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Ship Emissions Inventory and Social Cost in Shanghai Yangshan Port

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Abstract:
This study estimated the in-port ship emissions inventory (CO$_2$, CH$_4$, N$_2$O, PM$_{10}$, PM$_{2.5}$, NO$_X$, SO$_X$, CO, and HC) and the associated social cost in Shanghai’s Yangshan port. A activity-based methodology, supported by the ship-by-ship and real-time data from the modern automatic identification system (AIS), was introduced to obtain accurate estimates of ship emissions. The detailed spatial and temporal emission inventories can be used as input for air quality dispersion modeling in the port and vicinities. The social cost of the emission impact on the Yangshan port coastal regions was then assessed based on the emissions inventories. Finally, the ship emissions was combined with port’s basic operation profiles, i.e. container throughput, ship calls, and port revenue, in an attempt to assess the port’s “eco-efficiency”, which indicates the port performance with social-economic and environmental concerns. This study filled the gap of previous studies by providing the AIS-supported activity-based emission inventory to facilitate the social cost-benefit analysis for the emission abatement policies. The study shows that i) the amount of in-port ship emissions of CO$_2$, CH$_4$, N$_2$O, PM$_{10}$, PM$_{2.5}$, NO$_X$, SO$_X$, CO, and HC in Yangshan port area was 578,444 tons, 10 tons, 33 tons, 1,078 tons, 859 tons, 10,758 tons, 5,623 tons, 1,136 tons, and 519 tons, respectively, with ii) a total social cost of $226.4 million; iii) the values of the three parameters of the port eco-efficiency performance were $28,843 per 1,000TEU throughput, $34,738 per ship call, and $35 million per billion US$ port revenue (3.5% of port revenue) in 2009.

Key words:
Yangshan port; Ship emissions inventory; Social cost; Eco-efficiency; AIS; Air pollution
1. INTRODUCTION

In recent years, China’s coastal cities are paying higher attention to the in-port ship emissions and their impacts on the coastal communities. Although ship transport is widely acknowledged as the most eco-efficient mode in terms of emissions per cargo tonnage transported, the overwhelming share of global trade and increasing port traffic make ship a key contributor of the anthropogenic emissions (Corbett and Fischbeck, 1997; Agrawal et al., 2008; Eyring et al., 2010). Studies show that GHGs, nitrogen oxides (NO\textsubscript{X}), sulphur oxides (SO\textsubscript{X}), carbon monoxide (CO), particulate matter (PM) and hydrocarbon (HC) during engine combustion make up most of the ship emissions (Lloyd’s Register, 1995; Eyring et al., 2005). Ship emissions account for respectively 2.7%, 15%, and 4%-9% of the global anthropogenic CO\textsubscript{2}, NO\textsubscript{X}, and SO\textsubscript{2} emissions (Tzannatos, 2010b). Ship exhaust CO\textsubscript{2} emissions increased from 562 million tons in 1990 to 1.0 billion tons in 2007, taking 3.3% of global total CO\textsubscript{2} emissions, is expected to increase by 150%-250% by 2050 due to the growing freight volumes (Second IMO GHG study, 2009; Heitmann and Khalilian, 2011). In general, all ship emissions will go on having a significant increase in next 10-40 years due to the expanding of the international trade (Eyring et al., 2005).

In-port ship emissions contribute only a small share of the global shipping emissions (Dalsoren et al., 2009). However, they can have serious environmental effect on coastal regions in Europe, Asia and North America, which have dense seaports and busy shipping activities (Derwent et al., 2005; Dore et al., 2007). It is generally agreed that nearly 70% of the ship emissions occur within 400 km of land (Endresen et al., 2003; Eyring et al., 2005, 2010). These close-to-land ship emissions have the significant environmental impact on the coastal communities (Saxe and Larsen, 2004; Corbett et al., 2007). Moreover, as stated by Ng and Song (2010), most of the shipping-related environmental impacts are not brought by explicit accidents, but by routine operations like in-port ship activities. Evidence shows that emissions produced by in-port ships can specifically affect climate (GHGs), regional air quality (NO\textsubscript{X} and SO\textsubscript{X} on acidification; NO\textsubscript{X} on eutrophication and tropospheric ozone formation), and public health (NO\textsubscript{X}, SO\textsubscript{X}, PM and CO\textsubscript{2} for deteriorated lung function, lung cancer, allergies and asthma) particularly for coastal community (Corbett and Fischbeck, 1997; Bailey and Solomon, 2004; Eyring et al., 2010).

