System Dynamics Simulation of CO₂ Emissions from Typical Route Ships

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Abstract: With the development of the shipping industry, the issue of CO₂ emitted by ships has received increasing attention. It is urgent to carry out research on calculation and emission reduction of CO₂ emissions from ships. Ship CO₂ emissions involve multiple fuel consumption, the navigational condition, and other main and auxiliary engines aspects. Based on analysis of ship CO₂ emission calculation methods, this study describes the relationship between ship CO₂ and ship speed, ship status, and main and auxiliary engines. On this basis, the ship's CO₂ emission system dynamic model was constructed, and the ship's CO₂ emissions are simulated according to the actual data. The results show that the proposed ship CO₂ emission system dynamics model can simulate single ship’s CO₂ emission in real-time changes in the cumulative cases and total emissions, the main engine CO₂ emissions account for this voyage ship total CO₂ emissions 86.1%.

1. Introduction
The ship engine emit a variety of atmospheric pollutants into the atmosphere during combustion[1]: carbon dioxide (CO₂), nitrogen oxides (NOx), sulfur dioxide (SO₂), particulate matter (PM), volatile organic compounds (VOCs) and Black carbon (BC) and so on. According to the International Maritime Organization 2014 released in greenhouse gas research report[2], 2012 global shipping CO₂ emissions of about 7.96 Billion tons, accounting for the total global emissions that year of 2.2%.

Shipping is an important part of the global transportation industry and its importance is still increasing. Although shipping is an important means of transportation, the negative impact of greenhouse gases on climate change is also increasing.

The method system applied to ship emission inventory research is divided into fuel method[3], trade law[4] and dynamic method. Compared to the fuel law and trade law, the ship emission inventory based on the AIS dynamic method can obtain the spatial and temporal distribution characteristics of ship emissions.

In China, scholars have for all ship emissions within the target time and space for analysis, such as Wang Zheng, etc. to carry out emission inventories ship carbon dioxide surrounding waters of the Chinese computing[5]; Zhu Qian Ru, etc. based AIS data A refined ship emission inventory in the Pearl River Delta region was established[6]; Xu Wenwen et al. carried out research on inland ship emission inventory [7].

At present, China’s research on the inventory of marine air pollutants mainly focuses on the characteristics and impacts of regional emissions, and there are few studies on the refinement of single ships. System Dynamics (SD, System Dynamics) focuses on the dynamic and causal effects of the system, and can solve complex problems in the case of incomplete information. It is an effective
simulation method for studying information feedback behavior in complex systems [8]. This paper proposes a method for calculating the air pollutant emission of a single ship based on the system dynamics method. Taking a typical route ship as an example, the research on the emission inventory of the modified ship is carried out, and the emission characteristics of different navigational states are analyzed. It provides technical support for air pollution prevention and control of a single ship.

2. Research method

2.1. Research objective
The static information of the ship studied in this study is shown in Table 1. The ship route is shown in Figure 1.

| Ship type | Built year | Engine type                  | Main engine power | Auxiliary machine power | Maximum design speed | Sailing time | Fuel type          |
|-----------|------------|------------------------------|-------------------|------------------------|----------------------|--------------|--------------------|
| Bulk      | 1997       | Low-speed diesel engines     | 9929 kW           | 2200 kW                | 14 knots             | 17 days      | Residual oil (RO)  |

![Figure 1 The ship route](image)

2.2. Calculation method for CO₂ emissions of ships
In this study, it is assumed that the ship’s emission of atmospheric pollutant only come from the main engine and auxiliary engines. Main and auxiliary emissions are marine main, auxiliary ships and various output energy emission corresponding to the emission factor that is multiplied by the function formula based emission factor used in the calculation in g / kW*h for the unit of measurement.

Calculate the calculation formula of the ship's CO2 pollutant emissions based on the real-time power of the ship, be shown in Equation 1.

\[ E_i = MCR \times LF \times Act \times EF_i \times EF_{\text{lowload}} \]  

among them:

\( E_i \) is the emission of certain types of pollutants, the unit is: g ; \( MCR \) is the maximum continuous power of the ship's main engine, the output power of the ship's auxiliary machine (unit: kW*h ), \( Act \) is the time of the ship's navigation, the unit is : h. \( EF_i \) is the emission factor for this pollutant in g/kW*h. \( EF_{\text{lowload}} \) is a low load emission correction factor. \( LF \) is the real-time load of the ship's main engine, the formula is shown in Equation 2.
Ship main engine low load factor formula.

\[
LF = \left( \frac{\text{Speed}_\text{Actual}}{\text{Speed}_\text{Maximum}} \right)^3
\]  

among them:

\( LF \) is the ship's main engine low load adjustment factor, dimensionless unit. \( \text{Speed}_\text{Actual} \) is the actual speed of the ship sailing, unit: knot; \( \text{Speed}_\text{Maximum} \) is the maximum designed speed of the ship, unit: knot.

When the main engine load is less than 20%, the need to adjust the load power of the main engine, the values see Table 2. Auxiliary real output power in accordance with the different type of vessels need to be adjusted state, specific measures to adjust the auxiliary power multiplied by the scale factor ship accessory load, the present study reference ICF research \(^9\) to select an load factor between Table 3.

