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ESTIMATION OF SHIP EXHAUST GAS EMISSIONS

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Ships run almost 90 % of the world trade and due to their great capability to carry vast amount of goods or passengers, ships are preferred at an increasing rate. Besides their important and indispensable benefits, ships have considerable impacts on human health and environment. Ships' emissions to air have increased dramatically through the last decades and it is estimated that the amount of the emissions will increase depending on the need for bigger ships and more powerful engines. Ship exhaust gas emissions include carbon monoxide (CO), carbon dioxide (CO2), particulate matter (PM), oxides of nitrogen (NOx) and oxides of sulfur (SOx). In this paper, one ship is focused and the total air emissions are estimated by different methods in order to make a comparison.

Keywords: Ship exhaust gas, Emissions, Estimation.

INTRODUCTION

Shipping is a huge sector with manufacturing, operation, maintenance/repairing and dismantle/recycling phases and it has the major part of the world transportation. Ships have been used widely for commercial and military purposes over the centuries.

Ships' propulsion has been powered by human force and the wind for centuries. After the industrial revolution, ships began to use coal to gain steam power. This new power type provided much more energy than the previous ways. However, burning coal formed new kind of wastes; gas and particulate emissions. These emissions are formed due to the process of burning. Carbon dioxide (CO2), carbon monoxide (CO) and black carbon (BC) are formed by fossil fuels which include mainly carbon. Burning process occurs by the help of air and as a consequence, nitrogen oxides (NOx) are formed. Due to poor burning, particulate matter (PM) such as ash and soot are emerged. After World War II, diesel engines began to dominate the propulsion of ships. These new engine types have brought a new liquid fuel with more content of pre-emissions. Due to these contents, sulfur oxides (SOx) and volatile organic compounds (VOC's) have begun to emit.

Although it has been estimated that diesel exhaust contains almost 450 different compounds (Andreoni et al, 2008), generally, only some of them are considered and investigated due to the harmful impacts on environment and human health. Carbon dioxide, carbon monoxide, sulfur and nitrogen oxides and particulate matter are the main harmful emissions from internal combustion process of ships' diesel engines.

There are several and comprehensive studies on ship emissions amount and their impacts on environment and human health. Andreoni et al (2008), MEPC (2005), Elvingson & Ågren (2004) have studied nitrogen oxides. In addition, Elvingson & Ågren (2004), Corbett et al, (2007) have investigated sulfur oxides. Schreier et al, (2007), Lauer et al, (2007), Eyring et al, (2010), Corbett et al, (2007) have assessed particulate matter. Doney et al, (2009), Miola et al, (2010), Haglind (2008) have worked on carbon dioxide and carbon monoxide emissions.

While these studies investigated the impacts of the emissions, there are others that focused on the amount and fraction of emissions. Table 1 presents the NOx, SOx, CO2, CO and PM emissions from global shipping activities.

Table 1. Emission estimation of global shipping activities gathered from recent studies

Emissions	*E2003*[1]	*CK2003*[2]	*E2005*[3]
NO_x	11,92 Tg	22,57 Tg	21,38 Tg
SO_x	6,82 Tg	12,98 Tg	12,03 Tg
CO_2	557,32 Tg	912,37 Tg	812,63 Tg
CO	1,12 Tg	-	1,31 Tg
PM	0,912 Tg	1,64 Tg	1,67 Tg

[1]E2003: Endresen et al, 2003

[2]CK2003: Corbett & Köhler, 2003

[3]E2005: Eyring et al, 2005

As it can be seen in Table 1, shipping activities are one of the main causes of global emissions. According to some recent studies, global shipping activities are responsible for 2-4 % of total CO2; 10-15 % of total NOx; 5-8 % of total SOx emissions (Tzannatos, 2010; Lawrance & Krutzen, 1999; Eyring et al, 2005; Corbett & Köhler, 2003). According to an estimation made for the Mediterranean basin, NOx, SO2, PM and CO2 emission amounts are 2; 1.45; 0.157 and 87.6 million tons, respectively (Cofala et al, 2007). Besides, only 30 % of shipping activity occurs far from 200 nautical miles from shore and 36 % of shipping activity occurs within 25 nautical miles from shore (Dalsøren et al, 2009). Thus, considering the coastal population density is much more than inland density, shipping emissions have a great importance for the people living in a port city.

