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A Study on the Framework for Estimating Ship Air Pollutant Emissions—Focusing on Ports of South Korea

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Abstract: With the globalization of trade and the rapid development of the world economy, the problem of air pollution emissions produced by shipping is becoming more serious. The exhaust gas emitted by ships has become a significant source of air pollution in ocean and coastal areas. In recent years, governments have paid more attention to shipping emissions as a major source of environmental problems. Establishing ship emission inventories plays an important role in formulating ship emission control measures and regulations. This study aimed to propose a framework for calculating ship air pollutant emissions by comprehensively considering processes and methods officially used in developed countries such as the US and those in the EU, as well as South Korean circumstances and available data sets. The framework was divided into three sections: defining the inventory, data collection and analysis of the data, and ship air pollutant emission estimation. The results of this study provided a standard for South Korean domestic port emission inventories. A case study focused on the Gwangyang and Yeosu Ports, one of the leading port areas in South Korea, using adaptive data collection and emission-calculation processes. This study can be used as guidelines when the Ministry of Oceans and Fisheries (MOF) or the Ministry of Environment (MOE) adopts a standard process in South Korea in the near future. Subsequently, it is necessary to establish a national port emission management system to respond to world environmental changes.

Keywords: air pollution; ship emissions; air estimation; calculation framework; VTS data

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1. Introduction

More than 99% of the world's population breathes air that exceeds World Health Organization (WHO) guidelines and contains high levels of pollutants. According to the World Health Organization, air pollution causes 7 million premature deaths worldwide each year and affects the health of millions of people [1].

Shipping has become an essential mode of transportation between trading countries due to the globalization of trade and the rapid development of the world economy [2]. Simultaneously, the air pollution caused by shipping is becoming more serious; the exhaust gas emitted by ships has become a significant source of air pollution in the oceans and coastal areas. It is estimated that almost 70% of ship air pollutant emissions in global routes are emitted within 400 km of the coast [3]. As the issue of air pollution emissions becomes more serious, port supervision departments are paying closer attention to it. According to International Maritime Organization (IMO) statistics, the total shipping industry emissions grew by almost 10% from 2012 to 2018, accounting for 2.89% of total global anthropogenic emissions [4]. About 15% of worldwide nitrogen oxide (NOx) and 5–8% of sulfur oxide (SOx) emissions come from ships [5]. The emissions reduce cardiovascular and cardiopulmonary functions while increasing the rates of lung cancer and respiratory diseases in people living near a port [6]. Particles emitted by ships (such as $PM_{2.5}$) will increase the environmental concentration. In 2013, the WHO's International Agency for Research on

Cancer (IARC) classified air pollution and particulate matter as carcinogenic. Therefore, the hazards caused by ship air pollutant emissions cannot be ignored, and it is urgent to control the emissions of shipping pollutants.

To reduce the emissions of air pollutants from ships, international organizations have established emission reduction targets and policies. The IMO set the ambition to reduce the shipping industry's emissions by at least 50% by 2050 compared to 2008, reducing the carbon intensity of emissions by 40% by 2030, and reducing by 70% by 2050. In addition, IMO formulated MARPOL73/78 in order to prevent ships from polluting the marine environment for operational or unintentional reasons. It is an essential international treaty in which Annex VI was established on 26 September 1997, then went into force on 19 May 2005. It includes measures to control air pollutants from ships and limits on the discharge of volatile organic compounds from tanker cargoes, SOx from fuel oil combustion, and NOx from diesel engines into the atmosphere. The Baltic Sea, the North Sea, the North American Sea, and the American Caribbean Sea have all been classified as ECAs by the IMO. The United States, Europe, China, and South Korea have recently begun voluntarily participating.

To follow the international environmental protection trend, the South Korean government enacted a special act called the 'Port Air Quality Act' to improve air quality. This legislation, which went into effect on 1 January 2020, defines the spectrum of ship emission control areas for supervisory emission control. In addition, five major ports in South Korea (Incheon Port, Pyeongtaek and Dangjin Ports, Gwangyang and Yeosu Ports, Busan Port, and Ulsan Port) have been classified as ECA zones since September 2020 to better strengthen the management of air pollution. It stipulated that ships in the berthing and anchoring sectors must use fuels with a maximum sulfur content of 0.1%, as shown in Figure 1. All ships were required to utilize a 0.1% sulfur restriction as of 1 January 2022. Instead of shutting down the ship's engine, the 'Port Air Quality Act' requires an alternative maritime power (AMP) system to provide the necessary electricity when the ship is in port. A vessel speed reduction (VSR) area scope of 20 miles from a specific lighthouse must be maintained within a port, and ships must operate at a slower speed than the recommended speed from the starting point of the low-speed operation area to the arrival point of the corresponding port. The major five ports participating in VSR may define the ship type to adjust the recommended speed based on the air quality in the port area. Currently, the ships that generate high dust in ocean-going vessels (OGVs) of 3000 GT and above are the restricted targets (container ships, car carriers, LNG carriers, and semi-container ships) in general.

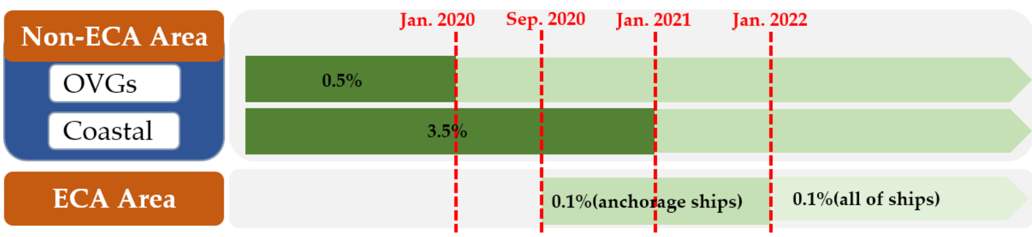

Figure 1. The sulfur limit status of South Korea. Source: Ministry of Oceans and Fisheries (MOF), 2020.

