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FEATURE ANALYSIS OF SHIP EMISSION UNDER CHINA'S ECA POLICY: A PERSPECTIVE FROM SHANGHAI

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ABSTRACT

The prosperity of maritime commerce brings economic benefits to port cities; however, the air pollution along with the calling of ships undermines the local environment. Being conscious of this, the Chinese government officially issued its agenda on emission control areas (ECA) along her coastal areas at the end of 2015. This paper measures the features of ship emission via an activity-based approach based on AIS data. The air pollutant emission from 24 filtered ocean-going vessels calling the port of Shanghai are calculated, where the emission reduction rates are identified and classified through ship type, engine model and sailing conditions. Findings show that the ECA scheme has an effective impact on reducing the ship emission. The average emission reduction rates of oil tankers/chemical ships, container ships, bulk carriers, liquefied gas ships, general cargo ships, cruise ships and roll-on-roll-off ships are 30.52%, 23.28%, 20.65%, 14.23%, 13.84%, 12.66% and 12.30% respectively. Implications for the next phase of ECA Act are proposed in enacting stricter emission control standards and expanding the scope of ECA after 2020.

Contribution/Originality: This study is one of few studies which analyze the feature of ship emission with AIS data. The primary contribution is combining ship activity with the implementation of China's ECA Act, implying the formation of future ECA scheme.

1. INTRODUCTION

The prosperity of maritime commerce brings economic benefits to port cities; however, the air pollution along with the calling of ships undermines the local environment. As one of the largest ports in China, port of Shanghai is backed by the broad economic hinterland of Yangtze River Delta. In 2017, the cargo throughput reached 705 million tons, with container throughput exceeding 40 million TEU. On the other hand, ships consuming HFO (Heavy Fuel Oil) emit large amounts of Green House Gases (GHG) such as SOx (Sulfur Oxides), NOx (Nitric Oxides), and PM (Particulate Matters) during marine navigation and berthing. These pollutants can invade hundreds of kilometers of inland areas under the action of Sea-Land Breeze (Eyring *et al.*, 2010) While China's coastal cities are densely populated, it will cause great harm to local air quality and public health. What's more, the source of SOx and PM is closely related to the sulfur content from marine fuel. So even if the ship is not equipped with emission control devices, the replacement of low sulfur fuel can reduce the emission of SOx and PM from ships (Yao *et al.*, 2011). In order to reduce the negative impacts of ship emission on global air quality and environment, International Maritime Organization (IMO) added an Annex VI "Prevention of Air Pollution from Ships" to the "International Convention for the Prevention of Pollution from Ships" (MARPOL) in 1997. Coming into force in 2014, it imposed strict restrictions on the emission of SO_X, NO_X and PM from ships calling the contracting states. Since 2006, four ECAs distributed in Baltic Sea, North Sea, North America and Caribbean Sea have been approved globally and more stringent emission limits have been imposed on ships sailing or berthing in the ECA (ICS, 2015; IMO, 2016b). In China, along with the rapid economic growth, pollution problems caused by ship emission have become increasingly serious, and most port cities fail to meet basic air quality standards. Therefore, the Ministry of Transport officially issued the ECA Act and decided to set up ECAs in the Pearl River Delta, Yangtze River Delta, and Bohai Sea Gulf to control emission from shipping and improve the air quality in China's coastal areas. It is an important step for China to control the air pollution of ships comprehensively in the future. The act indicates that the sulfur content of ship's bunker fuel should be limited to 0.5% m/m during berthing since 01/01/2017 in nominated ports of ECA and the scope is extended to the whole ECA after 01/01/2019, according to the Act.

Maritime transport is an economic mode of cargo transportation, however the emission caused by shipping activities contribute significantly to the total emission in global transport, becoming the important sources of air pollution. Due to the large size, high engine power and adoption of poor quality residue fuel oil, the pollution caused by ocean-going vessels is much more severe than ordinary vessels. Statistics show that ocean-going vessels account for less than 6% of the total number of ships entering and leaving Port of Shanghai, while SOx and PM emission shared 72% and 92% of all ships in 2010 (Fu *et al.*, 2012). Therefore, it is important to estimate the emission as accurate and detailed as possible in order to implement appropriate preventive measures. In doing so, we need to quantify the air pollutants emitted by ships and find out the characteristics of ship emission. In this way, we can better support the formulation and implementation of relevant policy set by the government.

The remainder of this paper is structured as follows: The previous studies on the emission of air pollutants from ships are discussed in Section 2. Section 3 describes the methodology with details on study domain, data source and calculation model. The parameters of the mode are also determined. The emission characteristics of ships are analyzed in Section 4. Finally, Section 5 summarizes the major conclusions and political implications.

2. LITERATURE REVIEW

Significant progress has been made for estimating ship emission in different regions of the world. The main methods to calculate the ship emission inventories can be classified as fuel-based (top-down) and activity-based (bottom-up) approaches (Tzannatos, 2010).

