



Sulfur Dioxide Emission Estimates from Merchant Vessels in a Port Area and Related Control Strategies

Ta-Kang Liu^{*}, Haw-Yang Sheu, Jhen-Yuan Tsai

Institute of Ocean Technology and Marine Affairs, National Cheng Kung University, 1 University Road, Tainan City, 70101, Taiwan

ABSTRACT

While maritime shipping is currently the most reliable form of cargo transport for global trade, it causes significant air pollution. The number of inbound and outbound vessels in the Port of Kaohsiung, as well as the cargo throughput, is the highest in Taiwan. These vessels emit considerable amounts of air pollutants. Two methods based on vessel activity intensity were adopted in this study to estimate the emissions of sulfur dioxide (SO₂) generated by the consumption of fuel oils by merchant vessels in the Port of Kaohsiung from 2006 to 2010. Emissions were estimated to be 3,229–3,889 tonnes and 1,395–1,777 tonnes using a method based on cargo capacity and vessel engine activity time, respectively. These estimates are equivalent to 3.7% to 4.5% of the overall SO₂ emissions in Kaohsiung City. The difference between these estimates was due to varying parameters being adopted for each method, such as cargo throughput capacity, vessel power and the emission correction factor related to fuel oils. The SO₂ emissions of merchant vessels can be mitigated with the use of an incentive discount system. It is also estimated that when the shore power facilities in the Port of Kaohsiung are used to reduce emissions during vessel hotelling, the additional power requirement would be 6.6% of the overall power consumption of Kaohsiung City for the year 2010.

Keyword: Sulfur dioxide; Vessel-source pollution; Policy instruments; Shore power.

INTRODUCTION

Maritime shipping trade is developing progressively. Marine navigation requires a great deal of fuel oils, and consequently emits large amounts of air pollutants, including: diesel exhaust, particulate matter (PM), volatile organic compounds (VOCs), nitrogen oxides (NO_x), ozone and sulfur dioxide (SO₂). These air pollutants appear to have a major impact on the environment and ecosystem. In order to prevent the pollution caused by maritime vessels, the International Maritime Organization (IMO) adopted the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1973. Later, IMO formally combined the MARPOL 1973 with the Protocol of 1978 (abbreviated as MARPOL 73/78). In 1997, Annex VI was added to MARPOL 73/78 to regulate the air pollutants emitted by maritime vessels (IMO, 2010).

In the 58th session of the Marine Environment Protection Committee (MEPC) held by the IMO in 2008, the contracting parties were requested to comply with regulations regarding

the sulfur content of fuel oils used in their vessels (MEPC, 2008). Restrictions on the sulfur content in fuel oils were even more stringent for parties within the special sulfur emission control areas (SECAs), including the Baltic Sea (entered into force on May 19, 2006), as well as the North Sea and the English Channel (entered into force on August 11, 2007). The global vessel-source SO₂ emissions from IMO-affiliated vessels in 1990 were approximately 4.5 to 6.5 million tonnes (IMO, 2010), escalating to 16.5 million tonnes in 2007 (Cofala *et al.*, 2007). This is approximately 4% to 9% of the overall global SO₂ emissions (Tzannatos, 2010). SO₂ emissions gradually increase in tandem with the prosperity of maritime shipping. Northern Germany and Denmark regions exhibit 50% higher sulfate aerosol concentrations in summer than during the other seasons due to vessel-source emissions (Matthias *et al.*, 2010). Emission of sulfur dioxide tends to acidify soil and surface water, or may even result in acid deposition (Streets *et al.*, 2001; Smith *et al.*, 2001).

In addition, numerous countries have redacted various control and mitigation measures to reduce pollution caused by vessels cruising in their ports. For example, the American Association of Port Authorities (AAPA) formulated the *Environmental Management Handbook* to effectively control and regulate the effects of port pollution, consequently protecting natural resources via this handbook (AAPA, 1998). The US government has established SECAs in sea

^{*} Corresponding author.

Tel.: +886-6-2757575 ext. 31146; Fax: +886-6-2753364
E-mail address: tkliu@mail.ncku.edu.tw

areas within its jurisdiction to further control the sulfur content in fuel oils used by both inbound and outbound vessels (USEPA, 2010). The European Commission (EC) restricted the sulfur content in fuel oils used by vessels of the member states in the Council Directive 1999/32/EC on April 26, 1999, and in an amendment to it, the Council Directive 2005/33/EC on July 6, 2005 (EU, 1999, 2005).