Shipping emissions are reduced as a result of various governments' policy formulations and implementations. The creation of a ship emission inventory is a critical step in developing ship emission control measures and related regulations [7]. As public institutions, the European Environment Agency (EEA) and US Environmental Protection Agency (EPA) recognize the seriousness of air pollution emissions. Based on the actual situation of the region, these organizations put forward the calculation method suitable for calculating pollution emissions. However, because the South Korean government has not provided detailed ship emission guidelines and ship-in port emission monitoring systems, scholars have different benchmarks for calculating port emissions, resulting in insufficient data comparability among domestic ports. Therefore, it is indispensable to establish a ship pollutant calculation system for the South Korean shipping industry. Due to the data collection system of South Korea being different from that abroad, it might not be easy to apply the methods proposed from abroad directly.

The objective of this study was to present adaptive data collection and methods based on the current data provided to establish the framework for ship pollution emissions in South Korean ports. This paper describes in detail the data collection methods for calculating shipping pollution and identifies the source of data extraction, classification, and sorting. A combination of methods for calculating pollutants was proposed to optimize the method. In addition, taking the Gwangyang and Yeosu Ports as an example, the method proposed in this research was applied and combined with domestic and overseas environmental protection regulations to evaluate ships' air pollutant emissions in 2020.

This study can guide other researchers' quantitative and qualitative information to calculate emissions at domestic ports in South Korea. It can solve the problem of a lack of a unified standard for calculating and comparing regional port emissions. It is expected to assist follow-up researchers and standardize South Korean domestic port emission inventory research. Furthermore, it combined the existing international society and overall development trends to provide theories and statistics for national emission reduction support.

2. Literature Review

Many organizations and countries have studied ship emission inventories in ports with frequent ship traffic, and numerous studies have suggested estimation approaches to generate ship air pollutant emissions. To more effectively manage air pollution from shipping transportation, many countries have formed relationships using a Memorandum of Understanding (MOU); several nations are members of many MOUs because they have ports in multiple regions. For example, Australia is a member of both the Indian Ocean MOU and the Tokyo MOU for its Pacific ports. Canada is a member of both the Paris MOU and the Tokyo MOU, which is mainly due to its Atlantic ports and Pacific ports [8].

IMO [9] reported two ways for estimating ship emissions based on AIS data, and suggested using AIS data to obtain ship movement information such as speed, location, and draught, and then combining the power and revolutions per minute (RPM) of the main engine and auxiliary to estimate air pollutant emissions. When the research conditions are insufficient to utilize the bottom-up approach, a top-down approach can be used to estimate emissions. EEA [10] suggested a method for estimating air pollutant emissions that varied based on the information obtained on shipping operations. It supposes that the category of the sources is determined to be a key source (ship activities, engine power) in the estimation. In that case, the emissions should be estimated using Tier 2 or Tier 3. Tier 1 only defaults on the basis of fuel consumption, as with the top-down approach. The EPA [11] published a guideline for calculating air pollutant emissions generated by port activities, and presented a method for calculating air pollutant emissions from ships. It uses an energy-based calculation method that utilizes the ship's engine power and activity data, and belongs to the bottom-up category. Methodologies by the National Institute of Environmental Research (NIER) were presented in South Korea, but most were carried out by referring to overseas methods.

Based on organizations' reports, two different methods can be commonly used to estimate and validate shipping air pollutants. One method is fuel-based, and estimates emissions based on observations [12]. The other approach is activity-based, and estimates emissions using statistical analyses of activity data in conjunction with country-specific emission factors. These two approaches can be classified as a top-down approach and a bottom-up approach, respectively [13].

2.1. Top-Down Approach

The top-down approach is a fuel-based method for calculating ship air pollutants based on data from marine fuel sales (such as fuel quantities and types) and fuel-related emission factors [13].

The calculation approach was applied to estimate the global seagoing-ships emission inventories based on the total fuel used by those ships, as obtained from the Energy Information Administration of America [14,15]. The top-down approach can provide a relatively accurate calculation result of ship exhaust emission inventories on a global scale. However, it underestimates the amounts of ship exhaust emissions on a regional scale [16]. Kasibhatla et al. [17] used the top-down method to calculate atmospheric carbon monoxide levels associated with fuel combustion across Asia. The researchers discovered that even though this strategy may increase efficiency in obtaining results, it may also lead to errors if aggregated data does not accurately represent local circumstances.

However, when the top-down method is used to calculate air pollutant emissions, it does not generally refer to the location information of ship activities. Instead, it picks the appropriate ship fuel consumption information based on the demands. Additionally, researchers are scant on this method to calculate the shipping air pollutant emissions. This method has significant uncertainty (e.g., lack of activity data) in estimates of ship air pollutant emissions because it does not reflect actual maritime traffic [13].

2.2. Bottom-Up Approach

The bottom-up approach is often more accurate than other approaches because it requires diverse, comprehensive data, which can help improve the reliability of the results. The first type of data regards ship activities or routes, also called activity-based. The second data category is ship specification, such as the engine workload, ship speed, position, duration, and so on [15,16]. This method, calculated via the activities of shipping, usually uses detailed information on the ship characteristics (e.g., ship identification number, ship size and type, engine power, and fuel type), as well as the survey and operational data (e.g., travel distances, maximum speed, and actual maneuvering and cruising speeds) for the harbor/marine activities in conjunction with emission and load factors [17].

The main advantage of such bottom-up emission inventories is that they can realistically describe the emitters while maintaining the connection between single emitters and large-scale inventories. In addition, it is possible to construct sophisticated emission scenarios [18].

When using the bottom-up approach to estimate shipping air pollutant emissions within the harbor region, such ship movement data, activity data, and emission factors per shipping activities are needed. The ships' operations are generally divided into three stages: cruising, maneuvering, and hoteling [19]. During the cruising phase, the ship moves inside the port border while all engines remain operational. The maneuvering phase is the time spent at a reduced speed while transiting between the breakwater (intersection of open sea and interior waterway) and berths. The hoteling phase is when ships are berthed while awaiting their next voyage or cargo load/discharge. The sum of the emissions from the activities equals the total ship air pollutant emissions [20].

