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DEVELOPMENT OF METHODOLOGY AND MODEL TO ASSESS AND MANAGE SHIP EMISSIONS

Jai Acharya[1]

Abstract

Emissions from international shipping can be estimated from activity data and also from international fuel statistics data. However, it is observed that the activity-based different ship sizes and types give a better prediction of global fuel consumption and emissions factors from international shipping than fuel statistics due to apparent under-reporting of marine bunker sales.

Considering the different activity-based estimates reported, the lower estimates of fuel consumed by the oceangoing world fleet in 2000 is around 200 Mt, while estimates as great as 290 Mt of marine oil would include all internationally registered ships including fishing vessels, the military fleet and auxiliary engines. This does not account for growth in emissions that may be reflected in estimates for more recent years. The latter is about 110 Mt higher than the reported total (*i.e*. sum IEA categories Internal Navigation and International marine bunkers) IEA marine sales (IEA, 2003). Despite the ongoing scientific debate regarding whether bunker fuel sale statistics are representative when estimating fuel-based emissions, and whether input data on engine operational profiles for different ship types and size categories are representative, these estimates demonstrate some convergence in terms of uncertainty bounds. More importantly, there is agreement among researchers that better input data on ship activity and improved means of allocating activity geospatially will reduce current differences among inventories.

The current methodologies in the Emission Factors Inventory provide an estimated and good framework for standard practice for estimating and reporting the emissions from ships activities.

The main difficulty and uncertainty lies in the several factors such as variations of fuel specifications between domestic and international use. Consequently, good practice methodologies are particularly needed in order to collect relevant and accurate data on domestic fuel used for marine transportation.

Keywords: Methodology and Model to Assess Ship Emissions, Review on Emission Factors (EF), Emission Factors Inventory System (EF Inventory), Ship Emissions Modelling.

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1. INTRODUCTION:

The proposed research studies focus on maritime environmental protection under the regulatory compliance of IMO MARPOL Annex VI addressing ships emission, emission factors (SOx, NOx and $PM_{2.5}$). The research is aimed to provide economically viable solutions to the maritime industry regarding management of emission from ships operating in different conditions and formulation of strategies for environment management for future ship design and operations.

Environmental impact and air pollution from ships have received increasing attention the last decades. Due to poor combustion characteristics of typical marine engines and a wide-spread use of residual unrefined fuel, the global fleet emits significant amounts of SO_2, NO_2 and particulate matter (PM) to air. Impact assessments and information on emitted amounts are important inputs to decision-making in regulation development and also for ship designers who aim at environmentally improved designs.

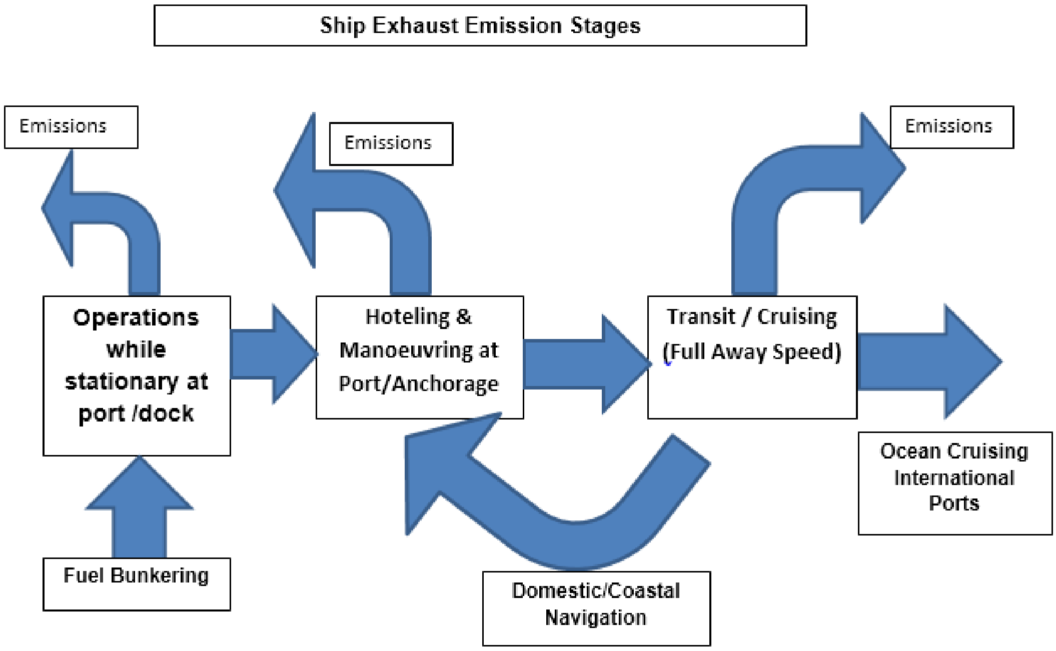
In order to assess the impacts caused by ship emissions to air, information on ships' activities in the regions or the corresponding fuel usage is essential. An emission factor (EF) can be defined as the "mass of pollutants emitted based on the work done or based on the mass of combusted fuel by ship engines or the mass of combusted fuel. The units of emissions factors generally expressed in g/kWh or g/kg fuel are related to each other by the specific fuel consumption (SFC) of the engine.

Ship engines are diverse and the emission factors are insufficiently quantified for certain operational modes and specific pollutants which makes assessments difficult. Measurements aboard ships are thus conducted in order to determine emission characteristics during manoeuvring periods and for engines operating on fuels of different qualities.

Exhaust emissions from ships includes emissions from the main propulsion engines as well as auxiliary engines used to generate electrical power and auxiliary services within vessels. General process of ship operation can be divided in three operational modes and corresponding stage of engines emission factors (Figure-1: Flow diagram):

Vessels alongside berth during the cargo operations (loading / unloading) or whilst they wait for next voyage are termed as "hoteling". They can cast off and manoeuvre from their mooring point before sailing away from the port. Upon departure from port / anchorage, the vessel cruises to high seas for its destination which may be coastal area or same country (domestic voyage) or a different country (international voyage). This simplistic pattern may get complicated by other stopping patterns, so does the engine operations and exhaust emission patterns.

Figure.1.: Flow diagram for the contribution from navigation to mobile sources combustion emissions



2. OVERVIEW OF IMPACTS OF AIR POLLUTION CAUSED BY SHIPS:

Pollutants such as Particulates Matter ($PM_{2.5}$ and PM_{10}), NO_X, Ozone, SO_2 and CO_2, all of which are products of combustion of fuel oil, can be classified as either primary or secondary pollutants. 'Primary pollutants' is a term used for the pollutants that are formed during the actual combustion process, while 'secondary pollutants' are formed in the atmosphere as a consequence of chemical reactions involving the primary species. The potential impact categories influenced by air pollution from oil combustion are health problems, acidification, eutrophication, photo-oxidant formation and climate change, to name the most important. An overview of these pollutants and their corresponding impact categories are illustrated below in Table-1.

3. SHIP ENGINES, FUELS AND POLLUTANT FORMATION:

Marine diesel engines are the predominant form of power unit within the marine industry for both propulsion and auxiliary power generation. In 2010 an analysis of about 100,000 ships indicated marine diesels powered around 99 % of the world's fleet, with steam turbines powering less than 1%.

In an earlier analysis, about 67% of these ships are powered by four-stroke compression-ignition engines (operating on the compression- ignition, or diesel cycle, and therefore referred to as diesel engines). Some 26% are powered by two-stroke diesel engines. Six percent of the ships have ‘‘unknown’’ diesel engines (*i.e.*, either two- or four-stroke) and only one percent are turbine-driven. Most turbine-driven vessels (80%) are steam turbines with oil-fired boilers; the number of aero-derivative gas turbine engines in the commercial fleet is very low. (Corbett and Koehler, 2003)

The only other type of engine highlighted was gas turbines, used virtually only on passenger vessels, and only used in around 0.1% of vessels (Trozzi, 2010). Diesel engines can be categorised into slow (around 18% of engines), medium (around 55%), or fast (around 27%) speed engines, depending on their rated speed. (Carlo Trozzi, EMEP/EEA)

Emissions are dependent on the type of engine, and therefore these will be reviewed further in details in subsequent submissions.

The majority of fuel types used by the international fleet today are variants of bunker heavy fuel oil (also called as Heavy Fuel Oil). Heavy fuel oil contains residues from refineries' processing of crude oil and are highly viscous and need heating before being used on board a ship. The trend in using heavy fuel oil (HFO) as a marine fuel started in the 1950s (Goodger 1982). In this paper, the term heavy fuel oil will be used for all fuel qualities containing refinery residues, also including so-called intermediate fuel oil (IFO), which is an HFO blended with refined oil qualities. There are HFO being used from Viscosity of 180 Cst to 380 and even up to 650 Cst at 40°C / 50°C and specific gravity from 0.92 to 1.01.

The marine heavy fuel oil is characterized by high sulphur content, high viscosities and densities and also high content of aromatics and minerals.

However, the limits are significantly higher than those for transport modes on land, which can be in concentrations of 10 to 50 ppm.

Table.1.: Primary pollutants from the combustion of Bunker Heavy Fuel Oil (HFO) and their major potential impacts.

	Pollutant					
Impact Categories	Particles	SO_2	NO_X	CO_2	HC	CO
Health Effects	X	X	X			X
Acidification		X	X			
Photo-Oxidant Formation			X		X	
Eutrophication			X			
Climate Change				X	X (CH_4)	

4. NITROGEN OXIDE EMISSION FROM SHIPS:

NO_X is a collective name for NO and NO_2, where NO is by far the most abundant in exhaust gases. About 5 - 7% of NO is converted to NO_2 in the exhaust system or engine (Henningsen 1998). The share of NO_2 in NO_X that leaves the combustion chamber is partly determined by local temperature conditions (Heywood 1988). According to MAN B&W Diesel, approximately 1% of NO will form N_2O (MAN-BandW, 1996) in slow speed engines than engines of higher speeds (Cooper and Gustavsson 2004).
Additional NO is formed from nitrogen in the fuel or via reactions between molecular nitrogen and the hydrocarbon species in the fuel. Whilst Heywood (1988) states an average nitrogen content of heavy distillates is 1.40% by weight, the nitrogen contents of nine marine HFOs from published emission measurement studies (Lyyränen *et al.*

1999; Cooper 2003; Fridell *et al*. 2008; Winnes and Fridell 2009; Winnes and Fridell 2010) were below 0.5%.

Nitrogen in fuel has been shown to be an important source for NO, especially at high air to fuel ratios (lean to stoichiometric conditions) during combustion (Bowman 1975). The lean combustion of diesel engines and a relatively high concentration of nitrogen in heavy fuel oils make fuel nitrogen a potential contributor to significant NO_X concentrations in ship exhausts.

5. EMISSION FACTORS:

The emissions produced by ships are a consequence of combustion of the fuel in an internal combustion (marine) engine. The principal pollutants are CO, VOC, NOx and PM_{10}, in this list $PM_{2.5}$ is derived from soot which is mainly have to do with engine technology, and CO_2, SOx, heavy metals and further PM (mainly sulphate-derived) which originate from the fuel speciation.