Internationally, numerous variables influence the monitoring and estimation methods for investigating vessel-source air pollution. These variables include the vessel-source air pollution in different areas (harbor or ocean), type of vessel or vessel power, different types of fuel oil consumed, and differences in the conceptualization of researchers (Corbett and Fischbeck, 1997; Dong et al., 2002; Maes et al., 2007). Since the cost of boarding inspections is reasonably high, theoretical methods are typically adopted to estimate air pollution emissions generated by vessels in port areas. These methods fall into two categories: top down assessment based on fuel intensity and bottom up assessment based on activity intensity of vessels. The top down assessment is used to gather statistics for global emissions data (Corbett and Fischbeck, 1997; Corbett and Koehler, 2003; Corbett et al., 2004; Endresen et al., 2005). Meanwhile, the bottom up assessment is currently the most commonly used method to estimate vessel-source air pollution (Trozzi et al., 1995; Hua, 1997; Whall et al., 2002; Vangheluwe et al., 2007; Schrooten et al., 2008; SCG, 2009). In Taiwan, although limited researches focused on vessel-source emissions of carbon dioxide and particulate matters, the emissions of vessel-source SO₂ has not been well investigated (Dong et al., 2002; Peng et al., 2005; Liao et al., 2010). Since top down method is typically used for global estimation, this study used bottom up method based on activity intensity to calculate SO₂ emissions of merchant vessels in the Port of Kaohsiung. The current available bottom up methods involves two types of activity intensity to evaluate the generation of SO₂: (1) the cargo that vessels carried during transit (Dong et al., 2002) and (2) the power consumed by vessel engines (Whall et al., 2002; Maes et al., 2007; SCG, 2009). In this study, methods based on these two types of activity intensity were explored to calculate SO₂ emissions of inbound and outbound merchant vessels in the Port of Kaohsiung from 2006 to 2010. The results were then used to explore management strategies for controlling vessel-source SO₂ emissions.

METHODS

Study Area and Data Acquisition

This study adopted the Port of Kaohsiung, the largest international commercial port in Taiwan, as the research location. The port accommodates 2 inbound and outbound ship channels, where the first port on the north side and the second port on the south side are located, respectively. Currently, the total length of the ship channels in the Port of Kaohsiung is 18 km, comprising a 12 km main ship channel and a 6 km branch ship channel. The commercial shipping transit information for all the merchant vessels arriving in the Port of Kaohsiung, Taiwan from 2006–2010

was retrieved from the database of the Kaohsiung Harbor Bureau (KHB). Merchant vessels are ships that transport cargo or passengers. KHB distinguishes merchant vessels into the following 8 categories: containership, cargo ship, bulk carrier, oil tanker, refrigerated ship, passenger/cargo ship, passenger ship, and others. Transit information includes: date of entry, vessel name in Chinese and English, IMO number, flag state, port of registry, type of vessel, last port of call, next port of call, voyage routes, Gross Tonnage (GT), Net Tonnage (NT) and Deadweight Tonnage (DWT). These data were utilized to estimate the SO₂ emissions of merchant vessels. The cargo throughput and transit information for the visiting vessels are presented in Table 1.

Emission Estimate

The objective of this study was to employ two activity intensity-based methods to estimate the amount of SO₂ emissions generated by merchant vessels in the Port of Kaohsiung from 2006 to 2010. The estimation methods were compared, and the reasons for the differences in the emissions were further discussed. Finally, management strategies for the control and mitigation of vessel-source SO₂ pollution were explored. Detailed descriptions of the activity intensity-based estimation methods are as follows:

- Method 1: based on cargo capacity.

This method modified the calculation formulas based on the Taiwan Emission Data System (TEDS) established by Taiwan's Environmental Protection Administration (TEPA). According to Dong et al. (2002), the average energy density consumed by vessels in Taiwan's water is 143.4 kcal/tonne-km. One kilogram of ship fuel oil generates 9,000 kcal of energy, corresponding to a fuel consumption of 0.016 kg/tonne-km of cargo moved. The emission and activity intensity adopts the following form:

$$\text{Emission (kg)} = \text{Emission Factor (kg SO}_2\text{/ kg fuel)} \times \text{Activity Intensity (kg)} \quad (1)$$

$$\text{Activity Intensity} = \text{Fuel Consumption of Vessel (kg)} = \text{Cargo Throughput (tonne)} \times 0.016 \text{ (kg/tonne-km)} \times \text{effective distance (9 km in the Port of Kaohsiung)} \quad (2)$$

- Method 2: based on vessel engine activity time.

This method modified the calculation formulas proposed by the Port of Long Beach in the USA (SCG, 2009) and Belgian ports in Europe (Maes et al., 2007). Emission estimations can be expressed as follows:

$$\text{Emission (kg)} = \text{Engine Output Power of Vessel (kW)} \times \text{Load Factor (unitless)} \times \text{Activity Time (hr)} \times \text{Emission Coefficient (kg/kW-hr)} \times \text{Fuel Correction Factor (unitless)} \quad (3)$$

The estimation process requires data analysis and synthesis. The content of the collected data from 2006 to 2010 includes: cargo throughput, number of inbound and outbound vessels and their type, distance of navigation in port, power output of the main and auxiliary engines for different vessel types, fuel emission coefficients, etc. The required parameters for estimation are listed in Table 2.

Table 1. Transit information: The cargo throughput and number of vessels and their visits during 2006–2010.

Year	2006		2007		2008		2009		2010	
	No. of vessel	No. of visit	No. of vessel	No. of visit	No. of vessel	No. of visit	No. of vessel	No. of visit	No. of vessel	No. of visit
Cargo throughput (ton)	7,335	135,082,013	6,679	149,225,026	6,201	146,728,880	6,576	123,570,262	6,538	124,952,433
Containership	665	186	268	119	167	70	427	178	463	226
Cargo ship	484	33	255	125	175	50	299	124	312	165
Bulk carrier	728	230	678	231	466	138	628	267	823	347
Oil tanker	0	0	0	0	0	0	9	8	20	18
Refrigerated ship	363	3	337	4	272	4	240	4	243	5
Passenger/cargo ship	1	1	0	0	0	0	1	1	1	1
Passenger ship	24	8	23	13	54	20	101	46	120	56
Others	9,600	1,306	8,240	1,233	7,335	1,063	8,281	1,487	8,520	1,636
Total										

Table 2. Required parameters and source of various parameters for estimating SO₂ emission.

