PORT SAID ENGINEERING RESEARCH JOURNAL
Faculty of Engineering – Port Said University
Volume (21) No. (2) September 2017 pp. 128:137

ASSESSMENT OF THE EMISSIONS FROM SEAGOING SHIPS IN SUEZ CANAL

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Abstract

Shipping is a significant air pollution source in ports and coastal areas. Recently, air quality has become a severe problem in many countries, and the interest to calculate and determine the emission values of the ships crossing the coastal area or harbors has increased.

The current investigation aims to quantify ship exhaust emissions and their contribution to local atmospheric air pollution in the Suez Canal area. The study is performed to evaluate the relevance of shipping as an air polluter, and predict the overall emissions rate from international ships in the canal. Therefore, the annual emissions are calculated for individual vessels of various types transiting the Canal. The annual average number of ships crossing the canal is about 15000 ships. The emissions during sailing in the channel are distinguished during different scenarios and modes of ship operation. The machinery exhaust emissions in the forms of nitrogen oxides (NO_X), sulfur oxides (SO_X), carbon monoxide (CO), carbon dioxide (CO_2), and unburned hydrocarbons (UHC) are reported. Two international marine emissions inventories are used in the present calculations. The first method is the US Environmental Protection Agency model (EPA), while the European model (ENTEC) is used for the comparison and verification. Empirical functions and correlations are predicted and derived for different ship types, to simplify the ship emission calculations using the data available of about 15000 ships per year which selected and collected from Suez Canal database.

The study indicated that Suez Canal is receiving annually several thousands of pollutant tonnes with a potential increase in the future and the container vessels are the main source of air pollution amongst the different types of vessel. Also, the total emissions values appear to be consistently higher in EPA model than the corresponding values in ENTEC model.

KEY WORDS: Suez Canal, Ship emissions, Auxiliary and propulsion machinery, energy based emission factor.

1. INTRODUCTION

Although shipping is supported the overwhelming majority of world global trade and is widely acknowledged as being environment friendlier than other transport modes, the shipping is a significant air pollution source in ports and coastal areas.[1]. The ship emissions from marine power plant are closely related to a set of parameters representing the use of the engine, mainly: the propulsion and auxiliary machinery, the fuel used, the temperature of combustion, the cruise speed and the different navigation phases (cruise, hoteling, maneuvering)[2]. Shipping emissions (NOx, SOx, COx, HC, PM) are an important contributor to several major environmental problems. GHG emissions are categorized as six different gases carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydro fluorocarbons (HFCs), perfluorooctane sulphonate (PFCs), and sulphur hexafluoride (SF6)[3]. They are contributing to climate change, while non-GHG emissions can cause acid rain, damage to monuments, a reduction of agricultural fields, water contamination, modification of soil biology and deforestation[4]. Emissions from shipping currently represent 3% of the world's total emissions and the industry's share is increasing. A continued increase in international marine transport without any significant gains in energy efficiency may result in shipping being responsible for 6% of the world's GHG emissions by 2020 and 15% by 2050[3]. Between 1990 and 2007, the emissions of basic pollutants from global shipping increased from 585 to 1096 million tonnes [4]. It was estimated that CO_x emissions from global shipping in 2007 were 943.5×10^6 tonnes[4], whereas according to another assessment report the global shipping inventory of CO_x in 2006 stood at around 1 billion tonnes[5]. Different studies noticed that the global annual range from ship emissions have been between 813×10^6 & 912×10^6 tonnes[6,7,8]. Emission calculations up to the year 2050 predicted that there will be an increasing in ship emissions in the near future if not controlled to be less[9]. Recently inventories of ship emissions are an effective way for monitoring trends and prioritizing policy- making for protecting the atmospheric environment at any region [10].

The existing methods of ship emission estimation depend mainly upon the application of ship activity-based or fuel-based methodologies[1]. Earlier inventories relied mainly on fuel-based emission factors. Recently, there is a general agreement in the marine sector that the use of fuel-based emission factors for vessels without direct fuel consumption data is not preferred. Instead, energy-based emission factors

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in (g/kWh) should be used, based on ship machinery load and operation modes[11]. So many research work had been carried out to estimate ship emissions in European seas [12-18] based on ship activity. Also different examples of local activity-based inventories are presented in Denmark[14], in Belgium[15], in Greece[16], in Turkey[17], in Sweden[18], and in Italian ports[19]. In addition, some examples of fuel-based emission methodology from shipping are introduced in Greece, Sweden, Norway and the United Kingdom[20], [21].

The main objective of the present study is to quantify ship emissions and their contribution to local atmospheric air pollution in Suez Canal navigation channel in Egypt. Also, the current investigation aims to evaluate the relevance of shipping as an air polluter, and predict the overall emissions rate from international ships in the canal. The annual emissions and resulting concentrations and deposition along the channel waterway from Port Said in the north to Suez gulf in the south are calculated for international sea going ships. Two international marine emissions inventories are applied in the present research for ship emission's calculations. The first method applied is US Environmental Protection Agency model (EPA)[22], while the European Commission model as done by ENTEC[22] is used as a second method for comparison and verification. The total emissions values appear to be consistently higher in EPA model than the corresponding values in ENTEC model. This variation may be attributed due to the difference assumptions between the methodologies. Also the variation may be happened due to the ship energy efficiency, the ship innovation renovation and fuel specifications.

2. DATA COLLECTION AND CASE STUDY

2.1 Study Area

Suez Canal is the shortest link between East and the West, with maritime transportation considered to be the cheapest form of transport, the Suez Canal continues to play an important role in trade. Suez Canal is one of the busiest transporting cargo waterways not only in Egypt but also all over the world. The Suez Canal is located in Egypt, west of the Sinai Peninsula. It connects Port Said on the Mediterranean Sea with the port of Suez on the Red Sea. As a result of the rapid economic development of the canal region and the importance of marine transportation, more concerns have been focus on the air quality along the waterway. Fig.1 shows the map view for Suez Canal waterway.