Based on the combination of data on marine fuel sales (e.g. fuel quantities and types) and fuel-related emission factors, the top-down method is popular among earlier researches (Song and Shon, 2011). The advantage of this method is that the statistics on fuel sales are recorded and can be calculated and applied to long-term, large-scale emission inventory calculations. Since the fuel statistics are not difficult to obtain, fuel consumption method is applicable to the calculation of global ship emission inventory (Miola and Ciuffo, 2011). However, further study found that the calculation depending on fuel consumption is not accurate enough. Without considering the location of each ship and distribution of fuel supply, it cannot reflect actual maritime traffic and the spatial-temporal features of ship emission.

Jin *et al.* (2009) conducted a survey of ships at Port of Tianjin, and established an inventory of air pollutants with the top-down approach, providing a reference for the formulation of regulations and policies on ship pollution control at Port of Tianjin. The fuel-based approach is also applied to estimate the emission of pollutants from fishery vessels in Guangdong Province. (Jin *et al.*, 2009; Ye *et al.*, 2014) The calculation was based on the average fuel consumption coefficient of typical fishery vessels, which represented the average fuel consumption level of different types of fishery vessel. Corbett *et al.* (1999) and Ye *et al.* (2014) used the emission test data at that time and a fuel-based approach to estimate the global inventory of ship emission. They estimated the global annual NOx and

SOx emission in 1993, where NOx emission accounted for more than 14% of all NOx emission from fossil fuel combustion and SOx emission exceed 5%. A study for the North of Portugal was reported by the Commission for the Coordination and Development of the Northern Region (CCDR-N) (CCDR-N, 2014). The emission of CO_2, SO_2, NO_x, VOCs and PM were calculated from ships at Leixoes Port. However, it only considered the emission during maneuvering, hotelling and loading/unloading.

With the development of AIS (Automatic Identification System), a new method of emission measurement based on ship activity emerged, namely the bottom-up approach. This method uses detailed information on the vessel characteristic, such as ship size, type, engine power, fuel category, and the operating data combing with emission factor and load factors. It can estimate emission over different time periods and sailing conditions. The emission inventory obtained by bottom-up method can also show the spatial distribution characteristics of ship emission because AIS can obtain the real-time position of ships, which is suitable for the calculation of high spatial resolution. So far, AIS data seem to be the most reliable and accurate approach to describe shipping activities (Nunes *et al.*, 2017).

What's more, the United States ICF Advisory Agency published a report on the calculation method of mobile emission inventory for US ports (ICF International, 2009). It introduced the method of measuring emission based on ship engine power and activity time. It also detailed the calculation and acquisition of the emission factor, engine power ratio, load factor and fuel correction factor, and has important reference value, which had important reference value. The United States (Starcrest Consulting Group, 2009) has been acquiring the Port of Los Angeles' annual ship activity data through AIS, and combining Lloyd's Register's ship characteristics information to estimate air pollutant (SCG, 2009). They found that the total amount of air pollution discharged by ocean going vessels is 39.5% of the total emission in port area. Perez *et al.* (2009) introduced how to use and process the data obtained from AIS to measure ship emission in detail, providing a technical reference to improve the accuracy of emission inventory (Perez *et al.*, 2009; Entec UK Limited, 2010) used AIS data to establish a list of UK air pollutant emission of ocean-going ships and inland river ships by estimating the engine power of different types of ships. They also calculated the emission of the ship engines and oil-fired boilers (Entec UK Limited, 2010). In addition, the uncertainty of the emission factors was also analyzed and evaluated. Berechman and Tseng (2012) conducted an emission inventory at Port of Kaohsiung in Taiwan to estimate the associated emission costs of ships and trucks that operate in that port during 2010 (Berechman and Tseng, 2012). Using a bottom-up methodology, they found that tankers, containerships and bulk ships were the major contributors to ship emission. Ng *et al.* (2013) obtained activity data and ship characteristics of 37152 ocean-going vessels which calling at Hong Kong in 2007 through AIS and statistical data of maritime bureau. The emission inventory showed that ocean-going vessels are the largest source of NOx, SOx and PM besides power plants in Hong Kong (Ng *et al.*, 2013; Tan *et al.*, 2014) calculated the emission of PM_{10}、NO_x、SO_x, HC and CO_2 from Port of Dalian based on AIS data and found that hoteling produced the largest amount of emission (Tan *et al.*, 2014). They also proposed the establishment of an emission control area to control the speed and fuel sulphur content of ships entering to reduce emission. Maragkogianni and Papaefthimiou (2015) used sea-web to obtain the characteristic and AIS data of inbound and outbound cruise ships from five major cruise ports in Greece and calculated the emission of SOx, NOx and $PM_{2.5}$ (Maragkogianni and Papaefthimiou, 2015). The total amount of air pollutants discharged during the cruise ship's arrival in Hong Kong accounted for 88.5% of the total discharge of cruise ships in the vicinity of the port. They also estimated the economic loss including the impact on residents' health and the diversity of species and crops. Song (2015) also used the activity-based approach to establish the emission inventories of Qinhuangdao, Qingdao, Tianjin and Huanghua (Song, 2015). The results showed that container ships and bulk carriers were the main types of ships discharged. The main engine was the primary source among the three engine types of ship discharge.