The data utilized in the approach is derived directly from each port's registration data, allowing for a more precise computation of the total emission of ship routes. When it comes to calculating fuel consumption, the bottom-up approach differs from the method of estimating fuel consumption using ship tonnage. It is calculated using engine power parameters and ship activity data [21]. When the bottom-up method is applied to actual calculations, the method can be divided into two parts: fuel consumption and total energy output.

If accurate sailing statistics are available (e.g., actual travel distance with speed and port calling records with real-time operations), there are two ways to estimate emissions.

One method uses total energy output (EO) and emission factors to calculate emissions, as shown in Equation (1):

$$E = Energy(P.LF.T) \times EF \tag{1}$$

Another uses all phases of fuel consumption (*FC*) to calculate the emissions, as shown in Equation (2):

$$E = FC \times EF \tag{2}$$

where *p* is the engine power, *LF* is the engine load factor; *T* is activity time, and *EF* is the emission factor.

There are plenty of researchers that have already calculated shipping emissions based on a bottom-up approach [21]; the list is shown in Table 1. A bottom-up estimate can provide significant insight into the specific source of emissions and what specific actions can be taken to reduce emissions. A bottom-up estimate is more likely to consider long-term conditions and variations [22]. Additionally, the data for this approach are derived from several sources. It will take a significant amount of effort to calculate global ship air pollutant emissions. As a result, this approach is more suited for assessing ship emissions at the regional or local level [23].

Several studies have been conducted to calculate the emission inventories of various ports. Fu et al. (2012) investigated air pollutant emissions from ships in Shanghai in 2010 and discovered that ocean-going ships were the most polluting source in Shanghai ports. Li et al. (2016) calculated the air pollutant emissions from ships in the Pearl River Delta (PRD) region using shipping movement data, revealing that container ships were a substantial source of pollution emissions. Zhao et al. (2019) [24] studied the air pollutant emissions for part of the hoteling in Gwangyang Port and Ulsan Port in South Korea by utilizing the bottom-up method. Lee et al. calculated the emissions at Incheon in 2020 based on vessel traffic system (VTS) data.

Several researchers inquired about case studies from different countries or continents. Wang et al. (2020) [25] used the AIS data dynamic method to establish a list of ships' Yangtze River Delta exhaust air pollutant emissions in 2017. The AIS dynamic method could obtain ship emissions' spatial and temporal distribution characteristics. Moreover, it showed the characteristics of air pollutants when ships under different movements and modes and atmospheric pollutants were included. Jalkanen et al. (2016) [26] estimated ship traffic contributions to European sea area emissions using AIS data to describe ship traffic activity, and quantized the air pollutant emissions totals and the seasonal variation, the geographical distribution of air pollutant emissions, and their disaggregation between various ship types and flag states from ship traffic in Europe in 2011.

Table 1. Summary of bottom-up approach studies.

Author	Year	Reference Agency	Operation Modes	Considered Pollutants	Research Object	Database
Corbett et al. [27]	2009	IMO	N/A	SOx, NOx, PM, CO_2	Container ships, US ports	Lloyd database
Tzannatos [13]	2010	ENTEC	Man, Hot	NOx, SO_2, PM	Piraeus Port, Greece	Ministry of Mercantile Marine, Greece
Trozzi [28]	2010	EEA	Cru, Man, Hot	NOx, NMVOC, PM	Mediterranean Sea	Lloyd database
Lonati et al. [29]	2010	ENTEC	Man, Hot	NOx, SOx, CO, VOC, PM_{10}	Ionian Sea, Southern Italy	Port Authority, Italy
Deniz and Kilic [30]	2010	EPA	Cru, Man, Hot	SO_2, NOx	Ambarlı Port, Turkey	Port Authority, Turkey
Winnes and Frindell [31]	2010	IMO	Man	NOx	Main engines of two ships	The Environmental Research Institute, Sweden