Specific emissions (mass of pollutant per work performed by the engine or mass of combusted fuel) of pollutant species differ between the operational modes due to the combustion characteristics at different loads and at transient operations. The units of specific emissions, g/kWh or g/kg fuel, are related to each other by the Specific Fuel Consumption (SFC). The SFC also depends on the fuel type due to the differences in specific heating values of fuels. The SFC for modern marine engines range between 165 g/kWh for the most efficient two-stroke engines to around 230 g/kWh for small four-stroke engines (Buhaug *et al.* 2009).

Emission Factors play an important role in inventories of air pollutants. In the Table shown below, the emissions factors for CO_2, NOx, SOx, PM, HC and CO in g/kg fuel used, obtained from emission inventory sources, are presented together with their cited sources.

Table.2.: A Typical Study of Researchers on Emission Quantity and Estimates of Fuel Consumption for the International Fleet from recent Global Inventories.

	Corbett and Koehler, 2003*	**Paxian *et al*., 2010**	**Dalsøren *et al*., 2008**	**Buhaug *et al*., 2009**
Source of emission factor	Entec, 2002	Test bed results, Eyring *et al* (2005)	Cooper, 2004, Entec, 2002	CORINAIR, IPCC (HFO/MGO)
Total Fuel consumption (MT/year)	289 (Year 2002)	221 Year (2006)	217 (Year 2004)	276 (Year 2007)
Included in the fuel estimate	International shipping, Military vessels	All ships	All ships	Non-military international shipping
CO_2 (g/kg fuel)	3179	2905	3179	3130/3190
PM (g/kg fuel)	6.1	6.0	7.6	6.7/1.1
NO_X (g/kg fuel)	82.5	76.4	41 – 92	85 and 56**
S content of fuel (%)	2.5%	2.4-2.6%	54 or 10 (g/kg fuel)	2.7%/0.5%
HC (g/kg fuel)	2.9	7.0	2.45	2.7
CO (g/kg fuel)	-	4.67	7.4	7.4

* Original emission factors are in the unit g/kWh; these values have been converted to emissions in g/kg fuel by division of a specific fuel consumption of 206 g fuel/kWh which is used in by Corbett and Koehler (2003)

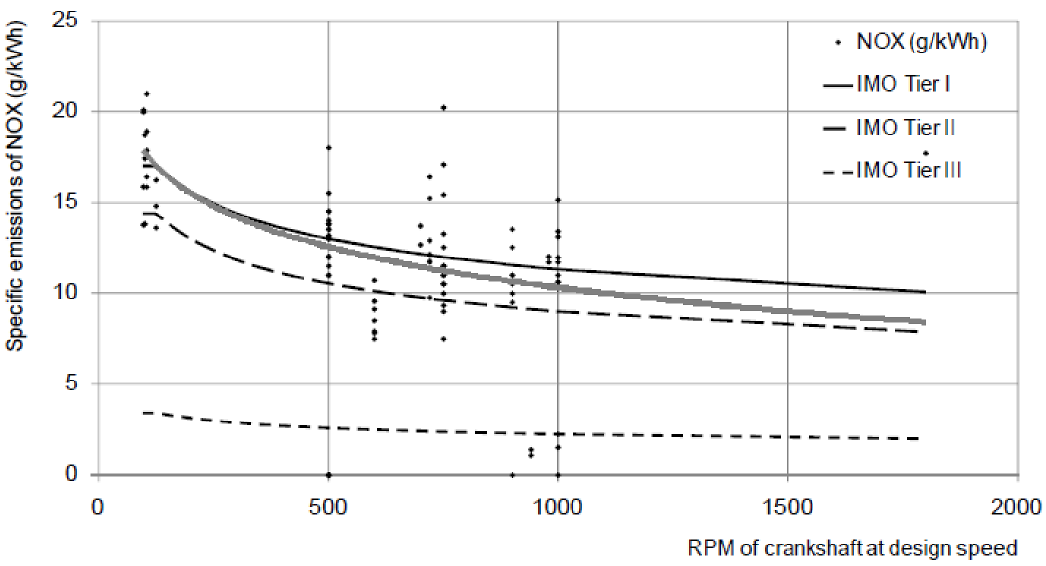
** kg NO_X / tonne fuel for slow-speed and medium-speed diesel engines, respectively, independent of fuel type.

The values presented in Table 2 merely demonstrate the difficulties of drawing conclusions on emission factors for even the most abundant pollutants from ship engines. It is to be noted that the inventories cover the global fleet, which makes aggregated factors like the ones presented subject to many estimates, *i.e*. estimates on average fuel type and average engine type.

Emissions from test bed engines can be suspected of deviating from emissions from engines in operation due to wear on the engine and how it is operated. However, correlations of specific emissions based on engine size or engine age, have proven to be difficult due to limited datasets and large variations in data (Whall *et al*. 2002).

The specific emissions from 155 measurements from ships and test bed measurements in Wärtsilä's facilities shown in Figure 2 (Whall *et al*. 2002; Agrawal *et al*. 2008; Winnes and Fridell 2009; Winnes and Fridell 2010). The measurements from Whall *et al*. are reported in an aggregated way. These measurements are presented as average emission factors at 500 rpm for medium speed diesel (MSD) engines and at 100 rpm for slow speed diesel (SSD) engines. They are also weighted by the number of measurements.

Figure.2.: The specific emissions measurements from ships and test bed measurements in Wärtsilä's facility
(Whall *et al*. 2002; Agrawal *et al*. 2008; Winnes and Fridell 2009; Winnes and Fridell 2010).



6. REGULATORY CONTROLS:

Pollutant emissions can be controlled by two mechanisms: control of the combustion technology, combined with exhaust gas treatment, and control of the fuel quality. Both these measures are used in practice under IMO MARPOL Annex VI - *i.e.* use of low sulphur fuel, applying Nox control measures by the use of exhaust gas scrubbers, catalytic converter technology on-board.

On the 22 July 2005 the International Marine Organisation's (IMO's) Marine Environment Protection Committee (MEPC) adopted guidelines on exhaust gas cleaning, CO_2 indexing, and minor amendments to MARPOL (short for 'Marine Pollution', International Convention for the Prevention of Pollution from Ships) Annex VI. The principal legislative instrument Marpol Annex VI controls:

- NOx limits [Regulation 13]; NECA;
- Ozone depleting substances [Regulation 12];
- Sulphur oxides, through sulphur in fuel [Regulation 14];
- Sulphur oxides further through the designation of Sulphur Dioxide Emission Control Area (SECA), [Regulation 14];
- Volatile organic compounds (VOC) from tankers [Regulation 15].

The measures in IMO MARPOL Annex VI describe the outcomes; they do not stipulate how they are to be achieved. For controlling emissions, various technologies are available.

The current MARPOL 73/78 Annex VI legislation on NO_X emissions, formulated by IMO (International Maritime Organisation) is relevant for diesel engines with a power output higher than 130 kW, which are installed on a ship constructed on or after 1 January 2000 and diesel engines with a power output higher than 130 kW which undergo major conversion on or after 1 January 2000.

The MARPOL Annex VI, as amended by IMO in October 2008, considers a three tiered approach as follows:

- Tier I: diesel engines (> 130 kW) installed on a ship constructed on or after 1 January 2000 and prior to 1 January 2011;
- Tier II: diesel engines (> 130 kW) installed on a ship constructed on or after 1 January 2011;
- Tier III (1): diesel engines (> 130 kW) installed on a ship constructed on or after 1 January 2016.

The Tier I – III NO_X legislation values rely on the rated engine speeds expressed in RPM (revolutions per minute)

7. EXISTING METHODOLOGY FOR EMISSION FACTORS ESTIMATIONS:

Tier 1 - Existing default approach

Algorithm used currently

The Tier 1 approach for navigation uses the general equation to be applied for the different NFR (*Nomenclature for Reporting Emission*) codes (Carlo Trozzi *et al*., EMEP/EEA emission inventory guide book 2013):

$$Ei = \sum_m (FC_m \times EF_{i,m}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where:

$\sum_m$ = Summation
Ei = emission of pollutant i in kilograms;
FCm = mass of fuel type m sold in the country for navigation (tonnes);
EFi,m = fuel consumption-specific emission factor of pollutant i and fuel type m [kg/tonne];
m = fuel type (bunker fuel oil, marine diesel oil, marine gas oil, gasoline).
The FCm x EF product is summed over a different types of fuel used to provide total emissions from ships. This approach incorporates the relationship between fuel composition and some emissions (notably SO_2 and heavy metals).

Tier 1 emission factors ($EF_{i,m}$) assume an average technology for the fleet.

Default emission factors

The Tier 1 approach uses emission factors for each pollutant for each type of fuel used. Some factors (*e.g.* SO_2) depend on the fuel quality, which may change from batch to batch, and from year to year, and consequently these emission factors include a 'Sulphur content of fuel' factor.

Activity data

The Tier 1 approach is based on the premise that the quantities of fuel sold for shipping activities are available by fuel type, from nationally collected data. Fuel data needs to be split by NFR code *i.e.* - national, coastal navigation (usually navigation statistics), international voyages using bunker fuel oil data (HFO-BDN).

Tier 2 - Technology Specific Approach

Algorithm

The Tier 2 approach, like Tier 1, uses fuel consumption by fuel type, but requires country specific data on the proportion of fuel used by fuel type and engine type (slow, medium or high speed engines).

For this approach the algorithm used is:

$$Ei = \sum_m [\sum FC_{m,j} \text{ x } EF_{i,m,j}] \quad \ldots\ldots\ldots\ldots \quad (2)$$

Where,

$\sum$ = Summation
E = annual emission (tonnes),
$FC_{m,j}$ = mass of fuel type m used by vessels with engine type j (tonnes),

EFi,m,j = average emission factor for pollutant i by vessels with engine type j using fuel type m,

i = pollutant

j = engine type (slow, medium, and high-speed diesel, gas turbine, and steam turbine for large ships and diesel, gasoline 2S and gasoline 4S for small vessels).

m = fuel type (bunker fuel oil, marine diesel oil/marine gas oil

Tier 2 engine and fuel-specific emission factors

(Carlo Trozzi *et al*., EMEP/EEA emission inventory guide book 2013):

For all pollutants except NOx, Non-Methane Volatile Organic Compound (NMVOC) and PM (PM_{10} and $PM_{2.5}$), the Tier 2 emission factors for a specific fuel type are the same as Tier 1 emission factors, for each of the different types of fuel. Tier 2 emission factors for NOx, NMVOC and PM together with specific fuel consumption (gram fuel/kWh) calculated separately.

Activity data

The Tier 2 approach is based on the total fuel split between coastal navigation (MGO/MDO) and international shipping using bunkers fuel oil (HFO). In order to apply the more detailed emission factors for NOx and NMVOC, port arrival statistics need to be aggregated / split by engine type using national /coastal inventory statistics and average factors for fuel type and ship activity.

1. The following steps are required to estimate emissions:
2. Obtain national statistical port arrivals data by type of vessel.
3. Compute total power installed by type of vessel.
4. Split total power installed for each type of vessel by engine speed/fuel type.
5. Compute total power installed by engine speed/fuel class as sum of figures derived in step 3.
6. Assume that fuel usage is proportional to total power installed to assign statistical fuel consumption to different engine speed/fuel class.