From the spatial distribution map of ship pollutants, 15 miles away from the port was the most densely discharged area. Fan *et al.* (2016) obtained the ship activity level data in the Yangtze River Delta region within 400 km of the coastline, and ship parameters on main and auxiliary engine power, design speed and gross tonnage from the Lloyd's Register of Shipping and CCS. The results showed that the emission in the Yangtze River Delta region within 100 km and 200 km of the coastline respectively accounted for 60% and 85% of the total ship emission (Fan *et al.*, 2016; Li *et al.*, 2016) indicated that SOx, NOx and PM_{10} emission from marine vessels in the Pearl River Delta accounted for 14.1%, 11.6 and 1.5% of the total amount (Li *et al.*, 2016). They also proposed that the residents' health effects and economic losses caused by ship discharge should be taken into consideration. Xing *et al.* (2016) stated that ship traffic in Bohai Sea was obtained based on AIS data and the marine emission inventory was calculated based on the determined model parameters (Xing *et al.*, 2016).

The bottom-up method based on AIS statistics is proved to be applicable for the calculation of regional maritime emission (Entec UK Limited, 2002; APA, 2016b).

3. METHODOLOGY

3.1. Study Domain

As shown in Figure 1, the study domain in this paper is based on the scope of the Yangtze River Delta ECA. The connection between point A, B, C, D, E, and F is part of the boundary of ECA. The enclosed area in Figure 2 covers the outer harbor channel waters of ocean-going vessels entering and leaving Port of Shanghai. Each dot represents a ship equipped with AIS.

Fig-1. The scope of Yangtze River Delta ECA
Source: Ministry of Transport of PRC

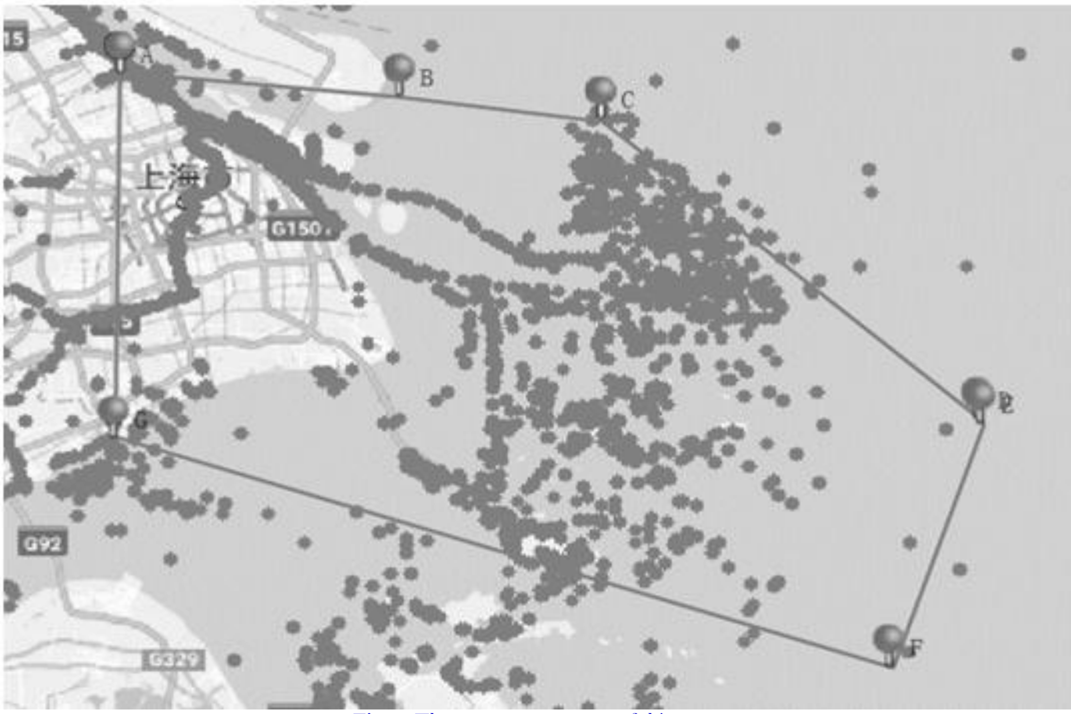


Fig-2. The measurement area of this paper

Source: Modified from www.shipxy.com

3.2. Data Collection

A certain number of ships are selected according to different types, sub conditions and emission sources. The classification of ship emission sources facilitates the establishment of ship emission source inventories and the study of feature analysis. In this paper, the main types of ocean-going vessels are classified into seven categories: oil tankers/chemical ships, container ships, bulk carriers, roll-on-roll-off ships, liquefied gas ships, general cargo ships and cruise ships. Since the AIS data is abundant, we select three vessels for each type of ship, thus 24 vessels' statistics are collected from 01/01/2017 to 31/12/2017. The emission sources are subdivided into host, auxiliary and oil-fired boilers for a single vessel.

