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Atmospheric Measurement Techniques Discussions

Emission-factor uncertainties in maritime transport in the Strait of Gibraltar, Spain

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Abstract

A reliable and up-to-date maritime emission inventory is essential for atmospheric scientists quantifying the impact of shipping. The objective of this study is to estimate the atmospheric emissions of SO_2, NO_x, CO_2 and PM_{10} by international merchant shipping in 2007 in the Strait of Gibraltar, Spain, including the Algeciras Bay by two methods.

Two methods (both bottom-up) have been used in this study:

1. Establishing engine power-based emission factors ($g\,kWh^{-1}$, EPA) or the mass of pollutant per work performed by the engine for each of the relevant components of the exhaust gas from diesel engines and power for each ship.

2. Establishing fuel-based emission factors (kg emitted/t of fuel) or mass of pollutant per mass of combusted fuel for each of the relevant components of the exhaust gas and a fuel-consumption inventory (IMO).

In both methods, the means to estimate engine power and fuel-consumption inventories are the same. The exhaust from boilers and incinerators is regarded as a small contributor and excluded. In total, an estimated average of 1 389 111.05 t of CO_2, 23 083.09 t of SO_2, 32 005.63 t of NO_x and 2972 t of PM_{10}were emitted from January 2007 until December 2007 by international and domestic shipping. The estimated total fuel consumption amounts to 437 405.84 t. The major differences between the estimates generated by the two methods are for NO_x (16 % in certain cases) and CO (up to 23 %).

A total difference for all compounds of 3038 t (approximately 2 %) has been found between the two methods but it is not a reasonable estimate of uncertainty.

Therefore, the results for both methods may be considered acceptable because the actual uncontrolled deviations appear in the changes in emission factors that occur for a given engine with age. These deviations are often difficult to quantify and depend on individual shipboard service and maintenance routines. Emission factors for CO and NO_x are not constant and depend on engine condition. For example, tests conducted

by the authors of this paper demonstrate that when an engine operates under normal in-service conditions, the emissions are within limits. However, with a small fault in injection timing, the NO_x emission exceeds the limits (30 % higher value in some cases). A fault in the maintenance of the injection nozzles increases the CO emission (15 % higher value in some cases).

1 Introduction

Shipping is estimated to have emitted 1046 million tons of CO_2 in 2007, which corresponds to 3.3 % of global emissions in 2007. International shipping is estimated to have emitted 870 million tons or approximately 2.7 % of global CO_2 emissions in 2007 (Second IMO GHG Study, 2009).

In Denmark, a fuel-consumption and emissions estimate was performed in the period 1990–2005 and published in 2008. In addition, a projection for the period 2006–2030 was performed that provided highly significant results. In 2009, the second IMO (International Maritime Organization) GHG (Green House Gases) study presented estimates of GHG emissions from ships (NERI and University of Aarhus, 2008). In 2008, Dalsøren et al. presented the estimates of CO_2, SO_2 and NO_x from the international fleet. A more detailed ship-emissions inventory for UK waters was presented by ENTEC in 2010 (UK Ships emissions inventory). Dabdub and Irvine studied the impact of ship emissions on air quality on the California coast (Dabdub and Irvine, 2008). In addition, the 2007 analysis of policy measures to reduce ship emissions, which was presented in the revision of the National Emissions Ceilings Directive, was an interesting contribution to ship-emissions estimation (International Institute for Applied Systems Analysis Schlossplatz, 2007).

Approaches to emission inventories can be categorized as bottom-up or top-down. A bottom-up approach considers spatially resolved ship-activity data, including engine size, engine load, fuel type, operating profile and other factors related to the combustion and ship to determine the emission load. A top-down approach analyzes

AMTD
5, 5953–5991, 2012

fuel-consumption data and attributes the emission totals to the emission sources. A top-down approach is less time-consuming than a bottom-up approach. In a bottom-up approach, the level of detail can be higher. Global inventories can use models with elements from both methods. Details on specific ships or ship types result in estimates of global fuel consumption and emissions and are combined with spatially resolved models on the activity of the global fleet (Endresen et al., 2007). The results of top-down approaches can deviate considerably from local port inventories performed using a bottom-up approach (Wang et al., 2007).