7. Estimate coastal/international navigating ships emissions with emission factors.

Table.3.: Tier 2 emission factors for NOx, NMVOC, PM and specific fuel consumption for different engine types/fuel combinations Tier 2 default emission factors (Carlo Trozzi *et al*. EMEP/EEA emission inventory guide book 2013)

Tier 2 Default Emission Factors							
Engine Type	Fuel Type	NOx 2000 (kg/ tonne)	NOx 2005 (kg/ tonne)	NOx 2010 (kg/ tonne)	PM_{10} (kg/ tonne)	$PM_{2.5}$ (kg/ tonne)	Specific Fuel Consumption (g fuel/kWh)
Slow-Speed Diesel	BFO	92.8	89.7	86.5	8.7	7.8	195
	MDO/MGO	91.9	88.6	86.5	1.6	1.5	185
Medium-Speed Diesel	BFO	65.7	63.4	61.3	3.8	3.4	213
	MDO/MGO	65.0	63.1	60.6	1.5	1.3	203
High-Speed Diesel	BFO	59.6	57.7	55.6	3.8	3.4	213
	MDO/MGO	59.1	57.1	55.1	1.5	1.3	203

Note: MDO – Marine Diesel Oil, MGO – Marine Gas Oil, BFO – Bunker Fuel Oil

Tier 3 - Ship Movement Methodology

The Tier 1 and Tier 2 approaches use fuel sales as the primary activity indicator and assumes average vessel emission characteristics to calculate the emissions estimates. The Tier 3 ship movement methodology is based on ship movement information for individual ships.

This methodology is recommended when detailed ship movement data as well as technical information regarding the ships (*e.g*. engine size and technology, power installed or fuel use, hours in different activities) are available. It is suited for estimating national and international emissions.

The methodology may be quite time consuming to perform. In order to meet the general reporting criteria for the country as a whole, a country must subsequently make fuel adjustments in other relevant fuel consuming sectors in order to maintain the grand national energy balance. The methodologies may be used to calculate the emissions following the UNECE/EMEP* definition of national and international shipping, as well as other definitions (flag, ownership, geographical area *etc*.)

*UNECE - United Nations Economic Commission for Europe.

*EMEP - European Monitoring and Evaluation Program (under the Convention of Long Range Transboundary Air Pollution - CLRTAP)

Algorithm

For commercial vessels, the Tier 3 approach calculates the emissions from navigation by summing the emissions on a trip by trip basis. For a single trip the emissions can be expressed as:

$$E_{Trip} = E_{Hoteling} + E_{Manovering} + E_{Cruising} \quad \text{...} \ (3)$$

The total inventory is the sum over all trips of all vessels during the year. In practice it may be that data is collected for a representative sample of vessels for trips over a representative period of the year. In this case, the summed emissions should be scaled up to give the total for all trips and vessels over the whole year.

When fuel consumption for each phase is known, then emissions of pollutant *i* can be computed for a complete trip by:

$E_{Trip,I,j,m} = \sum_p [FC_{j,m,p} \text{ x } EF_{j,m,p}]$

Where:

ETrip = Emission over a complete trip (tonnes),

FC = Fuel consumption (tonnes),

EF = Emission factor (kg/tonne)

i = Pollutant (NOx, NMVOC, PM)

m = Fuel type (bunker fuel oil, marine diesel oil/marine gas oil (MDO/MGO), gasoline),

j = Engine type (slow-, medium-, and high-speed diesel, gas turbine and steam turbine).

p = The different phase of trip (cruise, hoteling, manoeuvring)

Emissions of other pollutants than those mentioned above can be calculated using the Tier 1 method with the emission factors depending on the type of fuel. When fuel consumption per trip phase is not known, then a different methodology is proposed for computing emissions, based on installed power and time spent in the different navigation phases. Emissions can be calculated from a detailed knowledge of the installed main and auxiliary engine power, load factor and total time spent, in hours, for each phase using the following equation.

$$E_{Trip,I,j,m} = \sum_p \{ T_p \sum_e [P_e \text{ x } LF_e \text{ x } EF_{e,I,j,m,p}] \}$$

Where,

∑ = Summation

ETrip = emission over a complete trip (tonnes),

EF = emission factor (kg/tonne) from Table 3-10, depending on type of vessel,

LF = engine load factor (%)

P = engine nominal power (kW)

T = time (hours),

e = engine category (main, auxiliary)

i = pollutant (NOx, NMVOC, PM)

j = engine type (slow, medium, and high-speed diesel engines, gas turbine and steam turbine).

m = fuel type (bunker fuel oil, marine diesel oil/marine gas oil, gasoline),

p = the different phase of trip (cruise, hoteling, manoeuvring).

The cruise time, if unknown, can be calculated as:

$T_{Cruising}$ (hours) = Distance Cruised (km) / Average Cruising (km/hr)

Tier 3 - Engine, Fuel and Activity Specific Emission Factors

NOx, NMVOC and PM emission factors for the individual engine/fuel type combinations are used in units of mass of pollutant per tonne of fuel and in units of mass of pollutant per kWh. For the other pollutants, emission factors of Tier 1 can be used

Activity data

The LMIS (Lloyd's Maritime Information Service) database records all ship movements world-wide. The database includes ship size, destination, approximate time of arrival and departure, engine type and number, *etc*. The data are available in computerised form. The database covers all ships greater than 250 - 500 gross tonnes. The agencies like US / Canadian Coastguard, EU and Scandinavian Environment Agencies have built up their own database on emission factors inventory.

Port calling statistics are generally available from national sources (statistical offices or the harbour authorities) in all countries, in some countries covering the larger ports only. The information is similar to the LMIS data without engine details. On the other hand, it will give more accurate information about the actual time spent in port. The national port calling statistics may also be useful for validating information from other sources.

In some countries, detailed statistics on individual ships are collected. Such statistics may include, for example, a ship movement survey for a sample of the fleet.

In view of future trend of stringent regulatory compliance requirements, it would be appropriate to assume that many ship owner's/ ship managers would have their own emission data statistics of their fleet and may have to share with other stakeholders due to commercial compulsions.

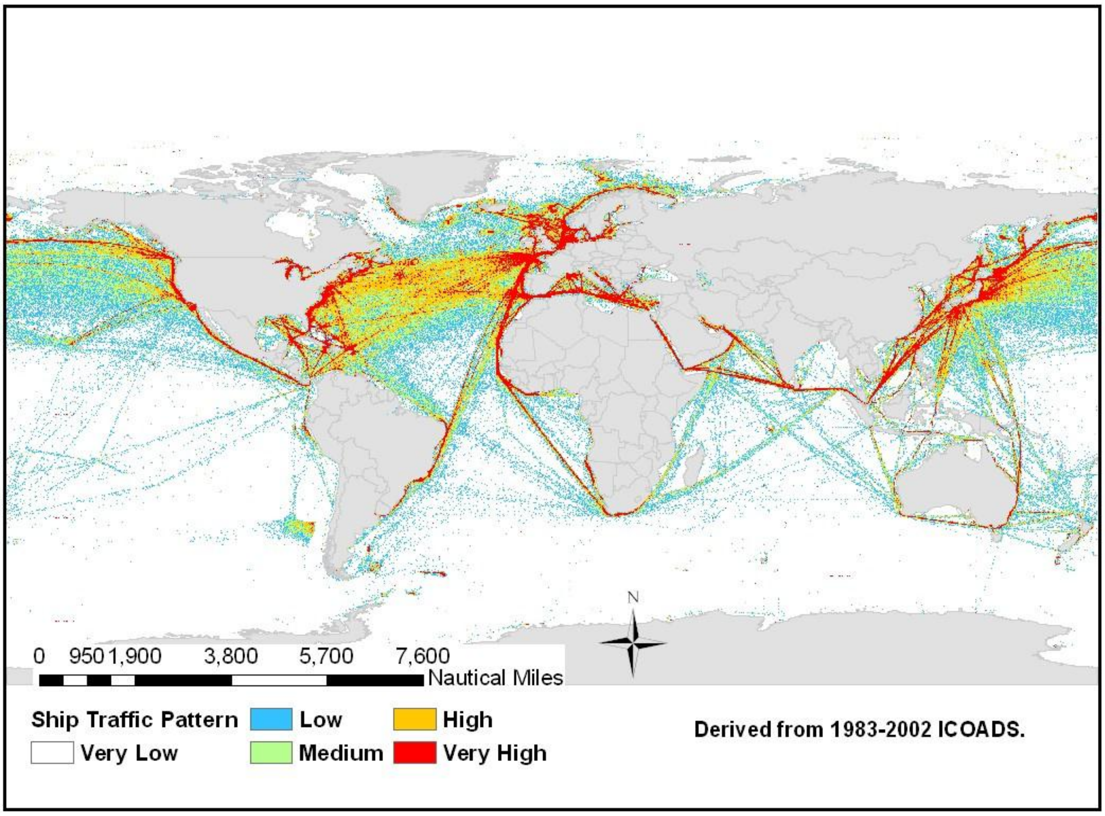
Geographic distribution of ship traffic and emissions

Global inventory estimates for fuel use or emissions derived from activity-based bottom-up estimates or from fuel sale statistics are distributed according to a calculated ship traffic intensity proxy per grid cell referring to the relative ship reporting frequency or relative ship reporting frequency weighted by the ship size. The accuracy of the resulting totals is limited by uncertainty in global estimates as discussed above and the representative bias of spatial proxies limits the accuracy of emissions assignment (spatial precision).

Spatial proxies of global ship traffic

Corbett *et al*. (1999) produced one of the first global spatial representations of ship emissions using a shipping traffic intensity proxy derived from the Comprehensive Ocean-Atmosphere Data Set (COADS), a data set of voluntarily reported ocean and atmospheric observations with ship locations which is freely available. Endresen *et al*. (2003) improved the global spatial representation of ship emissions by using ship size (gross tonnage) weighted reporting frequencies from the Automated Mutual assistance Vessel Rescue system (AMVER) data set. AMVER, sponsored by the United States Coast Guard (USCG), holds detailed voyage information based on daily reports for different ship types. Participation in AMVER was, until very recently, limited to merchant ships over 1000 GT on a voyage for 24 or more hours and the data are strictly confidential. The participation in AMVER is 12 550 ships but only around 7100 ships have actually reported. Endresen *et al*. (2003) observed that COADS and AMVER lead to very different regional distributions. Wang *et al*. (2007) addressed the potential statistical and geographical sampling bias of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and AMVER data sets, the two most appropriate global ship traffic intensity proxies, and used ICOADS to demonstrate a method to improve global-proxy representativeness by trimming over-reporting vessels that mitigates the sampling bias, augments the sample data set, and accounts for ship heterogeneity. Global ship traffic patterns are illustrated in Figure-3.

Figure.3.: Ship Traffic Patterns based on ICOADS data



Activity Data - Estimate of Emissions Factors from ships based on activity data

The amount of pollutants (SOx, NOx, $PM_{2.5}$ and CO_2) emitted from ships is a function of the amount of fuel that is combusted in the world fleet and the carbon content of the fuel. The carbon content of the present day marine fuels can be estimated with high accuracy. However, the estimation of fuel consumption entails a significant degree of uncertainty as evidenced by the differences observed in previous estimates (Corbett *et al*., 1999 [15]; Corbett and Köhler, 2003 [1]; Endresen *et al*., 2003, 2007 [5] [6]; Eyring *et al*., 2005a [3]; Olivier *et al*., 2001 [11]; Skjølsvik *et al*., 2000 [12], Gunner, 2007 [8]).