Required Parameters	Source Remark
Cargo throughput	Obtained from the monthly report of Taiwan's Ministry of Transport and Communications Global Website.
Emission factors	Adopted the 19.1S (S = sulfur content) assumed by the US Environmental Protection Agency (AP-42), as well as sulfur content 0.95% in the Port of Kaohsiung reported by Dong (2002).
Distance of navigation in port	The Port of Kaohsiung accommodates 2 inbound entrances with an overall length of the ship channels of 18 km, assuming that the effective distance is half of the overall length of the ship channel.
Vessel type	Shipping transit information from the database of the Kaohsiung Harbor Bureau was retrieved. Merchant vessels was classified into 8 categories: containership, cargo ship, bulk carrier, oil tanker, refrigerated ship, passenger and cargo ship, passenger ship and others.
Vessel power	Adopted the power of the inbound vessels in SCG's report that are of similar size to those in the Port of Kaohsiung (SCG, 2009).
Vessel maneuvering and hotelling times	Determined from Kaohsiung Harbor Bureau's integrated vessel status reporting system.
Emission coefficients	Adopted Whall <i>et al.</i> 's (2002) assumption regarding the main and auxiliary engine emission coefficients of various merchant vessels during maneuvering and hotelling operations, as well as the boiler coefficient assumed by SCG (2009).
Power load factors	Adopted Maes <i>et al.</i> 's (2007) assumption regarding the main and auxiliary engine power load of vessels.

RESULTS FOR SO₂ EMISSION ESTIMATE

Total Emissions Estimate

Merchant vessels typically burn high-sulfur Class C fuel oil in the high seas and switch to low-sulfur Class A fuel oil when entering the territorial sea of a coastal state. Current MARPOL's standard in SECAs requires using fuel oil with sulfur less than 1.5% and 1.0% for year 2008 and 2011, respectively. The Ministry of Transportation and Communications (MOTC) in Taiwan adopted MARPOL's standard and required merchant vessel switch to Class A fuel oil with sulfur less than 1.5% when entering Taiwan. The Port of Kaohsiung serves as an important transportation hub for 442 ports and 102 countries (Liu and Tsai, 2011). Since vessels come from various countries having different fuel grade standards, it is necessary to perform in-situ measurement in order to know the actual sulfur content in the fuel oil. Dong *et al.* (2002) reported that the sulfur content in Class A fuel oil surveyed in the Port of Kaohsiung is 0.1%–0.95% (average 0.5%). In this study, we estimated the SO₂ emission based on fuel oil sulfur content of 0.5%, 0.95%, and 1.5%, covering possible range of fuel oil sulfur in compliance with current requirements of MARPOL and MOTC, and the actual measurement results in the Port of Kaohsiung.

Table 3 shows the SO₂ emission of merchant vessels in the Port of Kaohsiung from 2006 to 2010 based on fuel oil sulfur content of 0.95%. Using the method based on cargo capacity, the SO₂ emissions for merchant vessels from 2006 to 2010 were, sequentially, 3,529, 3,899, 3,834, 3,229 and 3,265 tonnes, contributing 9.0%, 10.2%, 10.0%, 8.3% and 8.3%, respectively, of the total amount of SO₂ emissions in Kaohsiung City (TEPA, 2010a). This estimation method primarily referenced the variable of the cargo throughput capacity of inbound vessels every year. From 2006 to 2010, the cargo throughput capacity was, sequentially, 135.1, 149.2, 146.7, 123.5 and 125.0 million tonnes. In the context of Kaohsiung City's emission rates of SO₂, the EPA's data showed that the overall SO₂ emissions are increasing annually, mainly due to the steady industrial development and its increased SO₂ emissions. This caused the portion of SO₂ emissions from merchant vessels estimated using the cargo capacity-based method to exhibit a declining trend.

Using the method based on vessel engine activity time, the SO₂ emissions for merchant vessels in the Port of Kaohsiung from 2006 to 2010 were sequentially 1,777, 1,616, 1,395, 1,409 and 1,473 tonnes, contributing 4.5%, 4.2%, 3.6%, 3.7% and 4.4%, respectively, of the total amount of sulfur emissions in Kaohsiung City. In addition, using this method requires the collection and assumption of several variables, including vessel maneuvering and hotelling times, vessel power (main engine, auxiliary engine, and boiler), emission coefficient, modified engine power load factors and the corrected factor of fuel oils as shown in Eq. (3). When compared to the SO₂ emissions of Kaohsiung City, the portion of emissions from merchant vessels initially exhibited a declining trend, followed by an inclining trend, primarily because various emissions of engines were estimated during vessel transit. As the number of inbound vessels gradually

Table 3. The estimate emission of SO₂ (ton) from merchant vessel in Port of Kaohsiung during 2006–2010.