A ship has different navigational status during a complete voyage, which generally based on its sailing speed. And it has different emission characteristics under different operational modes. The operation modes of ships near port area are divided into the following four categories based on Entec UK Limited (2010); Ng *et al.* (2013) etc.

Table-1. Operation Modes of Ships

Ship operational mode	Speed
Fairway cruise	>12 knots
Slow cruise	8-12 knots
Maneuvering	1-8 knot (s)
Hotelling	<1knot

Source: Entec UK Limited (2010) and Ng *et al.* (2013)

3.3. Emission Model

This paper obtains the navigational trajectory data of target ships entering and leaving Port of Shanghai during the whole year of 2017 based on AIS data. And a ship emission estimation model is established according to the activity-based approach *so as to measure the air pollutant emission of ships including SOx, NOx and PM. With reference to the emission estimation models of Starcrest* (Ng *et al.*, 2013) and Entec UK Limited (2010) *the formula for calculating the total emission of a single vessel is as following:*

$$E = \sum_i \sum_j \sum_k \left(MCR_i \times Act_{ij} \times LF_{ij} \times EF_{ik} \times FCF \times CF \times 10^{-6} \right) \qquad (1)$$

Where E is the total emission of SOx, NOx, and PM of the target ship; MCR_i *(Maximum Continuous Rating) is the installed engine power of engine i (kw);* Act_{ij} *is the operation time of engine i under operation mode j (h);* LF_{ij} *is the load factor of engine i under operation mode j;* EF_{ik} *is the emission factor of engine i for air pollutant k* （g/kW·h）; FCF is the fuel correction factor; CF is an emission modifying factor; i (i=1, 2, 3) means the main engine (ME), auxiliary engine (AE) and oil-fired boiler (B) respectively; j (j = 1, 2, 3, 4) is the operation mode, which indicates fairway cruise, Slow cruise condition, maneuvering condition and hotelling condition; K (k=1, 2, 3) is the number of major air pollutants, namely SOx, NOx and PM.

According to the target ships of this paper, the power of main and auxiliary engines can be found in the ship records of Clarkson SIN and China Classification Society (CCS) through its MMSI and IMO numbers.

The function of boiler is to generate steam to meet the needs of marine oil heating and domestic water supply. When ocean going vessel is under cruise condition, fuel boiler is generally closed since the exhaust gas boiler can absorb a large amount of heat generated by the main engine to produce steam. When the ship is under hotelling and maneuvering conditions, the main engine is closed or operated at ultra-low load power, the fuel boiler is turned on to ensure adequate steam supply. Since neither IMO nor major classification societies require shipowners to provide data on the power of boiler, there is a lack of information on the boilers in ship archives. The average estimation data of boiler rated power are obtained from Entec UK Limited (2010) and ICF International (2009). (See Table 2) The *formula of main engine's load factor is* SCG (2014)*:*

Table-2. Average Rated Power of Oil-fired Boiler（kW)

Ship type	Average rated power of oil-fired boiler（kW)
Container ship	506
Oil tanker / Chemical ship	371
Bulk carrier	132
Liquefied gas ship	371
Ro-Ro ship	246
Cruise ship	1393
General cargo ship	137

Source: Entec UK Limited (2010) and ICF International (2009)

$$LF_m = (AS/DS)^3 \qquad (2)$$

Where $\mathbf{LF_m}$ *is the load factor of the ship's main engine; AS stands for the actual speed (knot); DS is the design speed (knot).*

The auxiliary engine runs in all modes to generate electricity for lighting, cooking, heating, pumps, auxiliary blowers, bow propellers, etc. The main reasons that affect the load factor of the auxiliary engine are the ship operation modes and types. The estimated values obtained by the VBP in Port of Los Angeles and Long Beach are generally used (SCG, 2007). The average load factor under the slow cruise condition is referenced in the report of the ICF in 2009 (ICF International, 2009). See Table 3 for details.

Table-3. Load Factor of Auxiliary Engine under Different Operation Mode

Ship type	Fairway cruise	Slow cruise	Maneuvering	Hotelling
Container ship	0.17	0.27	0.45	0.22
Oil tanker/Chemical ship	0.13	0.25	0.48	0.19
Bulk carrier	0.80	0.80	0.80	0.64
Liquefied gas ship	0.24	0.28	0.33	0.26
Ro -Ro ship	0.20	0.34	0.45	0.32
Cruise ship	0.15	0.30	0.45	0.26
General cargo ship	0.24	0.28	0.33	0.26

Source: ICF International (2009)

Since the fuel boiler is only turned on when the main engine is under low load rate or closed. It is considered that the boiler is in a high-load operating state during work and operates at its rated power during the working period to ensure sufficient steam supply on the ship. The load factor is assumed as 1 in this paper.

The emission factor is one of the most important parameters for estimating air pollutant emission from ships. This paper assumes that the ships use marine residue oil with 2.7% m/m sulfur content during non-berthing period. Referring to the SOx and NOx emission factors provided by Entec UK Limited (2002) and IVL (David and Tomas, 2004) the PM emission factors calculated by CARB (Sax and Alexis, 2007) and the NOx emission factor for ship diesel engines built in 2000 and 2011 is adjusted by Starcrest (SCG, 2007). The amended emission factors are shown in Table 4.

