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Costs and benefits analysis of sulfur emission reduction measures in liner transportation

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Abstract

Desulphurization provides a crucial challenge for the maritime industry, resulting in growing concerns about what measures can be adopted to achieve emission reduction in order to comply with IMO 2020 Sulphur Emission Control Areas (SECA). This paper constructs the cost present value model to analyze ship operators' different compliance measures based on the characteristics of sulfur limitation regulations and container liner transportation, and applies these to Atlantic specific liner route. The study considers the impact of fuel price differences between low-sulfur and high- sulfur fuels and distance ratio within SECA on decision making; and the environmental benefits brought by compliance measures are quantified. Under current conditions, scrubber installation is always the first choice in terms of emission reduction. Fuel switching remains a lower-cost option for ships when there is little difference in fuel price or a low SECA proportion.

Keywords

Sulfur emission control area, Cost present value, Fuel switching, scrubber.

1. Introduction

Shipping is regarded as an environment-friendly mode of transport. However, there are still significant emissions associated with shipping operations. About 95% of the world's shiping fleet has been driven by diesel engines that consume high-sulfur fuel. Container liners emit a large amount of pollution gases during operation, including SOx, NOx, greenhouse gases (COx) and particulate matter (PM) [1]. Air pollution is the main cause of the global burden of environmental disease, which has caused huge economic losses [2], and also brought great harm to people's health and ecological environment.

Compared with inland areas, the damage from ship emissions is more severe in coastal areas of Europe, East Asia and South Asia. Therefore, the International Maritime Organization has established sulfur emission control zones, where non-compliance can result in fines and loss of reputation, and where ship operators must choose to adopt sulfur reduction measures to meet sulfur emission requirements. The first strategy, fuel switching, is widely used because the initial investment is negligible compared with the other two options and ships need only change to low-sulphur fuel within the control areas. The second strategy is to install scrubbers, which were already installed on 2% of ships worldwide by the end of 2020. The third strategy is to use clean energy such as liquefied natural gas (LNG) as alternative fuel, which is not feasible for most ships due to its huge capital investment and space requirements on board. Therefore, this option is not considered in this study.

The paper is organised as follows. The second section reviews the relevant literature, paying special attention to the study of emission reduction measures under the emission control policy. Section 3 provides a complete description of the research questions and models that help determine compliance measures and emissions. In the fourth section, the model is applied to liner service of Atlantic line, estimating the economic cost and environmental benefit after the implementation of emission reduction measures, and comparing the present value of costs under different circumstances. Finally, the fifth section gives the research conclusion.

2. Literature References

Sulfide and carbon emissions are one of the main pollution sources of shipping. Global warming caused by carbon emissions threatens the survival of mankind. The total emissions of greenhouse gases (GHG) produced by shipping reach 972 million tons, accounting for about 2% of the total emissions [3]. Carbon tax is regarded as one of the effective means to curb carbon emissions. [4] analyzed the quantitative impact of Marine carbon tax on global economy and the important role of containerized goods in international trade, the result shows that the negative economic impact of carbon tax on European countries will be greater. [5] studied the economic feasibility of fixed carbon tax and progressive carbon tax under fixed line. In addition to carbon emissions, sulphide emissions also have a significant impact on health, resulting in increased mortality from cardiopulmonary diseases. In addition to carbon emissions, sulphide emissions also have a significant impact on health, resulting in increased mortality from cardiopulmonary diseases [6].

Under such circumstances, national and international organizations have proposed and implemented various measures to reduce ship emissions. The establishment of SECA has brought remarkable results in the control of Marine pollution, but at the same time it has also brought many impacts to the shipping industry, which has been highly concerned by industry practitioners and academic researchers. Relevant literature can be divided into three categories. The first category studies the potential impact of the setting of control area on the transformation of transportation mode. [7] analyzed the impact of implementation and the possibility of pattern transformation. The second is how ship operators adjust their operating patterns to reduce fuel consumption on voyage. Re-design routes and ship allocation 8, reduce low sulphur fuel consumption by optimizing speed [9, 10]. The third category studies the best choice of different sulfur reduction measures.[11]studied emissions-reduction technology options that take into account ship sailing patterns and suggests that the value of installing scrubbers without taking into account sailing patterns may be overestimated.[12] Studied the influence of old and new vessels on the decision of whether to install scrubbers. Many scholars have analyzed the effectiveness of these measures, but few scholars have conducted quantitative analysis of these measures from the perspective of investment cost.