The calculation of the ship emissions inventory is normally activity-based and/or fuel-based. An activity-based approach is generally more accurate than a top-down method (Eyring et al., 2010; Yau et al., 2012), because it requires detailed data such as routing, engine workload, ship speed, location, duration, etc. The activity-based emissions inventories can be found in the studies of Trozzi et al. (1995) for Italian ports, Saxe and Larsen (2004) for Danish ports, Yang et al. (2007) for the port of Shanghai, Tzannatos (2010a) for the port of Piraeus (Greece), Ng et al. (2012) for the port of Hong Kong, and Berechman and Tseng (2012) for the port of Kaohsiung. Some recent studies adopted Automatic Identification System (AIS) data into the activity-based methodology, to get even more accurate results. These results could be detailed on a ship-by-ship basis or even on a real-time ship moving-emission basis. AIS was required by IMO on the commercial ocean-going ships for traffic management and safety concern, but recent studies in Texas and the Netherlands (Perez et al., 2009; MARIN, 2011) proved that AIS real-time ship activity data (e.g. ship profile, position, speed, time information, duration, route, etc.) can be used to facilitate the detailed ship emission estimates. However, only a few researchers, such as Olesen et al. (2009), Perez et al. (2009), MARIN (2011), Ng et al (2012), and Yau et al. (2012), have adopted AIS into the full activity-based approach for their studies.

The social cost represents the sum of the private and the external costs (Iannone, 2012; Coase, 1960; Prud’honmme, 2001; Nash, 2003; European Commission, 2008). Some literatures specifically defined social cost as the sum of the external costs that are not internalized, which in transport sector include environmental costs (e.g. emissions, noise, other pollutants), congestion costs, and accident costs (Ozbay et al., 2007). The widely used “social cost of carbon” (SCC) includes “(but not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services” USEPA (2010). This study adopted the similar definition and applied the social cost theory to other emissions. However, work on the evaluation of ship emission social costs is still on its initial stages.
(Tzannatos, 2010b). Most works end at completing the emissions inventory instead of further evaluating the associated local social cost. Only a limited number of studies were found on transport and particularly on ship emission social costs, such as Tzannatos (2010a, 2010b) for Greece, Kalli and Tapaninen (2008) for Finland, Gallagher (2005) for the USA, and TRT reports (Maffii et al., 2007) on global and regional scales. No previous studies have been found on evaluating ship emission social cost in China.

Experience shows that most policy-makings in China’s transport sector regarding atmospheric environmental protection are not supported by extensive social cost-benefit analysis. This is mainly attributed to a lack of the up-to-date emissions inventories and the associated social cost evaluations. It is true as Gallagher (2005) stated that the reliable ship emissions inventories and their social costs, which highlight the environmental burden ship impose upon the society, are essential tools for facilitating the cost-benefit analysis for emission reduction policies and technologies. This study filled the gaps of previous studies on inventory and social cost methodologies, and provided an empirical study of Yangshan port in China’s busiest port cluster – Shanghai. The study features i) a sophisticated in-port ship emissions inventory estimates, by applying activity-based approach and accurate ship-by-ship AIS data; ii) emission associated social costs evaluation; and iii) the port’s eco-efficiency evaluation. The study estimated three GHGs i.e. CO₂, CH₄, and N₂O, and six key air pollutants i.e. PM₁₀, PM₂.₅, NOₓ, SOₓ, CO, and HC from in-port containerships in the Yangshan port area.

2. STUDY AREA

2.1. Geographical scope

Yangshan port is a deepwater container terminal located in Hangzhou Bay, south of Shanghai. The port belongs to Shanghai port cluster in Yangtze River Delta region and has berths over 15 meters water depth that can handle today’s largest containerships. The geographical area covered by this study is the “Yangshan port and close water area” defined by Shanghai Maritime Authority (2005). Fig. 1 shows the boundary line of the port area and the port geographic segments. Terminal I of the port, opened in 2005, can handle 2.2 million TEUs annually and accommodates 5 berths and 17 quay cranes (QCs). Terminal II was opened in December 2006, comprising 72 hectares with 4 berths and 17 QCs. Terminal III started operating since 2007, adding the capacity by 7 berths and 26 QCs. The fourth phase, which is expected to open in 2015, will add 4 million TEUs to the port’s annual capacity. The total cost of port construction may reach $12 billion over 20 years. When operating in full in 2020, the port will have 30 deep-water berths, capable of handling over 15 million TEUs annually (CPHA, 2010; SIPG, 2012).
Yangshan port is designed to be the biggest container terminal within Shanghai port cluster, in terms of water depth and handling capacity. In 2010, the total container throughput of all ports in Shanghai was 29 million TEUs, among which 10.1 million TEUs were handled in Yangshan port, accounting for 35% of the total container throughput in Shanghai. This share has increased from 15% in 2006 to 35% in 2010, indicating Yangshan port is likely dominating Shanghai TEU throughput in the future.