Ocean-going ships generally use low-speed and medium-speed diesel engines (ICF International, 2009). The main engine power and rotational speed of 24 target ships are recorded in Clarkson SIN, so each ship has the corresponding date and type of the main engine emission factor.

Table-4. Air pollutant emission factors of the main engines（g/kW·h）

Type of diesel engine	Year of manufacture	SOx	NOx	PM10
Low-speed diesel engine	2000-2010	10.5	17.0	1.5
Medium-speed diesel engine	2000-2010	11.5	13	1.5
Low-speed diesel engine	≥2011	10.5	15.3	1.5
Medium-speed diesel engine	≥2011	11.5	11.2	1.5

Source: SCG

The emission factors of marine auxiliary engines and oil fired boilers also refer to the research data of Entec UK Limited (2002) IVL (David and Tomas, 2004) and CARB (Sax and Alexis, 2007) and adjustments have been made to the NOx emission factors based on TierI, TierII, and TierIII for NOx emission in MARPOL Annex VI. The specific data is shown in Table 5 and Table 6.

Table-5. Air Pollutant Emission Factors of Auxiliary Engines（g/kW·h）

Year of manufacture	SOx	NOx	PM10
2000-2010	12.3	13.0	1.5
≥2011	12.3	11.2	1.5

Source: Entec UK Limited, IVL and CARB

Table-6. Air Pollutant Emission Factors of the Boiler（g/kW·h）

SOx	NOx	PM10
16.5	2.1	0.8

Source: Entec UK Limited, IVL and CARB

Since the actual type and sulphur content of the fuel differ from the emission factors in the calculation formula, it is necessary to add fuel correction factors to adjust the emission factors. This paper uses the fuel correction factors based on the oil with 2.7% mm sulfur content, according to Starcrest (SCG, 2007) and IMO 2014 (Sax and Alexis, 2007). (See Table 7)

Table-7. Fuel Correction Factors

Fuel type	Sulphur content	SOx	NOx	PM
RO	1.50%	0.820	1.000	0.560
MDO/MGO	0.50%	0.185	0.940	0.250
MDO/MGO	0.25%	0.093	0.940	0.200
MDO/MGO	0.10%	0.040	0.940	0.170

Source: SCG and IMO

4. RESULT AND DISCUSSION

The air pollutant emission from 24 ships in the study domain are calculated by Matlab based on ship activity data and emission factors. As shown in Table 8, it includes the full use of heavy oil with 2.7% m/m sulfur content and low sulfur oil with 0.5% m/m sulfur content during berthing after the implementation of the ECA Act.

Table-8. Air Pollutant Emission of Target Vessels

		2.7% m/m sulfur content			0.5% m/m sulfur content		
Ship type	MMSI	SOx	NOx	PM	SOx	NOx	PM
Container ship	357747000	2.03	1.56	0.20	1.30	1.53	0.15
	477189200	1.57	0.90	0.13	0.68	0.88	0.07
	371218000	2.87	3.07	0.34	2.22	3.03	0.28
Oil tanker/Chemical ship	412380030	0.79	0.34	0.06	0.41	0.33	0.04
	413630120	0.79	0.54	0.08	0.41	0.52	0.05
	413303250	1.50	0.75	0.12	0.65	0.73	0.07
Bulk carrier	414775000	1.65	1.50	0.19	1.29	1.48	0.16
	477100600	1.79	1.46	0.19	0.81	1.41	0.11
	413440160	0.37	0.30	0.04	0.29	0.30	0.03
Liquefied gas ship	311000373	1.17	1.30	0.15	0.85	1.29	0.12
	477413600	1.55	1.78	0.19	1.21	1.76	0.16
	477348600	2.74	2.93	0.27	2.15	2.90	0.22
Ro -Ro ship	412381120	0.63	0.51	0.07	0.50	0.50	0.06
	538004759	1.29	1.33	0.16	0.91	1.31	0.12
	413378790	0.56	0.45	0.06	0.46	0.45	0.06
Cruise ship	249054000	1.54	1.72	0.18	1.24	1.70	0.15
	247187600	5.22	6.13	0.64	4.03	6.06	0.52
	311000267	4.53	4.68	0.55	3.70	4.63	0.47
General cargo ship	477040800	1.25	1.65	0.16	1.07	1.64	0.14
	413301680	1.28	1.13	0.14	1.11	1.12	0.13
	412408080	0.60	0.41	0.06	0.36	0.40	0.04

It can be found that replacing low sulfur oil has a significant effect on reducing SOx and PM emission. And it has little effect on reducing NOx emission since they are almost independent of ship sulphur content.