Based on existing research, this paper constructs the present value cost model for fuel switching and hybrid scrubbers installation. Using the full life cycle method, not only considering the cost and profit of a certain stage, but through the quantitative analysis of the cost required in the whole process, and analysis of environmental benefits, integrating to get the best solution. The possible influence of additional fuel consumption from scrubber installation, government subsidies and low sulphur fuel surcharges on decision-making is also discussed.

3. Mathematical Models

This section establishes present value cost models for the two compliance options: fuel switching and scrubber installation. There are three types of scrubbers available for operators: open loop, close loop, hybrid. Among them, the hybrid scrubber has good performance and has been applied by many shipping companies. In this paper, the hybrid scrubber is also selected for research. The basic assumptions and parameter settings are as follows:

1) The study period is one year, and the departure frequency of container ships is weekly transportation. The service level and charging standard of each port on the route are consistent.

2) To comply with the IMO 2020 emission control policy, the fuel switching option use LSFO(Sulphur content 0.5%) outside SECA and switch to MGO (Sulphur content 0.1%) in SECA.

3) Ships with hybrid scrubber use HFO (Sulphur content 3.5%) fuel throughout the voyage.

Table 1. A list of the notation

Parameters	
i , j	Index of port
k	Compliance options for emission reduction, k∈[1,2]
n	Number of trips for vessels per year
r	discount rate
L_{ij}	Cycle distance from port i to port j (nautical miles)
L_{ij}^{SECA}	Distance in SECA from port i to port j (nautical miles)
N	Number of vessels in the service
V_S	Vessel speed (knots)
V_d	Nominal speed (knots)
T	Total voyage time (hours)
T^P	Average port call time at a port (hours)
P	Fuel price (USD/ton)
F^M	Main engine fuel consumption per day at sea (tons/day)
F^A	Auxiliary engine fuel consumption per day at sea (tons/day)
F_{ijk}	Fuel consumption of compliance method k from i to port j (tons/ voyage)
η^x	Emission coefficient of x polluting gases (ton/ton)
E^x	Emission of x polluting gases (tons/ voyage)
CB_{ijk}	Fuel cost of compliance option k from port i to port j (USD/voyage)
CV_{ij}	Fixed cost of ship (USD/day)
TC_{ij}	Total cost all the vessels operating on the cycle (USD/year)

3.1 Cost of emission reduction measures

The round-trip distance of container liner transport service from port i to port j is L_{ij}, the shipping frequency is weekly shipping, and the number of vessels is N. The following relations can be noticed:

$$V_S = \frac{L_{ij}}{168N - T^P} \tag{1}$$

Fuel consumption of ship's main engine is affected by vessel speed and type, fuel consumption is a cubic power of the vessel speed. The ship is powered by auxiliary engine at anchor.

$$F_{ijk} = [F^M (\frac{V_S}{V_d})^3 + F^A] \frac{L_{ij}}{24V_d} + T^P F^A \tag{2}$$

where F^M is daily fuel consumption of the main engine, and the value is the product of $SFOC^M$, EL^M and PS^M. $SFOC^M$ is the specific fuel oil consumption of the main engine of 206 g/kwh, EL^M is engine load during sailing of 80 %,PS^M is the power of the main engine(kw). Where F^A is daily fuel consumption of the auxiliary engine. Similarly, the values of $SFOC^A$ and EL^A are 221 g/kwh and 50% respectively.