Table 1. *Cont.*

Author	Year	Reference Agency	Operation Modes	Considered Pollutants	Research Object	Database
Villalba and Gemechu [32]	2011	IMO	Man, Hot	CO_2, NOx, CH_4	Barcelona Port, Spain	Port Authority, Spain
Shin and Cheong [33]	2011	IPCC	Man, Hot	CO_2, N_2O, CH_4	Busan Port, South Korea	Port Management Information System, South Korea
Chang and Wang [34]	2012	EPA	Cru, Man, Hot	NOx, PM, SO_2, HC, CO_2	Kaohsiung Port, Taiwan	Port Authority, Taiwan
Tai and Lin [35]	2013	IMO	Cru, Man, Hot	NOx, SO_2, CO_2, HC, PM	Container shipping carriers, Eastern Europe routes	The ship company
Chang et al. [36]	2013	EEA, EPA	Man	CO_2	Port of Incheon, South Korea	Port Authority, South Korea
Song and Shon [19]	2014	IMO	Cru, Man, Hot	NOx, SO_2, VOCs, CO_2, PM	Busan Port, South Korea	Port Authority, South Korea
Song. [3]	2014	EPA, ENTEC, IPCC, IMO	Cru, Man, Hot	CO_2, CH_4, N_2O, PM_{10}, $PM_{2\cdot5}$, NOx, SOx, CO, HC	Yangshan Port, China	AIS
Kilic and Tzannatos [37]	2014	IMO, EPA, ENTEC, EPA	Man, Hot	NOx, SO_2, CO_2, HC, PM	Piraeus Port, Greece	Port Authority, Greece
Papaefthimiou et al. [21]	2015	IMO, EEA,	Cru, Man, Hot	NOx, SO_2, $PM_{2\cdot5}$, CO_2, CH_4	Piraeus Port, Santorini Port, Mykonos Port, and 18 other ports in Greece	Port Authority, Greece
Maragkogianni and Papaefthimiou [38]	2015	EEA, ENTEC, IMO	Cru, Man, Hot	PM, NOx, SO_2	Piraeus Port, Santorini Port, Mykonos Port, and 5 other ports in Greece	The Sea-web database, Greece
Nunes et al. [39]	2017	IMO, ENTEC, IPCC	Cru, Man, Hot	PM_{10}, $PM_{2\cdot5}$, NOx, SO_2, CO, CO_2, N_2O CH_4, NMVOC, HC	Leixoes Port, Setubal Port, Sines Port, and Viana do Castelo Port, Portugal	AIS
Khan et al. [40]	2018	EEA, EPA	Cru, Man, Hot	CO_2	Port of Incheon, South Korea	AIS
Alver et al. [41]	2018	IMO, ENTEC	Cru, Man, Hot	SO_2, NOx, HC, PM_{10}	Samsun Port, Turkey	Port Authority, Turkey
Zhao et al. [24]	2019	EEA, EPA	Hot	CO, NOx, SOx, PM_{10}, $PM_{2\cdot5}$, VOC, NH_3	Gwangyang Port and Ulsan Port, South Korea	Vessel traffic service, South Korea
Zhang et al. [42]	2019	IMO	Cru, Dec, Man, Hot	NOx, CO, SOx, CO_2, HC, PM_{10}, $PM_{2\cdot5}$	Pudong Port, Gaoqiao Port, Yangshan Port, China	Baoshan meteorological station, China
Sorte et al. [43]	2019	EEA, EPA	Man, Hot	NOx	Leixoes Port, Portugal	The Portuguese Environmental Agency
Wan et al. [44]	2020	EPA, ENTEC	Cru, Dec, Man, Hot	NOx, CO, SOx, CO_2, HC, CH_4, NMVOC, PM_{10}, $PM_{2\cdot5}$	Bohai Bay, Yangtze River Delta, Pearl River Delta, China	Government data, China
Lee et al. [45]	2020	EEA, EPA	Cru, Man, Hot	CO, NOx, SOx, PM, VOC, NH_3	Port of Incheon, South Korea	Vessel traffic service, South Korea
Lee et al. [46]	2021	EEA, EPA	Cru, Man, Hot	CO, NOx, SOx, PM_{10}, $PM_{2\cdot5}$, VOC, NH_3, CO_2	Port of Incheon, South Korea	Vessel traffic service, South Korea
Ekmekcioglu et al. [47]	2020	ENTEC	Cru, Man, Hot	CO, CO_2, NOx, SO_2, PM, VOC	Ambarlı Port, Kocaeli Port, Turkey	Ministry of Transport, Turkey
Sorte et al. [48]	2021	EEA	Cru, Man, Hot	NOx, PM_{10}, $PM_{2\cdot5}$, SOx, CO, VOC, HC, BC, CO_2, N_2O, CH_4	Leixoes Port, Portugal	Port Authority, Portugal

2.3. Research Demand

The top-down and bottom-up approaches can sometimes provide different results, since they were conceived and created via separate disciplines and for different aims [49]. However, in a region study, the bottom-up approach can realize a more accurate emission inventory. The following question is regularly posed when the bottom-up approach is used: What is the total quantity of air pollutant emissions? If standardized measures are adopted, improved bottom-up reporting will eventually disseminate useful information to national management. This will lead to more accurate air pollutant emissions accounting, and the widespread use of inventories and tools will aid in identifying areas of green policy.

Most of the previous studies focused on calculating air pollutant emissions in the studied regions. Only a few studies supported organization and country guidelines at the national level. Most of the studies used either the EEA or EPA guidelines or combined them to calculate the air pollutant emissions in the studied region. However, a shipping emission inventory is typically determined based on calculations using different databases, and it always depends on the data and scope of the study for calculation. In addition to national emission inventories, only a few estimates of in-port ship air pollutant emissions have been conducted in South Korea.

In recent years, AIS has been applied to improve the estimation of air pollutant emissions. It is hard to collect them for free and obtain all the data from the port, and therefore most of the studies only used samples to calculate the emissions. Moreover, AIS lacks ship data for ships with a gross tonnage (GT) of less than 300. According to the Korean Aerospace Research Institute (KARI), satellites indicated that only 80 percent of the data is received due to a relatively low signal reception at the port, as well as an error in using AIS data. In South Korean regional studies, a few studies used VTS data. The main reason was that VTS data collected by the Korea Coast Guard (KCG) includes ships' activities in the port, and the accuracy is high.

Most of the existing studies focused on the emissions estimation for specific ports. The core of this study was to create a framework for estimating air pollutant emissions in South Korea. This study took into account the characteristics of local South Korean ports and defined all process details, from data use to methodology selection and estimation. Recently, the South Korean government has been interested in the emission management of important ports, and it is necessary to monitor the emissions at ports, so the framework presented in this study can be a standardizable guideline. The authors of this study suggest using the South Korean VTS database. VTS identifies maritime traffic conditions for ship entry and departure; operates ships; and observes risks such as departure from routes, access to dangerous areas, and ship collisions. The most important factor is the government agency's database, which is free to the public. The EEA and EPA supported the bottom-up approach. Through a framework of operational phases, geographical areas, and ship types, emissions of eight types of pollutants were studied: carbon monoxide (CO), NOx, SOx, total suspended particulates (TSP), PM_{10}, $PM_{2.5}$, volatile organic compounds (VOC), and ammonia (NH_3). In order to prove the proposed framework, the Gwangyang and Yeosu Ports were used as a case study.

3. Ship Emission Estimation Framework

As explained previously, the method for calculating ship air pollutant emissions is provided by authorized overseas organizations. However, it was proven that the calculating technique differed slightly based on the institution and data availability. This study considered current methods to set up a procedure for efficiently and correctly estimating air pollution from ships in South Korea.

The port emission framework was divided into three sections. The first step was defining the inventory; the second step was data collection and analysis of the data, and the third step focused on emission estimation.

3.1. Inventory Definition

This study proposed three factors that comprised the definition of inventory. First was the type of pollutant, second was the type of ship activity, and third was the area affected by air pollutant emissions.

3.1.1. Type of Air Pollutants

NIER proposed the types of air pollutants at the national management level: CO, NOx, SOx, TSP, PM_{10}, $PM_{2.5}$, VOC, and NH_3. A total of eight air pollutant emissions suitable for the port area were set as the targets for analysis.