2.2. Shipping Activities

As defined by Port of Long Beach (POLB, 2010), ship activities refers to a series of ship trips by geographic segment and activity mode. This study divided the ship activities in Yangshan port area in seven segments: anchorage, fairway, precautionary zone, precautionary zone to breakwater, harbor transit (within breakwater), docking, and berth. These segments are categorized into four activity modes – “at-sea”, “maneuvering”, “hotelling at anchorage”, and “hotelling at berth”. Segments in a same mode are a series of continuous actions (e.g. ship’s moving at fairway, precautionary zone, and precautionary zone to breakwater), which have very similar features and better to be treated as a whole. The ship activity features was then examined by the four activity modes. In traveling “at sea” (including the segments at fairway, precautionary zone, and precautionary zone to breakwater) all engines keep running, and the speeds range from 12 to 16 knots; in “maneuvering” (including the segment during harbor transit and docking) main engines are normally turned off during docking, and the ship can decelerate to as low as 3.5 knots; during “hotelling at anchorage” while waiting for berth call or “hotelling at berth” while loading/unloading, the main engines are normally turned off, and the speed is nil.

Table 1 shows the detailed activity data observed at each segment in Yangshan port area.
TABLE 1 Ship Activity Segments and Features in Yangshan Port Area

<table>
<thead>
<tr>
<th>Activity Segment</th>
<th>Mode Category</th>
<th>Main Engine</th>
<th>Auxiliary Engine</th>
<th>Boiler Engine</th>
<th>Actual Speed (knots)</th>
<th>Travel Distance (nm)</th>
<th>Duration (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Anchorage</td>
<td>Hotelling-Anchorage</td>
<td>Off*</td>
<td>On</td>
<td>On</td>
<td>0</td>
<td>2-4</td>
<td>Around</td>
</tr>
<tr>
<td>2 Fairway</td>
<td>At-Sea (moving)</td>
<td>On</td>
<td>On</td>
<td>On</td>
<td>12-16</td>
<td>48</td>
<td>Around</td>
</tr>
<tr>
<td>3 Precautionary Zone</td>
<td>At-Sea (moving)</td>
<td>On</td>
<td>On</td>
<td>On</td>
<td>12-16</td>
<td>9-10</td>
<td>0.6-0.9</td>
</tr>
<tr>
<td>4 Precautionary Zone to Breakwater</td>
<td>At-Sea (moving)</td>
<td>On</td>
<td>On</td>
<td>On</td>
<td>12-16</td>
<td>9-10</td>
<td>0.6-0.9</td>
</tr>
<tr>
<td>5 Harbor Transit (within breakwater)</td>
<td>Maneuvering (moving)</td>
<td>On</td>
<td>On</td>
<td>On</td>
<td>Around</td>
<td>Around</td>
<td>Around</td>
</tr>
<tr>
<td>6 Docking</td>
<td>Maneuvering (moving)</td>
<td>Off</td>
<td>On</td>
<td>On</td>
<td>Around</td>
<td>3.5</td>
<td>9</td>
</tr>
<tr>
<td>7 Berth</td>
<td>Hotelling-Berth</td>
<td>Off</td>
<td>On</td>
<td>On</td>
<td>0</td>
<td>0</td>
<td>16-52</td>
</tr>
</tbody>
</table>

Note: *Main engine turns on when ship going out of into anchorage area.

6,518 containership ships visited Yangshan port in 2009, which the statistics was obtained from Yangshan Customs (2011) and Shanghai International Port Group Co., Ltd (SIPG, 2012). This study focuses on the containership fleet because they hold the dominant share of Yangshan port ships. Other crafts, such as tankers, harbor crafts, fisher boats, etc., are not key concerns of the study, and were not reflected in number.

3. METHODOLOGY AND MATERIALS

3.1. Estimation equations

The activity-based methodology and AIS-based data were used in this study for the in-port ship emissions inventory and social cost assessment. The methodology was developed by referring and improving from the previous studies such as ENTEC (2002), IVL (2004), IMO (2009), and POLB (2010). Emissions are estimated as a function of the ship energy demand (in kWh) multiplying an emission factor (g/kWh). The energy demand is related to ship’s maximum continuous rated engine power (MCR), engine load factor (LF), speed (including the actual and maximum speed), duration of the activities (hours), and distance traveled (D). In certain cases the ship is equipped with emission reduction technologies, a control factor (CF) will be introduced in order to adjust the emission factor. In this study, the CF is assumed to be 1, meaning there are no specific technologies installed onboard for emission reduction. The social cost of ship emissions is estimated as a sum result of the emission amount (g or ton) multiplying each emission’s social cost factor ($/g or $/ton). The equations are as following:

\[
\text{Emission} = \sum_{i,j} (\text{Energy demand} \times \text{EF} \times \text{CF})
\]

\[
= \sum_{i,j} (\text{MCR} \times \text{LF} \times \text{Duration} \times \text{EF} \times \text{CF})
\]