Fuel consumption for the world fleet is estimated in an "activity-based bottom-up" approach where the fuel consumption is estimated for individual ship categories. The fuel consumption estimates are then added together to find the global total.

Previous activity-based estimates have relied on different sources of activity data resulting in differences in estimated emissions (*i.e*. when AIS not installed on-board).

The activity based model developed cannot differentiate between international and domestic emissions (Ref: Updated Study on Greenhouse Gas Emissions from Ships: Phase I Report; International Maritime Organization (IMO) London, UK, 1 September, 2008, MEPC 58/INF.6).

In order to provide an estimate for emissions from international shipping by use of on the activity based model, domestic emissions as reported in bunker statistics have to be subtracted from the total shipping emissions.

Methodology used:

The methodology to study GHG is based on main parts:

1. Annual inventories of emissions of greenhouse gases and other relevant emissions from shipping from 1990 to 2007;
2. Analysis of the progress in reducing emissions from shipping through implementation of MARPOL Annex VI;
3. Analysis of technical and operational measures to reduce emissions;
4. Analysis of policy options to reduce emissions;
5. Scenarios for future emissions from international shipping;
6. Analysis of the effect of emissions from shipping on the global climate
7. A comparison of the energy efficiency and CO_2 efficiency of shipping compared to other modes of transport

8. FUEL CONSUMPTION BASED EMISSION ESTIMATION V/S ACTIVITY DATA BASED EMISSION ESTIMATION:

Emission Factors Estimate based on Fuel Statistics (Top-down Estimate)

A global inventory was established based on statistical data for fuel use, derived from IEA summaries of marine fuel sales. The methodology used for the fuel-based estimate conforms to the methodology used and reported in the 2000 IMO Study of Greenhouse Gases. This approach is limited by the quality of the statistical data, and the way in which fuel sales volumes are assigned as either international or domestic. (MEPC 58/INF.6) The EF model here is purely based on global fuel sale to ships and estimated EF from the combustion of fuel. The data collection for the fuel sales from various sources *i.e*. International Bunkering Association (IBA) data base, Fuel testing laboratories, ship owner's/ship manager's/ship operators and Lloyds' Register Fairplay data base.

Activity-based estimate (Bottom-up Estimate)

A global inventory was established for all ships greater than 100 GT based on data from the Lloyds Register Fairplay database for the year 2007 and using the best available data on vessel activity, engine and fuel characteristics, and carbon dioxide emission rates. The methodology used for the activity-based estimate has been applied in a number of scientific studies. This approach was also used in the work of the Informal Cross Government/Industry Scientific Group of Experts established by the IMO Secretary General.

The input data must be estimated for each ship category based on available background data. Although there is uncertainty in all of these figures, some of them can be estimated with high accuracy (number of ships, average power of main and auxiliary engines, specific fuel oil consumption, and fuel carbon content), and emission rates based upon fuel and combustion conditions can be described within well-understood ranges that give a satisfactory level of confidence. Other activity inputs vary by vessel service and voyage conditions and these are more difficult to assess. Comparisons with estimates for different periods would result in expected differences (*e.g*., from year to year, among vessel types, among routes, and even voyage to voyage) as they depend on the transport demand and the fleet size.

Obtaining ttechnical information about ships by the combined use of data from Lloyd's Register of Shipping database with other sources such as port authority's databases, engine manufactures and ship-owners seem to be the best approach

In this study, an extensive set of AIS data collected from a global network found to be most reliable in the assessment of ship activity; AIS information and information on engine operating hours, fleet.

9. COMPARISON OF FUEL CONSUMPTION ESTIMATES:

Previous activity-based estimates have been reported for different years (2000, 2001, and 2007).

In order to be able to compare them with the results from this study (2007), back-casts and forecasts for these point estimates are calculated from the time evolution of freight tonne-miles from Fearnleys (2007). The result is shown in Figure-4 which also presents international bunker sales statistics and the historical estimates from Eyring *et al*. (2005a) and Endresen *et al*. (2003) from 1950 to 2007. Since some of these studies included emissions from military vessels, auxiliary engines and boilers while others did not, corrections have been applied to allow comparison as detailed in the main report. Also, these studies typically estimate totals for the fleet of ships listed in national ship registries, as summarized in the Lloyds ship registry data; therefore, they represent what has been termed the World Fleet within which international shipping as defined by IPCC (Inter Governmental Panel for Climate Change) would be a subset.

The activity-based estimate from the present study is shown as a blue dot in Figure-4. Light blue whisker lines extend from this point to indicate the range of uncertainty given by the high and low bound estimates. The activity-based estimate from the present study is lower than the estimate from the IMO expert group and forecasts based on Eyring *et al*. (2005a); however, when military vessels are removed from their original figures it agrees well with the result of Corbett and Kohler (2003). The 2007 estimate of this study is higher than that of Endresen *et al*. (2007), and higher than fuel statistics. Specific Ship categories for the emission factors assessment would be an appropriate option to choose so that they represent distinct ship types in terms of not only size but also typical operational patterns, which is beneficial to identify and assess activity data.

10. FUTURE SHIP TRAFFIC DEMAND AND TECHNOLOGY SCENARIOS:

In this section plausible scenarios for future ship traffic demands as well as specific technology scenarios used in this study are described (Figure-5). The ship traffic scenarios are determined by the assumed future growth of GDP, whereas the technology scenario are determined by the technological reduction factors for each of the pollutants and the fraction to what extent alternative energies and fuels will replace diesel engines in a future fleet.

10.1 Ship Traffic Demand Scenarios:

In this study, the annual growth of GDP of the four IPCC SRES (Special Report on Emission Scenario) storylines of Intergovernmental Panel on Climate Change (IPCC 2000) used as one of the main underlying assumptions to set up future ship emission scenarios. IPCC SRES scenarios are divided into four different storylines that correspond to different assumptions on economic, technical, environmental, and social development. All scenarios are treated as equally possible in the IPCC assessment. The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. The A2 storyline and scenario family describes a very heterogeneous world with high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines. The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures. The B2 storyline and scenario family describes a world with moderate population growth and intermediate levels of economic development, in which the emphasis is on local solutions to economic, social, and environmental sustainability.

For this study only the annual growth of GDP of the SRES scenarios is used. Over the time period between 1990 and 2050 the world's average annual economic growth rates are very high in the SRES A1 storyline (3.6%), high in the SRES B1 storyline (3.1%), and medium in SRES B2 (2.8%) and SRES A2 (2.3%).

Four different ship traffic demand scenarios DS1 to DS4 are developed in this study in order to span a wide range of possible future economic development, leading to a wide range in possible ship traffic demand. The ship traffic demand scenario DS1 follows the SRES A2 storyline, *i.e.*, an annual increase in GDP of 2.3% up to 2050 is applied, DS2 follows SRES B2 (2.8%), DS3 follows SRES B1 (3.1%), and DS4 follows SRES A1 (3.6%).

10.2 Technology Scenarios:

The diesel engine has to be adjusted to comply with future emission regulations as a number of international and national regulations have recently entered into force or will enter into force in the near future. An estimate of how future emissions change with time can be based on assumptions how rapid different technologies will be introduced. Depending on the technology, the average emission factor of the fleet will change. In this section we set up four different future technology scenarios to represent the range of possible technological change. The scenarios consider possible future technology improvements for diesel engines. Alternative propulsion plants and fuels are taken into account in the fuel consumption of three of our scenarios (TS1-3). In the study, it is assumed herewith that 25% of the calculated fuel consumption in 2050 will be saved by alternative propulsion plants. The fourth scenario (TS4) is based on a diesel-only fleet in 2050.

Figure.4.: World fleet fuel consumption (except military vessels) from different activity based estimates and fuel statistics. The blue square shows the consensus estimate from this study and the whiskers the high and low bound estimates - Ref: Updated Study on Greenhouse Gas Emissions from Ships: Phase I Report; International Maritime Organization (IMO) London, UK, 1 September, 2008, MEPC 58/INF.6

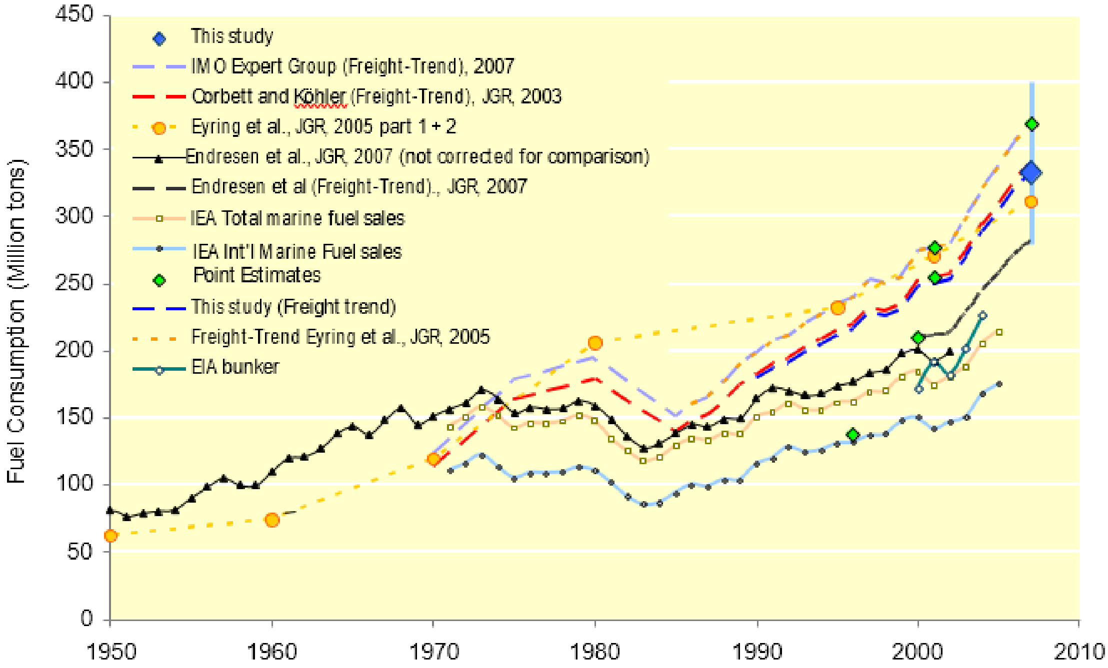
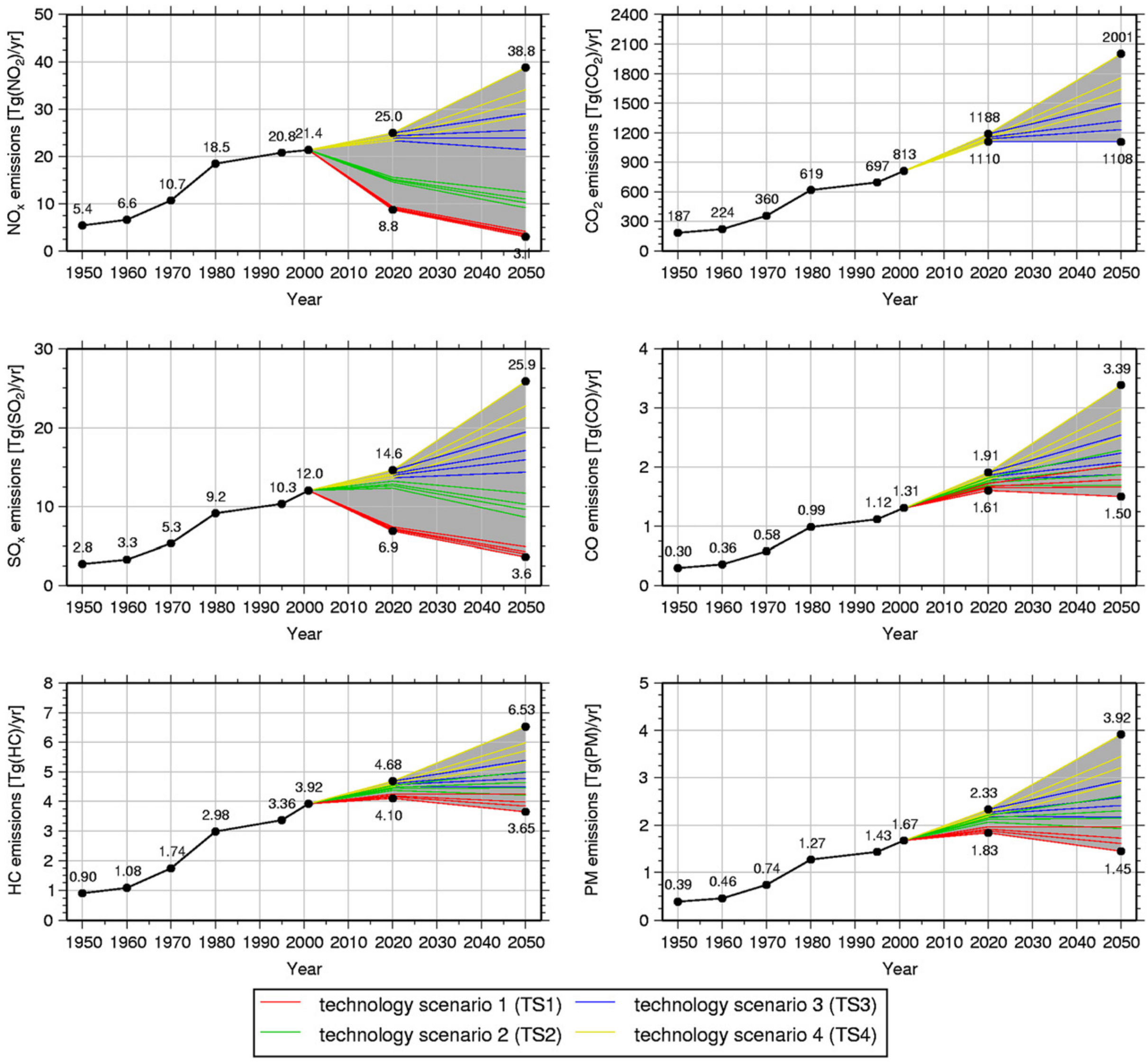


