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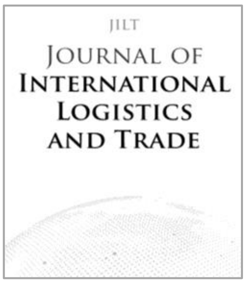
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Estimating socio-economic impact from ship emissions at the Port of Incheon

Young-Tae Chang, Eunbee Kim, Ahhyun Jo, Hyosoo Park*

Graduate School of Logistics, Inha University, Incheon, Korea

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ABSTRACT

Ports create harmful effects on their adjacent population because ships discharge noxious gases like SO_X, NO_X, and particulate matter (PM). To tackle this problem, some ports started to control emission through regulations such as Emission Control Areas (ECA) and Reduced Speed Zone (RSZ). This paper estimates the social cost of ship emission and eco-efficiency at the Port of Incheon (POI). We further examine how the ECA and RSZ designation can reduce the social cost. The estimation is based on the activity-based approach, where ship type, engine, and movement are used to measure fuel consumption and then emission. Results suggest that the social cost of ship emission at the POI amounts to \$90,805,478. The eco-efficiency of the POI, compared to the one at the Port of Las Palmas in another study, is substantially better. Under RSZ, the corresponding emission abatement values are \$4,485,308, \$2,642,009 and \$21,932,435 from SO_2, NO_X and PM reduction, respectively. If 1.0% and 0.1% sulfur fuel are used complying with rules of the ECA, the social cost savings amount to \$8,174,947 and \$12,868,842 from SO_2 reduction.

1. Introduction

Ports play a critical role as an interface between land and maritime transportation. Shipping industry has developed significantly due to containerization, developing intermodal networks, shipping alliance, and increasing vessel size (Bae et al. 2013, Yap and Lam 2006). The resulting reduction in shipping costs led to surge in maritime traffic and international trade (Blonigen and Wilson 2013, Hummels 2007). This could not have been accommodated without corresponding advancement in and support from port operations. In addition, ports generate positive industrial chain effect and value added in regional economy (Chang et al. 2014b). This is why many governments consider ports as strategic nodes and intend to support ports in their jurisdiction to be hubs, and tremendous government subsidies are given to ports.

Still, ports generate harmful effects on their adjacent population because ships discharge many noxious gases like SO_X, NO_X, and particulate matter (PM). These gases can be dangerous to human, increasing respiratory and cardiovascular diseases. For example, Wang and Corbett (2007) found that PM emission from ships worldwide caused 60,000 death each year. Similarly, Tian et al. (2013) estimated that nickel contained in PM_{10} has increased emergency hospital visits for cardiovascular diseases by 1.25% in Hong Kong.

Realizing this problem, policy-makers devised regulations to tackle this problem. The International Maritime Organization (IMO), for instance, designated Emission Control Areas (ECA) in Baltic Sea, North Sea, and North America. Ships in ECAs should use fuel with less sulfur contents or equip scrubbers to filter sulfur in the fuel automatically. In North America, some ports introduced Reduced Speed Zone (RSZ), e.g., the Port of Los Angeles/Long Beach since 2001, the Port of New York/New Jersey since 2009. By requiring ship speed below 12 and

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[*] Corresponding author: Graduate School of Logistics, Inha University, 100 Inha-ro, Nam-gu, Incheon, 22212, Korea
Email: hyosoo.p@gmail.com.

15 knots at these ports, ships consume less fuel and consequently less emission. Literature supports that ECA and RSZ could reduce emissions substantially (Chang et al. 2013, Wang and Corbett 2007).

Numerous studies estimated emission from ships in a port level, as reviewed in the next section. The significance of these papers lies on that measuring emission inventory and its associated social cost are vital to monitor pollution and serve as useful guidance for emission control legislation (Hammingh et al. 2007, Wang and Corbett 2007, Watanabe 2004). Relevant papers employed in this area have mostly used a bottom-up approach to improve estimation accuracy, where emission in an individual ship level is aggregated to obtain total emissions. To this end, they used ship movement, engine type, and fuel type data. Lately, some researchers went further to examine the social cost of ship emissions and measure ecological indicators like port revenue or vessel calls per emission (Maragkogianni and Papaefthimiou 2015, Song 2014, Tichavska and Tovar 2015). These papers, however, only focused on European ports not Asian ports. Asian governments in a potential ECA may be more interested in how emission regulations such as ECA or RSZ can decrease social cost.