For an operator choosing compliance option i∈[1, 2], where 1 represents fuel- switching and 2 represents hybrid scrubber. The fuel cost of selecting the option 1 is calculated as follows:

$$CB_{ij1} = [F^M (\frac{L_{ij}^{SECA} V_S^2 P^{MGO} + (L_{ij} - L_{ij}^{SECA}) V_S^2 P^{LSFO}}{168 V_d^3}) + F^A N P^{MGO}] \frac{L_{ij}}{24 V_S} + \frac{1}{24} T^P F^A N P^{MGO} \tag{3}$$

Ships equipped with hybrid scrubbers can use the cheaper HFO as fuel throughout their operation, but scrubbers run with additional energy consumption a(%).The fuel cost of selecting the option 2 is calculated as follows:

$$CB_{ij2} = \frac{1}{24}(1+a)[(F^M \frac{L_{ij} V_S^2 P^{HFO}}{168 V_d^3} + F^A N P^{HFO}) \frac{L_{ij}}{V_S} + T^P F^A N P^{HFO}] \tag{4}$$

Total annual costs include fuel consumption costs, fixed costs, initial equipment construction costs and annual maintenance costs. Where annual maintenance costs are only considered in option 2.

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$$TC_{ijk} = (CBi_{jk} + CV_{ij})n + (IC + MC)N \tag{5}$$

where the fixed cost (CVij) includes management fee crew, repair and maintenance, insurance, stores and lubes, fuel for auxiliary power, administration, and (possibly) capital costs; namely, all the costs incurred when the ship is not sailing. IC represents the initial construction of the equipment.MC is represents annual maintenance cost.

3.2 Cost present value of emission reduction measures

Using present value cost method to construct economic model of emission reduction measures and To assess the financial attractiveness.

$$CPV = IC + \sum_{t=1}^{\gamma} A_t (1+r)^{-t},\ A_t = C_1 + C_2 \tag{6}$$

$$C_1 = N[F^{MGO}(P^{MGO} - P^{HFO}) + F^{LSFO}(P^{MGO} - P^{HFO})] \tag{7}$$

in equations (6) ~ (7), CPV represents the Cost present value, γ is the lifespan of ship, A_t is the net cash flow in year t. C_1 is the increased annual fuel cost of option 1. For low-sulfur fuel consumed in SECA and low-sulfur heavy oil consumed outside SECA, the increased annual fuel cost is calculated according to the difference between the heavy oil. C_2 represents the additional fuel consumption and annual maintenance costs required to operate the hybrid scrubber. Fuel switching is a good choice if the CPV of fuel switching is lower than that of scrubber installation. Otherwise, scrubber installation is a good choice.

3.3 The amount of ship emissions

The level of ship emissions depends on certain factors: fuel type, ship operating conditions, etc. According to previous studies, Annual emissions of x(including CO_2,SO_2,NO_2) can be calculated by multiplying annual consumption all vessels by corresponding emission factor of marine fuels.

$$E_{ij1}^{X} = n \cdot N \cdot \eta^{X} \cdot F_{ijk} \tag{8}$$

$$E_{ij2}^{X} = CB_{ij2} = \frac{1}{24}(1-b^{X})(1+a)[(F^{M}\frac{L_{ij}V_S^2}{168V_d^3} + F^{A}N)\frac{L_{ij}}{V_S} + T^{P}F^{A}N] \tag{9}$$

where b^x is the percentage that can be reduced by installing scrubber.

4. Numerical Applications

In this paper, the Atlantic route is selected as the research object. The round-trip distance from port i to port j is 13,000 nautical miles, and the sailing distance within SECA is 1,700 nautical miles, accounting for 13% of the total voyage. 12 ports need to be served. By January 2021, the fuel price for HFO is 400 USD /t, LSFO are 450 USD /t and MGO are 635 USD /t. The initial investment cost of hybrid scrubbers is 4.75 million, and the annual maintenance cost is about 2% of the initial cost. In addition, scrubber installation adds an additional 1% of energy consumption. Operation data of container ships collected are shown in Table 2.In this section, we analyze the cost-effectiveness and environmental benefits of the two sulfur emission measures, as well as the factors that may vary during actual navigation. The discount rate is set at 5%, a figure that usually applies to Marine departments.