3.1.2. Type of Ship Activity

Port air pollutant emissions can be broadly divided into those emitted by ships, cargo-handling equipment, vehicles, and railways. Air pollutants emitted by ships account for a large proportion of these. The analysis object of this study was based on at-sea activities associated with shipping transportation. Ship activity emissions in port were mainly divided into at-sea and at-pier. At-sea activities are generally anchoring, cruising, and maneuvering, and at-pier activity is berthing.

3.1.3. Emission Effect Area

The effect area setting for air pollutant emissions is essential; it depends on the air pollution impact area. The EPA suggested that a ship's influence range of air pollutant emissions is the area within 5 km of the port limit line (PLL). However, most documents do not mention this, although the emission varies significantly depending on the range.

3.2. Data Collection and Analysis

In terms of ship information and activity data, various domestic institutions collect data for different study purposes or different research targets in South Korea. The Port-MIS data captures a ship's arrival time and departure time at major locations. Determining the exact time of other activities in the port is still challenging throughout the world. The VTS data added to Port-MIS is ship traffic control data collected by the KCG. It contains the data for detecting the ship location and confirming the ship's activities in the port. On the other hand, the Korean Register and Korea Maritime Transportation Safety Authority (KMOSA) provide ships' specification data, including engine type, power, RPM, and design speed. Moreover, an interview with a local pilot to obtain information on the port (such as speed for cruising, distance from the port limit lines to berth, etc.) was conducted.

The data-cleaning process was divided into three steps:

STEP 1: In the collected data, the call sign, ship's name, GT, and ship type were the main identification information for ships. The calling mark could be used as the vessel's identification information to match the vessel specifications of the VTS, the Korea Register Office, and KOMSA. It is significant to classify ships according to cargo transportation [11]. For a successful matching, it was necessary to reclassify the ship types according to the different types of ships and the ship classifications. This study suggested classification criteria from the EEA and EPA.

STEP 2: The port authority's data and pilot interview were important to understanding the port's geographic information and the ship's operating characteristics. By searching the port authority website, the geographical and spatial situation of the port was confirmed, the location of the port boundary was ensured, and the pier could be reclassified. The interview with the port operation expert provided important information on the average speed of the port ships, the average distance, and the speed of maneuvering. Moreover, surveys for the maximum anchoring time and berthing time were necessary to identify the outlier.

Data cleaning and time calculation were essential steps. A new code, including a call sign and control frequency of year code, trip code, and report sequence, were applied to rearrange the entire data set corresponding to the timeline of the ship call. All of the activity points corresponded to a status and a time. The typical status included: (1) entry; (2) cast anchor; (3) heave anchor; (4) inshore; (5) offshore; and (6) departure. The arrows in Figure 2 indicate the corresponding status and possible facilities (locations). A combination of two statuses identified the activity phase. The time of an activity phase was calculated as the subtraction of two corresponding statuses in time. It could be distinguished by position, whether in anchoring or berthing. If the ship anchored out of PLL, it was not included in the calculation range and was ignored.

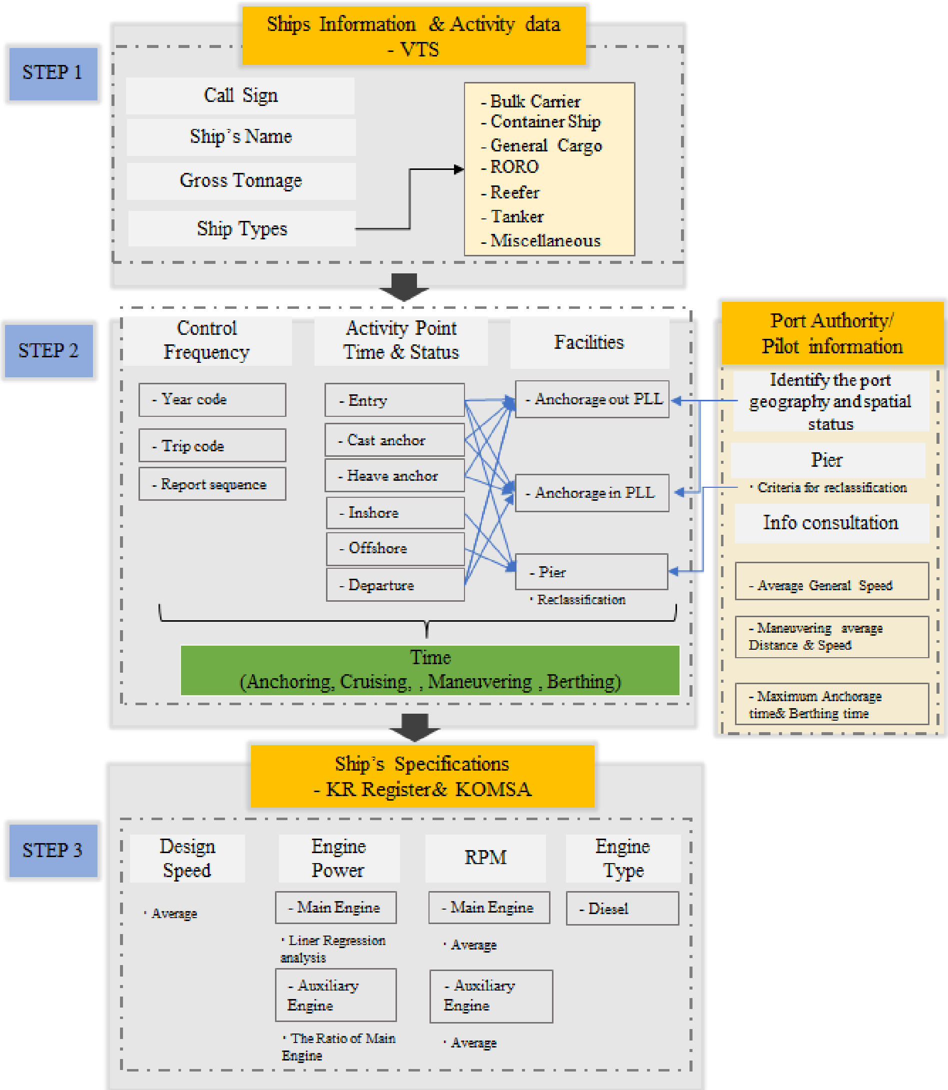

Figure 2. The process of data collection and analysis.