2.1.1 Study period

The present study covers the last recent eight years started from 2009 up to 2016. The data of different seagoing ships crossing the Suez Canal within one year period starting from 01/01/2014 to 31/12/2014 has been obtained. The study was carried on in details to calculate the exhaust emissions from all the international sea going ships crossing the Canal for one year period, then it can be generalized and extrapolated to predict all the study period.

2.2 Data collections

The ships examined in the present study were typical and actually international vessels passed the Suez Canal in the above mentioned period. The vessels are considered as ocean going ships. The domestic boats and units weren't considered due to its low contribution of the total exhaust emissions; e.g.: tugs, ferries, fishing and charter boats, etc. Sample datasets have been collected from main administration of Suez Canal Authority in Port Said Branch. Table.1 shows the sample collected versus the actual number of ships passed through the canal in 2014.

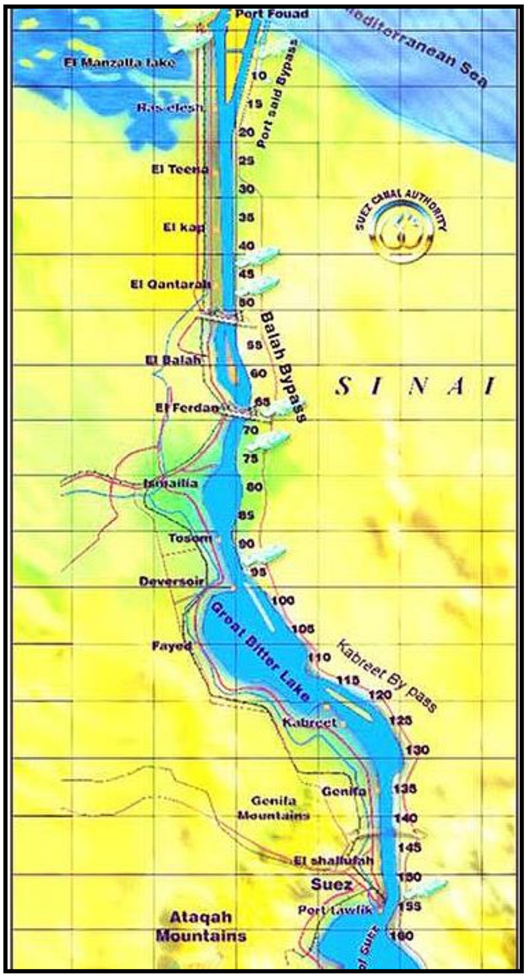

Fig (1): Map view of Suez Canal [23]

Table.1: Collected ships number of versus actual ships

No.	Ship Type	Collected ships	Actual number of ships [24]
1	Container Ship	15	6129
2	Bulk Carrier	12	3051
3	Car Carrier	8	1003
4	Ro-Ro	5	228
5	LNG	12	614
6	LPG	3	
7	Chemical Tanker	9	4053
8	Crude Oil Tanker	22	
9	others	64	
sum		**150**	**15078**

2.3 ship categories

Ships are characterized and categorized according to the type of cargo they are designed to carry. Table.2 lists the definitions of primary ship categories that have been used in the emissions inventory for this study.

Table.2: functions of ship category tested [4]

Ship type	Description
Container Ship	Is built to carry containerized cargo and nothing else, i.e. fully cellular ships designed to carry containers both on deck and under deck.
Bulk Carrier	Are ships designed to carry bulk goods such as grain, iron, coal and so.
Car Carrier	Is designed to carry cars, trucks and sometimes other special cargo on wheels.
Ro-Ro	Are ships that are loaded and unloaded by driving the cargo on wheels.
LNG	Are specialized tankers to carry Liquefied Natural gas.
LPG	Are specialized tankers to carry Liquefied Petroleum Gas and other products, such as Ammonia.
Chemical Tanker	Ships designed to carry different types of industrial chemicals.
Crude Oil Tanker	Include tankers which are intended for carrying crude oil.

2.4 Prediction of auxiliary engines as a function of propulsion machinery

In the present study, the international sea going ships crossing the Canal are classified in eight categories as shown in table 1. Ship particulars which contain the require sufficient information data are defined such as ship flag, ship main propulsion machinery, auxiliary engine power, Suez canal net tonnage, and all engine specifications. Table 1 indicates a big difference between the complete collected data used in the present study and the actual number of vessels crossing the canal. The reason for that is the lack of data and missing information regarding the international sea going ships. It is very hard to get the complete vessel characteristics (number, categories, dimensions, sailing speed, auxiliary and propulsion power) for each ship. The majority of ship parameters and specifications are missing and only few ships have complete data.

As a first preliminary calculation step to overcome the lake of data, a set of simple correlations are predicted between the Main Engines power values and the auxiliary engine power values for each ship category. The predicted correlations are established as, $P_{Aux}= C(P_{M/C})^N$ to estimate the missing corresponding value of auxiliary engine power for any ship, where C and N are regression constants. Some sample of the regression analysis correlations are plotted in figures 2, 3, 4 and 5 for containers, bulk carriers, oil tankers and LNG respectively. Generally, the auxiliary power of most ship types increases as the propulsion engine power increase. This relations is observed for container ships, car carriers, Ro-Ro, chemical tankers, and LNG. The different trend for bulk carriers correlation may be contributed to the specifications of ships in the collected data. The trend partially is contributed to the using of shaft generators and heat recovery systems in such types of ships.