Table-9. Emission Reduction Rates of Target Vessels

Ship type	MMSI	SOx	NOx	PM
Container ship	357747000	35.96%	1.92%	25.00%
	477189200	56.69%	2.22%	46.15%
	371218000	22.65%	1.30%	17.65%
Oil tanker/ Chemical ship	412380030	48.10%	2.94%	33.33%
	413630120	48.10%	3.70%	37.50%
	413303250	56.67%	2.67%	41.67%
Bulk carrier	414775000	21.82%	1.33%	15.79%
	477100600	54.75%	3.42%	42.11%
	413440160	21.62%	0.00%	25.00%
Liquefied gas ship	311000373	27.35%	0.77%	20.00%
	477413600	21.94%	1.12%	15.79%
	477348600	21.53%	1.02%	18.52%
Ro-Ro ship	412381120	20.63%	1.96%	14.29%
	538004759	29.46%	1.50%	25.00%
	413378790	17.86%	0.00%	0.00%
Cruise ships	249054000	19.48%	1.16%	16.67%
	247187600	22.80%	1.14%	18.75%
	311000267	18.32%	1.07%	14.55%
General cargo ship	477040800	14.40%	0.61%	12.50%
	413301680	13.28%	0.88%	7.14%
	412408080	40.00%	2.44%	33.33%

The current ECA in China is essentially a sulfur emission control area, which is different from the four major international emission control zones approved by IMO, and does not restrict the emission of marine NOx. Therefore, this is also a matter to consider when formulating the next stage of emission control zone standard.

The average emission reduction rates of the seven types are 30.52%, 23.28%, 20.65%, 14.23%, 13.84%, 12.66% and 12.30% respectively. Oil tanker/chemical ship ranks the first in emission reduction, followed by container ship, bulk carrier, liquefied gas ship, general cargo ship, cruise ship and ro-ro ship.

Figure 3 shows the emission reduction rate of air pollutants. As can be seen, oil tanker/chemical ship and container ship have the highest reduction in pollutant emission. Probably because that they have longer berthing time in comparison with other types of ships. SOx and PM emitted from auxiliary engines and boilers during the berth period account for a large proportion of the total emission. Therefore, the use of low-sulfur oil during berthing has a significant reduction in emission.

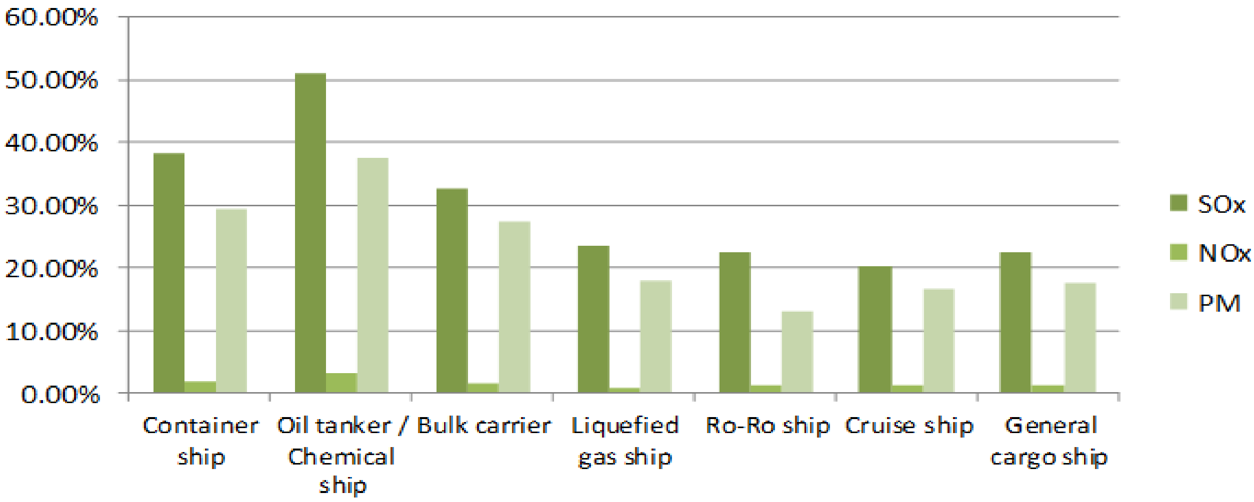


Fig-3. Average emission reduction rate of air pollutants when using 0.5% low sulfur oil

4.1. Emission Sharing Rate of Different Ship Type

Due to different purpose, actual sailing speed, port berthing time and engine power, the characteristics of emission vary with ship type. In order to better understand the impact of ECA on ship emission, it is necessary to analyze the air pollution emission sharing rate of different ship type.