Year	Method	Based on cargo capacity	Based on vessel engine activity
2006		3,529	1,777
2007		3,899	1,616
2008		3,834	1,395
2009		3,229	1,409
2010		3,265	1,473

declined from 2006 to 2008, and subsequently increased afterwards, the overall maneuvering and hotelling times declined from 2006 to 2008, followed by a gradual increase afterwards. Consequently, this resulted in an SO₂ emissions decline initially, followed by a gradual increase.

The estimations of SO₂ emissions from merchant vessels from 2006 to 2010 were initially based on fuel oil sulfur content of 0.95%. Fig. 1 also shows the vessel-source SO₂ emissions when the sulfur content of fuel oils was 0.5% and 1.5%, respectively. The findings indicate that when vessels used fuel oils with varying sulfur contents during transit, the subsequent SO₂ emissions of these vessels significantly differed. As shown in Fig. 1, when using the method based on cargo capacity to estimate the vessel-source SO₂ emissions when using fuel oils with 0.95% sulfur content, the estimation results ranged between 3,229 and 3,899 tonnes from 2006 to 2010. When using fuel oils with a sulfur content of 1.5% and 0.5% in the same time span, the emissions were 5,098–6,156 tonnes, and 1,699–2,052 tonnes, respectively.

The use of the cargo capacity method to estimate SO₂ emissions depends on the capacity of the cargo throughput. The findings indicate that the higher the cargo throughput, the higher the estimated emission of SO₂. The highest cargo throughput capacity during the study years was in 2007; consequently, the calculated SO₂ emissions were the highest in that year. The lowest cargo throughput capacity for the study years was in 2009, and its estimated emissions were also the lowest. Regarding the method based on vessel engine activity time, the emission levels exhibited an initial decline, followed by a gradual and steady growth trend. This was due to the number of inbound merchant vessels in 2006 being the highest during the study years, gradually declining in number in 2007 and 2008, and rebounding in 2009 and 2010. In brief, the emission levels initially exhibited a decline, followed by a gradual increase. A recent estimate from Taiwan's EPA reported that the vessel-source SO₂ emission in the Port of Kaohsiung was 8,074 tonnes in 2009 (TEPA, 2010b), much greater than our results shown in Table 3. The difference between TEPA's value and ours is that their estimate extends to 20 nautical miles outside the Port of Kaohsiung while ours represents the emission inside the port.

Emissions from Different Type of Merchant Vessels

The varying demands of commercial trade caused the different inbound merchant vessels to differ in number, consequently resulting in varying emissions from different type of merchant vessels. Using the method based on vessel engine activity time, the SO₂ emissions of different

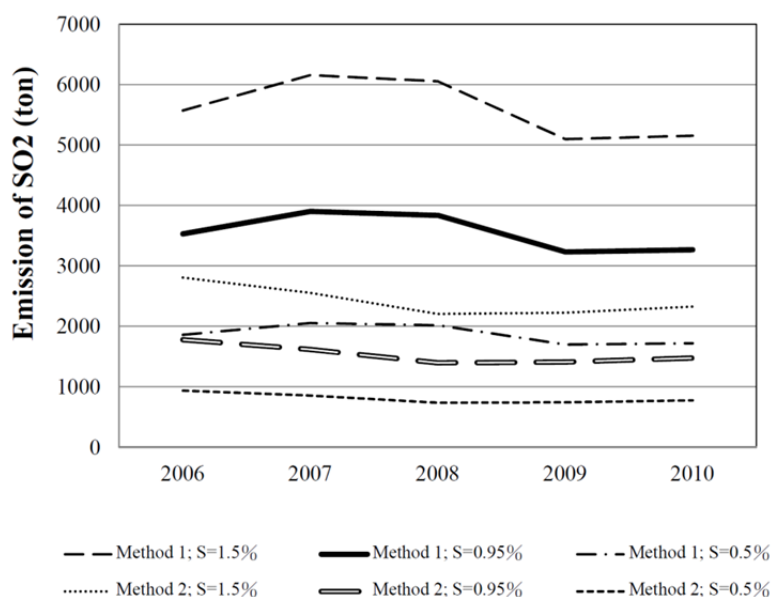


Fig. 1. Using two activity intensity-based methods to estimate vessel-source SO₂ emission in the Port of Kaohsiung. Sulfur content of fuel oils is shown at 0.5%, 0.95%, and 1.5%.

type of merchant vessels can be calculated according to their engine activity times. Table 4 shows the SO₂ emission levels of different type of merchant vessels using fuel oils with 0.95% sulfur content from 2006 to 2010; the result indicate that the pollution emissions of container vessels far exceeded those of other merchant vessels, since the Port of Kaohsiung is the primary container port for import and export in Taiwan, and the frequency of container vessel activity is comparatively higher.

