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COMPLIANCE AND IMPACT IN SULFUR EMISSION CONTROL AREAS FOR MARITIME TRANSPORTATION: OVERVIEW AND FUTURE RESEARCH

DAN ZHUGE[1], SHUAIAN WANG[1], LU ZHEN[2] and XIULING HEI[3]

[1]Department of Logistics and Maritime Studies, The Hong Kong Polytechnic University, Hung Hom, Hong Kong.
[2]School of Management, Shanghai University, 99 Shangda Road, Shanghai, 200444, China.
[3]School of Economics and Management, Ningxia University, Yinchuan, 750021, China.
E-mail: dan.zhuge@connect.polyu.hk, wangshuaian@gmail.com, lzhen@shu.edu.cn, xlhei@hotmail.com

This paper reviews the extant research on maritime sulfur Emission Control Areas (ECAs). The combination of two keywords, i.e., Emission Control Area and shipping, maritime, or marine, is used to search the relevant literature. We focus on three different areas on ECAs. First, the research of different alternatives for ECA compliance, i.e., fuel switching, scrubbers, shore power, Liquefied Natural Gas (LNG) and some new technologies, is explored. Then the emissions in ECAs are calculated to assess the environmental and health benefits. Finally, potential ECA implications, including speed change, rerouting and modal shift, are studied in our paper. We identify the directions for future research after analyzing the contributions and limitations of the extant literature. The summary of the existing work is important for both research and practice perspectives. The main purpose of our study is to help new researchers understand the measures for ECA compliance and the impact of ECA regulations quickly as well as boost the research field in more dimensions.

Keywords: Shipping, ECAs, ECA compliance, emission assessment, ECA impact

1 Introduction

More than 90% of global trade is transported by ocean-going vessels (IMO 2014), contributing greatly to air pollution. Due to the low quality of consumed fuel in shipping, ships emit a large amount of exhaust gases and particulates, including SO_x, NO_x and PM, from their operations at sea or in port areas. These emissions are major concerns in local areas, which may cause acid rain, photochemical smog and some serious diseases, such as respiratory, cardiovascular problems and asthma (Cullinane and Edwards 2010; Xu et al., 2018; Qu and Wang, 2015).

The International Maritime Organization (IMO) has taken measures to prevent the emission from shipping. One of the measures is the designated sulfur ECAs in several sea areas. Notably, ships trading in ECAs of the Baltic Sea, North Sea, North America and the United States Caribbean Sea have had to use the fuel with the limit of sulfur content to 0.1% since January 1, 2015. Outside ECAs, the current limit for sulfur content in fuel is 3.5%. China announced to establish Asia’s first ECAs in the Pearl River Delta, the Yangtze River Delta and the Bohai Bay rim area, in which a 0.5% sulfur limit will be implemented from 2019. The major target of these ECAs is to constrict sulfur emissions in the designated areas. The ECAs in North America and the United States Caribbean Sea also control the emission of NO_x and PM.

The introduction of ECAs into the Annex VI is an important policy in reducing air emissions from shipping. A wide range of literature thus focuses on the compliance and impact of ECAs, which is divided into three areas in our paper: studies on fuel switching, scrubbers, shore power, LNG and some new technologies to comply with the rules in ECAs, emission reduction in ECAs and health benefits due to ECAs, potential ECA implications. Finally, we will discuss the opportunities and directions for future research.

2 Research methodology

We employed a computerized literature search approach to find the extant literature on ECAs. Three databases, Science Direct, Scopus and Google Scholar, were searched with the combination of two keywords, i.e., Emission Control Area and shipping, maritime, or marine, in the field of title, keywords and abstract. We also traced the references cited in the collected papers to find more relevant work in the three databases. We decompose the literature on ECAs into three areas.

3 ECA compliance

Recently, Heavy Fuel Oil (HFO) is widely used in shipping, while the sulfur content of this fuel cannot satisfy the requirement in ECAs. To the best of our knowledge, several solutions are provided to facilitate the compliance of ECA regulations, including fuel switching, scrubbers, shore power, LNG, and some new technologies. In this section, we explore the previous body of research on these alternatives for ECA compliance.

