	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
External costs (Euro)								
<i>NO_x</i>	444	82,889	212	572	212	82,889	444	1,798
<i>SO₂</i>	286	72,982	88	121	88	72,982	286	589
<i>PM_{2.5}</i>	418	37,581	498	2,492	498	37,581	418	3130
<i>CO₂</i>	61	11,380	91	277	91	11,380	61	277
External costs of the round trip (Euro)				423,116 Euro (Air pollution 299,498 Euro, Climate change: 23,618 Euro)				

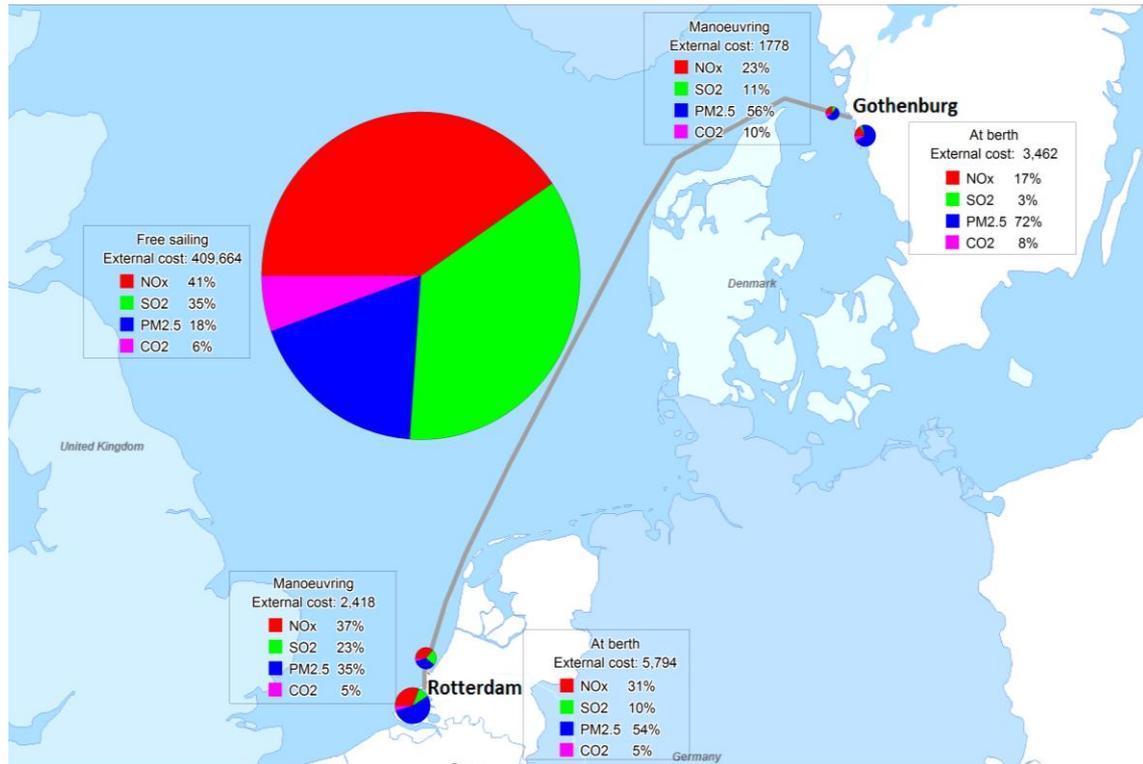


Fig. 1. External costs of the round trip between Rotterdam and Gothenburg.
(Map source: Netpas Distance 3.0)

5. Cost benefit analysis of emission reduction technology

The monetary valuation of shipping externalities provides a basis for the evaluation of emission reduction measures. Among them, an important application is to support investment decision by considering both costs and benefits associated with the emission reduction technology.