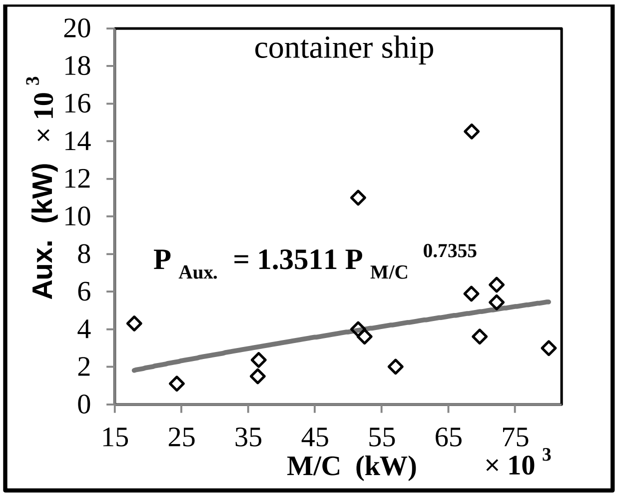

Fig.2: Machinery power (M/C) versus auxiliary (Aux) power for container ships

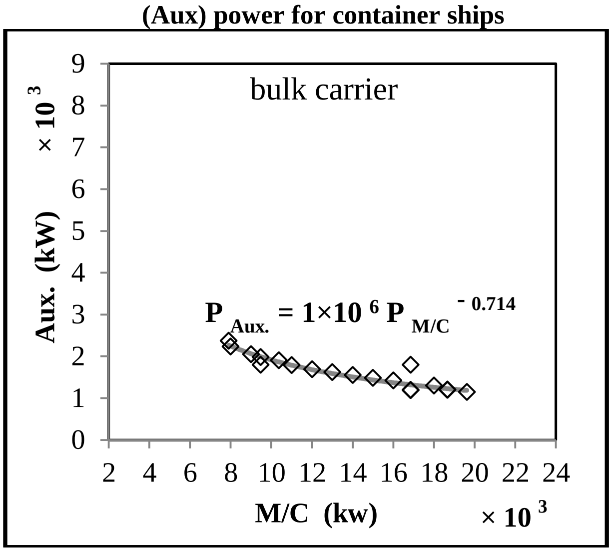

Fig.3: Machinery power (M/C) versus Auxiliary (Aux) power for bulk carriers

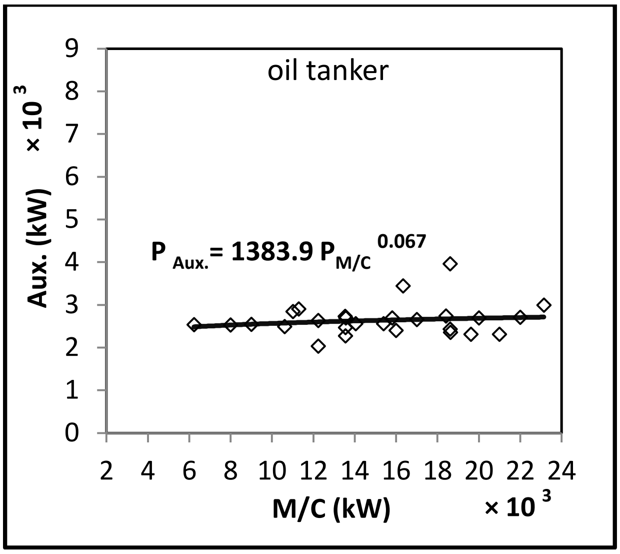

Fig.4: Machinery power (M/C) versus Auxiliary (Aux) power for oil tankers

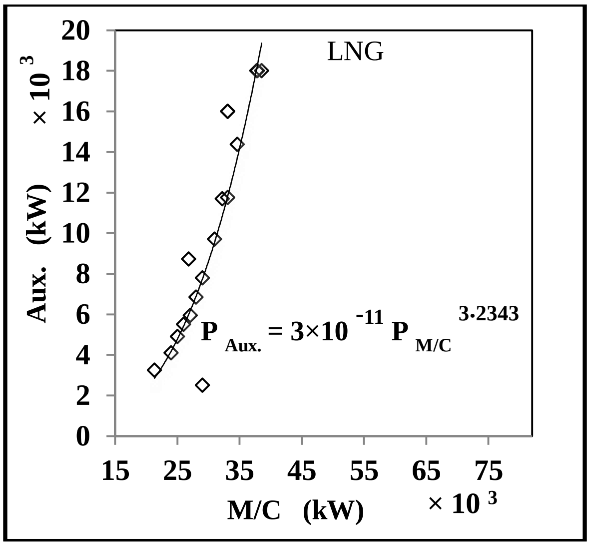

Fig.5: Machinery power (M/C) versus Auxiliary (Aux) power for LNG

The predicted correlations for most of ship categories result in auxiliary machinery values within a maximum deviation about 22%. The values of auxiliary power as a function of propulsion machinery power may differ within the same group of ships due to the ship machinery layout and arrangement. The value of auxiliary power is strongly related to propulsion power in LNG carriers due to the electric power required for NG re-liquefaction plant. The same trend is observed in RO-RO ship due to the big electric consumption in refrigerated trucks which need more electric load during operation.

2.5 Emissions Calculation Methodologies

2.5.1 EPA Methodology

In EPA method equation (1) is used to estimate the total emissions according to the type of vessel, the type of fuel consumption and the mode of operation[11]. The equation is as follow[11]:

Emissions (gm) = Engine power (kW) x Load factor(%) x Time(h)x Emission Factor $\left({}^{gm}/_{kW.h}\right)$ (1)

This equation is assumed to be valid for main propulsion machinery and also for auxiliary engines.

The emission factor may be estimated from equation (2) as follows and all the variables and regression analysis constants[22] are tabulated in table 3.

Emission factor = a (Load factor) $^{-x}$ +b (2)

Where: a, b and x are the dimensional less coefficients specific to each air contaminant.

The total emission from the ship transiting the Suez Canal (E_t) in the present study is calculated as:

E_t = (emission factor) (ship machinery power in kW) (trip time in h) (3)

the emission factor is estimated from equation 2.

In the present study, it has been applied the last version of EPA methodology that shown in equation 2.

Table.3: Marine Engine Emission Factor Coefficients[22]

Pollutant	Exponent (x)	Coefficient (a)	Intercept (b)
PM	1.5	0.0059	0.2551
NO_x	1.5	0.1255	10.4496
NO_2	1.5	0.18865	15.5247
CO	1	0.8378	NS
CO_2	1	44.1	648.6
HC	1.5	0.0667	NS

NS, not significant.