\[
= \sum_{i,j} [\text{MCR} \times (\text{AS}/\text{MS})^3 \times (\text{D}/\text{AS}) \times \text{EF} \times \text{CF}]
\]

\[
\text{ESC} = \sum_{i,j} (\text{Emission}_{ij} \times \text{SCF})
\]

where,

- MCR (kW) = maximum continuous rated engine power;
- LF = load factor = (AS/MS)^3;
- Duration (hours) = hours of ship’s actual activity, including “moving hours” (D/AS) and “hotelling hours” (hours spent at anchorage and berth);
AS (knots) = ship actual speed;  
MS (knots) = ship maximum speed;  
EF (g/kWh) = Emission factor;  
D (nm) = ship traveling distance;  
CF = correction factors for emission reduction measures;  
ESC ($) = Emission social cost of ships;  
SCF ($/ton) = Social cost factor of emission;  
i = ship name;  
j = emission type.

In this study, 2,006 sample ship calls were evenly selected from the entire fleet throughout the twelve months in 2009. Fig. 2 shows these sample ship calls summed up in a number of different TEU capacity categories, represents a clear develop pattern of ship numbers throughout the twelve months. The basic data and activity data of the sample ships were then examined and input into the equations above. The detailed explanations of the equation parameters, as well as the values and the sources of the parameters were provided in the section 3.2 to section 3.5. The emission results were then scaled up in order to reach the entire fleet – the 6,518 ship calls at Yangshan port in 2009.

![FIGURE 2 Number of the Sample Ship Calls in 2009](Image)

3.2. Ship basic data

**Maximum continuous rated engine power (MCR)**

MCR is defined as the manufacturer’s tested engine power (POLB, 2010). The values of the MCR for the ship’s main engines were drawn from Lloyd’s Data. By examining the sample ships collected in this study, it is found that the “correlation of determinations” (R^2) between ship capacity (in TEU) and MCR (in kW) is relatively high (R^2 = 0.8965). Fig. 3 shows that the larger designed capacity of ship normally requires the larger main engine MCR, which has relatively larger emission potential.

**Ship maximum speed (MS)**

Same as MCR, ship’s MS is also defined during the manufacturing period. Larger ship normally has larger MS, but MS will reach to a peak range (25-30 knots) regardless of the ship capacity (in TEU).
3.3. Activity data

Activity data represent the ship’s actual actions within port area, including the ship’s actual speed, load factor, travel distance, and moving and hotelling hours. The real-time ship activity data can be obtained from the online AIS platforms such as MarineTraffic, Shipxy, and BLM-Shipping, etc., for AIS is required by IMO on ocean-going ships for better traffic control and safety management. The AIS data used in this study to describe the ship activities are from the BLM-Shipping, which provides sophisticated ship activity information in China.

**Ship actual speed (AS)**

Ship AS can be identified ship-by-ship on the online AIS platform of BLM-Shipping. A fleet sample was selected and the average AS for each ship activity segment was estimated accordingly (Table 1). In Yangshan port, ship AS from fairway to breakwater is ranged from 12-16 knots, while the AS for harbor transit and docking is around 3.5 knots. No AS is found for anchorage and berth hotelling stages.

**Load factor (LF) for Main Engine and the Load Defaults**

LF is the ratio of an engine’s power output at a given speed to the engine’s MCR power. Main engine (propulsion engine)’s load factor is estimated using the Propeller Law (POLB, 2010), which says that main engine load varies with the cube of ship speed (LF=(AS/MS)^3). Usually ship operates at the nominal continuous rating which is 85% of the 90% of MCR. The 90% MCR is usually the contractual output for which the propeller is designed. Hence the usual output at which ship is operated is around 75% to 77% of MCR. However, for the ship traveled within port area, the main engine’s load factor is very low, normally below 20%.

Engine load defaults are usually introduced when the engine load factors are not available. Due to good data availability, the main engine load factor is estimated using the Propeller Law. For other engine types – auxiliary engine and boiler, the defaults were introduced for the engine loads. The information obtained from the Lloyd’s database about the installed power of the auxiliary engine is limited, because the IMO and the classification societies do not require ship owners to provide this information. Therefore this study referred the default data from the previous study (POLB, 2010) for ships with the capacities from 1,000 to 8,000TEUs, and estimated the other load defaults for the ships with the capacities larger than 8,000TEUs on the results of the regression model. Fig. 4 shows the auxiliary engine and the boiler load defaults used in this study.
Similar as AS, the sample fleet data were used to estimate the average D for each activity segment. The actual D is defined as ship’s real distance traveled for a round trip, rather than the direct geographical distance observed on the nautical chart. The average D of round trip ranged from 2 to 4nm in anchorages, around 48nm in fairway, 9-10 in precautionary zone and breakwater area, and around 9nm for harbor transit and/or docking (Table 1). These data came from the BLM-Shipping’s AIS platform on a ship-by-ship basis, and can also be obtained from the Shanghai Maritime Authority (2005).