The largest percentage of SO₂ emissions from merchant vessels in the Port of Kaohsiung was generated by container vessels. The second largest percentage of SO₂ emissions from merchant vessels in the Port of Kaohsiung was generated by oil tankers. Following containerships, the number of annual inbound oil tankers in the Port of Kaohsiung was not necessarily the most; moreover, their maneuvering and hotelling times were similar to those of cargo and bulk vessels. However, the SO₂ emissions of oil tankers from 2006 to 2010 remained steadily in second place. Their higher emissions are due to their higher vessel engine activity. Since domestic literature regarding the activity of vessel engine loads in the Port of Kaohsiung is deficient, the assumptions made by Maes *et al.* (2007) regarding the degree of engine loads of various vessel types during maneuvering and hotelling were adopted herein. The main and auxiliary engines of merchant vessels are typically under operation during maneuvering. During hotelling, the main engine is turned off except for oil tankers, relying only on the auxiliary engines to provide power (Maes *et al.*, 2007). Since the number of inbound oil tankers exhibits a gradual and steady growth trend, their SO₂ emissions outgrew other merchant vessel types due to the heavy use of the main and auxiliary engines, as well as auxiliary boilers, during hotelling. Using the method based on vessel engine activity, the annual SO₂ emissions for oil tankers during the study year exceeded 200 tonnes, except

for 2008 when the total number of inbound vessels was the lowest. The results indicate that containerships and oil tankers comprised the top two vessel types for SO₂ emissions in the Port of Kaohsiung; therefore, these two types of vessels should take precedence in plans to reduce air pollution emissions.

Comparison of Different Estimation Methods

This study adopts two methods based on cargo capacity and vessel engine activity time to estimate the SO₂ emission conditions of merchant vessels in the Port of Kaohsiung from 2006 to 2010. The Port of Kaohsiung is the largest harbor in Taiwan and the annual number of inbound and outbound merchant vessels accounts for over 50% of the overall merchant vessels of the country. Therefore, the vessel-source SO₂ emissions in the Port of Kaohsiung area comprise a considerable portion of the overall SO₂ emissions in Kaohsiung City, as shown in the results. The advantages and disadvantages of using these methods in the estimation are shown in Table 5. The method based on cargo capacity to estimate the SO₂ emissions of merchant vessels in the Port of Kaohsiung required collecting data regarding annual cargo throughput and the oil consumption of inbound and outbound vessels. These estimations primarily depend on the cargo throughput and emission factors, shown in Taiwan Emission Data System (TEDS). However, most of the emission factors in TEDS were adopted from the Compilation of Air Pollution Emission Factors (AP-42) of USEPA since this information is generally absent in Taiwan (TEPA, 2010c). The results indicate that the fluctuation of emissions matches the trend of cargo throughput, implying that cargo throughput is a determining parameter when using this estimation method. Nonetheless, this method does not consider the activity types or times of the vessels inside the port, and does not account for the air pollution generated from fuel oil consumption during hotelling.

Table 4. Emissions of SO₂ (ton) from difference type of merchant vessels in Port of Kaohsiung during 2006–2010 based on engine activity time.

Type \ Year	2006	2007	2008	2009	2010
Containership	1,373	1,258	1,182	1,052	1,130
Cargo ship	36	16	8	23	23
Bulk carrier	47	29	14	26	19
Oil tanker	242	235	127	227	227
Refrigerated ship	0	0	0	1	5
Passenger/cargo ship	73	77	60	68	58
Passenger ship	2	0	0	3	0.5
Others	4	2	4	10	10

Table 5. Comparison of different estimation methods for determining emission of SO₂ in the Port of Kaohsiung.

Method	Advantage	Disadvantage
Method 1: based on cargo capacity	The calculation is much simple since required information such as cargo throughput and emission factors are easier to obtain.	The activities when vessels are berthed are not accounted for.
Method 2: based on vessel engine activity time	Emissions are estimated as a function of vessel power demand. The method is suitable and precise for small regional scale study.	Various information such as vessel type and power, maneuvering and hotelling times, and emission coefficients, needs to be collected. Surrogate or assumption may be used since some information are not readily available.

In contrast, the method based on vessel engine activity time used to estimate the SO₂ emissions required collecting numerous data, including vessel power and load factors, the time required for different activity patterns of vessels in the port and the assumption of a fuel oil emission coefficient. By analyzing the time spent on maneuvering and hotelling activities as acquired from the Integrated Vessel Status Reporting System, this method can effectively estimate the emissions from the main engines, auxiliary engines and boilers of the vessels. However, there are no detailed estimations on the emission coefficients of vessel-source air pollution in Taiwan and the collection of various vessel power data is extremely difficult in practice. Estimations conducted using this method must adopt some assumptions from literature reviews; this process introduces uncertainties to the estimates. In both methods, several assumptions were adopted from the literature, thereby limiting the accuracy of this study. The accuracy can be greatly improved if some parameters, such as emission factors, vessel power and load factors, can be tailored to reflect the vessel activity in the Port of Kaohsiung.

MANAGEMENT STRATEGIES FOR VESSEL-SOURCE SO₂ CONTROL

The current policy instruments employed to mitigate and control vessel-source air pollution emissions can be categorized into 2 types: command and control, and market-based mechanisms (i.e., incentive-based mechanisms) (Wang et al., 2007). Command and control mechanisms typically establish a set of regulations for limiting vessel-source air pollution emissions; compliance to the rules is enforced.