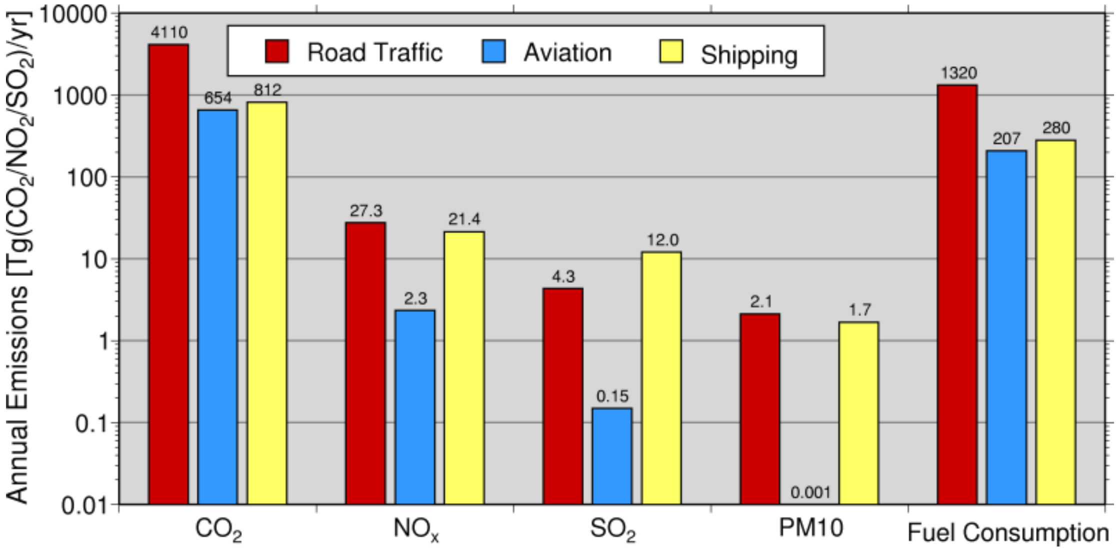
Figure.5.: Possible range of future NOx emissions in Tg(NO_2), CO_2 in Tg(CO_2), SOx in Tg(SO_2), CO in Tg(CO), HC in Tg(HC), and PM in Tg(PM) according to four different technology scenarios (TS1–4) and four different ship traffic demand scenarios (DS1–4). Results for the technology scenario 1 (TS1) are shown for different ship traffic demand scenarios (DS1–4) with solid lines in black, those for TS2 with long dashed lines, for TS3 with short dashed lines, and for TS4 with dotted lines (from Eyring *et al*., 2005b).



10.3 Transport-related Annual Emissions – Comparative study

Comparative study to Illustrate road, aviation and shipping sectors are shown in Figure-6 for reference purposes, indicating contributions of estimated emissions in the year 2000.

Figure.6.: [Transport-related annual emissions of CO_2, NOx, SO_2 and PM_{10} and the fuel consumption in Tg (1 Tg = 1 × 10^{12} g = Mt) estimated for the year 2000; *Eyring et al.* (2005a)].



11. UNCERTAINTY ASSESSMENT AND DETECTION OF MITIGATION MEASURES:

As practiced in the aviation industry, the uncertainty assessment could be an effective tool to obtain near accurate sampling of emission factors. There is uncertainty connected to both activity data and fuel consumption data. The uncertainty will depend on the data collection methodology. Determination of uncertainty ranges will be subject to further research study. Mitigation measures may be directed towards changes in specific fuel use or activity based specific emissions of a ship specific.

As the currently recommended methodologies are based on a fuel balance, measures directed towards reductions in specific fuel use could be seen as reductions in total fuel consumption.
(Ref: Aircraft Emissions - Kristin Rypdal (Statistics Norway).

12. DEVELOPMENT OF EMISSION MODEL FOR A SHIP TYPE:

Activity Based Emission Models and Methodologies

The activity based ship emission model is designed to calculate emissions and energy consumption for the different stages of navigation for every voyage and hoteling period. For every voyage, the following information is determined:

1. The route (stages of navigation)
2. The duration of the total voyage or hoteling (at berth / anchorage) time
3. The ship characteristics through reliable database (*i.e*. Lloyds' Register database)
4. The duration of different stages of navigation for every voyage
5. The percentage of the maximum continuous rate (MCR) of engine power utilized for the different stages of navigation.

There are different methodologies for the mapping of emissions from sea-going vessels, which are available in the available literature. The described methodologies are based on the ships activity. Following emission models and monitoring programmes are currently used in different applications:

01. ENTEC (**EN**vionme**T**al and **E**ngineering **C**onsultancy, UK)
02. EMS (**E**missieregistratie en – **M**onitoring **S**cheepvaart)
03. MEET (**M**ethodologies for **E**stimating air pollutant **E**missions from **T**ransport)
04. TREMOVE (**TR**ansport **E**mission and **M**obility –Leu**VE**n)
05. TRENDS (**TR**ansport and **EN**vironment **D**atabase **S**ystem)
06. REALISE (**RE**gional **A**ction for **L**ogistical **I**ntegration of **S**hipping Across **E**urope) and,
07. MOPSEA (**MO**nitoring **P**rogram on air pollution from **SEA**-going vessels)

Table.4.: A comparative study on ENTEC, EMS and MEET is tabulated below:

ENTEC	EMS	MEET
ENTEC, UK conducted study on ship emission for EC in 2000 onwards	EMS, developed by DGG, Netherlands for sea-going vessels and Inland Dutch Shipping	MEET aimed to provide a basic, Europe-wide procedure for evaluating the impacts of transport on air pollution. This would include comprehensive and up-to-date information on emissions rates and traffic characteristics, as well as methods of calculation.
Ship Activity based model covers in subdivision of navigation stages *i.e*. Cruising, Manoeuvring, hoteling and cargo operations in harbours	Ship Activity based model covers in subdivision of navigation stages *i.e*. Hoteling in Dutch Harbours, Cruising and Manoeuvring stage.	Ship Activity based model covers in subdivision of navigation stages *i.e*. Cruising, Manoeuvring, hoteling, tanker off-loading and auxiliary generators in operations.
Covers all type of ships over 500 GT	Covers all type of ships	Covers all type of ships
Emission calculations based on Fuel Dependent and Technology Dependent Emissions	Emission calculations based on Fuel Dependent and Technology Dependent Emissions	Emission calculations based on Fuel Dependent and Technology Dependent Emissions
The Model Includes Ship type, Fuel (MGO, MDO, RO) type and Engine type (SSD, MSD, HSD, GT, ST) are taken into account during emission calculations.	The Model Includes Ship type, Fuel type (FO, DO, GO, LMGO) and Engine (ME, AE, Boilers) type are taken into account during emission calculations. Daily fuel consumption [(through database of Lloyds' Maritime Intelligence Unit (LMIU)] directly used in calculations.	The Model Includes Ship type, Fuel type (BFO, MDO, MGO, Gasoline Fuel) and Engine (ME, AE, Boilers) type are taken into account during emission calculations. Data of daily fuel consumption of the ships are taken from

ENTEC	EMS	MEET
(However, there is no direct role of fuel consumption in calculations.		LMIU. Regression analyses on fuel consumption (full power) as a function of gross tonnage (GT) are performed for each ship type.
Average Emission Factors taken from LMIU and other database	Average Emission Factors taken from CBS / TNO (Netherlands), ENTEC-study and other database	Average Emission Factors taken from existing available literature LMIU and other database
On the basis of average speed per ship type, fuel type and capacity, the amount of kWh per covered kilometre determined. Through LMIU database, EFs are formulated by kWh per engine type and fuel type. Emission Calculations Methodology: Cruise Mode: E_{SEA}(g) = A_{SEA} (km) x EF_{SEA} (g/km); EF_{SEA} (g/km) = EF_{ENERGY} (g/kWh) x E_{SEA} (kWh/km) Hoteling/Manoeuvring/cargo ops mode: $E_{HARBOUR}$ (g) = A_{VISIT}(no. of visits) x EF_{VISIT} (g/visit) EF_{VISIT} (g/visit) = EF_{ENERGY} (g/kWh) x V (Kw) x T (hours by visit)	Hoteling stage Emissions calculated as: $EM_{S,V,F,M} = F_{V,R,M}$ x $EF_{S,F,M}$ Where, $EM_{S,V,F,M}$ = Emission (kg) $F_{V,R,M}$ = Amount of fuel used per ship type, fuel type and engine type (kg). $EF_{S,F,M}$ = EF per pollutant, fuel type and engine type (kg/kg) TNO (The Netherlands Organization for Applied Research) has determined “technological dependent emission factors (V). They do not work with ageing factors. Amount of fuel used specified to fuel type and engine type is calculated as: $F_{V,F,M} = F_{V,F}$ x $F_{V,M}$ x F_V Where, $F_{V,F,M}$ = Amount of fuel used per ship type, fuel type and engine type (kg) $F_{V,F}$ = Fraction fuel per ship type (%) $F_{V,M}$ = Fraction engine per ship type (%) F_V = Amount of fuel used per ship type (kg) TNO has subjected 89 ships to survey in 2003 in harbour in Rotterdam and estimated data for hoteling on the basis of – (1) the subdivision of used fuel types per type of ship To calculate amount of fuel used per ship type.	MEET emission calculations works on the formula derived as: (∑ is as Summation of) $E = \sum_{,J,K,L,M} E_{I,J,K,L,M}$ with $E_{I,J,K,L,M} = S_{J,K,M}$ x $t_{J,K,L,M}$ x $F_{I,J,L,M}$ Where: E_I = Total Emission of pollutant I. $E_{I,J,K,L,M}$ = Total Emission of I from use of fuel J on ship type K with Engine type L $S_{J,K,M}$ = Daily consumption of fuel J in Ship type K as a function of GT. $t_{J,K,L,M}$ = No. of days in navigation of ships of type K with Engine type L using fuel J. $F_{I,J,L,M}$ = Average emission factor (EF-g/kg of fuel) of pollutant I from fuel J in Engine type L.