STEP 3: The ship specification data included the ship's call sign, name, type, engine type, main and auxiliary engine powers, RPM, gross tonnage, and design speed. Regression analysis is widely used to find the mathematical relationship between two or more variables. If the main engine information was missing, simple linear regression analyses by ship type between ship tonnage and the main engine power were applied to estimate the main engine power for each ship [45]. In this study, data on 1363 ships that visited South Korean ports were collected and analyzed according to the type of ship. On the basis of classification of ship type, the results showed that GT and the main engine power were significantly correlated. Figure 3 shows the results of linear regression analyses, with more than 95% reliability.

Figure 3. Regression models for estimating main engine power by ship type.

The EPA [11] provides the ratio of main engine power and auxiliary engine power, which can be used to calculate the auxiliary engine power. The design speed can be calculated using the collected ship specification data.

3.3. Estimation Framework for Ship Emission

In the current emissions calculation formula for ships, the emission factor for each air pollutant refers to data published by international organizations. Developing indicators for air pollutant emission guidelines for South Korean ships suitable for the domestic shipping industry environment is necessary.

The approach to calculating air pollutant emissions from ships depends on the data availability and quality. Considering the data collection situation in South Korea, a few years ago, NIER suggested a top-down (fuel-based) approach. This study suggested combining the guidelines of two organizations, the EEA and EPA, to increase accuracy and reliability. Since the EEA was most recently updated (2019), and activity tracking for individual vessels is possible through Tier 3, it was judged to be a more detailed method. To apply the EEA method, it is necessary to calculate fuel consumption. The EEA provided the fuel consumption factor for each type of ship engine. EPA data providing a more detailed factor set were applied for other factors. Figure 4 shows the process of the calculation method.

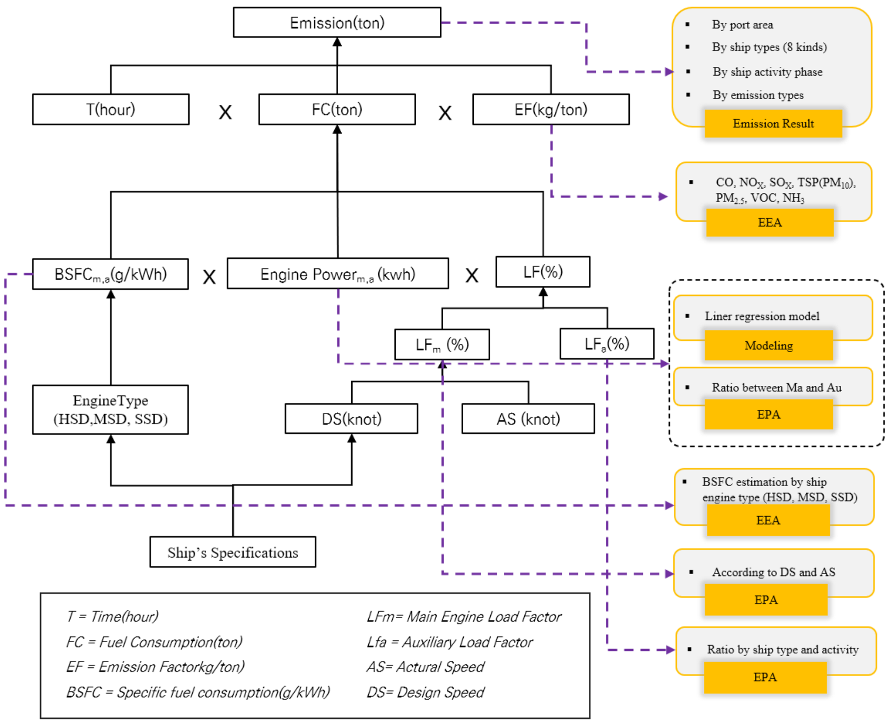

Figure 4. The process of the calculation method.

In order to calculate air pollutant emissions, it is necessary to apply the fuel consumption factor and emission factor, which reflects the figures presented by the EEA and EPA. To apply the EEA method, it is required to calculate the fuel consumption, and the fuel consumption factor must be used for this purpose. Therefore, the fuel consumption factor for each type of ship engine is presented in the EEA. The EPA offers the main engine load factor according to the relationship between the design speed and operating speed. It was judged to be more accurate than the EEA load factor, which provided a single numerical value. Because the auxiliary engine load factor is identified through the relationship with the main engine, applied EPA value is better for research. For emission factors, the EEA provides values for CO, NOx, Sox, TSP(PM_{10}), $PM_{2.5}$, VOC, and NH_3, and applies them.

4. Case Study

According to the proposed procedure, this part presents a case study of the Gwangyang and Yeosu Ports. The total amount of ship emissions were calculated as of 2020. The emission effect area was the activity within 5 km of the PLL. The inventory definition, data collection and cleaning, and emission calculation were conducted sequentially. The PLL and effect area are shown in Figure 5.

