Evaluation model and Measurement for Reducing Carbon Emission Considering Port Activities

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Abstract. This study employs a "bottom-up approach" to analyze the unique characteristics of production activities at container terminals in Shanghai Port. The activities are divided into two processes: ship docking and in-port operations. The "emission factor method" is applied, where the greenhouse gas emission coefficient is multiplied by the activity energy consumption to determine the emissions. By developing the STEAM model under specific conditions such as engine energy selection, activity time, and operation volume, the emissions of container ships in the port are quantified. Furthermore, a numerical calculation model is created to measure the emissions resulting from in-port operations at container terminals. Comparing carbon emission intensities reveals that ships in port and in-port operations contribute the highest emissions. Finally, this study proposes countermeasures to mitigate the environmental impact, including increasing the utilization rate of shore power and clean energy, optimizing loading and unloading procedures at container terminals, and transitioning from oil to gas or electricity for in-port equipment. The feasibility and rationality of these measures are thoroughly analyzed.

Keywords: Emission Control; Evaluation Model; Port Operations; Bottom-up Method

1 Introduction

Transportation, responsible for approximately 24% of global greenhouse gas emissions, is a major contributor to carbon emissions [1]. To achieve the goal of carbon neutrality, it is essential to exert stronger control over carbon emissions from the transportation sector. Waterway transportation, as a vital mode of transport, plays a crucial role in promoting economic development and urban growth in coastal regions along rivers [2].

Shanghai Port serves as a comprehensive national transportation corridor and a significant hub for domestic and international logistics. It handles a substantial volume of foreign trade material flow, accounting for approximately 20% of the total foreign trade throughput of major coastal ports in China [3]. However, the operations of container

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terminals within Shanghai Port result in significant greenhouse gas emissions, particularly from ship fuel consumption during arrival and departure, as well as the energy consumption of port production and operational machinery [4].

Therefore, accurately quantifying the carbon emissions generated by container terminals at Shanghai Port and formulating effective emission reduction measures in line with national emission reduction policies are crucial.

2 Analysis of emission sources of Shanghai Port Container Terminal

Shanghai Port, strategically located along China's mainland coastline in the Yangtze River Delta region, holds a crucial position as a transportation hub. It serves as the main access point to the Yangtze River basin, Jiangsu, Zhejiang, and Anhui inland river regions, as well as the Taihu Lake basin[5]. Moreover, it is a key intersection point for the east-west transport channel of the Yangtze River and the north-south transport channel of the coastal area. Presently, Shanghai Port encompasses 57 mainline and feeder container berths, covering a total shoreline length of 16,420 meters. These berths are primarily located in three major coastal port areas within Shanghai[6].

During the ship berthing process at container terminals in Shanghai Port, the combustion of diesel fuel gives rise to air pollution. This combustion releases significant amounts of carbon dioxide, sulfur dioxide, and nitrogen oxide gases, leading to substantial pollution[7].

3 Model construction

3.1 STEAM model-based carbon emission measurement method for container terminal ships in Shanghai port

According to the principle of STEAM model, the ship emission calculation equations such as (1), (2), (3), and the emission calculation equation (4) when the ship does not use shore power can be listed.

$$E_g = \sum_i P_{ij} \times LF_{ij} \times T_j \times EF_i \times LLA \tag{1}$$

$$E_b = P_b \times T_j \times EF_b \times LLA \tag{2}$$

$$\text{Eship=Eg+Eb} \tag{3}$$

$$E_s = P_{m_j} \times LF_{m_j} \times T_j \times EF_m \times LLA \tag{4}$$

Where: i is the engine type of the ship (including main and auxiliary engines), j is the different working conditions, Eg is the diesel carbon emission of the main and auxiliary engines of the ship in different working conditions in port, Pij is the rated power of the main and auxiliary engines of the ship, LFij is the load factor of the main and auxiliary engines of the ship in different working conditions, Tj is the activity time of the ship in different working conditions in port, EFi is the carbon emission factor of the ship engine, LLA is the correction factor; Eb is the boiler carbon emission, Pb presents boiler power, EFb is boiler emission factor; Es is the ship engine emission when using shore power, m is the main engine.

3.2 Numerical calculation model of carbon emission of Shanghai port container terminal based on mobile mode loading and unloading process

According to the numerical calculation method of carbon emission of container handling process in mobile mode, the carbon emission measurement equations (5), (6) and (7) of each link of in-port handling operation in Shanghai Port Container Terminal in 2020 can be listed.

$$E_{Mk} = N_k \times (C_k + V_k \times L_k) \times EF_M \tag{5}$$

$$E_{Ek} = N_k \times e_k \times EF_E \tag{6}$$

$$E_n = T_n \times E_k \tag{7}$$

Where: k is the in-port equipment of the container terminal, EM is the CO2 emission per unit container displacement completed by the diesel powered container terminal equipment, EkEk is the CO2 emission per unit container displacement completed by the power powered container terminal equipment, Nk is the number of container movements per unit container completed by the container terminal equipment k, Ck is the fixed diesel consumption per unit operation completed by equipment k, Vk is the variable diesel consumption per unit distance for equipment k to complete unit operation, Lk is the distance per standard container operation completed by equipment k, ek is the electricity consumption per unit operation completed by equipment k, EFM is the diesel CO2 emission factor, and EFE is the grid CO2 emission factor; n is the port production link, and Tn is the average annual operation of the representative equipment in each link.