3.1 *Straightforward alternative*

Fuel switching is the most straightforward alternative to operate ships within and outside ECAs. Usually, a fuel with lower sulfur content, such as Marine Gas Oil (MGO), is used within ECAs, and HFO is still the main fuel outside the area (Fagerholt and Psaraftis 2015, Fagerholt et al. 2015). Browning et al. (2012) confirmed that switching to MGO in ECAs resulted in significant reduction in emissions of SO_x and $PM_{2.5}$ as well as small reduction of NO_x, but the operating cost increased as a result of the higher price of MGO.

3.2 *Alternatives with high capital cost*

Different from fuel switching, some alternatives (e.g., scrubbers, shore power and LNG) require high initial investment for the construction of infrastructure. Scrubbers are often used to dispose of the sulfur content in the emissions. SO_x can be absorbed in the water or react chemically and become a solid substance (Gausel 2014). The after-treatment technology, scrubbers, is often compared with fuel switching in some literature (Panasiuk and Lebedevas 2014, Patricksson et al. 2015, Carr and Corbett 2015).

Shore power refers to the use of shore-side electricity while the ships are at the berth to mitigate emissions for ECA regulations. Based on two types (fixed and movable) of shore power on-board installation, Hou (2017) studied a dynamic berth allocation problem considering ship emissions and continuous berthing position.

Using LNG as the alternative of HFO can eliminate SO_x emissions and reduce NO_x and PM. Due to the high capital cost for retrofitting existing ships to LNG carriers, the investment of LNG vessels is a major concern in recent studies, e.g., Acciaro (2014a, b) and Chen et al. (2016).

In order to find out the optimal abatement solution, the abatement options are compared and examined in some studies. Considering the revenue generated with a cap-and-trade system, Nikopoulou et al. (2013) suggested that distillates are not economic for ECA regulations, seawater scrubbers, Selective Catalytic Reduction (SCR), and Humid Air Motor (HAM) are the attractive alternatives, and LNG is the optimal abatement solution. Brynolf et al. (2014) evaluated three alternatives, HFO combined with open loop seawater scrubbers and SCR, MGO combined with SCR, and LNG, to satisfy regulation requirements for SO_x and NO_x. Lindstad et al. (2015) analyzed several options, including fuel switching, Exhaust Gas Recirculation (EGR), scrubbers, LNG and methanol, in ECAs and revealed that it is difficult to determine the optimal one.

3.3 *New technologies*

Aside from the mentioned alternatives, some new projects are put forward to fulfill the ECA regulation. An Innovative After-Treatment System for Marine Diesel Engine Emission Control (DEECON) project is studied by Antes et al. (2013). The project aims to design a new on-board after-treatment unit such that each unit can remove a specific pollutant. Some new technologies are introduced to reduce SO_x, NO_x, PM, CO and Volatile Organic Compounds (VOC).

Nehter et al. (2017) reported a 50 kW Solid Oxide Fuel Cell (SOFC) demonstrator started on commercial road diesel. The experiments showed that this demonstrator can clear out all SO_x from the exhaust gas and reduce NO_x to below the limits in ECAs.

4 Emission assessment in ECAs

In this section, we examine the literature on the calculation of emissions, such as SO_x, NO_x and PM, produced by marine fuels to identify the pollution severity. The reduction of air emissions can be regarded as the improvement of the environment, which may benefit the public health and reduce premature death.

4.1 *Environmental benefits*

The sulfur ECA can lead to environmental benefits in the designated area. A large number of papers estimate the air pollution reduction in ECAs, including SO_2 (e.g., Kattner et al. 2015), SO_2 and NO_x (e.g., Tran and Mölders 2012), and SO_2 and PM (e.g., Tao et al. 2013).

Chang et al. (2014) pointed out that the ECA can decrease more noxious gases (SO_2, NO_x and PM) emissions and stricter rule in ECAs can be more efficient. Svindland (2016) supported the stricter SO_x regulations in shipping to improve a green image of marine transportation.