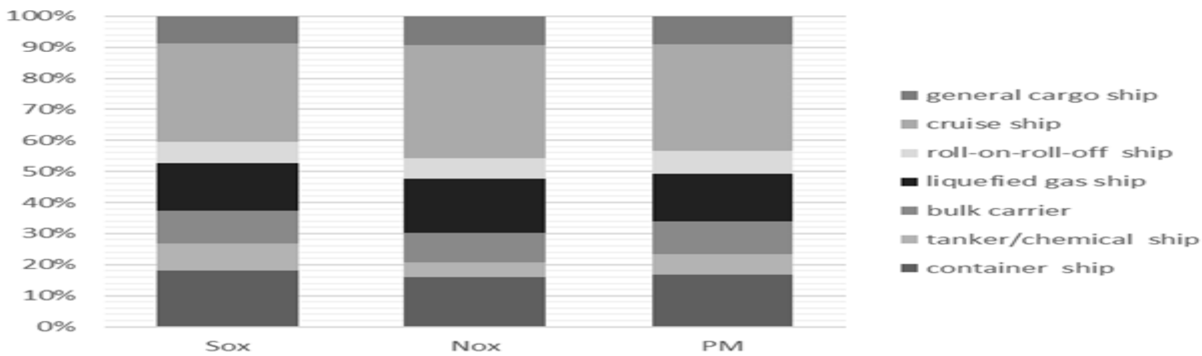


Fig-4. Emission Sharing Rate of Different Ship Type

As shown in Figure 4, among the seven types of ocean-going vessels, cruise ships, container ships and liquefied gas ships have the highest share of pollutant emission. The total amount of SOx, NOx and PM emitted by them accounted for 65.01%, 69.89% and66.58% of all ship types respectively. The main reason is that the average tonnage and main engine rated power of these three types of ships are higher than others. In addition, the design speed and cruising speed of cruise ships and container ships are higher than others. Therefore, the heavy load of the main engine during cruising and slow cruising conditions will discharge more pollutants. Accordingly, law enforcement officers can give priority to inspection of ships such as cruise ships, container ships and liquefied gas ships with large tonnage and high emission.

4.2. Emission Sharing Rate of Different Engine Type

The air pollutant emissions of different engine type are shown in Figure 5. It can be seen that three kinds of air pollutants discharged by main engine head the list. And the SOx, NOx and PM emitted by main engine account for 54.3%, 56.4% and 60.9% of the total emission. Because of the large tonnage of ocean-going vessels, the output power of the main engine is much larger than that of auxiliary engine and boiler. What's more, the main engine discharges large amounts of pollutants at high load under fairway cruise and deceleration conditions.

Engine type has significant influence on ship emission, and the air pollutants discharged by main engines and auxiliary engines account for the major part. The reason is that their rated power is much larger than that of boilers. However, the SOx emission sharing rate of boilers reaches 13.2%. This is because the berthing time of ocean-going ships is long, and the SOx emission factor of boilers is larger than that of main and auxiliary engines. Therefore, compared with NOx and PM, the boiler shares more in SOx emission.

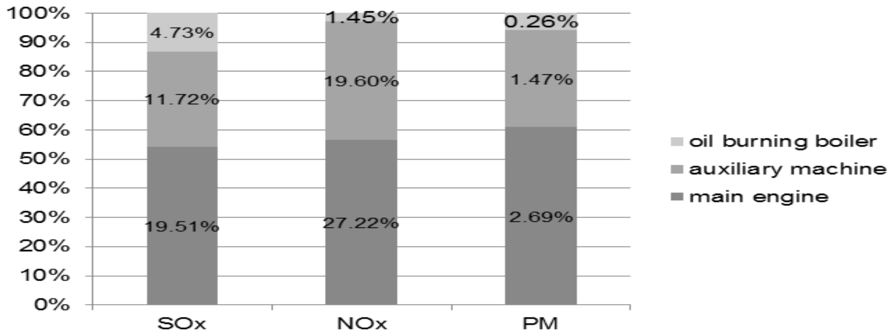


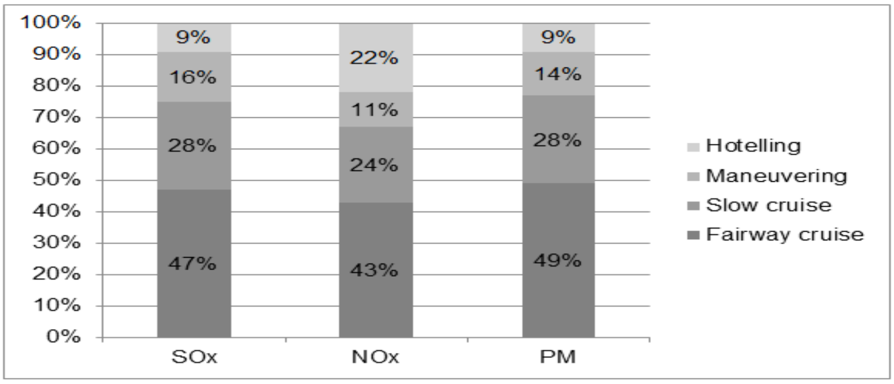
Fig-5. Air Pollutant Emission Sharing Rate of Different Engine Type