Currently, many countries worldwide primarily enact legislation to limit the emissions of vessel-source air pollution according to the standards set by the Annex VI of IMO's MARPOL convention. This legally binding instrument effectively holds contracting flag states responsible for reducing air pollutants dispersed by vessels flying their flags. It also facilitates coastal states effectively controlling the emissions of inbound and outbound vessels in their ports, thereby preventing the vessel-source air pollution from contaminating their coastal environments. In recent years, the market-based mechanism, i.e., the use of incentive-based economic tools for air pollution emissions control became an effective policy tool incorporated by numerous countries to control vessel-source air pollution emissions in various ports. The Port of Kaohsiung is the largest port in Taiwan and the air pollution generated by merchant vessels presents an extra burden on Kaohsiung City. The substitutes for low sulfur fuel oils, utilization of an alternative power supply, and installation of pollution-reducing equipment and devices on ships are all capable of effectively reducing vessel-source pollution in the Port of Kaohsiung. In this section, we explore management strategies such as economic tools and alternative power supply in response to the potential reduction vessel-source SO₂ pollution.

Economic Tools

Currently, several economic tools are used for mitigating air pollution in ports, including rate discounts for switching fuel oils to marine distillates, and fairway and port dues for maritime shipping. For example, Sweden and Norway implemented differentiated fairway dues or tonnage tax, requesting vessels entering the ports to comply with the

rules of the port state. The Swedish government adopted a differentiation scheme for fairway dues, granting discounts to inbound vessels that use fuel oils with low sulfur content (Swahn, 2002). The requirement for these discounts is that passenger ships and cargo ships use fuel oils with sulfur contents of less than 0.5% and 1.0%, respectively. Qualified inbound vessels are granted a discount of 0.9 SEK (Swedish Krona) on fairway dues per tonne. An additional 3.40 SEK per tonne is charged for nitrogen dioxide emissions less than 2 g/kWh and 5 SEK per tonne for emissions greater than 12 g/kWh. The Norwegian government adopted an environmental differentiation of the tonnage tax based on the Ship Environment Index System (SEIS), which evaluates vessels based on up to seven different parameters, including sulfur emission (Kågeson, 1999). Vessels receive environmental credits based on their types and the sulfur content in their fuel oils or the NO_x emissions generated by their engines. Accordingly, the port authority can then charge different tonnage tax amounts based on earned environmental credits.

It would be beneficial for Taiwan's port authority to adopt measures similar to those in Sweden and Norway, to reward vessels using fuel oil with low sulfur content. For vessels using fuel oils with high sulfur content, higher port dues can be charged. These fees and penalties collected for non-compliance of other vessel-source pollution can serve as a fund for environmental protection and maintenance of the port, including installation of shore power facilities. These economic tools cultivate the incentives for vessel owners to utilize low sulfur fuel oil. Since the emission of SO₂ is proportionally related to the sulfur content in fuel oils as show in both methods, the reduction of SO₂ emission can be determined at a known decrease of fuel oil sulfur content. For example, it can be seen in Fig. 1 that a decrease of fuel oil sulfur content of 0.5% in 2010 results in the SO₂ reduction of 1,718 tonnes based on Method 1 and 775 tonnes based on Method 2.

Alternative Power Supply

The use of shore power is an emerging trend for the abatement of vessel-source air pollution. Utilization of shore power reduces the emissions from vessel engines during hotelling. Currently, successful cases regarding the

implementation of shore power exist in Europe and America. The use of shore power presents a burden to the power consumption of coastal cities; the estimated power consumption for maneuvering and hotelling of merchant vessels in the Port of Kaohsiung in 2010 is presented in Table 6, where power consumption is the product of power multiplies, load factors and activity times. The power usage of all merchant vessels was approximately 77.7 million kw·hr during maneuvering, and approximately 179.8 million kw·hr during hotelling in 2010. The ratio for the power consumption of these two activities was about 1:2.3.

If the power required for hotelling was provided by shore power, the overall annual power consumption of Kaohsiung City in 2010 would have risen from 2,720 million kw·hr to 2,900 million kw·hr, i.e., a 6.6% increase of the annual power consumed. The additional shore power cost for vessel owners is NT\$ 535 million (= 17.8 million USD) per year, based on the Tai-Power rate of NT\$ 2.975 per kw·hr. Shore power for hotelling of vessels contributes to a small portion of the total power consumption of Kaohsiung City, while it would considerably reduce the vessel-source air pollution. In Table 6, it can be seen that hotelling required much more power than maneuvering for all types of merchant vessels, especially for passenger ships. Based on Method 2, the reduction of SO₂ when using shore power during hotelling is 1,008 tonnes in 2010 when sulfur content is assumed 0.95%. However, based on the energy portfolio of Tai-power and TEPA's TEDS, the average SO₂ emission rate for power generation equals to 0.72 tonnes SO₂ per million kw·hr (TPC, 2013). The use of alternative shore power may therefore result in additional 129 tonnes of SO₂ emission. Overall, the reduction of SO₂ using shore power equals to 879 tonnes in 2010, when considering the additional emission during power generation.

The Way Forward

The port of Kaohsiung plays a very important role in the national economic development of Taiwan, handling 57% of the import and export volume of cargo and 73% of containers. Although it was ranked 3rd among the world's busiest container ports in 2000, the rise of China's economy and its seaports, such as the ports of Shanghai, Shenzhen, Ningbo-Zhoushan, Guangzhou, and Qingdao have encroached

Table 6. The estimated electricity consumed for merchant ships in Port of kaohsiung during maneuvering and hotelling in 2010.