Against this back drop, this paper estimates the social cost and eco-efficiency of ship emissions at a potential ECA, the Port of Incheon. This paper further examines how introducing ECA or RSZ can reduce the social cost or enhance eco-efficiency in the POI. This study extends Chang et al. (2014a), who estimated emissions in the POI by ship and activity type but did not measure social cost and eco-efficiency. Our main contribution to literature is twofold. First, we calculate the social cost and eco-efficiency of ship emissions in a port level through the bottom-up approach, which were conducted by few studies. Second, this paper assesses benefits of the ECA and RSZ in terms of the emission social cost, which none of existing studies did.

The rest of sections are organized as follows. Section 2 surveys the literature on shipping emission inventory. Section 3 explains methodology to obtain the social cost and eco-efficiency and describes data collection process. Section 4 reports emission estimates, and section 5 concludes.

2. Literature review

Studies that measured emission inventory can be divided into two categories. The first adopts top-down approach (also called fuel-based approach). The method measures emissions using macro-level fuel consumption data. For example, Tzannatos (2010a) examined emissions at Greek ports from both domestic and international shipping. Due to multiple years of port data, they used fuel sales statistics to estimate the emissions. Recently, more studies employed the bottom-up approach. Unlike the top-down method, the bottom-up one requires detailed ship characteristics, engine type, and ship movement data to capture fuel consumption and then emission level. Tzannatos (2010b) measured noxious gases emitted from passenger and cruise ships at the Port of Piraeus, Greece. The method requires shipping movements to be divided into several phases, e.g. maneuvering or at berth, to incorporate difference in fuel consumption and engine usage by phase. Another interesting application of this method is by Liao et al. (2010). They addressed a very specific policy question, ‘what would be the emission reduction benefit by repositioning the current transshipment port to the one closer to major cities in Taiwan?’ Overall reduction was notable under repositioning because it reduced trucking emission significantly. This study, however, overlooked the health damage inflicted to nearby population. Similarly, Park et al. (2007) estimated the emission reduction benefit of the Alameda Corridor, a railway connecting Port of Los Angeles and Port of Long Beach.

Chang et al. (2013) also performed a similar analysis for the Port of Incheon in South Korea. They estimated carbon emissions by different vessel movement phase, e.g., approaching to dock, maneuvering, and hoteling, and further by ship type. In an extension of the previous paper, Chang et al. (2014a) analyzed NO_X, SO_2 and $PM_{2.5}$ emissions at the same port. Their main research question this time was not the emission inventory itself but estimating emission reduction potential from such policies as the ECA and RSZ. The findings are surprising: the RSZ could reduce overall emission by 67% and the ECA 93%. Different from the studies thus far, Geerings and Van Duin (2011) measured emissions in port terminals. Cargo movement and land-side emissions from equipment were calculated. Moreover, a counterfactual analysis of replacing low quality fuel with bio-diesel and electrical power is another interesting aspect of the study. These studies, however, only center on emission inventory per se. More important analysis should be to quantify the impact of vessel emission on society that includes human health impact.

An increasing number of studies estimated social cost from emission as well as emission inventory. Song (2014) used a ship movement data at Yangshan Port in China to estimate its social cost and eco-efficiency. To this end, he averaged the social cost estimates of pollutants from several studies. Berechman and Tseng (2012) calculated emissions at the Port of Kaoshiung, Taiwan. Diverse ship types, such as bulk, container, and general cargo ships, were examined. When estimating the social cost of total emission, they used BeTa database that calculates the emission cost factor (i.e., the social cost per emission) in numerous region. McArthur and Osland (2013) investigated ships at berth in Port of Bergen, Norway. They mostly followed the line of previous studies except that they collected the emission cost factor from several sources, including BeTa, and CAFE. Tichavska and Tovar (2015) did more sophisticated analysis on the Port of Las Palmas (PLP) using ‘Automatic Identification System (AIS)’ data. The AIS data enabled them to locate ship movement by minute and distance, undeniably providing most elaborate emission estimates. The cost factor, on the other hand, was taken from previous studies.

Reviewing existing studies, we find that the literature has several gaps. First, the social cost and eco-efficiency of ship emission is less studied. Even though some studies already analyzed them, these mostly focus on European ports. Second, more critically, none of the existing studies to the authors' knowledge examined benefits of the ECA and RSZ through measuring the social cost of emission.