2.5.1.1 Vessel Operating Modes

Generally, the ship is operating in four different modes, the first one is the approaching and docking in ports; the second is the hoteling or berthing in port, the third is the departure and arrival in port and the last is the cruising [17],[25]. In the present study, the operating modes of all ships crossing Suez canal is considered to be the maneuvering mode as general case without applied specific condition for port departure, and port arrival.

2.5.1.2 Engine load factor

As explained in EPA method, the load factor of ship machinery is defined as the ratio of actual output to rated output based on maximum continuous rating. The calculation are steps applied on each vessel category according to the complete ship data collected from SCA. The Load factors used in the present calculation for main and auxiliary engines are 40% and 100%, respectively.

2.5.1.3 Marine Emissions Factors Results

The emission factors and total emissions for both propulsion machinery and auxiliary engines for different pollutant are calculated from equations 2 and 3 and given in table 4.

Table.4: EPA Emission Factors calculations (gm/kW.h) according to maneuvering mode of operation

	Load Factor		Emissions Factor(gm/kW.h)	
Air pollutant	M/C	Aux.	M/C	Aux.
PM	0.40	1.0	0.2784	0.2610
NO_x	0.40	1.0	10.9457	10.5757
NO_2	0.40	1.0	16.2704	15.7134
CO	0.40	1.0	2.0945	0.8378
CO_2	0.40	1.0	758.850	692.70
HC	0.40	1.0	0.2637	0.0667

EPA Methodology is evaluated for six air emission components, as seen in table 3. Due to the lack and shortage of data regarding the type of fuel applied onboard ships, the present study assumed that all the international ships crossing the Canal are using Marine Diesel Oil (MDO) with Sulfur free and the So_x Emissions are Zero.

2.5.2 ENTEC Methodology

The European Commission model as known by ENTEC[22] is also used to calculate the ship emissions transiting the Suez Canal for comparison and verification. Equation (4) is applied to estimate the ship emissions rate as a function of engine power and emission factor.

Emissions rate {pollutant (kg/hr) =
Engine Power(kW) × Emission Factor (g/kW.h) (4)

The total emissions values appear to be consistently higher in EPA model than the corresponding values in ENTEC model. The emission factors for main machinery are shown in table 4 as a sample. The difference may be attributed due to the variations of ship mode operations, the engine type specifications and the emission factors of the engines as an example given in table 5. The values are differs due to the applied coefficients in each methodology.

Table.5: Lists Some of Emissions Factors (gm/kW.h) for M/C in Maneuvering Mode

Engine type	Fuel Type	No_x	Co_2	HC	SFC
SSD	MDO	13.6	647	1.8	204
MSD	MDO	10.6	710	1.5	223
HSD	MDO	9.6	710	0.6	223

SSD: Slow Speed Diesel Engine, MSD: Medium Speed Diesel Engine, HSD: High Speed Diesel Engine, and MDO: Marine Diesel Oil.

3.0 RESULTS AND DISCUSSION

The total number of ships passing in Suez Canal within the last 8 years of study period is given (data), after acceptance of Suez Canal Authority, and plotted in figure 6. The biggest number of ships passing in the canal were 15638, 15312 and 15078 in 2011, 2010 and 2014 respectively and the lowest number was 13495 in 2015.

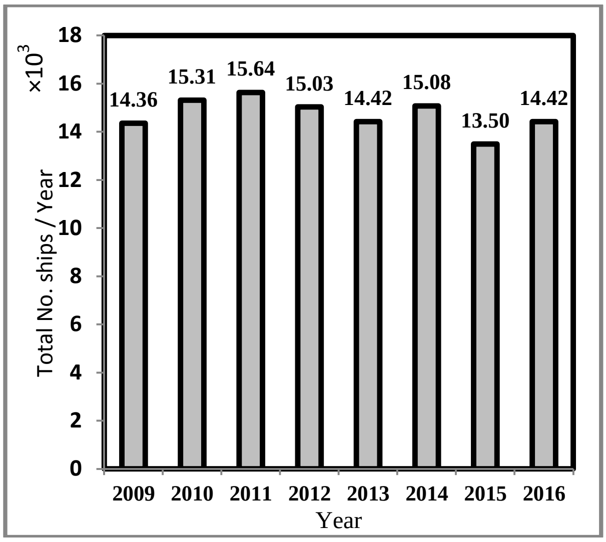

Fig.6: Annual total number of vessels crossing Suez Canal [24],[26]–[30]

Suez Canal navigation rules and sailing speed for each ship category is provided. The main parameters and information collected and completed for each ship is the ship flag, the power of ship propulsion machinery and auxiliary, Suez Canal net tonnage, engine specifications and ship particulars.

3.1 Calculation of ship emissions and correlations

EPA emission model is used to calculate the exhaust gases emitted from each ship transiting the Canal. Air Emissions components (PM, NO_x, NO_2, CO, CO_2, HC) in tonnes are estimated for each ship per trip as a function of Main and auxiliary engines power. The output of each ship categories is calculated, tabulated and plotted in curves. A sample of the results is plotted in figures 7a, 8a and 9a as a function of propulsion machinery and in figures 7b, 8b and 9b as a function of auxiliary engines for containers, bulk carriers and oil tankers respectively. All the output results for all ship categories are estimated and plotted in the same manner. The results are correlated using a regression analysis technique to simplify further calculations.