There are a number of technologies available today to reduce ship emissions, particularly for NO_x and SO_2 (Entec, 2005a, b; Kristensen, 2012). Most of them focus on the combustion process optimization, exhaust gas treatment or cleaner fuel (Löbblad and Fridell, 2006). Sea Water Scrubbing (SWS, also known as Sea Water Scrubber) is one of most promising and emerging technologies to reduce SO_2 . It is possible to reduce the sulphur emissions by 98 per cent and a significant amount of particular matter with a small increase in fuel consumption for electrical power generation (Kristensen, 2012). Due to the fuel sulphur limit for ship operation in the Emission Control Areas (ECA) and relatively high costs of low-sulphur fuel, SWS is

receiving more and more attention (Entec, 2005b). In this section, we apply the SWS to the vessel in the case study and assess the SWS from a cost-benefit perspective.

5.1 Costs and benefits of SWS

In general, the costs of SWS consist of two parts; a one-time investment costs and operating and maintenance costs (Table 3). Therefore, the total annual costs of SWS is the sum of annual investment costs (one-time investment costs depreciated over a 15 years lifetime with 5 per cent interest rate), annual operating and maintenance costs. The costs are adopted from Entec report for both new build and retrofit ships and are converted to year 2010 values (Entec, 2005c). With the projected technical improvements and wide application of SWS, its annual costs may reduce in the future, so the present calculation may be seen as using conservative cost figures. The environmental benefits of investing in SWS equal to the difference in external costs between pre-installing and after-installing of the technology. The annual benefits depend on the number of round trip per year. There is very limited environmental benefit between new build and retrofit, because the emission largely depends on the engine and reduction technology and not on vessel age.

Table 3
Costs and environmental benefits of Sea Water Scrubbing (€/year, 2010 price).

	Capital costs	Operating & Maintenance costs	Lifespan	Annualized Costs ⁶	Environmental benefits
	Euro	Euro per year	year	Euro per year	Euro per round trip
New Build	3,709,240	37,093	15	377,432	189,118
Retrofit	5,298,914	37,093	12.5	589,727	189,118

Source: Entec (2005b) and authors' calculation

⁶ Annualized costs = $NPV(C) \times a(q, T) = NPV(C) \times \frac{q}{1-(1+q)^{-T}}$, where $NPV = \sum_{t=1}^T C_t \times (1+q)^{-t}$, q represents to the discount rate which is assumed to be 5 %, T represents the lifespan, C_t is the value of the project costs in year t .

5.2 Results and discussions

By assuming different numbers of annual round trip, the benefit-cost ratios (B/C, defined as the discounted benefits divide by the discounted costs) of SWS are calculated and plotted in Fig. 2. The round dot refers to the circumstance where the ratio is one. If the ratio is greater than one, it implies that the environmental benefits of SWS exceed its costs.