3. Theoretical model

3.1 Methodology

While we mostly adopted emission inventory results in Chang et al. (2014a), this section briefly summarizes their methodology to help readers' understanding. Following Chang and Wang (2012), the amount of fuel consumption is measured by

$$F_{trip,k} = \begin{cases} (MF_k \frac{s_{1k}}{s_{0k}} + AF_k)t_{trip} & \text{if } trip \in \{cruising,\ maneuvering\} \\ AF_k t_{trip} & \text{if } trip = hoteling \end{cases}$$

where $F_{trip,k}$ is the amount of fuel consumed by vessel k for each phase of $trip \in \{cruising, maneuvering, hoteling\}$, MF_k average daily fuel consumption of a vessel's main engine, AF_k average daily fuel consumption of a vessel's auxiliary engine, S_{0k} the design speed of vessel k, S_{1k} its operating speed, and t_{trip} the duration of a ship travel (days).

Next, total emissions can be obtained by multiplying fuel consumption and emission factor, and then summating emissions at each trip type.

$$E_{kpgf} = \sum_{trip} \left(F_{gf,trip} EF_{pgf,trip} \right)$$

where E_{kpgf} is emissions throughout a complete trip of vessel k (tons), $F_{gf,trip}$ amount of fuel consumed by vessel k, EF_{pgfm} emission factor. Subscript p is the pollutant type (PM, SO_2, NOx), f the fuel type (bunker fuel, marine diesel oil/marine gas oil, gasoline), and g the engine type (e.g., slow-, medium-, and high-speed diesel, gas turbine, steam turbine). See Chang et al. (2014a) for detailed data descriptions on fuel type, engine type, and emission factor.

Next, we estimated the social cost of noxious gas emission SC_{kpgf} by

$$SC_{kpgf} = E_{kpgf} v_p$$

where v_p is the cost inflicted by pollutant type p per ton. Then eco-efficiency is calculated through

$$Eco_{kpgf} = \frac{E_{kpgf}}{indicator}$$

where *indicator* means divergent measures on port output such as the number of passengers, the number of vessels, and port revenue.

3.2 Social cost factor and eco-efficiency data

Most studies refer to the Clean Air for Europe (CAFE) (Holland et al. 2005, Amann et al. 2005), the New Energy Externalities Development for Sustainability (NEEDS) (Preiss and Klotz 2007) and the Benefits Table (BeTa) databases to obtain the social cost factor of emission. These sources, however, are based on European region and therefore can differ significantly from the actual cost factor in the POI region. As an alternative, we employ results by Lee et al. (2010), who estimated the external cost of emission in Taiwan. This can be justified for two reasons. First, Taiwan is close to Korea, which shares similar geographical characteristics. Second, previous studies, e.g., Preiss and Klotz (2008) and Dragović et al. (2015), used cost factors in other regions that share similar GDP per capita level. In our case, Taiwan and Korea have similar per capita GDP, \$22,044 and \$27,633, respectively (International Monetary Fund, 2016).

Table 1 summarizes employed external cost factors. SO_2, NO_X and PM_{10} cause social cost \$13,960, \$4,992 and \$375,888 per ton respectively. Unfortunately, the factor was not available for $PM_{2.5}$ from Lee et al. (2010). Thus, BeTa was used to calculate it: $594,042. In a ton basis, the most harmful noxious gas is PM$_{2.5}$, causing $594,042 external cost per ton.

To calculate eco-efficiency, the revenue of the POI was obtained from its annual report. The ship emission data were available only from January to October in 2012 while port revenue covered the whole year. Hence, we approximated the revenue between January to October by multiplying the ship movement ratio to the annual revenue in 2012, where the ratio is the number of ships between January and October divided by the total number of ships entered.

Table 1. External cost factor by emissions

Noxious gas type	External cost factor ($/ton)
SO$_2$	13,960
NO$_X$	4,992
PM$_{2.5}$	594,042
PM$_{10}$	375,888

Source: Lee et al. (2010)

4. Results

4.1 Total external cost

Table 2 shows external costs by ship activity stage and pollutants. Total external cost of Port of Incheon from January to October 2012 is $90,805,478. The most harmful pollutant in terms of social cost is the PM$_{2.5}$ causing 42,414,627$ or 42% of total social cost. The most environmentally costly phase is 'Passing thorough lock gate' causing 52,142,427$accounting for 57% of total cost. Figure 1 shows external costs by vessel movement.