Data on ships’ moving duration can be either obtained from the BLM-Shipping AIS data or calculated from ships’ average AS and D. Both approaches were employed in this study, the results were compared, and the average moving duration hours were smoothed out. The average moving hours estimated in this study is around 3 hours at fairway, 0.6-0.9 hours at precautionary zone to breakwater, and 2.6 hours at harbor transit and/or docking (Table 1).

Ship hotelling hours depend on port traffic, cargo handling efficiency, and ship capacity (i.e. TEUs to be handled). By using the fleet sample’s AIS data from the BLM-Shipping, it can be determined that the anchorage hotelling takes an average of 6 hours; while the berth hotelling hours depends highly on ship’s TEUs handled at berth, and then was observed with the range from 16 to 52 hours for containerships from 1,000TEU up to 20,000TEU capacities (Table 1).

There are no local EFs estimates for Shanghai, therefore the EFs used in the emission equation here were adopted from the studies of the other countries. Because most ships visited Yangshan port area are “international water-borne navigation” as defined by IPCC (2006), the base EFs used for international ocean-going ships in previous studies (POLB, 2010; ENTEC, 2002; CARB, 2007; IVL, 2004; ICF, 2009) are deemed adoptable for this study. Table 2 below shows the base EFs in g/kWh, by engine type.
### TABLE 2 Base Emission Factors by Engine Type (g/kWh)

<table>
<thead>
<tr>
<th>Emission</th>
<th>Main Engine</th>
<th>Aux Engine</th>
<th>Boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>683.000</td>
<td>683.000</td>
<td>970.000</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.010</td>
<td>0.008</td>
<td>0.002</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.031</td>
<td>0.031</td>
<td>0.080</td>
</tr>
<tr>
<td>PM₁₀₀₀</td>
<td>1.500</td>
<td>1.500</td>
<td>0.800</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>1.200</td>
<td>1.200</td>
<td>0.600</td>
</tr>
<tr>
<td>NOₓ</td>
<td>13.000</td>
<td>14.700</td>
<td>2.100</td>
</tr>
<tr>
<td>SOₓ</td>
<td>11.500</td>
<td>12.300</td>
<td>16.500</td>
</tr>
<tr>
<td>CO</td>
<td>1.100</td>
<td>1.100</td>
<td>0.200</td>
</tr>
<tr>
<td>HC</td>
<td>0.500</td>
<td>0.400</td>
<td>0.100</td>
</tr>
</tbody>
</table>

In general terms, diesel-cycle engines are not as efficient when operating at low loads. Energy and Environmental Analysis, Inc. established a formula for calculating EFs for low engine load conditions such as those encountered during harbor maneuvering and when traveling slowly at sea (e.g. in the reduced speed zone) (EEIA, 2000; POLB, 2010). It is illustrated that compression-cycle combustion engines are less efficient at low loads usually below 20% (Yau et al., 2012; Ng et al., 2012; Jalkannen et al., 2009; POLB, 2010). Under such circumstance, the main engine’s low load adjustment multipliers (LLAM) were used for the correction of the base EFs. Fig. 5 shows the main engine’s LLAMs for the base EFs. For main engine loads below 20%, LLAM increase so as to reflect increased EFs (on a g/kWh) due to engine inefficiency. The influence of low engine load operation on the results of CH₄ and HC is strong, while on other types of emissions is limited.

![FIGURE 5 Main Engine’s LLAMs for the Base EFs](image)

#### 3.5. Emission social cost factors (SCF)

Table 3 shows the range of the SCF (in US$/ton) for each type of emission. Due to the insufficiency of studies on the emission SCFs in China, this study abstracted the average values from the international studies with the consideration of China’s local social-economic development level, therefore gained the SCFs close to China’s reality. The emission SCF for CO₂, CH₄, N₂O, PM₁₀₀₀, PM₂.₅, NOₓ, SOₓ, CO, and HC was estimated to be 29$/ton, 812$/ton, 7,461$/ton, 53,386$/ton, 74,265$/ton, 4,885$/ton, 5,876$/ton, 1,691$/ton, and 1,641$/ton, respectively, for Yangshan coastal region.
TABLE 3 Emission SCFs and Data Sources