As shown in Figure 1, under the current fuel price difference, scrubber installation option is not suitable when the remaining service lifespan of the ship is less than 9 years, and the fuel switching option is more economical. Otherwise, it is more appropriate to install scrubber.

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Table 2. Parameter values of the route and container ships

Data of ship particulars		
Container capacity	9500	TEU
Main engine power	74000	kW
Auxiliary engine power	3081	kW
Design speed	25	knots
Average port call time	32	hours
Fixed daily costs	38320	USD/day
Number of vessel in service	7	
Number of trip for vessel	5	

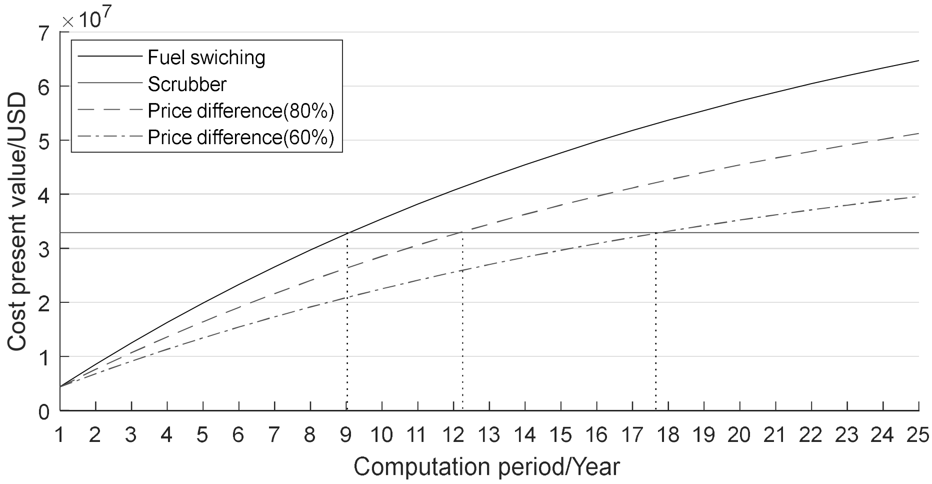

Figure 1. Cost present value of different options

4.1 The impact of fuel price fluctuations

Studies show that fuel consumption costs account for 50%~60% of the total cost, so the difference in fuel prices is a key factor. After installing the hybrid scrubber, this part of the fuel price difference can be saved. Set the fuel price difference to be reduced by 20% and 40% respectively, as shown in Figure 1. The cost present value continues to decrease as the fuel price gap decreases, and the return cycle of hybrid scrubber is also affected by the fuel price gap. The lower the fuel price gap is, the longer the return cycle will be. Ship operators should be more inclined to use the fuel switching option. It is applicable to install scrubber for new ships or ships with more than 12.15 years of remaining service life when the fuel difference is reduced by 20%.

4.2 The impact of SECA distance ratio

The SECA distance ratio of different routes is different. Figure 2 sets three horizontal lines that represent different cast present value of hybrid scrubber. Because the SECA distance does not affect the costs, the cost present value does not vary with the ratio. Based on the current initial scrubber cost of 4.75 million, the cost present value of fuel switching is the same as scrubber installation when the SECA distance ratio is 38.5%. As the distance within the SECA increases, the cost present value of fuel switching continues to grow. If the initial cost of installing scrubber increases by 30%, scrubber is the best option only if the distance within the SECA is more than 57%. If the initial cost of scrubber is reduced by 30%, the payback period is reduced, and the distance within the SECA is more than 19%, scrubber installation will be the best choice.