The external costs by ship and pollutant type are listed in Table 3. International car ferry, full-container vessel, car carrier and general cargo vessel are the largest damage inflictors with social costs $30,343,305, $16,933,369, $12,243,705 and $9,339,728, respectively. Specifically, car carrier and international car ferry are the most expensive emitters, which is consistent with Chang et al. (2014a). This means that vessels that carry automobiles should be the main target of emission control. Figure 2 illustrates external costs by vessel type.

Table 2. External cost by vessel movement and pollutant (unit: $)

Pollutant	Anchorage	Maneuvering to lock gate	Passing thorough lock gate	Approaching to dock	Docking	Total
SO$_2$	3,634	426,402	7,932,118	5,360,649	90,895	13,813,699
NO$_X$	2,036	238,880	4,443,753	3,003,157	50,922	7,738,748
PM$_{2.5}$	11,158	1,309,257	24,355,376	16,459,743	279,092	42,414,627
PM$_{10}$	7,061	828,450	15,411,179	10,415,115	176,599	26,838,403
Total	23,889	2,802,989	52,142,427	35,238,664	597,509	90,805,478

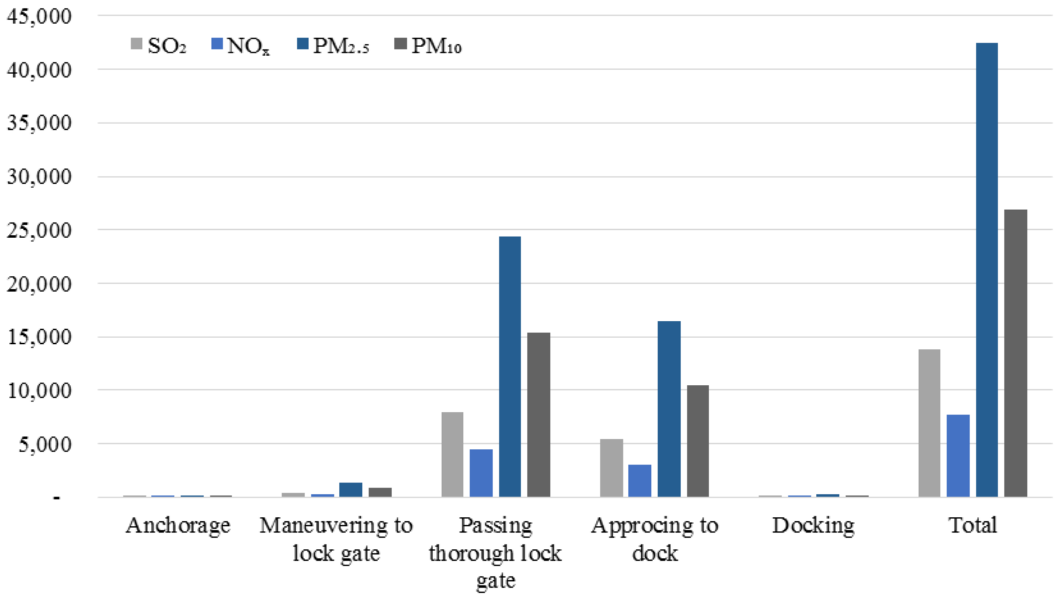

Figure 1. External cost estimates by vessel movement (unit: $1,000)

Table 3. External costs by ship type

Pollutant	LNG carrier	LPG carrier	Towing tug ship	International car ferry	Fuel supplies ship	Other tug ship	Other chemical tanker
SO_2	282,182	177,403	363,180	4,615,947	69,084	283,291	12,681
NO_X	158,085	99,385	203,462	2,585,958	38,702	158,706	7,104
$PM_{2.5}$	866,432	544,710	1,115,135	14,173,153	212,120	869,837	38,935
PM_{10}	548,246	344,673	705,616	8,968,246	134,221	550,401	24,637
Total	1,854,944	1,166,171	2,387,393	30,343,305	454,127	1,862,235	83,357