Type of vessel	Electricity consumed	
	Manuvering (kw·hr)	Hotelling (kw·hr)
Containership	65,656,009	116,776,242
Cargo ship	1,102,833	2,010,658
Bulk carrier	922,746	1,874,203
Oil tanker	8,921,269	47,455,043
Refrigerated ship	58,010	213,657
Passenger/cargo ship	356,496	10,416,452
Passenger ship	7,405	66,120
Others	689,229	1,015,312
Sum	77,713,997	179,827,687
Manuvering:Hotelling	1:2.3	

the market share of the port of Kaohsiung and dropped its ranking to 12th in 2012 (KHB, 2012). In Table 1, it can be seen that the number of visits in the Port of Kaohsiung fluctuates between 7,335 to 9,600 during 2006–2010. Considering that Taiwan's government tries to develop the port of Kaohsiung into an intercontinental container center with expansion of current facilities and other developments as well, such as a modernized passenger terminal under construction, the visits of merchant vessels, especially cruise liners, are expected to rise in the near future (KHB, 2012). From Table 1, there are very few visits of passenger ships in the past and the increase of visits in the future may cause additional burden of SO₂ emission compared to the current conditions. The cruise ships are known for their much higher auxiliary boiler usage rates during hotelling than the other vessel types, due to the number of passengers and need for hot water (SCG, 2009). Installation of shore power facilities is a global trend for green ports and seems to be a promising alternative for the port of Kaohsiung to reduce the SO₂ emission during hotelling in the future. In order to develop the port of Kaohsiung as a green port, more stringent limit for fuel oil sulfur should be pursued as well, along with economic tools to induce compliance.

CONCLUSION

In this study, it was found that based on the two estimation methods, the SO₂ emissions in the port of Kaohsiung contribute 3.7%–4.5% and 8.3%–10.2%, respectively, to the overall SO₂ emissions in Kaohsiung City. The reasons for the differences can be attributed to the various assumptions adopted in both methods. In actuality, the sulfur content in the fuel oils of each individual vessel should be determined by random sampling to obtain a more precise estimate for both methods. With a more comprehensive data collection regarding the emission conditions of merchant vessels, a more accurate estimate of vessel-source pollution emissions can be derived. While Taiwan has enacted the “Air Pollution Control Act”, regulatory restrictions and standards are only established for particulate pollutants emitted from vessels, with no rules specified for gaseous pollutants, such as SO₂, which accounts for the large volume of the pollutants emitted. Feasible management strategies for vessel-source SO₂ control include: a market-based instrument to promote switching to low sulfur content fuel oils or using flue gas desulfurization technologies; enacting stringent regulations and training for environmental inspectors for enforcement; and installing alternative shore power facilities. The annual electricity required for shore power is 6.6% of the total power provided for Kaohsiung City. This does not present an immediate burden; the installation of shore power seems to be a plausible first step to transform the Port of Kaohsiung into a green port.

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REFERENCE

- AAPA, American Association of Port Authorities (1998). *Environmental Management Handbook*, South Carolina State Ports Authority.
- Cofala, J., Amann, M., Heyes, C., Wagner, F., Klimont, Z., Posch, M., Schopp, W., Tarasoon, L., Jonson, J. E., Whall, C. and Stavrakaki, A. (2007). Analysis of Policy Measures to Reduce Ship Emissions in the Context of the Revision of the National Emissions Ceilings Directive, IIASAS, European Commission, DG Environment.
- Corbett, J.J. and Fischbeck, P. (1997). Emissions from Ships. *Science* 278: 823–824.
- Corbett, J.J. and Koehler, H.W. (2003). Updated Emissions from Ocean Shipping. *J. Geophys. Res.* 108: 4650.
- Corbett, J.J., Winebrake, J.J., Chapman, D. and Woods, D. (2004). An Evaluation of Public-Private Incentives to Reduce Emissions from Regional Ferries. Alan M. Voorhees Transportation Center, U.S. Department of Transportation and Federal Transit Administration.
- Dong, C.D., Haung, K.L., Chen, C.W., Lee, C.W., Lin, H.Y. and Chen, C.F. (2002). Estimation of Air Pollutants Emission from Ships in the Kaohsiung Harbor Area. *Aerosol Air Qual. Res.* 2: 31–40.
- Endresen, Ø., Bakke, J., Sørsgard, E. and Berglen, T.F. (2005). Improved Modeling of Ship SO₂ Emissions – A Fuel-based Approach. *Atmos. Environ.* 39: 3621–3628.
- EU, European Union (1999). Council Directive 1999/32/EC of 26 April 1999 Relating to a Reduction in the Sulfur Content of Certain Liquid Fuels and Amending Directive 93/12/EEC. *Off. J. Eur. Union* 121: 13–18.
- EU, European Union (2005). Directive 2005/33/EC of the European Parliament and of the Council of 6 July 2005 Amending Directive 1999/32/EC. *Off. J. Eur. Union* 191: 59–69.
- Hua, C. (1997). Vehicle Exhaust Mitigation Technologies: Vessel-source Air Pollution and its Control Strategy, Taiwan's Environmental Protection Agency.
- IMO (2010). MARPOL Annex VI Website, http://www.imo.org/Environment/mainframe.asp?topic_id=233 (Accessed on December 7, 2012).
- Kågeson, P. (1999). Economic Instruments for Reducing Emissions from Sea Transport. Air Pollution and Climate Series No. 11/T & E Report 99/7, The European Federation for Transport and Environment.
- KHB, Kaohsiung Harbor Bureau (2012). KHB annual Statistics Report 2012, Kaohsiung, Taiwan.
- Liao, C.H., Tseng, P.H., Cullinane, K. and Lu, C.S. (2010). The Impact of an Emerging Port on the Carbon Dioxide Emissions of Inland Container Transport: An Empirical Study of Taipei Port. *Energy Policy* 38: 5251–5257.
- Liu, T.K. and Tsai, T.K. (2011). Vessel Traffic Patterns in