Dulebenets (2017) compared two mixed-integer non-linear programming models: one considers the existing IMO regulations and the other combines the IMO regulations and the quantity restrictions of SO_2 emissions. The findings demonstrated the effectiveness of emission restrictions in ECAs for reducing pollution levels.

4.2 *Health assessment*

The literature reviewed in sub-section 4.1 only focuses on assessing environment benefits from ECA regulations. There also exist some papers evaluating the health benefits with respect to the ECA. Brandt et al. (2013) investigated the decline of the health-related external cost and the premature deaths in Europe from 2000 to 2020. Due to the regulation in the sulfur ECA, the contribution from international marine transportation of the Baltic Sea and the North Sea in health-related cost mitigates 36%. Viana et al. (2015) estimated the influence of the ECA in the Marmara Sea and the Turkish Straits. The reduction of SO_2 and PM emissions prevents lots of hospital admissions from exposing to air pollution as well as alleviates some premature deaths.

5 Potential ECA implications

The expected performance of the designated ECA is to reduce air emissions, especially SO_x, in these areas. However, with the adoption of ECAs, some potential implications in shipping operations may appear. To recognize and analyze these consequences, the research on speed change, rerouting and modal shift is reviewed in this section.

5.1 *Sailing patterns change*

Plenty of work explores the change of sailing patterns, i.e., speed (Adland et al. 2017) and rerouting (Chen et al. 2017), due to the ECA regulation. Doudnikoff and Lacoste (2014) concluded that the different speeds within and outside ECAs can decrease total costs (bunker cost and fixed cost) but increase CO_2 emissions.

According to the research of Fagerholt and Psaraftis (2015) and Fagerholt et al. (2015), shipping lines operate ships at different speeds within and outside ECAs and reroute ships between ports to burn less low-sulfur fuel (e.g., MGO) as MGO is more expensive than HFO, where rerouting may contribute to the increase of the total emissions. Gu and Wallace (2017) claimed that the value of scrubbers may be overestimated if sailing pattern is not considered. Note that the speed of a ship is determined by economic reasons rather than by the traffic flow as in urban transport (Wang, 2013).

5.2 *Modal shift*

The route service cost may increase for complying with the rules in ECAs (Dulebenets 2016). Cargo transport shifting from land to sea is encouraged in recent years. However, the increased cost in shipping as a result of the ECA regulation may lead to a backshift.

Panagakos et al. (2014) compared two transport alternatives, a combination of ferry and truck, and a road-only option, and predicted that the ECA regulation might result in a modal shift to the road-only option by between 5% and 17%. Bergqvist et al. (2015) explored the forest industry in Sweden affected by the sulfur ECA. The results revealed that the transport of the products in this industry would be transferred from sea to land. Vierth et al. (2015) inferred that transferring flows from the Swedish east coast to other areas or modest modal shifts from sea to road and rail may occur because of the sulfur ECA in Europe. In contrast, Holmgren et al. (2014) displayed that a modal backshift was impossible for the shipment of relatively high-value cargos from the east of Lithuania to the west of Britain.

6 Future directions

This paper reviews three areas of the extant literature on sulfur ECAs. The large quantity of literature reveals that the ECA has received plenty of attention in academic circle. Some major issues are concerned and studied in the existing work. However, there are still several significant topics on ECAs that deserve to be focused on in future.

First, the total emissions of maritime transportation may increase despite of the decrease in the ECA. Although most emissions are in the deep-sea areas, it will affect the air quality and impair public health ultimately. Yet, little research has been directed at the reduction of total emissions in shipping on ECAs.

Second, the value of some alternatives for reducing emissions is likely to be overestimated. For instance, shore power is regarded as an option without emissions used by ships while berthing, which overlooks the air pollution emitted with the production of electricity. It will therefore be important to consider more correlative factors in this analysis.

Finally, it is concluded that transport modal may shift from sea to land. As the change will increase the air emissions on road, a challenge here is to curb the backshift under ECA regulations. The primary cause of modal backshifts is the increased shipping cost. Some measures, for example, a subsidy from the government to vessel operators with route services in ECAs, may be effective to reduce the transport price at sea.

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