<table>
<thead>
<tr>
<th>Emission</th>
<th>Range (US$/ton)</th>
<th>Sources</th>
<th>Value used in this study (US$/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>15-42</td>
<td>USEPA (2010); IPCC (2006); Imperial College London (2008); World Bank (2010); Berechman and Tseng (2012)</td>
<td>29</td>
</tr>
<tr>
<td>CH₄</td>
<td>250-2,500</td>
<td>VTPI (2012); Marten and Newbold (2012)</td>
<td>812</td>
</tr>
<tr>
<td>N₂O</td>
<td>2,700-28,000</td>
<td>VTPI (2012); Marten and Newbold (2012)</td>
<td>7,461</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>2,000-375,888</td>
<td>VTPI (2012); USEPA (2002); Funk and Rabl (1999); UK DEFRA (2004)</td>
<td>53,386</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>1,000-554,229</td>
<td>Funk and Rabl (1999); Berechman and Tseng (2012)</td>
<td>74,265</td>
</tr>
<tr>
<td>NOₓ</td>
<td>269-9,500</td>
<td>Imperial College London (2008); VTPI (2012); World Bank (2010); Gallagher (2005); Berechman and Tseng (2012)</td>
<td>4,885</td>
</tr>
<tr>
<td>SOₓ</td>
<td>379-11,373</td>
<td>Yuan and Cheng (2011); VTPI (2012); World Bank (2010); Gallagher (2005); Berechman and Tseng (2012)</td>
<td>5,876</td>
</tr>
<tr>
<td>CO</td>
<td>160-3,200</td>
<td>VTPI (2012), Funk and Rabl (1999)</td>
<td>1,691</td>
</tr>
<tr>
<td>HC</td>
<td>750-2,500</td>
<td>VTPI (2012), UK DEFRA (2004)</td>
<td>1,641</td>
</tr>
</tbody>
</table>

4. RESULTS AND DISCUSSION

The results include the in-port ship emissions inventory, the emission social costs, and the eco-efficiency of Yanghan port in 2009. All the results are for the entire fleet, namely the 6,518 ship visited in Yangshan port area.

4.1. Emissions inventory

Table 4 shows the estimated in-port ship emissions inventory (in ton) by activity mode and engine type in 2009. The amount of the ship emissions of CO₂, CH₄, N₂O, PM₁₀, PM₂.₅, NOₓ, SOₓ, CO, and HC in Yangshan port area is 578,444 tons, 10 tons, 33 tons, 1,078 tons, 859 tons, 10,758 tons, 5,623 tons, 1,136 tons, and 519 tons, respectively. The emissions during “at-sea” and “hotelling at berth” took the dominant share of the amount during a ship’s entire in-port activity experience. The share of emissions of the two segments in all ranged from 79% to 89%, depending on the emission types. In general, for the in-port ship, the amount of emissions by the main engine and the auxiliary engine is around the same. The main and auxiliary engine altogether accounts for 73% to 98% of the ship emissions, depending on the emission types. However, the main engine is turned off when a ship is hotelling at berth during cargo handling, and the auxiliary engines and boilers are then the dominant contributors in all emissions.

Table 4 Ship Emissions Inventory by Activity Mode and Engine Type (ton)

<table>
<thead>
<tr>
<th>CO₂</th>
<th>CH₄</th>
<th>N₂O</th>
<th>PM₁₀</th>
<th>PM₂.₅</th>
<th>NOₓ</th>
<th>SOₓ</th>
<th>CO</th>
<th>HC</th>
</tr>
</thead>
<tbody>
<tr>
<td>At-sea</td>
<td>252,274.2</td>
<td>7.6</td>
<td>13.7</td>
<td>610.5</td>
<td>488.4</td>
<td>5,817.1</td>
<td>2,394.5</td>
<td>759.1</td>
</tr>
<tr>
<td>Maneuvering</td>
<td>63,465.5</td>
<td>0.7</td>
<td>3.3</td>
<td>104.3</td>
<td>83.1</td>
<td>1,178.2</td>
<td>633.5</td>
<td>90.8</td>
</tr>
<tr>
<td>Hotelling–berth</td>
<td>207,532.7</td>
<td>1.7</td>
<td>12.2</td>
<td>289.7</td>
<td>229.2</td>
<td>3,019.6</td>
<td>2,051.2</td>
<td>229.3</td>
</tr>
<tr>
<td>Hotelling–anchorage</td>
<td>55,171.4</td>
<td>0.4</td>
<td>3.4</td>
<td>73.5</td>
<td>58.1</td>
<td>743.0</td>
<td>543.6</td>
<td>56.6</td>
</tr>
<tr>
<td>Total Emissions</td>
<td>578,443.8</td>
<td>10.4</td>
<td>32.5</td>
<td>1,078.0</td>
<td>858.8</td>
<td>10,758.0</td>
<td>5,622.7</td>
<td>1,135.8</td>
</tr>
<tr>
<td>Main Engine</td>
<td>229,751.7</td>
<td>7.3</td>
<td>13.7</td>
<td>571.0</td>
<td>456.8</td>
<td>5,335.1</td>
<td>2,166.3</td>
<td>725.2</td>
</tr>
<tr>
<td>Auxiliary Engine</td>
<td>241,145.0</td>
<td>2.8</td>
<td>10.9</td>
<td>434.3</td>
<td>347.4</td>
<td>5,190.1</td>
<td>2,431.9</td>
<td>388.4</td>
</tr>
<tr>
<td>Boiler</td>
<td>107,547.2</td>
<td>0.2</td>
<td>9.9</td>
<td>72.7</td>
<td>54.5</td>
<td>232.8</td>
<td>1,024.5</td>
<td>1,024.5</td>
</tr>
<tr>
<td>Total Emissions</td>
<td>578,443.8</td>
<td>10.4</td>
<td>32.5</td>
<td>1,078.0</td>
<td>858.8</td>
<td>10,758.0</td>
<td>5,622.7</td>
<td>1,135.8</td>
</tr>
</tbody>
</table>