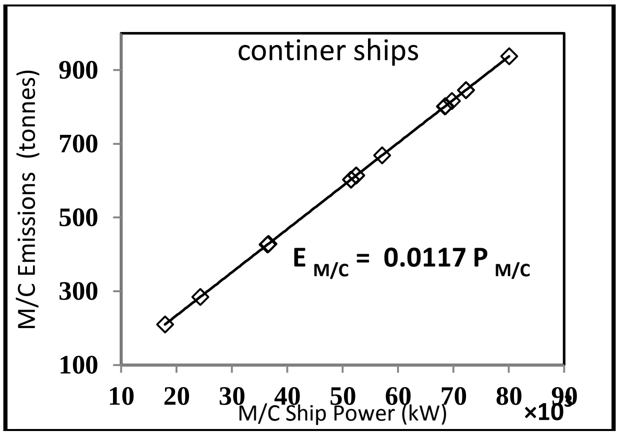

Fig.7a: Correlation of ship propulsion power and emissions for container ships per trip

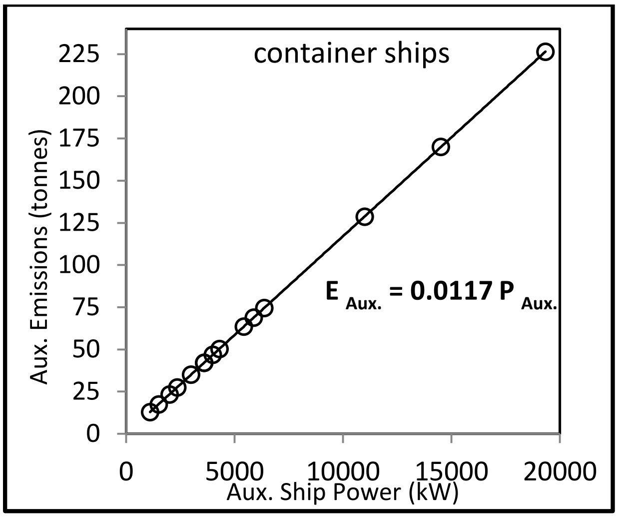

Fig.7b: Correlation of Aux machinery power and emissions for container ship per trip

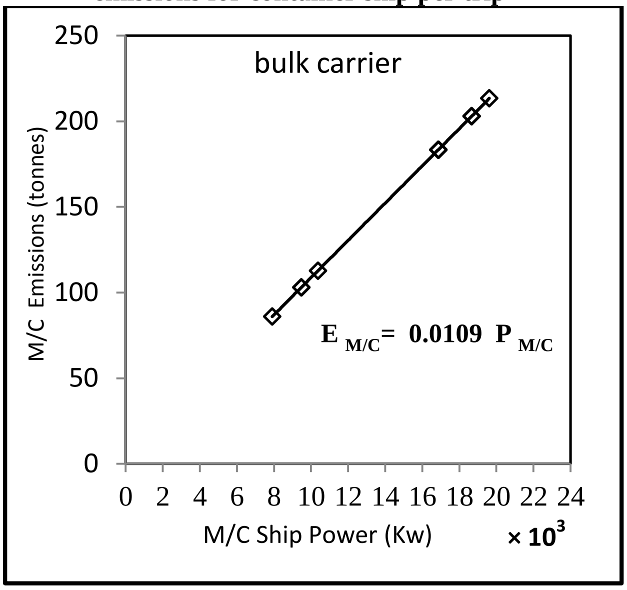

Fig.8a: Correlation of ship propulsion power and emissions for Bulk Carrier per trip

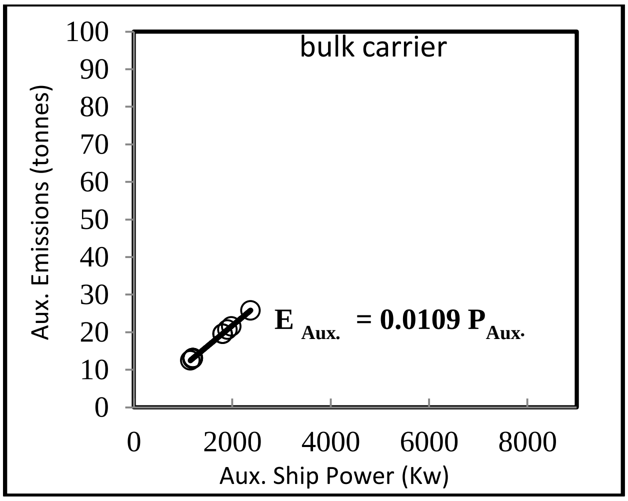

Fig.8b: correlation of Aux machinery power and emissions for Bulk Carrier per trip

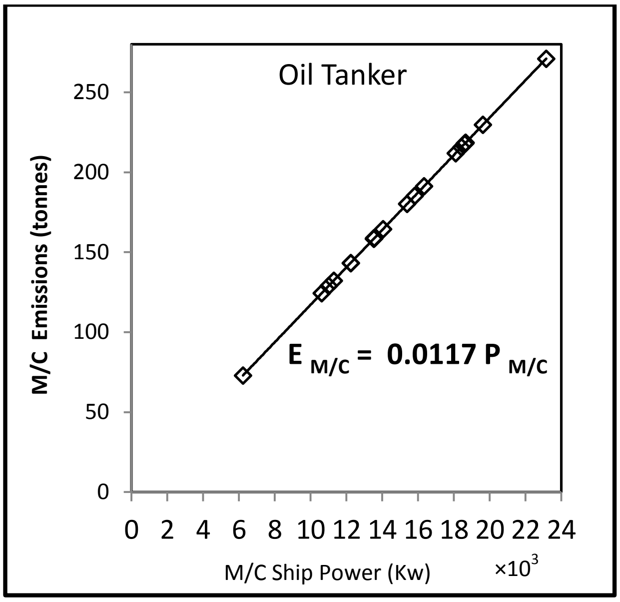

Fig.9a: Correlation of ship propulsion power and emissions for Oil Tanker per trip