Pollutant	Other cargo ship	Refrigerated cargo ship	Sand carrier	Dry bulk carrier	Chemical tanker	Semi-con. ship	Cement carrier
SO_2	27,751	4,332	47,440	419,322	562,237	66,989	141,994
NO_X	15,547	2,427	26,577	234,914	314,978	37,529	79,548
$PM_{2.5}$	85,209	13,302	145,664	1,287,518	1,726,336	205,688	435,988
PM_{10}	53,917	8,417	92,171	814,694	1,092,361	130,152	275,877
Total	182,425	28,479	311,852	2,756,448	3,695,912	440,357	933,406

Pollutant	Passenger ship	Deep-sea fishing ship	Crude oil carrier	General cargo ship	Car carrier	Chemical prod. carrier	Scrap carrier	Full-con. ship
SO_2	175,972	2,966	77,463	1,420,798	1,862,562	477,130	147,004	2,575,973
NO_X	98,583	1,662	43,397	795,963	1,043,450	267,299	82,355	1,443,119
$PM_{2.5}$	540,316	9,107	237,848	4,362,524	5,718,952	1,465,017	451,371	7,909,462
PM_{10}	341,892	5,763	150,502	2,760,444	3,618,741	927,008	285,611	5,004,815
Total	1,156,763	19,498	509,209	9,339,728	12,243,705	3,136,455	966,341	16,933,369

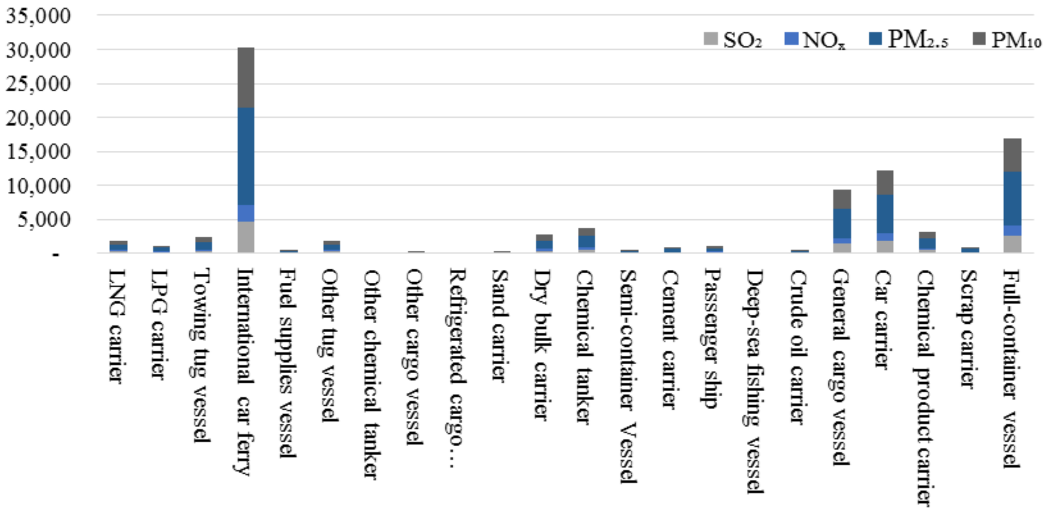

Figure 2. External cost by ship type (unit: $1000)

4.2 Eco-efficiency

Eco-efficiency was obtained by using the ratio of social costs to port performance indices, i.e., the number of passenger, ship call, and revenue. This gives useful insights on emission from ships at the POI, providing measures of environmental and economic performance. To evaluate the performance of the POI, we compare its eco-efficiency to the Port of Las Palmas (PLP) (Tichavska and Tovar 2015). The eco-efficiencies of the POI and PLP are reported in Table 4 and 5, respectively.

Overall, the eco-efficiency of the POI is better than that of PLP. Inspecting external cost per passenger, one can see that the figures are much lower for the POI by half to four times relative to the PLP. For instance, every passenger carried at the POI, the social cost associated with SO_2 emission at the port is 8.3, which is four times lower than the one at the PLP. The difference is even more drastic for external cost per ton of cargo: from as low as 5.86 times (SO_2) to as high as 24.7 times (NO_X). The similar argument holds for the external cost per ship call. The highest difference is observed for NO_X emission (12.41 times) and the lowest one for $PM_{2.5}$ (3.33 times). Lastly, external cost of SO_2 per port revenue is significantly higher for the PLP than the POI.