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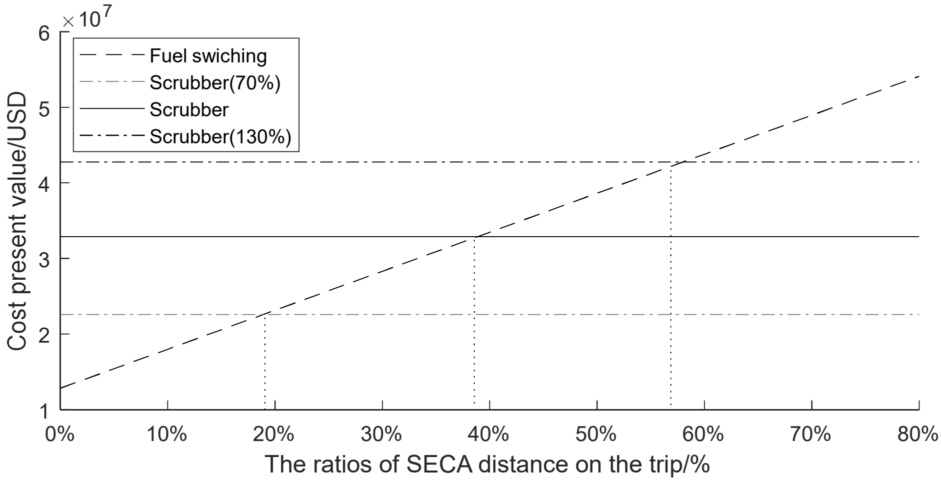

Figure 2. Change of cost present value at different ratios of SECA distance

4.3 Environmental benefit analysis

Shipping has significant externalities, and the environmental damage related to ship emissions is borne by the society. Reducing air pollutant emission reduces health and environmental impacts, and the welfare changes resulting from those impacts are translated into monetary values. We define ship emissions without Emission reduction measures as basic, compared with emissions after implementing the two compliance measueres. The external costs of ocean SO_2 emissions range from 2252USD/t to 8303USD/t, we chose an average of 5277USD / t in this paper. The external cost of CO_2 emissions is based on us 25 USD/ t for all regions.

Table 3. Emissions and environmental benefits of compliance option

	CO_2	SO_x	NO_2
Base case	234130.8	3892	37667.7
Emission amount of option 1	236789.7	561	37667.7
Emission amount of option 2	236172.9	274	37667.7
Environmental benefits(k=1/k=2)	-66472.5/-51052.5	17577687/19092186	0

The implementation of emission reduction measures can effectively reduce SO_X emissions. As shown in Table 3, the use of fuel switching and hybrid scrubber installation can reduce sulfur emissions by 85.5% and 93% respectively. However, the greenhouse gas emissions are slightly higher, probably due to the carbon emission coefficient of different fuels and the increased fuel consumption caused by the installation of scrubbers. By contrast, neither measure has an effect on nitrogen emissions.

5. Conclusion

The economics of emission reduction measures depend on factors such as the remaining lifespan of the ship, the distance operating in SECA and fuel price difference, etc. From an economic point of view, the scrubber installation option is suitable for ships with longer voyage in SECA. New ships and ships with long remaining lifespan cycle are more suitable for scrubber installation than old ships. Scrubber installation is also a better choice in terms of environmental benefits. However, due to the high initial cost and the need to pay this cost to equipment manufacturers and repair yards in a short period of time, fuel switching option is widely used in the market today.

The IMO is striving to reduce emissions from shipping. As a result, emissions regulations are becoming more stringent. It is highly likely that areas such as the Mediterranean will be designated as emission control areas around 2025, which will push up MGO fuel use to an estimated 30 per cent, LSFO to 40 per cent and the number of vessels installed with desulphurisation equipment will increase. In addition, the initial cost of scrubber installation greatly influences the choice of ship operators. Lower installation costs mean less payback time, faster revenue for operators, and government subsidies or low sulphur fuel surcharges (LSS) can make scrubber installation a more attractive option.

The selection of emission reduction measures becomes vital for shipping companies with business inside the control areas. The choice will not only affect compliance with regulations, but also have a significant impact on the financial costs of shipping companies substantially. This study only considered the benefits of installing scrubber and fuel switching independently, ignoring that even scrubber-equipped ships have to convert their tanks to more expensive fuel when entering ports where the technology is banned in their waters. Therefore, in the future with more stringent sulfur emission rules, the study of combined sulfur reduction measures will better meet the actual needs.

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