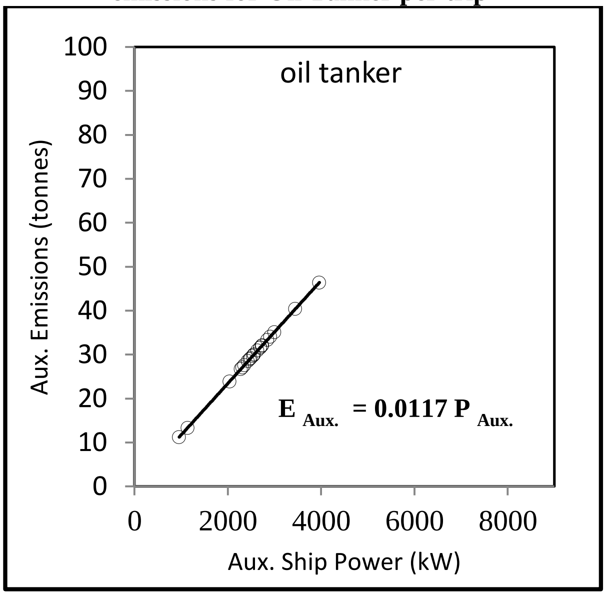

Fig.9b: Correlation of Aux machinery power and emissions for Oil Tanker per trip

All the predicted correlations used to calculate the emissions per trip from the eight ship categories transiting the Suez Canal are combined and plotted in figure 10 for propulsion power emissions and in figure 11 for auxiliary machinery emissions. The plotted emission values for different ship categories are generalized in only one equation as: $E = C.P^N$, where E is the emissions in tonnes and P is the total machinery power aboard ship per kW. C and N are the regression analysis constants. The given correlation covers a wide range of ship machinery power with a maximum deviation of ±1.3%.

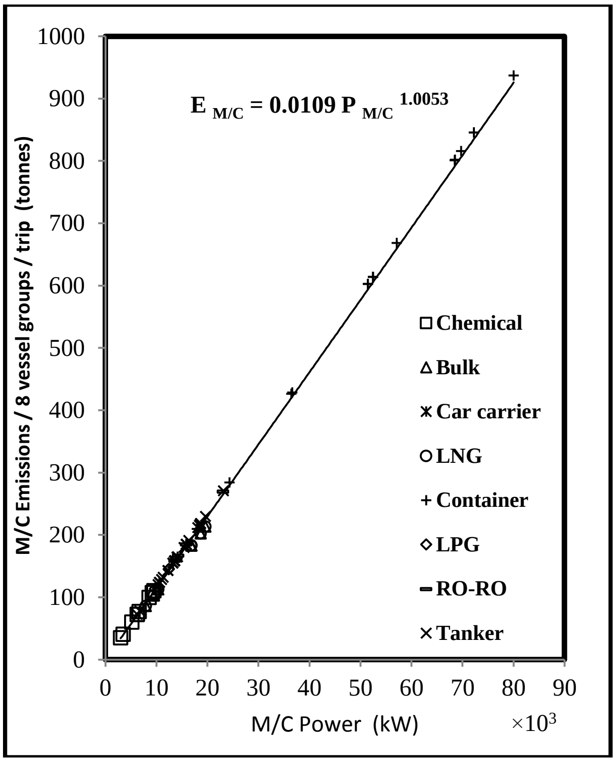

Fig.10: Ship emission correlation as a function of propulsion machinery

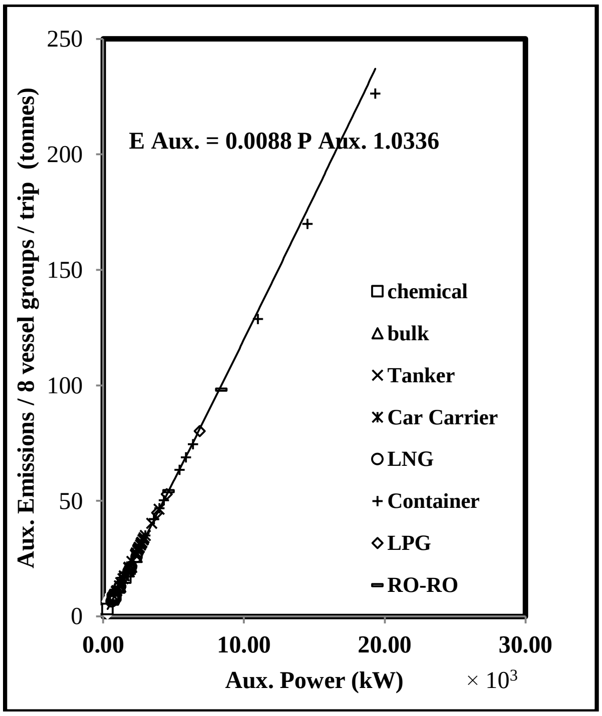

Fig.11: Ship emission correlation as a function of auxiliary power

3.2 Prediction of Annual ship Emissions

After estimating the total air emissions from each vessel during its trip in the Canal, the average annual values of emission in tonnes of each ship categories can be determined. Referring to the SCA annual report and the actual numbers of vessels passing Suez Canal [31], see figure 5, the total emission per tonnes for different vessel types can be estimated in tonnes annually.

A total annual emissions as a function of ship types are predicted and plotted in figures 12, 13 and 14 for the last three years 2014, 2015 and 2016 respectively. The annual average of ships passing in the canal is about 15000 ships. All the annual emission values of the study period is collected and plotted in figure 14. The total annual emissions emitted from ships were varied between 6.58 and 7.63 million tonnes annually. The total ship emissions of CO_2, NO_X, SO_X, CO, and PM in European sea areas, Baltic sea, North sea and Mediterranean sea for year 2011 were estimated to be 121, 3.0, 1.2, 0.2 and 0.2 million tonnes respectively[3]. The average annual emissions from the international ships crossing Suez Canal were evaluated to be 7.036 million tonnes whereas the corresponding values in European sea are estimated to be 125.6 million tonnes annually.

The analysis of the results given in figure 15 indicated that the container ships have the higher values of emissions followed by tankers and bulk carriers. The maximum emission values from container ships were about 5 million tonnes in 2011 and the minimum values were 3.8 million tonnes in 2016. The reduction in total ship emissions is contributed to the decrease of the container ships crossing the Canal. The container ships are mainly responsible of 60% of the total ship emissions.