The emissions have become an important issue for the last two decades. It has been estimated that the emissions will become a greater concern in the near future unless new and strict regulations are determined and forced by the authorities.

ESTIMATION of ANNUAL EMISSIONS of a SHIP

Estimation Method

There are two main estimation methods that can be used to calculate the emissions: Using the fuel consumption data and using the engines' power (Trozzi, 2010). Fuel consumption data are gained from the noon reports of ships. Due to the real-time data taken from ships, this method is more reliable way to calculate the emissions. Fuel consumption method is presented in Equation 1.

$$E_{Trip,i,j,m} = \Sigma(FC_{j,m,p} * EF_{i,j,m,p}) \quad (1)$$

In Equation (1);

E_{Trip}: emission over a complete trip (tons)
FC: fuel consumption (tons)
EF: emission factor (kg/tons)
i: pollutant
j: engine type (slow-medium-high speed diesel, gas turbine, steam turbine)
m: fuel type (bunker fuel oil, marine diesel oil, - /marine gas oil, gasoline)
p: the different phase of trip (cruise, hoteling (docking), maneuvering)

The other method is implemented by using the engines' power data. In this method, some new data are needed such as engines' power and cruising time to make a realistic estimation. Engine power method is presented in Equation 2.

$$E_{Trip,i,j,m} = \Sigma[T_P \, \Sigma(P_e * LF_e * EF_{e,i,j,m,p})] \quad (2)$$

In Equation (2);

E_{Trip}: emission over a complete trip (tons)
EF: emission factor (kg/kWh)
LF: engine load factor (%)
P: engine nominal power (kW)
T: time (hours)
e: engine category (main, auxiliary)
i: pollutant
j: engine type (slow-medium-high speed diesel, gas turbine, steam turbine)
p: the different phase of trip (cruise, hoteling, maneuvering)

Calculation of the Emissions

In this study emission estimation is made using the real-time fuel consumption data of a commercial bulk carrier ship (ship C) in 2012. A comparison is made considering the both methods offered by Trozzi. It has been aimed to compare two different emission estimation approaches, which use real fuel consumption and engine power data. Table 2 shows main characteristics of ship C.

Table 2. Ship C's main characteristics

	Ship C
L_{OA}	189.99 m
L_{BP}	185 m
B	32 m
D	18 m
T	12.8 m
DWT	56667.47 tones
Main Engine Power	9480 kW
Auxiliary Engine Power	3 x 600 kW
Speed	14 knots

Although size and capacity data will not be used for the calculations, they provide general information about the ship. Ship's main engine is a slow speed diesel engine and the auxiliary engines are medium speed generators. This data is important to decide the engines' emission factors. Engines' powers are also used in estimation calculations.

Fuel Consumption Approach

As it can be seen in Equation 1, fuel consumption method only needs fuel consumption data and emission factors. In order to estimate the emission as accurate as possible, fuel consumption data must be obtained from both transit and hotelling modes.

In Table 3, annual fuel consumptions of Ship C during transit and hoteling modes are given.

Table 3. Annual fuel consumption of ship C (2012)

Fuel Type	*Transit*	*Hoteling*
Heavy Fuel Oil (HFO)	5909.09 tones	676.30 tones
Marine Diesel Oil (MDO)	51.10 tones	142.40 tones

Both main engine and auxiliary engines are run during transit mode. Unlike transit mode, only auxiliary engines are run during hoteling. The main engine uses only HFO while the auxiliary engines use both HFO and MDO. Thus, although it is known that all of the MDO is used by the auxiliary engines, a numerical analysis has been realized to calculate how much HFO is used by the main engine and the auxiliary engines.