This paper describes two bottom-up methods. The only difference between these methods concerns the emissions-factor values. Although both methods use the engine power of each ship, the methods display uncertainty if their measurements are compared with measurements made on board the ships (Durán et al., 2012).

The specific emissions (typically, the mass of the pollutant per work performed by the engine or per mass of combusted fuel) of a pollutant species differ according to the operational mode due to the different combustion characteristics of different loads and transient operations. The units of the specific emissions, $\mathrm{g\,kWh^{-1}}$ or $\mathrm{g\,kg^{-1}}$ fuel, are related to each other by the specific fuel consumption (SFOC), which differs among engine types. In addition, the SFOC depends on the fuel type due to the differences in specific heat among fuels.

The GHG and pollutant emissions in exhaust gases can be estimated by establishing fuel-based emission factors for each of the relevant components of the exhaust gas and a fuel-consumption inventory. Fuel-based emission factors are values for conversion from consumed fuel to the emissions that occur during combustion. The emissions are subsequently estimated by multiplying the fuel consumption (tons of fuel) by the emission factors (kg emitted/t of fuel).

Another approach is to multiply the total engine power in kilowatts by the emission factor for the pollutant of interest in $\mathrm{g\,kWh^{-1}}$ (mass of pollutant per work performed by the engine.) In this study, both models have been used.

AMTD
5, 5953–5991, 2012

Since 2005, all of the activities of ships larger than 300 GT (Gross Tonnage) in the Strait of Gibraltar have been registered (radar location and velocity). This data system's availability has enabled the compilation of emission inventories. In 2011, the project "Maritime transport emissions at the Strait of Gibraltar" was conducted by the authors on behalf of the Spanish Environment Ministry. The project assesses the SO_2, NO_x, CO_2 and particulate emissions in the air over Algeciras Bay for 2007.

The present paper describes the emission inventory and the calculated emission results according to both methods and the uncertainties that occur when the results of the methods are compared with measurements on board the ships. A short summary of the methods will be presented, including descriptions, vessel data, engine load functions, fuel consumption and emission factors. In addition, relevant assumptions for ship engines depending the model will be discussed. In the results section, the focus is on fuel consumption and the SO_2, NO_x, CO_2 and particulate emissions for 2007.

The ship inventories include emissions from both propulsion and auxiliary engines installed on board Category 3 vessels (ships whose engines have a per-cylinder displacement of 30 l or more). These vessels are most likely to be affected by the MARPOL Annex VI.

2 Experimental (materials and methods)

2.1 Maritime traffic in the bay of Algeciras and the Gibraltar Strait

The Strait of Gibraltar is a natural strait that connects the Atlantic Ocean to the Mediterranean Sea. The Gibraltar strait also acts as a sort of political boundary between two countries: Spain and Morocco. The Strait of Gibraltar separates the two continents of Europe and Africa. The length of the Strait of Gibraltar is approximately 40 km with a width varying from 29 km to 13 km on the narrowest point of the strait.

The Strait of Gibraltar has both national and international marine traffic which covers transit, non-transit ships as well as domestic ships. This study is divided into eight main parts as follows:

a. Emissions from ships passing the Strait of Gibraltar from Atlantic Ocean to Mediterranean Sea (21 nautical miles, course E–W),

b. Emissions from ships passing the Strait of Gibraltar from Mediterranean Sea to Atlantic Ocean (21 nautical miles, course W–E),

c. Emissions from domestic ships in the Strait of Gibraltar from Tangier (Morocco) to Algeciras (Spain) and vice verse (30 nautical miles),

d. Emissions from domestic ships in the Strait of Gibraltar from Tangier Med (Morocco) to Algeciras (Spain) and vice verse (15 nautical miles),

e. Emissions from domestic ships in the Strait of Gibraltar from Tangier (Morocco) to Tarifa (Spain) and vice verse (16 nautical miles),

f. Emissions from domestic ships in the Strait of Gibraltar from Algeciras (Spain) to Ceuta (Spain) and vice verse (16 nautical miles),

g. Emissions from domestic ships in the Strait of Gibraltar from Tarifa (Spain) to Ceuta (Spain) and vice verse (16 nautical miles),

h. Emissions from domestic ships in the Strait of Gibraltar from Tangier Med (Morocco) to Tarifa (Spain) and vice verse (15 nautical miles).