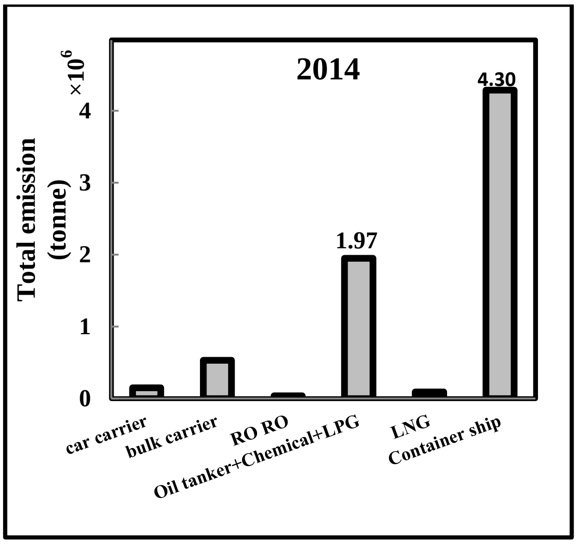

Fig.12: total emissions for different ship types in 2014

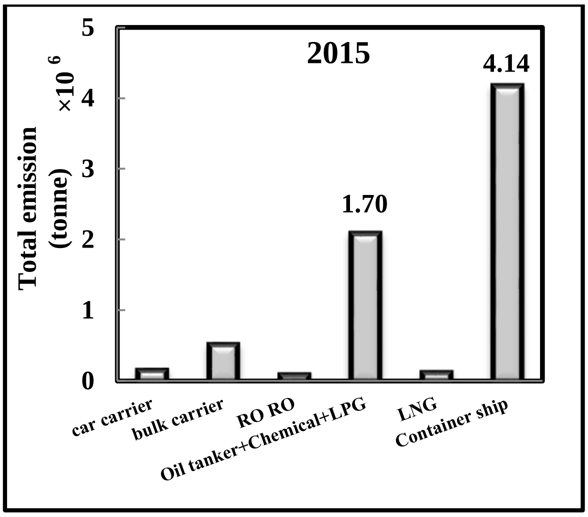

Fig.13: total emissions for different ship types in 2015

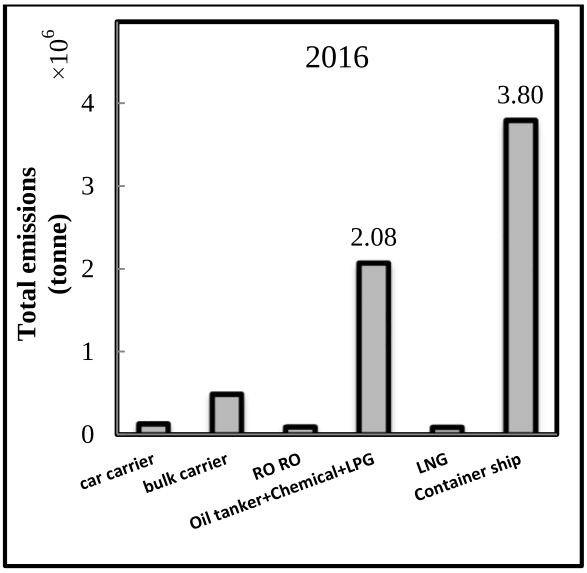

Fig.14: total emissions for different ship types in 2016

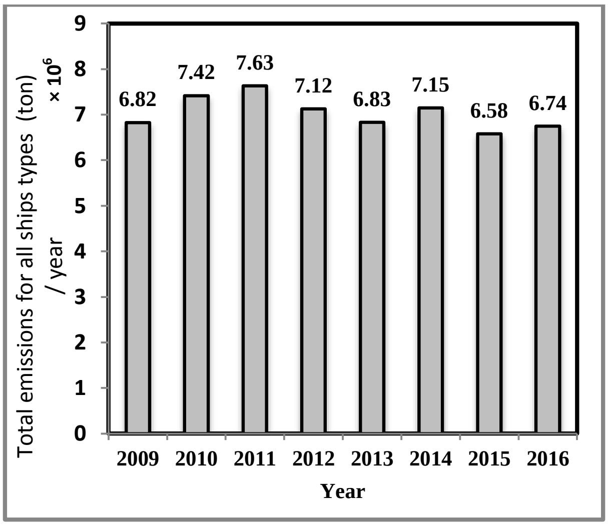

Fig.15 shows the total Emissions per year from (2009-2016)

4.0 COMPARISON OF EPA OUTPUT RESULTS AND ENTEC MODALS

The output emission calculations of the international ships transiting the Suez Canal using EPA Methodology are compared with the results obtained using ENTEC Methodology[22]. EPA calculations were carried out accordance to the maneuvering mode of operation for either propulsion machinery or auxiliary engines. The comparison between EPA and ENTEC methodologies, is made using the same load factors for M/C and Aux (0.4 and 1) respectively. The present study assumes that all the ship machinery is running with marine Diesel Oil (MDO) with low sulfur content when passing through Suez Canal. A simple calculation example for container ship is presented in table 6 for propulsion machinery and table 7 for auxiliary engines. The tabulated results calculated by EPA method indicated that NOx emissions rates were 0.8 times lower than those from ENTEC, while CO_2 Emissions rates were 1.7 times higher than those from ENTEC. HC air emissions rates in ENTEC were 11 times higher than those in our study.

Table.6: M/C Emission Rates calculations using EPA / ENTEC Methodologies

Air pollutant	Emissions Rate (kg/hr)	
	ENTEC Method	EPA Method
NO_x	80056 (KW) ×[13.6 $(\frac{g}{KW-hr})$ × 0.001] = 1089	80056 kw × [(0.1255 ×(0.4)$^{-1.5}$ +10.4496) $\frac{g}{KW-hr}$ × 0.001] = 876
CO_2	80056 (KW) ×[647 $(\frac{g}{KW-hr})$ * 0.001] =51796	80056 kw×[(44.1× (0.4)$^{-1.0}$ + 648.6) $\frac{g}{KW-hr}$ × 0.001] = 60702
HC	80056 (KW) × [1.8 $(\frac{g}{KW-hr})$ * 0.001] =144	80056 kw × [(0.0667 × (0.4)$^{-1.0}$+0) $\frac{g}{KW-hr}$ × 0.001] = 13