ENTEC	EMS	MEET
	(2) the subdivision of the use of different engines per type of ship. To calculate amount of fuel used per ship type: $F_V = N_V \times V_V \times T_V \times E_V$ Where F_V = Amount of fuel used (kg) N_V = No. visits in harbour V_V = Volume of the ship (GT) T_V = Time of hoteling (hours) E_V = Amount of fuel used (kg/GT x hour) Cruising stage Emissions calculated as: $EM_T = E_S \times EF_{T,M,F,Y}$ Where EM_T = Emission of pollutant that are engine specific (kg) E_S = Amount of energy used (kWh) $EF_{T,M,F,Y}$ = EF of pollutant, engine type, fuel type and year of construction (kg/kWh). ES is calculated by installed capacity (kW), fraction used capacity, total distance covered and designed speed (knots) Fuel dependent emission (SO_X, $PM_{2.5}$) are calculated as: $EM_F = Q_S \times EF_{F,B}$ Where EM_F = Emission of Pollutant that ae fuel specific (kg) Q_S = Amount of fuel used $EF_{F,B}$ = Emission factors for pollutants, fuel (kg/kg)	

ENTEC	EMS	MEET
	The amount of fuel used from each ship on cruising mode is calculated as: $Q_S = E_S / R_{M,F,Y} \times W_F$ Q_S = Amount of fuel used (kg) E_S = Amount of energy used (kWh) $R_{M,F,Y}$ = Performance of engine type, fuel en year of construction (kWh/kWh) W_F = Energy content of fuel (kWh/kg) For manoeuvring stage, The emission calculations for manoeuvring by type of ship is likewise derived from the emission calculations for navigating Manoeuvring Mode: emission factor is transformed from navigating on cruising speed to an emission factor that is time dependant Then take into account the reduced capacity demand (average used capacity as a percentage from the available maximum continuous capacity). There is no reduced capacity demand by auxiliaries Taken into account the manoeuvring time, together with the amount of visits to the harbour en the volume of the ship (GT) the manoeuvring time of the different ship types by dividing the process into several steps:	

ENTEC	EMS	MEET
	<u>Navigate into the harbour</u> 1. navigate (the distance that ships cover between starting to manoeuvre and the quayside, the speed by which this happens is dependent on the volume of the ship); 2. turning (the turning speed (°/min) is dependent on the volume of the ship); 3. align with the quayside; 4. more alongside the quayside <u>Navigate from the harbour</u> 1. more by the quayside 2. start to move 3. turning 4. navigate The manoeuvring time is mainly dependant on the volume of the ship and the geometry of the harbour.	

13. TREMOVE:

Transport and Mobility Leuven recorded maritime shipping in their transport model TREMOVE. The emissions from sea-going vessels are calculated with the Methodology of ENTEC.

14. TRENDES:

The model developed a methodology to determine the emissions from four most important transport modes:

01. Road Transport
02. Railway
03. Maritime Shipping
04. Aviation

The module for the calculation of emissions from sea-going vessels in the study 'Energy Consumption and Air Pollutant Emission from Rail and Maritime Transport is based on TRENDS.

In TRENDS methodology, a subdivision is made for ship types, fuel type and engine type for the calculation of emissions from sea-going vessels. The emissions from sea-going vessels are calculated for different countries for the time period. The mathematical formula for the calculations of total emissions from sea-going vessels for all countries per ship type, fuel type and engine type have been deriving as:

$E_i = A_i \times EF_i$

Where,

E_i = total emission in all countries

A_i = total covered distance

EF_i = the emission factor

Emission factors (g/km) for whole set of time period (*i.e*. for the year of 2000) is used, which are dependent on country, ship type, fuel type and engine type.

The total covered distance calculations are based on tonnes of cargo moves and passengers transported per year. The statistical data provided by Eurostat and MCA (UK).

Using the number of vessels and the goods-tonnage or passengers carried by each type of ship, vessel-kilometre, passenger-kilometre and ton -kilometre estimates were calculated based on the average distance travelled by each vessel type in the chosen year.

It attributes the emissions to the different countries on the basis of import and export. The division of emissions is shared equally to origin and destination. The aggregation of statistics from MCA creates a lot of problems for the estimation of distances travelled while introducing significant accuracy to the calculation.

15. REALISE:

REALISE is a thematic network on Short Sea Shipping which provides prices of external costs from both sea and road transport. The REALISE project took the datasets in the EIG (2002), based upon the COPERT III calculation module, which were the most recent and complete available. The data are given in g/km. The air emission factors in g/kg fuel were calculated taking the fuel consumption into account. Since not all the pollutants were listed in the EIG report, additional information was extracted from the CBS database with regards to SO_2 and CO_2 emissions. It is to be noted here that the S has a negative cost impact value (*i.e*. a positive environmental impact). Its cost had to reflect this positive impact.

The results of emissions of vessels for the year 2009 in Mediterranean Short Sea Shipping routes considering two emission models, REALISE and MOPSEA models. Emissions calculated with MOPSEA model are on average 27.7% bigger than emissions calculated with REALISE model. MOPSEA model uses more accurate parameters for the calculation of the emissions compared with REALISE model (Martinez and Marcel).

16. SHIP TRAFFIC EMISSION ASSESSMENT MODEL (STEAM):

This modelling approach uses as input values the position reports generated by the automatic identification system (AIS); this system is globally on-board every vessel that weighs more than 300 t. The AIS system provides automatic updates of the positions and instantaneous speeds of ships at intervals of a few seconds. This model has been extensively used for emission assessments focussing on Fuel based emissions, fuel type and especially the fuel sulphur content (FSC), which affects significantly the SO_X and $PM_{2.5}$ emissions [Jalkanen *et al*. (2009, 2012 and 2013)].

The STEAM model is assisted by the AIS based information with the detailed technical knowledge of the ships. The model predicts as output both the instantaneous fuel consumption and the emissions of selected pollutants. The fuel consumption and emissions are computed separately for each vessel; by using archived regional scale AIS data results in a regional emission inventory. The STEAM emission model allows for the influences of the high-resolution travel routes and ship speeds, engine load, fuel sulphur content, multiengine set-ups, abatement methods and waves (Jalkanen *et al*., 2012).

17. MOPSEA EMISSION MODEL – THE METHODOLOGY:

To generate an emission inventory two approaches can be adopted, these being: the so-called "bottom-up" and "top down" approach. The top-down approach, starts with data describing the total potential polluting activity throughout the whole geographical area of interest, for example the total marine fuel sales for a country. The fuel sold can then further be subdivided into different types of oil: residual bunker fuel oil (heavy fuel oil) and distillate fuel (gas oil and marine diesel oil), or other fuel types.

A geographical break-down of the calculated emissions can then be performed when necessary (M. Vangheluwe, J. Mees and C. Janssen).

The bottom-up method starts, with geographically disaggregated data, for example the number of ship movements on a shipping route. Emission data are calculated for each individual ship or per ship type. To obtain the total emissions for a geographical area the different contributions are summed up. This method requires detailed data and may be quite time consuming to perform.

A bottom-up emission quantification study requires as much information as possible regarding ship movements, shipping routes and ship characteristics to obtain a predetermined accuracy level. This data is provided by several sources like national authorities, private companies, questionnaires and the internet. After analysis, adaptation and correction if necessary, all information is processed into calculation models. Due to analysis and comparison with other data sets, it is possible to determine accuracy, advantages and disadvantages of each data source. The main data sources are shipping companies, ports authority database, Lloyd's register (LMIU), internet shipping schedules and seafarer questionnaires.

A different engine load indicates a divergent emission value. This implies that the engine load (of the main and auxiliary engines) is the most important factor in the calculation process of ships' emissions in combination with the different marine areas and observation methods. The different aspects of the methodology are presented in Figure 1.

Two main classes are identified:
(1) Sea emissions and
(2) Port emissions.

The sea emissions indicate all emissions from shipping in the at Sea. This class is subdivided into two types of activities that take place in the sea area (however with different engine load patterns), namely cruising and anchoring.

“Sea emissions” are divided into emissions from (a) cruising vessels, and (b) vessels at anchor. Cruising vessels represent all merchant ships including dredgers and tugboats that are ‘underway’

18. CALCULATION OF TECHNOLOGY RELATED EMISSIONS:

NOX, CO, HC, and PM are technology related emissions.

Energy use (kWh)

The energy used is calculated by multiplying the used power and the duration:

Energy use (kWh) = power (kW) x duration (h)

The used power is dependent on the maximum installed power and the percentage of the maximum continuous rate (MCR) that is used:

Power (kW) = % of MCR x maximum installed power (kW)

Technology related emissions (ton) are calculated according to the following mathematical expression:

Emission (tons) = Emission factor (g/kWh) x energy use (kWh) x 10^6………(4)

19. SEA EMISSION CALCULATIONS (CRUISING):

For sea emissions, a specific methodology is developed, based on the best available data with regards to the study area. The methodology is summarized in the following formula:

$$\sum SE_{1,\, st,\, rs} = \sum (T_{st,\, rs} * P_{st,\, me} * EF_{st,\, rs} * LF_{st,\, me} / CF_{me}) + \sum (T_{st,\, rs} * P_{st,\, ae} * EF_{st,\, rs} * LF_{st,\, ae} / CF_{ae}) \quad \ldots\ldots\ldots\ldots (5).$$

Where,

*Multiplying sign

$SE_{1,\, st,\, rs}$ Sea emissions from ships determined per ship type and voyage route segment

$T_{st,\, rs}$ Sailing time as acquired by an average speed value route segment,

	multiplied with the sailed distance per route segment per ship type
$P_{st, me/ae}$	Average installed main or auxiliary engine power per ship type
$EF_{st, rs}$	Emission factors per ship type and activity in gm/kWh
$LF_{st, me/ae}$	Load factor of main engine or auxiliary engine, per ship type while sailing (% of MCR)
$CF_{me/ae}$	A correction factor to compensate for loss of efficiency at reduced load.