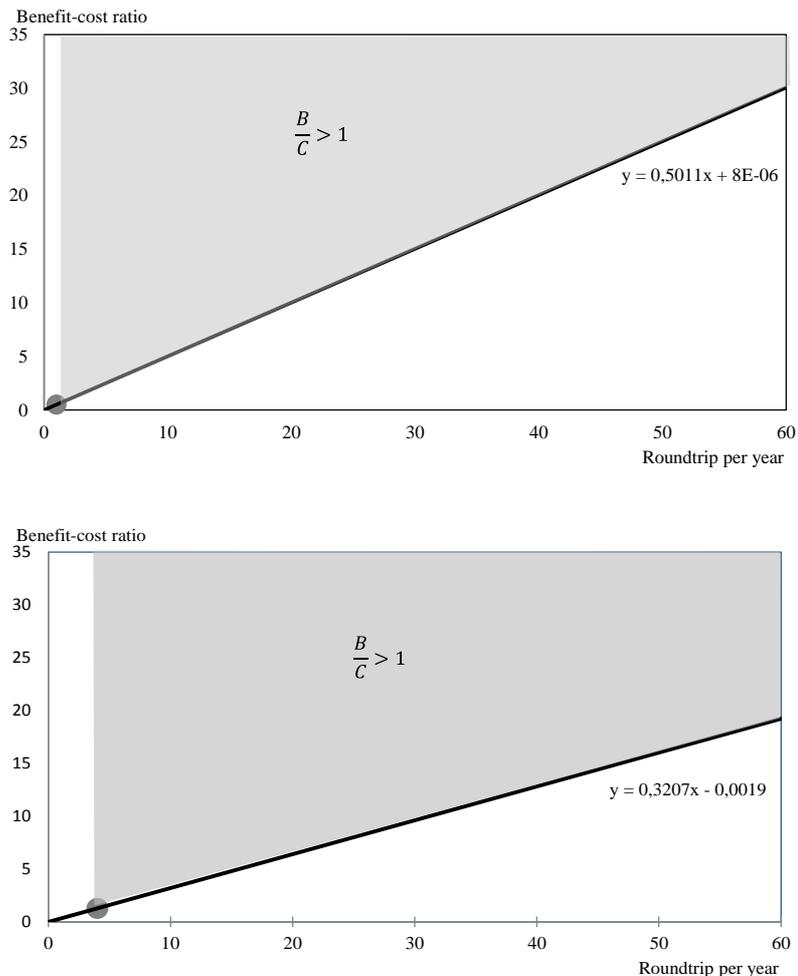


Fig. 2. Benefit-cost ratio of SWS for new build (top) and retrofit (below)

In most cases, the environmental benefits of SWS are sufficient to offset its costs, and the benefit-cost ratio increases with the number of round trips. With the same number of round trip per year, the ratios associated with the new build ship are higher than the retrofit. For the new build, the benefit-cost ratio equal to one with only one annual round trip whereas for the retrofit, the container ship needs roughly four round trips per year before the benefits outweigh the costs. These two numbers of annual round trip are simple to achieve, given the scheduled feature of container shipping

service. A containership making 52 round trips per year (one round trip per week) for example, it will result in 9.83 million Euro worth of environmental benefits per year and thus the benefit-cost ratio will be 26 if the SWS has been fitted to a new build and 17 if it has been fitted as a retrofit.

These figures suggest that SWS is an economically efficient solution for reducing ship emissions. Within a foreseeable future, energy efficient and environmentally friendly technologies will be even higher on the shipping agenda. This provides an ample room for innovation and application of new efficient technologies and operational standards, but in the meanwhile it requires rational decision-making. The analysis applied here is applicable for policy considerations on green ship technologies. Such tool is also useful for ship owners who wish to select among the reduction measures for their fleets or individual vessels sailing on specific routes.

6 Conclusion

This paper proposes a voyage-based model to estimate the environmental external costs of shipping. The model is applied for a specific container ship sailing between Rotterdam and Gothenburg. This bottom-up perspective enables to assess the environmental impact of shipping at micro-level. It shows that the round trip would cause 399,498 Euro in external costs of air pollution and 23,618 Euro in climate change, summing up to 423,116 Euro in total external costs. The estimation highlights the need for ship emission control with a special attention for particulate matter. The estimated external costs are deemed crucial for any further step towards pricing and regulating ship emissions. Furthermore, a cost-benefit study to evaluate the Sea Water Scrubbing technology in term of economic efficiency has been performed. The result justifies the SWS as a sound investment for both new build and retrofit cases. More importantly, the cost-benefit analysis can be applied to other reduction alternatives, thus facilitating the decision-making for both regulators and ship owners. In the light of green shipping, the cost-benefit analysis may also provide shipping companies a clear picture of their social contributions by investing in green technologies and thus instilling environmental awareness in their long-term strategy making.

The analysis however also raises another extremely important question regarding the distribution of benefits and costs. As it is today the benefits and costs are totally separated, meaning that ship-owners pay all the technology costs and the society gains

all benefits. With a B/C ratio ranging from 17 to 29 for a quite ordinary container service, one might consider whether the society actually gets too much out of the regulatory regime that they have imposed or will impose. The danger with this kind of regulation is that shipowners have no other place to put the additional costs than on the users – thereby increasing the costs of sea transport compared to road and rail transport. In the end, this will distort the competition in favour of road and rail thereby creating an uneven playing field among the transport modes. The result could very well be that sea transport would be uncompetitive and freight will make a modal backshift to road or rail.

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