Fig. 6 describes the ships’ monthly CO₂ development for the four activity modes in Yangshan port 2009 (CH₄ and N₂O are not shown in this figure due to their extremely small
volumes in tons). The total amount of CO₂, CH₄, and N₂O emission is 578,444 tons, 10 tons, and 33 tons, respectively. The average monthly ship emissions are 48,204 tons, 1 tons, and 3 tons for CO₂, CH₄, and N₂O, respectively. GHG emissions during ship “at-sea” and “hotelling at berth” took the dominant share of the GHGs from the entire ship activity in port. Fig. 7 presents the monthly development of the six air pollutants from the ships in 2009. Total emission amount of PM₁₀, PM₂.₅, NOₓ, SOₓ, CO, and HC is respectively 1,078 tons, 859 tons, 10,758 tons, 5,623 tons, 1,136 tons, and 519 tons, with the monthly average of 90 tons, 72 tons, 897 tons, 469 tons, 95 tons, and 43 tons, respectively. Same as the GHGs, air pollutant emitted during “at-sea” and “hotelling at berth” dominate in all pollutant types emitted along the entire ship trip in port. The monthly emissions of the three GHGs and the six air pollutants reflect the number of ship calls, i.e. the heavier ship traffic founded in port area, the more emissions were identified.
4.2. Emission social cost

In this study, the emission social cost is defined as the sum of the social and environmental costs caused by emissions from ship activities within the Yangshan port area. Fig. 9 shows the estimated amount and the share of the social costs for different types of ship emissions throughout 2009. The total social cost for all ship emissions in the Yangshan port area was estimated to be around $226 million in 2009, accounting for 3.5% of the total port revenue. The social costs of the GHG emissions and other air pollutants are $16.7 million and $209.7 million, respectively, accounting for 7% and 93% of the social cost of all emissions. The four most “costly” pollutants are PM$_{2.5}$, PM$_{10}$, NO$_X$, and SO$_X$, with their social costs being $63.8 million, $57.5 million, $52.5 million, and $33.0 million, respectively, accounting for 28%, 25%, 23%, and 15% of the total emission social cost. Although CO$_2$ emissions has the largest amount (in tonnage) among all types of emissions, its social cost is comparatively low, being $16.5 million in 2009, only taking 7% of the total social cost of all emissions. The reason is, as described in Table 3, that the SCF for CO$_2$ is much lower than other emissions. It is also found that although the amount of PM$_{2.5}$, the most harmful air pollutant to human health, is only 859 tons; its social cost reaches as much as $64 million, due to its high SCF as assessed by Berechman and Tseng (2012), VTPI (2012), USEPA (2002), UK DEFRA (2004), and Funk and Rabl (1999). The social cost of PM$_{2.5}$ and PM$_{10}$ in all is $121.3 million, accounting for 54% of the total. This result agrees with the similar findings from the studies of Tzannatos (2010a), and Berechman and Tseng (2012). Fig. 9 also shows that the emission social cost throughout the twelve months of 2009 is relatively stable, though with certain peaks during March and August due to the increase of ship calls.

FIGURE 8 Correlation between Ship Capacities vs. CO$_2$ Emissions

FIGURE 9 Social Cost of Ship Emissions by Month in 2009
4.3. Port eco-efficiency

Estimating the ship emissions inventory and the social costs is not sufficient for assessing the port operation efficiencies in terms of social-economic and environmental concern. The study combined the inventory and social cost estimates with the port’s operation profiles, in order to evaluate the “eco-efficiency” of the port performance and the ship activities. World Business Council for Sustainable Development (WBCSD, 1992) defined eco-efficiency as the character that can create more goods and services while using less resource and generating less waste and pollution. The “emission efficiency”, defined based on the concept of the “eco-efficiency”, is “the product or service value per environmental influence” (Tahara et al., 2005). In this study, three eco-efficiency parameters were adopted for Yangshan port, which are the emission social cost per port throughput (US$ per 1,000TEUs handled in port), emission social cost per ship call (US$ per call), and the emission social cost per billion US$ port annual revenues (US$ per billion US$ revenue). These parameters can be used to evaluate the port handling efficiency and ship call density in terms of emission impact, as well as the share of the emission cost to the entire port revenue. Table 5 summarizes these eco-efficiency parameters for the port performance. Note that the entire pie of the social cost describes not only the emissions from the ships, but also from harbor craft, heavy-duty vehicles, and cargo handling equipment, etc. However, such port-related land-based emission sources are out of the scope of this study.