- the Port of Kaohsiung and the Management Implication for Preventing the Introduction of Non-Indigenous Aquatic Species. *Mar. Pollut. Bull.* 62:602–608.
- Maes, F., Vanhaecke, P. and van Ypersele, J.P. (2007). Emissions of CO₂, SO₂ and NO_x from Ships. Scientific Support Plan for a Sustainable Development Policy, Belgian Science Policy.
- Matthias, V., Bewersdorff, I., Aulinger, A. and Quante, M. (2010). The Contribution of Ship Emissions to Air Pollution in the North Sea Regions. *Environ. Pollut.* 158: 2241–2250.
- MEPC (2008). Environment Meeting Adopts Revised Regulations on Ship Emissions, Briefing 46, IMO Marine Environment Protection Committee (MEPC), 58th Session: 6–10 October 2008.
- Peng, C.Y., Lin, C.Y. and Jong, T.C. (2005). Emissions of Particulate and Gaseous Pollutants within the Keelung Harbor Region of Taiwan. *Environ. Monit. Assess.* 109: 37–56.
- SCG, Starcrest Consulting Group (2009). Port of Long Beach Air Emissions Inventory – 2009. Port of Long Beach.
- Schrooten, L., Vlieger, I.D., Panis, L.I., Styns, K. and Torfs, R. (2008). Inventory and Forecasting of Maritime Emissions in the Belgian Sea Territory, an Activity-based Emission Model. *Atmos. Environ.* 42: 667–676.
- Smith, S.J., Pitcher, H. and Wigley, T.M.L. (2001). Global and Regional Anthropogenic Sulfur Dioxide Emissions. *Global Planet. Change* 29: 99–119.
- Streets, D.G., Tsai, N.Y., Akimoto, H. and Oka, K. (2001). Trends in Emissions of Acidifying Species in Asia, 1985–1997. *Water Air Soil Pollut.* 130: 187–192.
- Swahn (2002). Environmentally Differentiated Fairway Charges in Practice – The Swedish Experience. Implementing Reform on Transport Pricing: Identifying Mode-Specific issues, Brussels.
- TEPA, Taiwan's Environmental Protection Administration (2010a). Total Allowable Load of Air Pollutants in the Kaohsiung and Pingtung Area, TEPA Report, Taipei, Taiwan.
- TEPA, Taiwan's Environmental Protection Administration (2010b). Establishment of Port Air Pollutant Emissions Inventory and Drafting of Management Strategies, TEPA Report, Taipei, Taiwan.
- TEPA, Taiwan's Environmental Protection Administration (2010c). Air Pollutants Emission Query System. <http://iv.y2.epa.gov.tw/air-ei/Default.asp> (Last Accessed on Jun 10, 2013).
- TPC, Tai-Power Company (2013). Installed Capacity and Electricity Generated. http://www.taipower.com.tw/content/new_info/new_info-c34.aspx?LinkID=13 (Last Accessed on Jun 10, 2013)
- Trozzi, C., Vaccaro, R. and Nicolo, L. (1995). Air Pollutants Emissions Estimate from Maritime Traffic in the Italian Harbours of Venice and Piombino. *Sci. Total Environ.* 169: 257–263.
- Tzannatos, E. (2010). Ship Emissions and Their Externalities for Greece. *Atmos. Environ.* 44: 2194–2202.
- USEPA (2010). Designation of North American Emission Control Area to Reduce Emissions from Ships, Office of Transportation and Air Quality, EPA-420-F-10-015.
- Vangheluwe, M., Mees, J. and Janssen, C. (2007). Monitoring Programme on Air Pollution from Sea-Going Vessels. Scientific Support Plan for a Sustainable Development Policy, Belgian Science Policy.
- Wang, C., Corbett, J.J. and Winebrake, J.J. (2007). Cost-Effectiveness of Reducing Sulfur Emissions from Ships. *Environ. Sci. Technol.* 41: 8233–8239.
- Whall, C., Cooper, D., Archer, K., Twigger, L., Thurston, N., Ockwell, D., McIntyre, A. and Ritchie, A. (2002). Quantification of Emissions from Ships Associated with Ship Movements between Ports in The European Community, European Commission, Entec UK Limited.

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