20. EMISSION CALCULATIONS DURING MANEUVERING:

During manoeuvres, vessels employ variable loads resulting in higher emission levels. This implies the establishment of port boundaries as an important factor in emission calculation process. The employed methodology for manoevring operations is summarized in the following mathematical expression:

$$\sum MA_{1, st, p} = \sum (T_{st, p, ma} * P_{st, me} * EF_{st, ma} * LF_{st, ma, me} / CF_{st, me}) + \sum (T_{st, p, ma} * P_{st, ae} * EF_{st, be} * LF_{st, ma, me} / CF_{st, ae}) \quad \ldots\ldots\ldots\ldots\ldots\ldots(6).$$

Where,

$MA_{1, st, p}$	Port emission from manoeuvring vessels determined per ship type and port
$T_{st, p, ma}$	Manoeuvring time as acquired by the specific port database per ship type and port
$P_{st, me}$	Average installed main or auxiliary engine power per ship type
$EF_{st, ma}$	Emission factor per ship type for ‘manoeuvring activities’ as determined by database provider (LMIU/ENTEC or similar) in g/kWh
$LF_{st, ma, me/ae}$	Load factor per ship type for main or auxiliary engine per ship type at berth (% load of MCR)
$CF_{me/ae}$	A correction factor to compensate for loss of efficiency at reduced speed

*Multiplying sign

21. EMISSIONS CALCULATIONS FROM BERTHED VESSELS (HOTELING PHASE):

During the vessel at berth, most of the time main engines are shut down and auxiliary engines are used to supply electrical power to boilers, galley equipment, refrigeration/air conditioning plants, cargo gear equipment on board like cranes, pumps, ventilation system *etc*.

The methodology used for these calculations is shown in the following mathematical expression:

$$\sum BE_{1,\,st,\,p} = \sum (T_{st,\,p,\,be} * P_{st,\,me} * EF_{st,\,be} * LF_{st,\,be,\,me} / CF_{st,\,me}) + \sum (T_{st,\,p,\,be} * P_{st,\,ae} * EF_{st,\,be} * LF_{st,\,be,\,me} / CF_{st,\,ae}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (7).$$

Where,

*Multiplying sign

$BE_{1,\,st,\,p}$ Port emission from berthed vessels determined per ship type and port

$T_{st,\,p,\,be}$ Lay time at berth as acquired by the specific port database per ship type

$P_{st,\,me/ae}$ Average installed main or auxiliary engine power per ship type

$EF_{st,\,be}$ Emission factors per ship type for ‘activities at berth’ provided by EF database provider agencies (ENTEC/LMIU *etc*.)

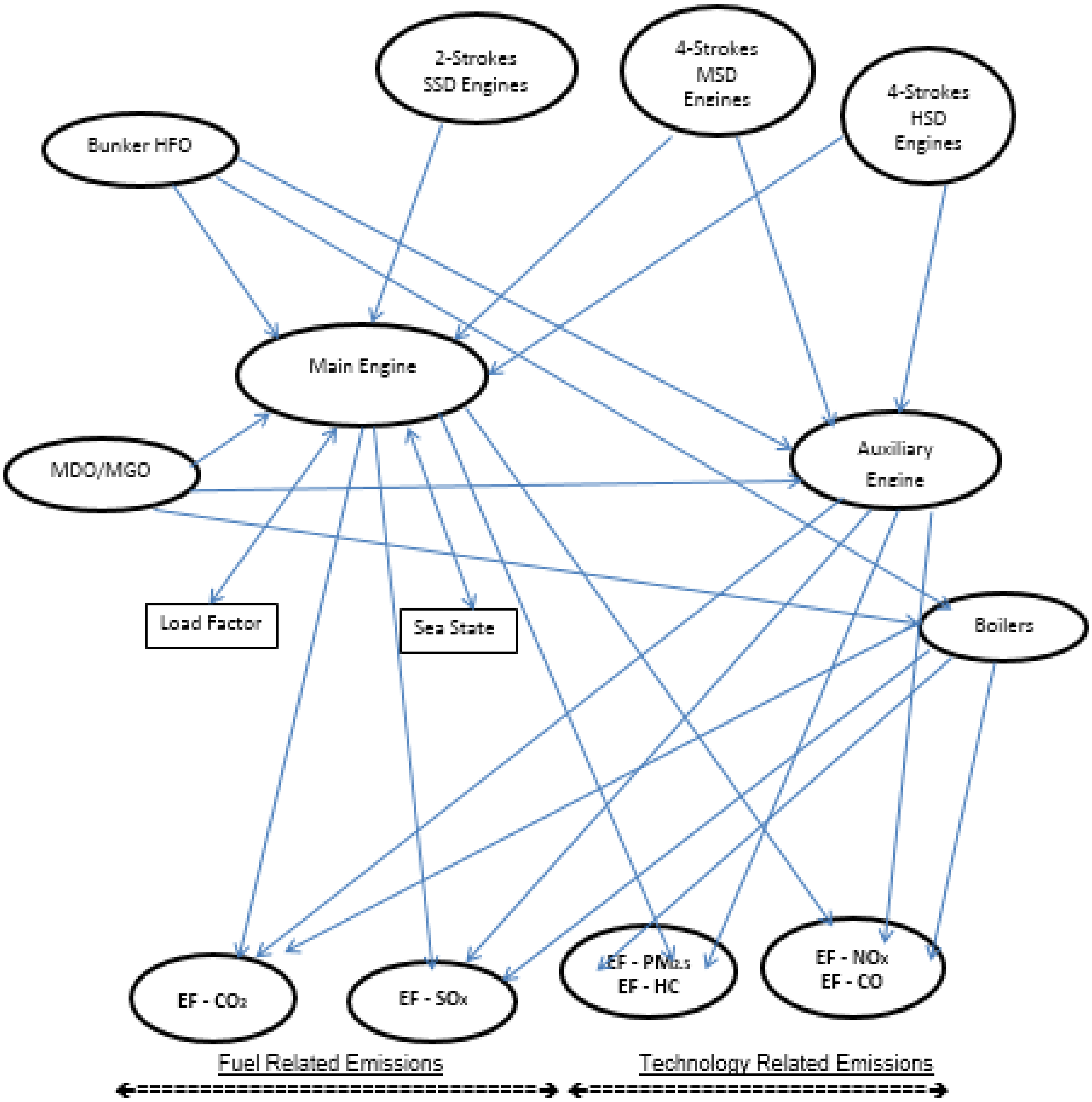
$LF_{st,\,be,\,me/ae}$ Load factor per ship type for main or auxiliary engine per ship type at berth (% load of MCR)

$CF_{me/\,ae}$ A Correction factor to compensate for loss of efficiency at reduced load

In above study, it is observed that EMS, MEET and MOPSEA Emission Model are very close in methodology and overlap on several points.

22. PROCESS MODEL FOR SHIP EMISSION:

Figure - 7



23. EMISSION MODEL AND METHODOLOGY ADOPTED FOR THIS RESEARCH TASK:

The emission model and methodology adopted for our research in assessment of ship emissions would be of "bottoms up" activity based MOPSEA basic model with novel methodology and new approach to bring further accuracy in emission assessment addressing the specific requirement of IMO directives illustrated in MARPOL Annex VI and various MEPC on reductions of CO_2, SO_X, NO_X and $PM_{2.5}$ through technical and operational measures.

In March 2010, the MEPC began consideration of making the technical and operational measures mandatory for all ships irrespective of flag and ownership; this was expected to be completed by July 2011 and concluded accordingly. The activity based emission models have made it possible to forecast the emissions from sea-going vessels for near future.

The approach adopted in our emission model is consistent with the methodology for quantifying ship emissions on following information:

- Vessel Type
- Installed engine power
- Type of fuel consumed
- Vessel route, speed and distance travelled (or the time spent during the sea passage)
- Time Spent in port, during maneuvering and anchorage (hoteling phase)
- Main and Auxiliary engines load factor during various phases of vessel activities
- Emission by boiler operations

The research study though our selected emission model and methodology would develop a novel ship emission calculation and inventory with comparative lesser uncertainties due to integration of current methodologies after considerable phasing out of potential uncertainty. Along with the fuel consumption, the following pollutants have been taken in to account in the emission calculations:

- Oxides of Sulphur (SO_X) - Sulphur Dioxide (SO_2)
- Carbon Dioxide (CO_2)
- Oxides of Nitrogen (NO_X)
- Particulate Matter (PM2.5)
- Non-Methane Volatile Organic Compounds (NMVOC) – HC
- Carbon Monoxide (CO)

The development of a suitable new emission model is based on shipping movement. It is intended to create a model that is specific vessel type which can be validated on various types of ship operations at different locations, fuel type and other parameters. The integration of the technological aspects of the sea-going vessels is an important selection criterion for a reproducible emission assessment methodology. Both are important for the scientific relevance for ship emission policy making, economics and for the feasibility.

The ship type selected for emission model is a handy-size bulk carrier installed with a 2 stroke slow speed diesel engine (SSD) powered by bunker fuel oil (HFO 380 cSt) and four-stroke auxiliary engines (MSD) powered by marine diesel (MDO) /(MGO) marine gas oil. The Auxiliary Boilers of the ship type consume marine diesel oil (MDO). The activity data consists of times spent at sea with cruising speed, maneuvering activity time duration, arrival / departure of ports and duration of stay at port and anchorage.

The model itself is based on voyages and hoteling periods of ocean going vessels. The voyage is defined here as the journey of a ship between an entry and exit point. Therefore, a round trip comprises at least two voyages. Further, all the integrated emission factors in the proposed emission model would compute:

- Fuel related emissions - Oxides of Sulphur (SO_X) - Sulphur Dioxide (SO_2) and Carbon Dioxide (CO_2) for SSD and MSD engines and auxiliary boilers.
- Technology related emissions – NO_X, PM2.5, HC and CO for 2-stroke SSD engines.

24. KEY FINDINGS FROM THE THIRD IMO GHG STUDY 2014:

Shipping emissions during the period 2007–2012 and their significance relative to other anthropogenic emissions further analyzed in subsequent years during MEPC sessions.

For the year 2012, total shipping emissions were approximately 949 million tons CO_2 and 972 million tons CO_2e (CO_2 equivalent) for GHGs combining CO_2, CH_4 and N_2O. International shipping emissions for 2012 are estimated to be 796 million tons CO2 and 816 million tons CO_2e for GHGs combining CO_2, CH_4 and N_2O. International shipping accounts for approximately 2.2% and 2.1% of global CO_2 and GHG emissions on CO_2 equivalent (CO_2e) basis; respectively. MEPC 67 (25 July 2014) provides in the annex the complete final report of the "Third IMO GHG Study 2014", which provides an update of the estimated GHG emissions for international shipping in the period 2007 to 2012. A comparative analysis of GHG illustrated in MEPC 67 in Table (a) and (b)

Table.5(a): Shipping CO_2 emissions compared with global CO_2 (values in million tonnes CO_2

Year	Global CO21	Third IMO GHG Study 2014 CO_2			
		Total Shipping	% of Global	International Shipping	% of Global
2007	31,409	1,100	3.50%	885	2.80%
2008	32,204	1,135	3.50%	921	2.90%
2009	32,047	978	3.10%	855	2.70%
2010	33,612	915	2.70%	771	2.30%
2011	34,723	1,022	2.90%	850	2.40%
2012	35,640	949	2.70%	796	2.20%
Average	33,273	1,016	3.10%	846	2.60%

Table.5(b): Shipping GHGs in CO2e (compared with global GHGs (values in million tonnes CO:2e).