<table>
<thead>
<tr>
<th>Emission</th>
<th>Social Cost per Throughput ($/1,000TEU)</th>
<th>Emission Social Cost per Ship Call ($/call)</th>
<th>Emission Social Cost per Port Revenue ($/billion $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>16,485,649</td>
<td>2,100.08</td>
<td>2,529.25</td>
</tr>
<tr>
<td>CH₄</td>
<td>8,432</td>
<td>1.07</td>
<td>1.29</td>
</tr>
<tr>
<td>N₂O</td>
<td>242,748</td>
<td>30.92</td>
<td>37.24</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>57,549,312</td>
<td>7,331.12</td>
<td>8,829.29</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>63,775,063</td>
<td>8,124.21</td>
<td>9,784.45</td>
</tr>
<tr>
<td>NOₓ</td>
<td>52,547,485</td>
<td>6,693.95</td>
<td>8,061.90</td>
</tr>
<tr>
<td>SOₓ</td>
<td>33,039,126</td>
<td>4,208.81</td>
<td>5,068.91</td>
</tr>
<tr>
<td>CO</td>
<td>1,921,167</td>
<td>244.73</td>
<td>294.75</td>
</tr>
<tr>
<td>HC</td>
<td>851,615</td>
<td>108.49</td>
<td>130.66</td>
</tr>
<tr>
<td>TOTAL</td>
<td>226,420,598</td>
<td>28,843.39</td>
<td>34,737.74</td>
</tr>
</tbody>
</table>

Yangshan port received 6,518 ship calls, handled 7.85 million TEUs, and generated revenues of $6.5 billion in 2009 (Yangshan Customs, 2011). The three port eco-efficiency parameters were evaluated by combining the emission social costs with the above operation profiles. Therefore, it cost $28,843 of ship emissions for every 1,000 TEUs handled in Yangshan Port, and $34,738 per ship call. For every billion US$ of port revenues gained in Yangshan Port in 2009, the ship emission social cost generated is $35 million, accounting for about 3.5% of the port revenue.

For GHG emissions, it generated the social cost of about $2,132, $2,568, and $2,586,601 for every 1,000 TEUs handled at berth, for every ship call, and for every billion US$ revenues generated in Yangshan Port in 2009, respectively. CO₂ takes the largest share of the emission social costs among the three GHGs. For other six air pollutants in all, the values for the three eco-efficiency parameters are $26,711, $32,170, and $32,405,673, respectively. Among the three GHGs and six air pollutants in all, PM₂.₅, PM₁₀, NOₓ, and SOₓ take the dominant shares, accounting for about 28%, 25%, 23%, and 15% of the total social cost of all ship emissions, respectively.

5. CONCLUSIONS

As one of the busiest container ports of China, Yangshan port provides data suitable for the empirical study of in-port ship emission estimates. The activity-based methodology with the
ship-by-ship real-time AIS data ensured an accurate emissions inventory, based on which the
associated social cost to the coastal region was evaluated accordingly. The port eco-efficiency
performance was also assessed to facilitate the social cost-benefit analysis for the emission
abatement policies. The meaning of this study is that the AIS-data-based methodology can be
used to set up detailed activity-based emissions inventories and the social cost estimates for a
large port area, encouraging other ports to adopt similar methodology for their ports. Moreover,
the detailed spatial and temporal emission results can be used as input for air quality dispersion
modeling in the port and vicinities.

However, the main uncertainty in this study comes from the emission social cost
evaluation. Because studies on the emission SCFs in China is limited, experts have to refer the
literatures of other countries, and then assume China’s own SCF’s values with the consideration
of local specific social-economic situation. The huge deviation of SCF results among the
existing literatures (especially for PM$_{2.5}$, Table 3), showing that the factors are highly locally
sensitive, which means the SCFs are more suited on a local level. Unfortunately, the local data
shortage in China makes it difficult to conduct extensive research on the local SCFs and gain the
values in a range with high confidence level. The accuracy of emission social cost results in China
is therefore in compromise. This piece of finding implicates that future studies in China should
focus more on the development of the local-specific emission social cost methodology, as well as
the improvement of a more detailed local data system, to facilitate more efficient emission
policy-makings in China. Moreover, other port related emission sources, such as harbor craft,
heavy-duty vehicles, and cargo handling equipment, were not included in this study. In the future
studies, port emissions inventory and the associated social cost results can also be further
improved by including these land-based emission sources.

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