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Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port

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HIGHLIGHTS

- Activity-based ship emissions inventory in Yangshan port based on AIS data.
- Social cost evaluation for ship emission impact on Yangshan coastal region.
- Port eco-efficiency for emissions per throughput, ship call, and port revenue.
- Estimated $287 million social costs of nine emissions in 2009.
- Emission social cost accounted 4.4% of port revenue; NO_x contributed the most.

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ABSTRACT

This study estimated both the in-port ship emissions inventory (CO_2, CH_4, N_2O, PM_{10}, $PM_{2.5}$, NO_x, SO_x, CO, and HC) and the emission associated social cost in Yangshan port of Shanghai. A sophisticated 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. The social cost covers the impact on human health, the environment, and the climate of the coastal community. 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 result shows that i) the amount of in-port ship emissions of CO_2, CH_4, N_2O, PM_{10}, $PM_{2.5}$, NO_x, SO_x, CO, and HC in Yangshan port area was 578,444 tons, 10 tons, 33 tons, 1078 tons (PM_{10}, inducing $PM_{2.5}$), 859 tons ($PM_{2.5}$ only), 10,758 tons, 5623 tons, 1136 tons, and 519 tons, respectively, with ii) a total social cost of $287 million; iii) the values of the three parameters of the port eco-efficiency performance were $36,528 per 1,000 TEU throughput, $43,993 per ship call, and $44 million per billion US$ port revenue (4.4% of port revenue), respectively in 2009.

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_x), sulfur oxides (SO_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_2, NO_x, and SO_2 emissions (Tzannatos, 2010b). Ship exhaust CO_2 emissions increased from 562 million tons in 1990 to 1.0 billion tons in 2007, taking 3.3% of global

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total CO_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 (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_x and SO_x on acidification; NO_x on eutrophication and tropospheric ozone formation), and public health and ecosystems (NO_x, SO_x, PM, CO and HC for deteriorated lung function, lung cancer, allergies and asthma) particularly for coastal community (Corbett and Fischbeck, 1997; WHO, 2000; 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'homme, 2001; Nash, 2003; European Commission, 2008). Some literature 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 all 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. CO_2, CH_4, and N_2O, and six key air pollutants i.e. PM_{10}, $PM_{2.5}$, NO_x, SO_x, 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 m 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 ha 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).

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