Year	Global CO22	Third IIMO GHG Study 2014 C02e			
		Total shipping	%of Global	International shipping	% of Global
2007	34,881	1,121	3.20%	903	2.60%
2008	35,677	1,157	3.20%	940	2.60%
2009	35,519	998	2.80%	873	2.50%
2010	37,085	935	2.50%	790	2.10%
2011	38,196	1,045	2.70%	871	2.30%
2012	39,113	972	2.50%	816	2.10%
Average	36,745	1,038	2.80%	866	2.40%

This study estimates multi-year (2007-2012) average annual totals of 20.9 million and 11.3 million tonnes for NOx (as NO_2) and SOx (as SO_2) from all shipping, respectively {corresponding to 6.3 million and 5.6 million tonnes converted to elemental weights for nitrogen and sulphur, respectively). NOx and SOx play indirect roles in tropospheric ozone formation and indirect aerosol warming at regional scales. International shipping is estimated to produce approximately 18.6 million and 10.6 million tonnes of NOx (as NO_2) and SOx (as SO_2) annually; this converts to totals of 5.6 million and 5.3 million tonnes of NOx and SOx (as elemental nitrogen and sulphur, respectively). Global NOx and SOx emissions from all shipping represent about 15% and 13% of global NOx and SOx from anthropogenic sources reported in the latest IPCC Assessment Report (AR5), respectively; international shipping NOx and SOx represent approximately 13% and 12% of global NOx and SOx totals, respectively.

Over the period 2007-2012, average annual fuel consumption ranged between approximately 250 million and 325 million tonnes of fuel consumed by all ships within this study, reflecting top-down and bottom-up methods, respectively. Of that total, international shipping fuel consumption ranged between approximately 200 million and 270 million tonnes per year, depending on whether consumption was defined as fuel allocated to international voyage (top-down) or fuel used by ships engaged in international shipping (bottom-up), respectively.

Correlated with fuel consumption, CO_2 emissions from shipping are estimated to range between approximately 740 million and 795 million tonnes per year in top-down results, and to range between approximately 900 million and 1150 million tonnes per year in bottom-up results. Both the top-down and the bottom-up methods indicate limited growth in energy and CO2 emissions from ships during 2007 - 2012, as suggested both by the IEA data and the bottom-up model. Nitrous oxide (N2O) emission patterns over 2007- 2012 are similar to the fuel consumption and CO2 patterns, while methane (CH4) emissions from ships increased due to increased activity associated with the transport of gaseous cargoes by liquefied gas tankers, particularly during 2009 - 2012.

25. REDUCTION OF GHG EMISSIONS FROM SHIPS:

The IMO led MEPC 69 had agreed to discuss and work on further reducing GHG emissions from ships, taking into account the documents submitted and the related documents referred by MEPC 69 and onwards, *i.e*. MEPC 69/7/1 (ICS), MEPC 69/7/2 (Belgium *et al*.), MEPC 69/7/3 (CSC) and MEPC 69/7/4 (WSC *et al*.), as well as comments made at MEPC 69.

International shipping CO_2 estimates range between approximately 595 million and 650 million tonnes calculated from top-down fuel statistics, and between approximately 775 million and 950 million tonnes according to bottom-up results. International shipping is the dominant source of the total shipping emissions of other GHGs: nitrous oxide (N_2O) emissions from international shipping account for the majority (approximately 85%) of total shipping N_2O emissions, and methane (CH_4) emissions from international ships account for nearly all (approximately 99%) of total shipping emissions of CH_4.

In continuation, MEPC 70 further considered in subsequent document MEPC 70/7/2 highlighting a perceived regulatory barrier to the use of non-petroleum fuel oils, related to the general application of regulation 18.3.2 of MARPOL Annex VI.
The Committee noted the information provided by Institute of Marine Engineering, Science and Technology (IMarEST) and invited Member Governments and international organizations to submit relevant proposals for a new output in accordance w this regard, the Committee also noted information provided by the observer from ISO with regard to a currently ongoing revision of ISO 8217:2012 related to specifications of marine fuels, including changes in its scope allowing it to include synthetic and renewable fuels and their blends.

26. FUEL RELATED EMISSION FACTORS:

The pollutants CO_2 and SO_2 are fuel related. The emission factors for CO_2 in this emission model are corresponding to IMO and IPCC published CO_2 emission factors.
The SO_X emission factors would be corresponding to IMO MARPOL Annex VI fuel oil Sulphur content requirements for MDO/MGO and HFO (380 Cst) globally and in "Sulphur Emission Control Areas (SECAs) governed by Regulation 14 of MARPOL

Annex VI.

Table.6.: CO_2 and SO_2 emission factors (kg/ton fuel)
[Ref: MOPSEA Project EV43]

EF (kg/tonne)	Heavy Fuel Oil (HFO)	Diesel and Gas Oil (MDO/MGO)
CO_2	3110	3100
SO_2 (… -18/05/2006)	54	4
SO_2 (19/05/2006 – 2009)	30	4
SO_2 (2010 …)	30	4 or 2*

*2 kg of SO_2 /ton diesel or gas oil at berth (minimum duration of 2 hours)

27. TECHNOLOGY RELATED EMISSION FACTORS FOR:

The technology related emission factors for NO_X, $PM_{2.5}$, HC and CO for 2-stroke SSD engines are those taken from EMS/ENTEC and other sources. The EMS emission factors are modelled as combination of basic emission factor and correction factors for the technology (age and NO_X Regulation) and the percentage of maximum continuous rate (MCR) of the ship engines.

Emission Factor (g/kWh) = Basic emission factor
(g/kWh) X CorrAge X CorrNO_X X CorrMCR

Correction for technology

Two correction factors have to be implemented on the basic emission factor to take account into the technology of the sea-going vessels:

01. Emissions are dependent on the year of construction of vessels because of evolution in engine technology

02. Main engines built after the year 1999 have restrictions for their NO_X emissions (IMO MARPOL Annex VI Chapter 2)

28. CORRECTION FACTOR FOR % OF MCR:

The basic emission factors are based on a test cycle. This is an average of all stages of navigation. Therefore, they are not representative for the individual stages of navigation (expressed in % of MCR). A correction factor has to be implemented on the basic emission factor to get emission factors for the individual stages.

Table.7.: Basic emission factors (g/kWh) for a 2-stroke SSD engine

EF (g/kWh)	Heavy Fuel Oil (HFO)	Diesel and Gas Oil (MDO/MGO)
HC	0.60	0.60
CO	3.00	3.00
NO_X	16.00	16.00
PM	1.70	0.50

Table.7(a): Correction factor for the NO_X Regulation (IMO MARPOL Annex VI)

Date of Building	$g/NO_X/kWh$	RPM	$g/NO_X/kWh$	$CorrNO_X$
>2000	14.5	290 - 2000	$45*n^{-0.2}$	$3.10*n^{-0.2}$
>2000	14.5	>2000	9.8	0.68

Table.7(b): Correction factors for the age of the 2-stroke SSD engine

Date of Building	Heavy Fuel Oil (HFO)				MDO /MGO			
	HC	CO	NO_X	PM	HC	CO	NO_X	PM
<1974	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1975 – 1979	1.00	1.00	1.13	1.00	1.00	1.00	1.13	1.00
1980 – 1984	1.00	1.00	1.19	1.00	1.00	1.00	1.19	1.00
1985 – 1989	1.00	0.83	1.25	1.00	1.00	0.83	1.25	0.80
1990 -1994	0.83	0.67	1.13	1.00	0.83	0.67	1.13	0.60
1995 – 1999	0.67	0.67	0.94	0.88	0.67	0.67	0.94	0.60
>2000	0.50	0.67	0.91	0.88	0.50	0.67	0.91	0.60

Table.7(c): Correction factor for the % of MCR for 2-stroke SSD engine

% of MCR	HC	CO	NO_X	PM
85	0.84	0.70	0.97	0.97
80	0.87	0.76	0.97	0.98
75	0.89	0.82	0.98	0.98
70	0.92	0.88	0.98	0.99
65	0.95	0.94	0.99	0.99
60	0.98	1.00	0.99	1.00
55	1.00	1.06	1.00	1.00
50	1.03	1.12	1.00	1.01
45	1.09	1.23	1.01	1.01
40	1.16	1.38	1.02	1.03
35	1.27	1.56	1.03	1.05
30	1.42	1.80	1.04	1.08
25	1.65	2.14	1.06	1.12
20	2.02	2.66	1.10	1.19
15	2.74	3.51	1.17	1.32
10	4.46	5.22	1.34	1.63
0	0.00	0.00	0.00	0.00

Technology Related emissions factors for 4-stroke MSD engines

The technology related emission factors for HC, CO, NO_X and PM for 4-stroke engines are taken in same way from EMS/ENTEC and other sources as mentioned for 2-stroke engines. They are modelled just like for a 2-stroke engine, as a combination of a basic emission factor and correction factors for the technology (age and NO_X regulation) and the percentage of the maximum continuous rate (MCR), which is same as for 2-stroke engine.

Table.7(d): Basic emission factors (g/kWh) for a 4-stroke MSD engine

EF (g/kWh)	Heavy Fuel Oil (HFO)	Diesel and Gas Oil (MDO/MGO)
HC	0.60	0.60
CO	3.00	3.00
NO_X	12.00	12.00
PM	0.80	0.50

Table.7(e): Correction factors for the age of the 4-stroke MSD engine

Date of Building	Heavy Fuel Oil (HFO)				MDO /MGO			
	HC	CO	NO_X	PM	HC	CO	NO_X	PM
<1974	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1975 – 1979	1.00	1.00	1.17	1.00	1.00	1.00	1.17	1.00
1980 – 1984	1.00	1.00	1.25	1.00	1.00	1.00	1.25	1.00
1985 – 1989	1.00	0.83	1.33	1.00	1.00	0.83	1.33	1.00
1990 -1994	0.83	0.67	1.17	1.00	0.83	0.67	1.17	0.80
1995 – 1999	0.67	0.67	0.92	0.88	0.67	0.67	0.92	0.60
>2000	0.50	0.67	1.21	0.88	0.50	0.67	1.21	0.60

The use of different emission factors influences the emission figures. For the purpose of sensitivity analysis, MOPSEA model has been run with the widely used ENTEC (2005) emission factors. Emissions for the year 2004 have been calculated by using the ENTEC average emission factors per ship instead of the detailed EMS emission factors per individual ship. This resulted in emission figures which are higher than those calculated with the EMS factors.

Illustration on the EF Model for a ship type by EF Estimation:

Development of Emission Factor (EF) Model for a ship type would be based on methodology which covers emission during activities of all the phases (cruising, maneuvering, hoteling, berthing/anchorage). The basic algorithm for the technology related emission calculations for each activity is adopted from MOPSEA model with a different approach and innovative inputs.

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[1]Global comparator represents CO_2 from fossil fuel consumption and cement production, converted from Tg Cy^{-1} to million metric tonnes CO_2, Sources: MEPC 67, Boden *et al*. 2013 fur years 2007-2010; Peters *et al*. 2013 fur years 2011-2012, as referenced in IPCC (2013)

[2]Global comparator represents N_2O from fossil fuels consumption and cement production. Source: IPCC (2013).

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