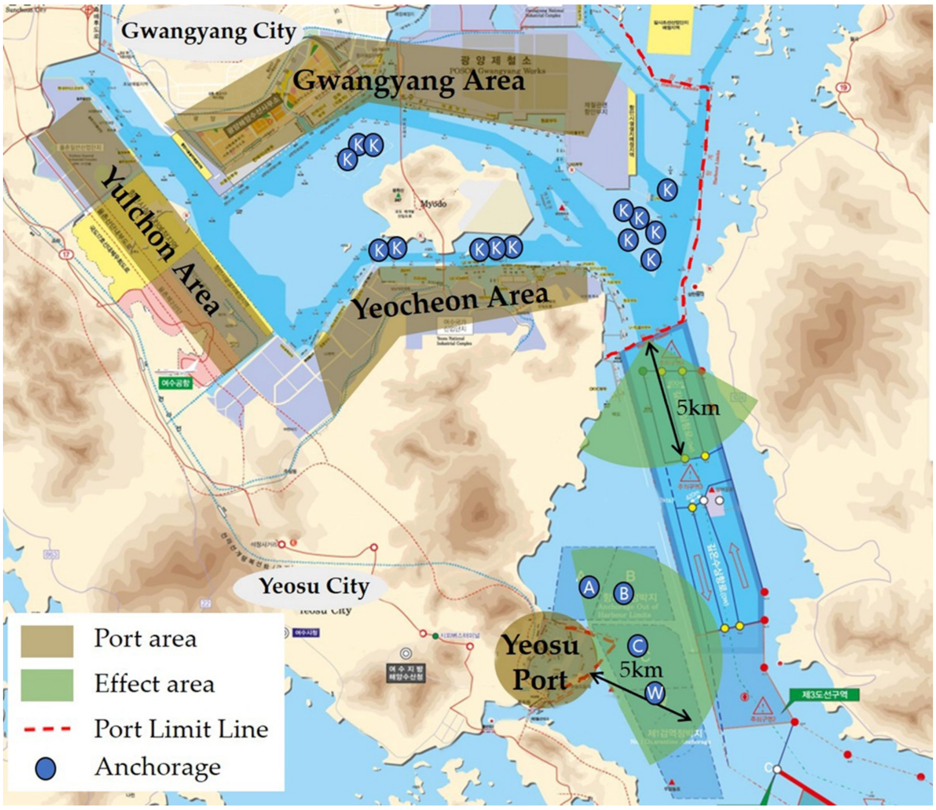

Figure 5. Gwangyang and Yeosu Ports emission effect area and facilities.

4.1. Data Collection and Analysis

After collecting the data on the Gwangyang and Yeosu Ports, the existing ship types were reclassified and analyzed. The data processing and time calculation were required as well. The information provided by the port authority and pilot interview allowed us to ascertain the full extent of the port and its geographic scope of activity, reclassify terminal facilities, and correct error data from previous steps.

A total of 27,966 ship calls were recorded from VTS data. The Gwangyang Port accounted for 84% of the total number of ship calls, while the Yeosu Port only accounted for 16%. The ship calls by ship type are shown in Table 2.

Table 2. Ship call statistics (unit: ship call).

Ship Type	Gwangyang Port				Yeosu Port	Total	Ratio
	Gwangyang Area	Yeocheon Area	Yulchon Area	Subtotal			
Bulk Ship	2469	458	28	2955	17	2972	10.6%
Container Ship	3532	-	2	3534	21	3555	12.7%
Passenger Ship	-	-	-		5	5	0.05%
General Cargo Ship	2209	339	357	2905	10	2915	10.4%
RORO Ship	311	12	-	323	5	328	1.2%
Reefer	-	-	-		6	6	0.05%
Tanker	2327	11,272	93		4418	18,103	64.7%
Miscellaneous	7	30	7		32	82	0.3%
Total	10,855	12,111	472	23,452	4514	27,966	100.0%

Source: VTS.

According to the information provided by the port authority, the maximum speed was normally assumed as 14 knots (12 knots for dangerous goods carriers). However, since this is a port area with only one channel with many restrictions, it is difficult for ships to navigate at maximum speed, so this research assumed that the sailing speed of ships was 12 knots. The distance from the hypothetical PLL to the outer anchorage was about 11 km.

The average cruising time and berthing time for each area are shown in Table 3, and the ship types are shown in Table 4.

Table 3. Average time of cruising and berthing by area.

Sector	Area	Average Time of Cruising	Average Time of Berthing
Gwangyang Port	Gwangyang	1.2	21.1
	Yeocheon	1.0	16.0
	Yulchon	1.8	28.0
Yeosu Port	-	0.5	21.2

Table 4. Average time of berthing by ship type.

Sector	Average Time of Berthing
Bulk Ship	48.3
Container Ship	11.1
Passenger Ship	70.5
General Cargo Ship	34.0
RORO Ship	23.7
Reefer	168.0
Tanker	14.0
Miscellaneous	75.5
Total	19.0

4.2. Air Pollutant Emissions Results for Gwangyang and Yeosu Ports

The results showed that NOx was the most significant emission with 5732.2 tons/year, followed by SOx, CO, VOC, TSP (PM_{10}), $PM_{2.5}$, and NH_3. The total amount of emissions from the sea accounted for more than half of the ports total emissions. The Gwangyang area showed the highest emissions, followed by the Yeocheon area, Yeosu Port, and Yulchon area. As shown in Table 5, the emission sequence of the regions was nearly the same, in the order of NOx, SOx, CO, VOC, TSP (PM_{10}), $PM_{2.5}$, and NH_3.

Table 5. Air pollutant emissions by port area.

Sector		Gwangyang Port				Yeosu Port	At Sea	Total
		Gwangyang Area	Yeocheon Area	Yulchon Area	Subtotal			
CO	Emission	189.2	94.0	3.7	286.9	25.9	374.6	687.4
	Ratio	28%	14%	1%	43%	4%	55%	100%
NOx	Emission	1500.5	754.1	29.0	2283.6	203.1	3245.5	5732.2
	Ratio	26%	13%	1%	40%	4%	57%	100%
SOx	Emission	185.7	96.2	4.1	286	26.7	542.4	855.2
	Ratio	22%	11%	1%	34%	3%	63%	100%
TSP (PM_{10})	Emission	19.7	10.0	0.4	30.1	2.8	51.5	84.4
	Ratio	23%	12%	1%	26%	3%	61%	100%
$PM_{2.5}$	Emission	18.4	9.3	0.4	28.1	2.6	48.1	78.8
	Ratio	23%	12%	1%	26%	3%	61%	100%
VOC	Emission	46.0	22.9	0.9	69.8	6.3	113.9	190.0
	Ratio	24%	12%	1%	37%	3%	60%	100%
NH_3	Emission	0.2	0.1	0.0	0.3	0.0	0.4	0.7
	Ratio	28%	14%	1%	43%	4%	55%	100%

According to the analysis results of air pollutant emissions from ship activities shown in Table 6, we found that the emission order of most pollutants was berthing, cruising, and anchoring. The results showed that the highest NOx emissions were 2486.82 tons/year (43.4%) in berthing, 2147.42 tons/year (37.6%) in cruising, and 1088.06 tons/year (19.0%) in anchoring. In the case of SOx, there were 403.36 tons/year in cruising, 312.75 tons/year in berthing, and 139.1 tons/year in anchoring, showing proportions of 47.2%, 37.0%, and 16.3%, respectively.