2.2 Registered vessels

Vessels are registered by radar (VTS). The covered area for the reference period is limited to the Strait of Gibraltar, meaning that only vessels visiting one of the four sea ports (Algeciras, Tarifa, Ceuta and Tangier) could be taken into account. The vessels transiting in the directions W–E and E–W have been also included.

2.3 Study area

The study area is divided according to basic criteria for emission calculation. Two topics are specified as follows:

1. Domestic traffic between Spain and Morocco (from c to h)

2. The second phase identifies only cruising activities per area (a and b).

The total sea area is estimated at 1172 km^2. The ports and anchorage zone are not included.

According to the Spanish Safety Agency (SASEMAR), the number of ships passing through the Strait of Gibraltar was 92 406 in 2007. The ship are described according to number and type as follows: 4258 ro-ros, 778 reefers, 10 145 containers, 17 131 tankers (all types, crude, product, chemical etc.), 2871 ferries, 56 077 passenger ships and 1146 others. The emissions of dredgers, fishing boats, naval ships and tugboats are not included in this study.

Activity times (At) for sailing at sea are calculated by adding the distance of the separate route segments and dividing this figure by an average speed value per vessel type.

2.4 Methods

This study's approach is based on two quantitative research methods, as follows:

1. First method: Establishing engine power-based emission factors ($g\,kWh^{-1}$, EPA) or the mass of pollutant per work performed by the engine for each of the relevant components of the exhaust gas from diesel engines and power for each ship.

2. Second method: Establishing fuel-based emission factors (kg emitted/t of fuel) or mass of pollutant per mass of combusted fuel for each of the relevant components of the exhaust gas and a fuel-consumption inventory (IMO).

AMTD
5, 5953–5991, 2012

In both methods, the means to estimate engine power and fuel-consumption inventories are the same. In each case, the methods are consistent with the method used by the EPA's (Environmental Protection Agency) North American ECA (the first method) and the IMO (the second method).

The approach is summarized below.

The inventory method consists of several parts. First, an inventory for 2007 for the entire Strait of Gibraltar region was compiled taking into account vessels that cross the Strait of Gibraltar sea lanes, which extend 21 × 30 nautical miles in all directions, outside of ports but within the inventory domain. These inventories were obtained using the SASEMAR Database.

Certain engine-emission factors depend on how the engine is being operated. Idling and rapid load changes produce more pollutants associated with incomplete combustion as CO, non-methane volatile organic compounds (NMVOC) and PM, for example. Therefore, indirectly, the style of ship operation will affect the demands on the engine and the engine's emissions.

The emissions are usually estimated for four modes of operation. However, in this case, only the cruise mode will be considered because most ships cross the Strait of Gibraltar at approximately 85 % main engine load (SASEMAR Database). The cruise-mode emissions in the near-port analysis extend 25 nautical miles beyond the end of the RSZ (Reduced Speed Zone) lanes.

Generally, ship propulsion is provided by main engines while on-board electricity is generated by auxiliary engines. In number and emission magnitude, main (ME) and auxiliary (AE) diesel engines predominate by far. The ship inventories include emissions from both propulsion and auxiliary engines installed on board the Category 3 vessels included in the analysis.

Rather than by size, diesel MEs and AEs are categorized according to engine speed at the crankshaft: high speed diesel (HSD), medium speed diesel (MSD) and slow speed (SSD). Slow and medium speed engines are far more abundant than high-speed engines as main engines.

AMTD
5, 5953–5991, 2012

Emissions are calculated separately for propulsion and auxiliary engines.

For this analysis, SASEMAR information data for 2007 and Lloyd's Register Fairplay (now HIS Fairplay) data for ship characteristics were used to identify average ship characteristics and calls by ship type for each port. Information on the number of calls, propulsion-engine power, and cruising speed was obtained from these data.