Table 4. Eco-efficiency at the POI

Pollutant	Total external cost ($)	External cost per passenger ($/Pax)	External cost per ton of cargo ($/1,000 tons)	External cost per ship call ($/call)	External cost per port revenue ($/1,000$)
SO_2	13,813,699.2	8.3	140.7	998.9	24.8
NO_X	7,738,748.2	4.4	78.8	559.6	139.4
$PM_{2.5}$	42,414,627.2	25.5	431.9	3067.1	764.1
PM_{10}	26,838,403.2	16.1	273.3	1940.7	483.5
Total	90,805,477.8	54.6	924.9	6566.4	163.0

Table 5. Eco-efficiency at the PLP

Pollutant	Total external cost ($)	External cost per passenger ($/Pax)	External cost per ton of cargo ($/1,000 tons)	External cost per ship call ($/call)	External cost per port revenue ($/1,000$)
SO_2	83,151,625.0	25.3	2,119.2	9,109.9	1,680.4
NO_X	63,357,311.0	13.0	1,928.1	6,941.5	1,280.3
$PM_{2.5}$	93,391,745.0	25.5	2,527.9	10,231.2	1,887.3
Total	239,900,681.0	73.0	6,114.1	26,283.0	4,848.1

4.3 Effects of the ECA and RSZ

Lastly, benefits of ECA and RSZ are examined. Note that we only report results of SO_2 for the ECA, for the policy only regulates SO_2 and the effect of the ECA on other pollutant type is not clear yet (Chang et al., 2014a). In Table 6, introducing RSZ can reduce approximately a third of total emissions. Even more drastic cut in emission is observable if the POI initiates ECA: 59% and 93% of SO2 emission reduction when the sulfur content per fuel is 1.0 and 0.1%, respectively. Using these estimates, the social benefits of the RSZ and ECA at the POI are listed in Table 6. Under RSZ, the corresponding emission abatement values are $4,485,308, $2,642,009 and $21,932,435 from SO_2, NOX and PM reduction, respectively. If 1.0% and 0.1% sulfur fuel are used due to the ECA, the social cost savings amount to $8,174,947 and $12,868,842 from SO_2 reduction.

Table 6. External cost and reduction percentage under various scenarios

Pollutant	Status quo ($)	RSZ ($)	RSZ (%)	ECA 1.0% ($)	ECA 1.0% (%)	ECA 0.1% ($)	ECA 0.1% (%)
SO_2	13,813,699	9,328,391	32.47	5,638,752	59.18	944,857	93.16
NO_X	7,738,748	5,096,739	34.14	–	–	–	–
$PM_{2.5/10}$	69,253,030	47,320,595	31.67	–	–	–	–

5. Conclusion

This paper measured the social cost and eco-efficiency of vessel emissions at the POI. To this end, we used emission data in Chang et al. (2014a), whose analysis adopted an activity-based approach incorporating ship engine, vessel type, and ship movement data. Findings suggest that the total social cost of ship emission at the POI amounts to $90,805,478. The eco-efficiency of the POI, compared to the one of the Port of Las Palmas in another study, is substantially better. For instance, external cost per ton of cargo including all pollutant types is lowered by eight times, external cost per ship call four times and external cost per $1000 revenue three times. Under RSZ, the corresponding emission abatement values are $4,485,308, $2,642,009 and $21,932,435 from SO_2, NOx and PM reduction. If 1.0% and 0.1% sulfur fuel are used due to the ECA, the social cost savings amount to $8,174,947 and $12,868,842 from SO_2 reduction.

The method employed in this study may be applied to other Korean ports. For example, according to Korea Ministry Oceans and Fisheries, container traffic at the Port of Busan and Gwangyang is greater than that of Incheon. Estimating social cost and eco-efficiency at these ports may help policy makers to measure benefits of introducing ECA and RSZ in the nearby area. Moreover, the tool can be used to assess emission from airplanes. Interested readers may refer to Kim et al. (2010).

This paper has room for improvement. First, using more sophisticated data from AIS can yield more accurate estimates. Second, one may employ the emission cost factor fine-tuned for an analyzed port (in our case, the region surrounding POI). Lastly, even though eco-efficiency suggests that the POI is much more environmentally efficient than the PLP, one need to caution that including other external factors is necessary. An example is life-cycle emission of port operation. Port operation involves constructing berth, positioning cranes, and also inland-side terminal operations. Neglecting emissions from these sources can possibly result in biased estimates of emission from ships.

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