4.3. Emission Sharing Rate under Different Navigation Conditions

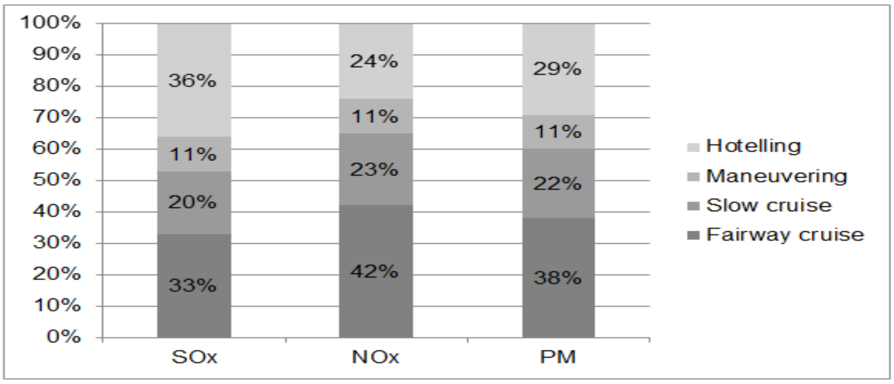
The analysis of the pollution degree under different conditions will help the relevant departments to understand the emission characteristics of each stage, namely fairway cruise, decelerating, maneuvering and hoteling, and provide basis for establishing more specific emission reduction measures. Comparative analysis is conducted based on the use of low sulfur oil before and after 01/01/2017. (See Figure 6 a and b).

It can be seen from Figure 6 that the emission sharing rate of NOx and PM occupy the largest amount under fairway cruise when heavy oils with 2.7% m/m sulfur content are used, reaching 42% and 38% respectively. This is because the ship is sailing in high speed under fairway cruise, under which both main engine and auxiliary engine are operated at high loads. The SOx emissions under hotelling are slightly higher than fairway cruise before the oil change measures are taken.

There are two reasons lead to such circumstances. On one hand, the time under hotelling is the longest. Although the rated power of auxiliary engine and boiler are smaller than that of the main engine, long-term operation results in a large amount of emission. On the other hand, the SOx emission factor of boiler is larger than that of the main engine and auxiliary engine based on the same sulfur content of fuel. So in comparison with NOx and PM, the sharing rate of SOx under hotelling is slightly higher than that of fairway cruise. When the ships use the fuel with 0.5% m/m sulphur content, it is obvious that the emission sharing rate of SOx under hotelling have dropped from 36% to 9%. The air pollutant emission during this period has noticeably reduced.



a) Without Oil Change



b) With Oil Change

Fig-6. Air pollutant emission sharing rates under different conditions

4.4. Implications for the Next Phase of ECA Act

The previous comparative analysis provides some references for whether and how to formulate new ECA emission control requirements after 2020. As regulated by IMO, the time limit for ships to use the fuel with less than 0.5% sulphur content in a global level from 01/01/2020 is more and more stringent. China's emission control requirements in the current stage should be consistent with this standard. If the existing standards are still implemented in the future, ECA will lose its practical significance. Therefore, more stringent emission control requirements must be formulated to reflect the significance of ECA. If referring to the current ECA emission standards of sulfur oxides, ships are required to change fuel from less than 0.5% sulphur content to less than 0.1%. This is an enormous challenge for regulators, oil supply enterprise and shipping companies.

Therefore, this paper proposes to implement new emission standards after 2020. During the period from 01/01/2020 to 31/12/2020, fuel with less than 0.5% sulphur content is required for ships entering the ECA, and the fuel with less than 0.1% sulphur content should be used during berthing in ECA. After 01/01/2021, ships should use the fuel with less than 0.1% sulphur content when enter the ECA. At the same time, the scope of China ECA could extend to 24 sea miles along the coast, and even part of the exclusive economic zone (EEZ) could also be included.

5. CONCLUSION

In this paper, 24 typical ocean-going vessels at Port of Shanghai are selected as research objects. The activity-based approach is used to measure the air pollutant emission of in two phases before and after the implementation of China's ECA Act. Feature analysis of ship emission is then conducted and categorized as different ship type, engine type and navigation condition. First, the average emission reduction rate of oil tankers/chemical ships, container ships, bulk carriers, liquefied gas ships, general cargo ships, cruise ships and roll-on-roll-off ships are 30.52%, 23.28%, 20.65%, 14.23%, 13.84%, 12.66% and 12.30%. Therefore, the ECA Act has a significant effect on the control of air pollutant emission. Second, main engine is the largest source of emission. The SOx, NOx, and PM emission share rates are 54.3%, 56.4%, and 60.9%. Therefore, changing the use of low sulfur oil during fairway cruise and slow cruise can reduce more pollutant emission. The auxiliary engine is the second largest source, and the emission sharing rates of SOx, NOx and PM are 32.6%, 40.6% and 33.3%. Increasing the proportion of using shore power will reduce the emission from ships. Third, NOx and PM have the largest share of emission under fairway cruise conditions, and SOx has the largest share of emission under hotelling. The emission sharing rate of SOx, NOx and PM dropped from 35%, 24% and 29% to 9%, 23% and 9% respectively when the ships use low sulfur oil. Air pollutants emitted by ships in ports are significantly reduced.

Finally, Implications for the next phase of ECA Act are proposed in enacting stricter emission control standards and expanding the scope of ECA after 2020.

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