Equation (5) and (6) can be used to find the CO2 emissions per unit operation of each equipment in the production activities of Shanghai Port Container Terminal, and from this (7) can further calculate the CO2 gas emissions of the loading and unloading link (bridge crane), horizontal transportation link (collector truck) and yard operation link (tire crane) of Shanghai Port Container Terminal in one year.

The comparison of the emission of each link of Shanghai port container terminal can be analyzed according to the carbon dioxide emission intensity of each link. In this paper, carbon emission intensity is defined as the carbon dioxide emissions (unit: kg/TEU) generated by the activity links to complete unit port throughput in one year, and the throughput is calculated on an annual basis, taking the container throughput data of Shanghai port in 2020 as 43.5 million TEU, with an average daily throughput of 120,000 TEU, and calculating and comparing the carbon dioxide emission intensity of each link of Shanghai port container terminal.

4 Analysis of carbon emission measurement results of Shanghai Port Container Terminal

4.1 Calculation of carbon emissions of container ships calling at Shanghai port

When the ship uses the same energy source for power generation (0.5% light diesel), the emission of each link of the ship arriving at Shanghai port can be found by equations (1), (2) and (3), and the emission of the ship without and with shore power can be found by equation (4). The calculation results are shown in Table 1, and the comparison of the emission situation of each link under the two cases is shown in Figure 1. In the case of no shore power, the mooring session relies on auxiliary engines and boilers to generate electricity, which emits the highest percentage of CO2, because the active time of the mooring session is much longer than that of the rest of the session. Therefore, the mooring condition without the use of shore power has the highest emissions.

According to Figure 1, it can be seen that after the ship is connected to shore power, because the shore power system replaces the auxiliary engine and boiler for ship berthing power supply, so the energy consumption of the ship at berthing is negligible, and the emission depends on the energy consumption of the main engine, when the ship cruises within the port waters, the ship does not start to slow down, and the ship speed in this state is much larger than the ship speed in and out of the port and the maneuvering link, so the load factor of the main engine is high when the ship cruises. The actual power is high and the energy consumption of the ship's main engine is high, so the carbon emission is the highest when the ship is driving in this link.

Table 1. Carbon dioxide emissions from ships arriving at Shanghai port by segment

Shore power usage	Activity Sessions	CO2 Emissions (kg)
No shore power	Cruise	3154.37
	Port of entry and exit	1028.76
	Motorized	619.23
	Mooring	9301.77
Use of shore power	Cruise	2928.03
	Port of entry and exit	738.6
	Motorized	31.65
	Mooring	0

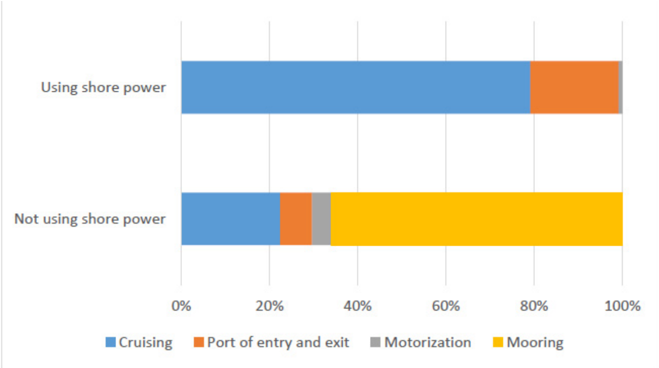

Fig. 1. Comparison of CO2 emissions of container vessels calling at Shanghai port per day

4.2 Calculation and Analysis of Carbon Emissions from In-port Operations at Shanghai Port Container Terminal

Table 2. CO2 emissions per unit TEU of in-port equipment movement at Shanghai Port Container Terminal.

Ring	Equipment	CO2 emissions per unit (kg/TEU)
Lifting	Bridge crane	2.27
	Barge crane	0.91
Stacking	Tire crane	3.94
	Automatic stacker	2.91
	Front cranes	0.06
Horizontal transportation	Container straddle truck	2.91
	Collecting cards	7.49
	Container Forklift	0.28
	Container Tractor	1.35

After the calculation of equations (5) and (6), the carbon emission results of different equipment per unit of operation in Shanghai port container terminal can be obtained as Table 2.

As can be seen from Table 2, in the horizontal transportation link, the emissions per unit of container mobile operation are from high to low: container truck, straddle truck, tractor and forklift, and the highest CO2 emissions per unit of container truck. In the stacking link, the emission intensity of the unit container operation from high to low: tire crane, automatic stacker and frontal crane.