The records from the SASEMAR entrances database were matched with Lloyd's data on ship characteristics. Ships with main propulsion engines with less than 30 l per cylinder displacement were eliminated from the data set. The dataset for vessels with Category 3 propulsion engines was binned by ship type, engine type and dead-weight tonnage (DWT) range. The number of entrances in each bin is counted. In addition, propulsion power and vessel cruising speed are considered constant during the 21-mile W–E or E–W transit of the strait (from the Atlantic Ocean to the Mediterranean Sea and vice versa) or during the 21-, 15-, 16- and 30-mile N–S or S–N course (domestic ferries).

The following inputs are required to estimate emission inventories for each vessel in the cruise mode:

- Number of calls and ship characteristics (main-engine power, cruising speed, and load factors.
- Cruise distance
- RSZ distances and speeds for each port
- Auxiliary-engine power and load factors
- Main emission factors
- Auxiliary emission factors
- Low-load adjustment factors for main engines (not applicable)
- Maneuvering time-in-mode ($\mathrm{h\,call^{-1}}$) (not applicable)

AMTD
5, 5953–5991, 2012

– Hotelling time-in-mode ($h\,call^{-1}$) (not applicable)

2.5 Calculation

2.5.1 First method

Establishing engine power-based emission factors ($g\,kWh^{-1}$), (ENTEC).

Main-engine power and load-factor equations

Supporting information provides the specific equations used to calculate propulsion and auxiliary emissions for each activity mode (Eqs. A1 and A2).

Main-engine emission factors

An analysis of emission data was prepared and published in 2002 by ENTEC (Entec UK Limited). The resulting ENTEC emission factors include individual factors for three speeds of diesel engines: slow-speed diesel (SSD), medium-speed diesel (MSD), and high-speed diesel (HSD), and the two types of fuel studied here: residual marine (RM) and marine distillate oil (MDO). Table 4 lists the propulsion-engine emission factors for NO_x and HC that were used for the 2002 port inventory (Corbett and Koehler, 2003). The CO, PM, SO_2 and CO_2 emission factors shown in the table come from other data sources, as explained below. Because PM and SO_2 emission factors depend on the fuel sulfur level, the fuel types and fuel sulfur levels used in this analysis are described at the end of this section.

Ships consume a variety of fuels classed primarily by viscosity and ranging from marine distillates (MD) to heavier residual oils (RO). All the domestic-traffic ships in the Strait of Gibraltar consume MDO (0.05 % S maximum). The remaining ships (cargo ships included) that transit the Strait consume RO (2.5 % S, Lloyd's database). Certain pollutant emissions are predetermined solely by their fuel content irrespective of the engine's combustion conditions. Examples are CO_2, SO_2 and PM emissions.

AMTD
5, 5953–5991, 2012

The calculations assume that tankers, reefer ships and container ships use heavy fuel oil and that general cargo ships use gas oil.

The brake specific fuel consumption (BSFC) used for SSDs was 195 $g kWh^{-1}$, while the BSFC used for MSDs was 210 $g kWh^{-1}$ based on Lloyd's 1995 database.

Auxiliary-engine power and load factors

In the method used in this analysis, the auxiliary-engine maximum continuous power ratings and load factors were calculated separately from those of propulsion engines, and different emission factors (EFs) were applied. All auxiliary engines were treated as Category 2 medium-speed diesel (MSD) engines.

In the Lloyd's database, auxiliary-engine power data are limited. Therefore, this power must be estimated. The approach was to derive ratios of average auxiliary-engine power to propulsion power based on survey data. The California Air Resources Board (ARB) conducted an Oceangoing Ship Survey of 327 ships in January 2005 that was the principal source of data for this analysis. Average auxiliary-engine power to propulsion power ratios were estimated by ship type and are presented in Table 1. These ratios by ship type were applied to the propulsion-power data to derive auxiliary power ratings for the ship types at each port.

The auxiliary-engine to propulsion-engine power ratio varies by ship type and operating mode approximately from 0.19 to 0.40. The auxiliary load, shown in Table 4, is used with the total auxiliary-engine power to calculate auxiliary-engine emissions. Starcrest's Vessel Boarding Program showed that auxiliary engines operate constantly except when the ship is using shoreside power during hotelling. The highest power load often occurs during maneuvering and the minimum under normal cruising (Table 4).