Table.7: Aux. Emission Rates calculations using EPA/ ENTEC Methodologies

Air pollutant	Emissions Rate (kg/hr)	
	ENTEC Method	EPA Method
Nox	3000 KW × [10.9 $\frac{g}{KW-hr}$ × 0.001] = 32.7	3000 kw× [(0.1255 × (1.0)$^{-1.5}$ + 10.4496) $\frac{g}{KW-hr}$ × 0.001]= 31.7253
CO2	3000 KW×[690 $\frac{g}{KW-hr}$ × 0.001] =2070	3000 kw [(44.1 × (1.0) $^{-1.0}$+ 648.6) $\frac{g}{KW-hr}$ × ×0.001 = 2078.1
HC	3000 KW × [0.4 $\frac{g}{KW-hr}$ × 0.001] = 1.2	3000 kw [(0.0667× (1.0) $^{-1.0}$+ 0) $\frac{g}{KW-hr}$ × 0.001 = 0.2001

Some selected samples of emissions calculation results of both methods are plotted and compared in figures 15 for bulk carriers.

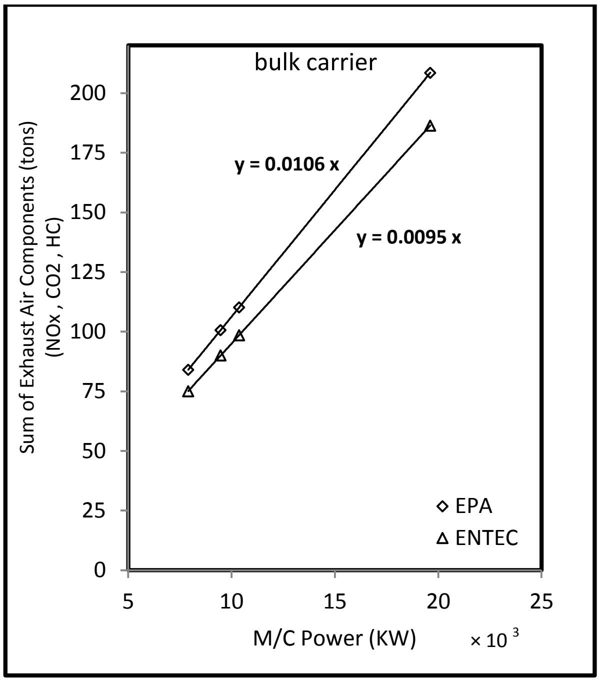

Fig.16: Total emission values of EPA and ENTEC methods for Bulk Carrier

The comparison of emitted emissions with both methodologies revealed that there are some differences between the output emission values of the two inventories for the emissions of selected ships crossing the Suez Canal. The total exhaust emissions evaluated in the present study using EPA method were 12, 9 and 15% higher than the corresponding values in ENTEC inventories for bulk carrier, oil tanker and container ships respectively as seen in figure 16 for bulk carrier. The same conclusion is observed in fig 17 for oil tanker in the present study and for only existing calculations [22]. The plotted emissions values of existing data and present shows a good matching and provide the same conclusion. The values of emissions calculated using ENTEC method were about 15% lower than those indicated by EPA emission inventory. The variation may be attributed due to the difference assumptions between the methodologies. Also the variation may be happened due to the ship energy efficiency, the ship innovation renovation and fuel specifications.

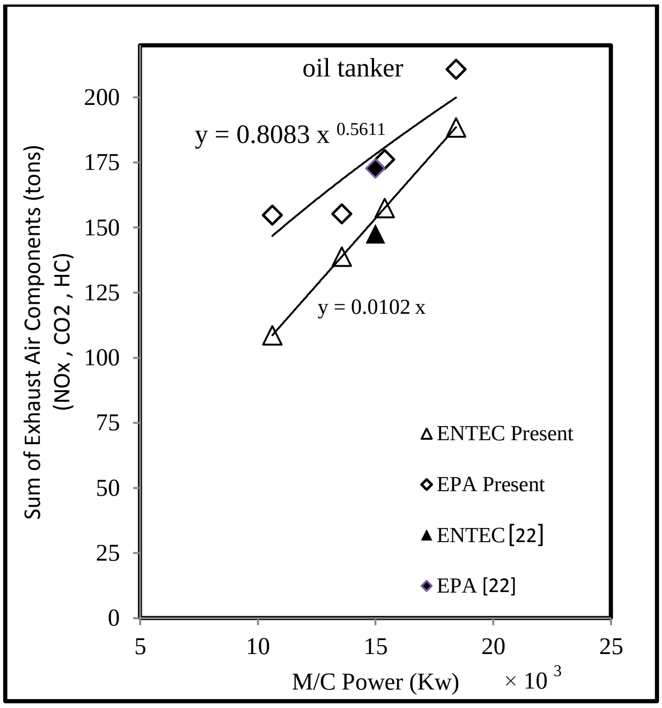

Fig.17: Total emission values of EPA and ENTEC methods for Oil Tanker

5.0 CONCLUSION

1. Shipping is a significant source of pollution in ports and coastal areas. The air pollution and emissions from international ships crossing Suez Canal waterway is evaluated and assisted. The ship emissions mainly depends on the type of propulsion and auxiliary machinery, the specifications of used fuel, the sailing and operating modes and the cruise speed. The machinery emission factor and fuel consumption are good alternative for the emissions estimates taking into account both the main and auxiliary engines at different navigation phases (cruise, hoteling, maneuvering).
2. A set of empirical correlations is developed to help the users to estimate the unknown parameters and complete the missing data of any ship and its machinery specifications according to the ship categories within a maximum deviation of ±10%.
3. All the predicted empirical correlations used to calculate the emissions for 8 ship categories transiting the Suez Canal are combined and generalized as: $E = C.P^N$. The given correlation covers a wide range of ship machinery power within a deviation of ±1.3%.
4. Suez Canal is receiving annually 7.036 million tonnes of pollutant, as an average value in the last 8 years of study period. The container ships are mainly responsible of 60% of the total ship emitted emissions followed by tankers and bulk carriers.
5. More studies and researches are required to verify the reasons of results variations

between EPA methodology and ENTEC model.

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