Table 2 Ship main engine low load emission adjustment factor

| Load factor LF | CO\(_2\) low load emission adjustment factor |
|---------------|--------------------------------------------|
| 1%            | 5.82                                       |
| 2%            | 3.28                                       |
| 3%            | 2.44                                       |
| 4%            | 2.01                                       |
| 5%            | 1.76                                       |
| 6%            | 1.59                                       |
| 7%            | 1.47                                       |
| 8%            | 1.38                                       |
| 9%            | 1.31                                       |
| 10%           | 1.25                                       |
| 11%           | 1.21                                       |
| 12%           | 1.17                                       |
| 13%           | 1.14                                       |
| 14%           | 1.11                                       |
| 15%           | 1.08                                       |
| 16%           | 1.06                                       |
| 17%           | 1.04                                       |
| 18%           | 1.03                                       |
| 19%           | 1.01                                       |
| 20%           | 1                                           |

Table 3 Ship auxiliary machine load proportional coefficient

| Ship type       | Sailing state | Cruise | Low speed | Maneuvering | Berth |
|-----------------|---------------|--------|-----------|-------------|-------|
| Bulk carrier    |               | 0.17   | 0.27      | 0.45        | 0.22  |

Study calculated ship CO\(_2\) emission, the emission sources consider only the main engine and auxiliary engines, and the calculation process will be divided into five types: cruise, slow speed, maneuvering, berth and anchor . The method for judging the navigation status in the calculation of greenhouse gas emissions\(^3\), the specific determination parameters are shown in Table 4.
| Ship speed                     | Status                  |
|-------------------------------|-------------------------|
| Speed < 1 knot                | Berth                   |
| 1 knot ≤ Speed ≤ 3 knots      | Anchor                  |
| Speed greater than 3, and less than 20% of the MCR | maneuvering          |
| MCR greater than 20%, while less than 65% of the MCR | Low speed             |
| More than 65% of MCR         | cruise                  |

### 2.3. System dynamics model construction

According to the function relationship and parameter setting in Section 1.2, this paper uses Vensim PLE software to establish the dynamic model of ship CO$_2$ emission system. The flow chart of system dynamics model is shown in Figure 2.

![Figure 2](image)

#### Figure 2 The ship CO$_2$ emission system dynamic model flow diagram

The model made of 2 level variables, 2 rate variables, 6 auxiliary variables and 5 intermediate auxiliary variable. The two 2 level variables respectively represent the ship main engine CO$_2$ emission amount and the auxiliary ships CO$_2$ emissions; the two rate variables were the rate of ship main engine CO$_2$ units of real time emission amount and the rate of auxiliary ships CO$_2$ units of real time emissionsm, respectively.

The initial conditions of the system dynamics model and the initial values of the model auxiliary variables are shown in Table 5.

### Table 5 The system dynamic model variables and initial values

| Variables                               | Initial value | Unit  |
|-----------------------------------------|---------------|-------|
| main engine CO$_2$ emission factor      | 620.62        | g/kW·h|
| auxiliary engine CO$_2$ emission factor | 772.54        | g/kW·h|
| main engine maximum continuous power    | 9929          | Kw    |
| auxiliary machine total power           | 2200          | Kw    |
| maximum speed of ship design            | 14            | Knot  |
| ship real-time speed                    | By real-time data | Knot |

INITIAL TIME | 0 | Minute
FINAL TIME | 25000 | Minute
TIME STEP | 1 | Minute

### 3. Results and analysis

In this study, the ship's CO$_2$ emission system dynamics model was used to simulate the ship's speed, navigation status and CO$_2$ real-time emissions. The smiulation of ship real speed was shown in Figure3.
The simulation results show, in the voyage of the ship CO\textsubscript{2} total emissions of 1126 tons, of which the main engine CO\textsubscript{2} emissions 969.48 tons, auxiliary CO\textsubscript{2} emissions 157.13 tons. Main engine and auxiliary engines accounted for 86% and 113.9% of the total emissions respectively% and 17% of the total emissions respectively.

The cumulative emissions of the ship's main engine and auxiliary engines are shown in Figure 4.

It can be seen from Fig. 4 that the main engine emission occurs mainly during the dynamic voyage of the ship, and the main engine is closed during the ship's port return. In the figure, the reaction is that the main engine emission increment is 0. The auxiliary engines of the ship has been in the open state, and the cumulative emission curve of the auxiliary engines has been rising. The ship's total emission cumulative curve is the sum of the main engine and auxiliary engines emissions. Its characteristics are similar to the main engine cumulative curve, but the growth rate is slightly larger than the main engine emission growth rate.

The real-time emissions of the ship's main engine and auxiliary engines is shown in Figure 5. It can be seen from Fig. 5 that the ship's main engine emissions significantly with the ship's navigational state, and its change trend and the ship's ship speed situation are always the same. This is because the ship's speed is the external performance of the ship's real-time power output. The ship's CO\textsubscript{2} emission is the real-time performance of the ship's energy consumption. The two are consistent.
4. Conclusion

The system dynamics method can calculate the CO$_2$ emissions of a single ship. The system dynamics method can calculate the CO$_2$ emission of a single ship. The ship CO$_2$ system dynamics model constructed by system dynamics method can clearly show the causes of ship CO$_2$ production and the external conditions related to CO$_2$ emission.

During the 17-day voyage of the ship studied, the total CO$_2$ emission from the ship was 1126 tons, and the CO$_2$ emission from the main engine accounted for 86.1% of the total emission. Auxiliary engines accounts for 13.9% of total emissions.

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