In this study, only the RSZ mode has been considered.

However, considering the resolution IMO MEPC.212 (63) adopted on 2 March 2012, the estimation procedures given in the 2012 guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships could be used. According to the guidelines, two equations might be used, one for ships with a main engine power of 10 000 kW or above, and the other one for ships with a main engine with a power output lower than 10 000 kW (MEPC 63/23 Annex 8, p. 7, 2012). This resolution has not been considered in this study because the amendments to MARPOL Annex VI adopted at its sixty-second session by inclusion of a new chapter 4 for regulations on energy efficiency for ships, are expected to enter into force on 1 January 2013 upon their acceptance on 1 July 2012.

Auxiliary-engine emission factors

The most current set of auxiliary engine emission factors is that of ENTEC except as noted below for PM and SO_2. Table 5 provides the auxiliary-engine emission factors.

The auxiliary-engine emission-factor averages by ship type are obtained by combining the ratios of RM versus MDO as shown in Table 8 with the emission factors shown in Table 5.

Calculation of all emission factors

The SO_2 emission factors ($g\,kWh^{-1}$) were based on a fuel sulfur to SO_2 conversion formula that was supplied by ENVIRON (Eq. A3).

The CO_2 emission factors were calculated from the BSFC assuming a fuel carbon content of 86.7 % by weight 14 and a ratio of molecular weights of CO_2 and C at 3.667 (Eq. A4). The fuel specific CO_2 emission values are detailed in Table 7 for residual oil and gas oil (3.130 $kg\,CO_2\,kg^{-1}$ fuel for heavy fuel oil and 3.190 $kg\,CO_2\,kg^{-1}$ fuel for marine diesel oil, IPPC 2006 database, Second IMO GHG Study 2009). However, IMO has established new conversion factors in its guidelines IMO, 2010, Report of the Working Group on Energy Efficiency Measures for Ships, Annex 2, Paper MEPC 61/WP.10, 2012 (3.1144 $kg\,CO_2\,kg^{-1}$ fuel for heavy fuel oil and 3.206 $kg\,CO_2\,kg^{-1}$ fuel for gas/diesel oil).The IPPC database has been used in this study because the inventory was done for the year 2007.

AMTD
5, 5953–5991, 2012

Emission-factor uncertainties in maritime transport

J. Moreno-Gutiérrez et al.

The CO emission factors were developed from information provided in the ENTEC appendix because these factors are not explicitly stated in the text. The CO emission factors were confirmed by a recent US government review (EPA-HQ-OAR-2007-0121, 2009).

The SO_2 emission factors were calculated from the fuel sulfur levels.

The PM_{10} values were determined based on existing engine test data in consultation with ARB. The value of $PM_{2.5}$ is assumed to be 92 % of PM_{10} (Eq. A5).

Marine engines use primarily three types of fuel: residual marine (RM), marine diesel oil (MDO), and marine gas oil (MGO) with varying levels of fuel sulfur (EPA420-D-07-006, 2006). Generally, MDO and MGO are described as distillate fuels.

For this analysis, RM and MDO fuels are assumed. Because PM and SO_2 emission factors depend on the fuel sulfur level, the calculation of port inventories requires information about the fuel sulfur levels associated with each fuel type and which fuel types are used by propulsion and auxiliary engines.

The procedure for each ship is illustrated in Fig. 1.

2.5.2 Second method

Establishing fuel-based emission factors (kg emitted/t of fuel) (CORINAIR/IPPC, 2006).

In this method, the fuel consumption is estimated for individual ships. The main-engine (ME) fuel consumption of each ship is estimated by multiplying the MCR ME power (Lloyd's Database) of navigation through the Strait of Gibraltar for the operating hours of the main engine and the average engine-load factor. Next, the fuel consumption is estimated by multiplying the power outtake by the specific value of fuel-oil consumption that is applicable to the engines of the given category ($g\,kWh^{-1}$). The process of estimating the fuel consumption of a ship category is illustrated as follows. The same principle is applied to estimate the fuel consumption of the auxiliary engine. Emissions from boilers have not been estimated for tanker ships.