Because the main ship emissions are CO, CO_2, PM, NO_x and SO_x, the calculations have been made for these gas emissions. In order to make the calculations, emission factors are needed. The emission factors utilized are presented in Table 4. In fuel consumption approach, the emission factors' unit is kg/ton fuel.

Table 4. Emission factors for gas compounds (kg/ton fuel)[1]

Gas Component	HFO (ME)	HFO (AE)	MDO (AE)
CO_2	3179	3179	3179
CO	2.545	5.727	3.687
SO_x	46	46	8
NO_x	87.136	52.673	54.182
PM	6.667	2.203	1.843

[1]Cooper and Gustaffson, 2004

The annual emission amount results for ship C, obtained by using Equation 1 and emission factors from Table 4, are presented in Table 5.

Table 5. Annual emission amounts for Ship C using fuel consumption (FC) approach

Emission Types	Emission Amounts
CO_2	21550.37 tones
CO	21.93 tones
SO_x	304.47 tones
NO_x	536.07 tones
PM	38.01 tones
Total	22450.85 tones

Engine Power Approach

Engine power approach is far more complicated than fuel consumption approach, as it can be seen in Equation 2. While fuel consumption approach only needs fuel consumption amount and emission factors, engine power approach needs main engine and auxiliary engines' power, load factor of the engines, duration of transit and hoteling modes and respective emission factors.

Engine powers of ship C can be found in Table 2. Run durations of the engines are presented in Table 6.

Table 6. Run durations of the engines

Engine and Mode Type	Duration
Main Engine (Transit)	4597 hours
Main Engine (Hoteling)	4160.6 hours
Auxiliary Engines (Transit)	4597 hours
Auxiliary Engines (Hoteling)	4160.6 hours

Engine load factors are accepted as 0.8 for main engine, 0.3 for auxiliary engines during transit mode; 0.4 for auxiliary engines and 0.2 for main engine during hoteling mode (ENTEC, 2002)

Table 7 presents the emission factors for engine power approach.

Table 7. Emission factors for gas compounds (g/kWh)[1]

Gas Component	HFO (ME)	MDO (AE)
CO_2	620	690
CO	0.5	0.8
SO_x	9	1.7
NO_x	18.1	11.8
PM	1.3	0.4

[1]Cooper and Gustaffson, 2004

The obtained results are shown in Table 8.

Table 8. Annual emission amounts for Ship C using engine power (EP) approach

Emission Types	Emission Amounts
CO_2	29832.28 tones
CO	25.24 tones
SO_x	392.95 tones
NO_x	830.68 tones
PM	57.50 tones
Total	31138.65 tones

Results and Discussion

Table 9 shows the average annual emission production of a standard bulk carrier (ship C). As it can be seen in Table 9, there are some differences between the two estimation methods. It has been found that the emission amounts calculated by fuel consumption method are less than the results of engine power method.

Table 9. Comparison of fuel consumption (FC) and engine power (EP) approaches' results

Approach	CO_2	CO	SO_x	NO_x	PM	Total
FC	21550.37	21.93	304.47	536.07	38.01	22450.85
EP	29832.28	25.24	392.95	830.68	57.50	31138.65

As it can be seen from the results, ships have a great potential to produce harmful emissions. Thus, this issue must be considered for the future.

Both methods have different advantages and disadvantages. Fuel consumption method uses the real fuel consumption data so it may be more reliable. On the other hand, reaching the fuel consumption data accurately is a difficult matter. Thus, in situations in which the researcher only has the general information about ship, using the engine power method is the only way to make calculations. Each method has been developed for different circumstances.

The root cause of difference between emission amounts is emission factors. Calculated emission amounts strongly depend on emission factors. Thus, emission factors in this study are taken from only one source in order to make a reliable comparison. In addition, the different data and values that are used by these approaches cause difference, too. While fuel consumption method can be used for the need for more certainty, due to the difficulties on gaining the real data of used fuel for all ships cruising across the world, engine power method can be used for global estimation calculations.

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