Table 6. Air pollutant emissions by activity phase.

Sector		Anchoring	Cruising (Cru, Man)	Berthing	Total
CO	Emission	137.3	237.2	312.8	687.4
	Ratio	20.00%	34.50%	45.50%	100.00%
NOx	Emission	1088.1	2157.40	2486.8	5732.2
	Ratio	19.00%	37.60%	43.40%	100.00%
SOx	Emission	139.1	403.4	312.7	855.2
	Ratio	16.30%	47.20%	36.60%	100.00%
TSP (PM_{10})	Emission	14.5	37.0	32.8	84.4
	Ratio	17.20%	43.90%	38.90%	100.00%
$PM_{2 \cdot 5}$	Emission	13.5	34.6	30.7	78.8
	Ratio	17.20%	43.90%	38.90%	100.00%
VOC	Emission	33.4	80.5	76.1	190.0
	Ratio	17.60%	42.40%	40.10%	100.00%
NH_3	Emission	0.1	0.2	0.3	0.7
	Ratio	20.00%	34.50%	45.50%	100.00%

In terms of the berthing section, the emissions of CO, NOx, VOC, and NH_3 calculated in this study were more than in the previous study [28]. On the other hand, SOx, TSP (PM_{10}), and $PM_{2 \cdot 5}$ were lower. Many factors influenced the air pollutant emissions, such as the sizes and types of the ships, the ships' trips, etc. However, the impact of the ECA policy implemented in 2020 was judged to be the greatest. The representative effect of the ECA policy was to reduce SOx, TSP (PM_{10}), and $PM_{2 \cdot 5}$.

According to the results for air pollutants divided by the ship types shown in Table 7, NOx emissions were the largest among the air pollutants, of which the air pollutant emissions of tankers were 2508.3 tons/year, accounting for 43.8%; container ships were 1694.2 tons/year (29.6%); general cargo ships were 772.9 tons/year (13.5%); and bulk carriers were 564.1 tons/year (9.8%). In terms of SOx emissions, tankers accounted for 46.8% with 400.2 tons/year, container ships emitted 220.6 tons/year (25.8%), general cargo ships emitted 132.5 tons/year (15.5%), and bulk carriers emitted 75.1 tons/year (8.8%).

Table 7. Air pollutant emissions by ship type.

Sector		Bulk Ship	Container Ship	Passenger Ship	General Cargo Ship	RORO Ship	Reefer	Tanker	Miscellaneous	Total
CO	Emission	60.3	195	1.1	97.3	15.5	1.1	310.2	6.9	687.4
	Ratio	8.80%	28.40%	0.20%	14.10%	2.30%	0.20%	45.10%	1.00%	100%
NOx	Emission	564.1	1694.20	7.2	772.9	128.4	9.3	2508.30	47.9	5732.2
	Ratio	9.80%	29.60%	0.10%	13.50%	2.20%	0.20%	43.80%	0.80%	100%
SOx	Emission	75.1	220.6	1.6	132.5	17.1	1.1	400.2	7	855.2
	Ratio	8.80%	25.80%	0.20%	15.50%	2.00%	0.10%	46.80%	0.80%	100%
TSP (PM_{10})	Emission	7.7	23	0.1	12.5	1.8	0.1	38.4	0.7	84.4
	Ratio	9.10%	27.30%	0.20%	14.80%	2.10%	0.10%	45.50%	0.90%	100%
$PM_{2 \cdot 5}$	Emission	7.2	21.5	0.1	11.7	1.7	0.1	35.9	0.7	78.8
	Ratio	9.10%	27.30%	0.20%	14.80%	2.10%	0.10%	45.50%	0.90%	100%
VOC	Emission	19.1	55.2	0.3	25.8	4.2	0.3	83.4	1.7	190
	Ratio	10.10%	29.10%	0.10%	13.60%	2.20%	0.10%	43.90%	0.90%	100%
NH_3	Emission	0.1	0.2	0	0.1	0	0	0.3	0	0.7
	Ratio	8.80%	28.40%	0.20%	14.10%	2.30%	0.20%	45.10%	1.00%	100%

5. Conclusions and Discussion

With the increasingly severe port air pollution, international organizations and communities have paid more attention to controlling such pollution. As a result, the limitations on air pollution emissions in Annex VI of the MARPOL 73/78 treaty have been constantly reinforced. The sulfur content of fuel oil for global shipping ships began to be regulated at the beginning of 2020. The EU, the US, China, South Korea, and other countries enacted laws to reduce air pollutant emissions accordingly.

From the standpoint of air pollution emissions by ship, this research considered international approaches and the existing data for South Korea. It proposed a framework for providing the process of calculating emissions from ports in South Korea. A case study using the Gwangyang and Yeosu Ports, one of the leading port areas in South Korea, was conducted to show how the proposal worked step by step. Moreover, when we suggested the missing data on main engine power through a simple linear regression model, the R^2 was relatively high. The study identified a process to estimate a ship's emissions more accurately and reasonably when using the given official data.

The implications of this study have four aspects. First, MOF has been striving to provide national guidelines for calculating air pollutant emissions for several years. However, its performance has been sluggish. This study can be used as guidelines for the MOF or the MOE when providing a national standard of port emissions calculations, focusing on the ship part. Second, since international organizations are currently tightening regulations on port air pollution, it is necessary to prepare a national management system to systematically calculate and continuously control air pollutants to respond to the strong regulations appropriately. Third, VTS data is already linked with Port-MIS. Therefore, it is necessary to establish a platform to calculate air pollutant emissions, simulate and evaluate eco-friendly policies, and manage information by linking related data. In the long run, it is an ideal choice for big data analysis, AI (artificial intelligence), deep learning, and prediction of emissions. Four, since it is challenging to calculate real-time emissions accurately at the current technology level, increasing the accuracy of AIS data through continuous technology development and investments is necessary.

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