5 Analysis of carbon emission measurement results of Shanghai Port Container Terminal

5.1 Analysis of countermeasures for the use of low sulfur oil fuel for ships

From 3.1, it can be seen that the auxiliary engines and boilers no longer provide electricity when the ship is using shore power, and the ship only consumes energy generated by the main engine when it is moving, so the cruising condition is the highest emission link of the ship under the situation of using shore power. The main reason for the high energy consumption of the engine during cruising is the high energy consumption and high actual power of the ship unit. Therefore, the emission reduction countermeasures for cruising can be considered from the perspective of reducing the energy consumption when the ship is moving.

Therefore, the sulfur dioxide emissions of light diesel fuel with 0.5% sulfur content and light diesel fuel with 0.2% sulfur content can be measured according to the fuel correction factor of 3.2, assuming that all ships use the same shore power, and the results are shown in Table 3.

Table 3. Sulfur dioxide emissions from container ships using different diesel engines at the port of Shanghai in one day (kg)

Ship Type		Sulfur dioxide emissions (kg)
0.5% light diesel	Cruise	9.95
	Port of entry and exit	3.24
	Motorized	1.95
	Mooring	29.28
0.2% light diesel	Cruise	3.87
	Port of entry and exit	1.26
	Motorized	0.76
	Mooring	11.38

When light diesel fuel with 0.2% sulfur content is used for power generation instead of light diesel fuel with 0.5% sulfur content, the sulfur dioxide emissions will be significantly reduced, and the reduced sulfur dioxide gas emissions will be about 60%. Therefore, in order to reduce emissions in the cruising segment, the use of clean energy such as low-sulfur oil light fuel and LNG in ships of shipping companies can be increased. However, the lower the sulfur content of light diesel fuel, the higher the price of light diesel fuel, and the strategy to increase the utilization rate of low sulfur fuel for ships will add additional costs to shipping companies, so it is suggested that the government increase the subsidies for shipping companies to provide economic support for the use of clean energy as ship engines.

5.2 Analysis of countermeasures for the use of shore power on ships

According to the analysis in 4.1, the highest carbon emissions are generated in the berthing session when the ship is in port using auxiliary engines and boilers for power generation and supply. Therefore, reducing the energy consumption of diesel auxiliary engines is the main means to reduce the emissions from berthing conditions. The implementation of shore power policy has enabled the development and use of shore power system, and the use of shore power can replace the energy consumption of fuel engines for ship berthing to a certain extent and achieve emission reduction.

According to the STEAM model of 3.2.2, the sum of emissions from the main engine, auxiliary engines and boilers of container ships in Shanghai port can be calculated by equations (1), (2) and (3), i.e. the ship emissions when no shore power is used; the emissions from the ship when only the main engine generates electricity can be calculated by equation (4), i.e. the ship emissions when shore power is used. The results of comparing the two emissions are shown in Figure 2.

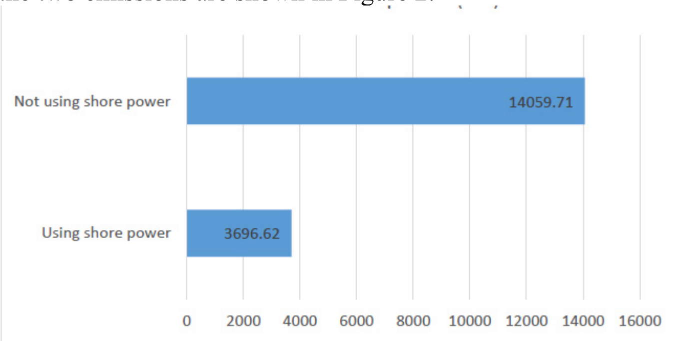

Fig. 2. Comparison of vessel emissions in one day with and without shore power (kg)

From Figure 2, it can be seen that the carbon emissions of container ships in Shanghai port are significantly reduced when using shore power in port, and the reduction ratio of emissions of container ships are all over 60%. Therefore, the use of shore power has a significant effect on the emission reduction of container ships in Shanghai port, and some strategies should be adopted to further improve the utilization rate of shore power for container ships in Shanghai port.

However, due to the standardization of shore power usage, the lack of policy leadership and the fact that the cost of shore power is higher than that of fuel oil, the average utilization rate of shore power for domestic cargo ships is less than 20% (the data of "Asia Clean Air Center" in 2020), which is far from the target. Therefore, up to now, the percentage of emissions from the berthing of ships in Shanghai port is still very high.

6 Summary

This study conducts a comprehensive analysis and review of relevant literature pertaining to transportation carbon emissions, port carbon emission accounting, and research on mitigation measures both domestically and internationally. Additionally, it quantifies the emissions resulting from the production activities of container terminals at Shanghai Port, considering factors such as geographical location, container terminal development, and production characteristics.

Using the STEAM model, the study determines that the highest emission rate of container ships at Shanghai Port occurs during the berthing process when shore power is not utilized. Conversely, the highest emission rate is observed during cruising in port waters when shore power is employed. To effectively reduce ship emissions, the study proposes several strategies. For instance, enhancing the utilization of low-sulfur oil and clean energy for ship engines during cruising in port waters can help reduce the energy consumption of the main engines, thereby achieving a reduction in carbon dioxide and sulfur dioxide emissions.

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