AMTD
5, 5953–5991, 2012

Main- and auxiliary-engine fuel consumption

Fuel consumption for 2007 was estimated by an activity-based method for individual ships. This method represents a change compared with the 2009 IMO study on GHG emissions from ships because no fuel statistics were available. The investigations that are presented in this study suggest that both international and domestic shipping have been estimated by an activity-based method (a bottom-up approach) for all the vessels transiting the Strait of Gibraltar.

In the activity-based approach, the fuel consumption is estimated for individual ship categories.

The annual power outtake (kWh) is estimated by multiplying the installed power by a category-specific estimate of the operating hours of the main engine and the engine-load factor for each ship speed. Next, the fuel consumption is estimated by multiplying the power outtake by the specific value of fuel-oil consumption that is applicable to each engine ($g\,kWh^{-1}$).

The process of estimating the fuel consumption of each ship is shown in Fig. 2. The same principle is applied to estimate the fuel consumption of the auxiliary engine.

Main and auxiliary engine emission factors

Fuel-based emission factors are conversion values that are used to calculate emissions and based on consumed fuel.

To compile the basic emission inventory in accordance with recognized standards, default emission factors prepared by IPCC and the UNECE/EMEP CORINAIR program, 2006 are used except for NO_x, where the impact of the IMO NO_x regulation requires special analysis (Table 7).

Three NO_x emission factors shown in this table represent a weighted fleet average that applies to 2007. The weighting to determine the 2007 emission factor is based on the fraction of total power in the world fleet installed on or after 1 January 2000.

The process of estimating the total emissions of each ship is illustrated in Fig. 3.

3 Results

Tables 10 and 11 show the total average fuel consumption and total emissions based in the first method. Tables 1 and 2, show the results for each pollutant for both methods.

Passenger vessels are the main emitters and represents more than 65 % of the atmospheric emissions in certain cases (62.6 % for CO_2, 68.7 % for SO_2, 67.4 % for PM_{10}, 66 % for $PM_{2.5}$ and 62 % for NO_x). The high share of emissions of container vessels is remarkable despite representing only 18 % of all entries in the VTS Tarifa.

The results coincide except for NO_x and CO emissions.

Most differences appear with respect to NO_x and CO emissions. The reasons for these differences will be discussed below.

4 Uncertainties and discussion

The activity-based estimate of consumption of marine bunkers is based on a series of inputs. An uncertainty is associated with each of these inputs. Therefore, the uncertainties of this study may be divided in two sections, as follows.

4.1 Uncertainties common to both methods discussed in this study

4.1.1 Lloyd's Register Fairplay database

Ninety-five percent of the calls in the input data were directly matched with the Lloyd's data, and the remaining 5 % were estimated based on other information (Second IMO GHG Study, 2009), although no significant difference exists between "Lloyd's database" and the results applied from Table 8.

AMTD
5, 5953–5991, 2012

4.1.2 Engine load

Default values were calculated from AIS average speed and Fairplay design speed. The calculations are sensitive to vessel-design speed data from the extended Lloyd's database and errors in estimating the AIS at-sea speed. Moreover, engine load will be over-estimated when a ship is in ballast or lightly loaded. However, in this case, most of the vessels studied (65 %, including passenger ships, ferries and ro-ros) cruise the strait with the same load in both directions N–S and S–N. The remaining ships usually cruise loaded in one direction and in ballast in the opposite direction E–W and W–E. Therefore, the calculation of the average main engine load can be considered acceptable.

4.1.3 Vessel cruise speed

The third common uncertainty could be related to the AIS calculations used for propulsion-engine power, and cruising speed. The number of entrances in each bin is counted. In addition, propulsion power and vessel cruise speed are considered constant during navigation across the strait. However, the vessel cruise speed depends on meteorological conditions, and only one bin and only one speed register may not suffice. However, in this case, most of the vessels that ship through the strait complete the passage in a relatively short time (1.50 to 3 h) and weather conditions that decrease the speed in one direction will be beneficial when sailing in the opposite direction. The average time spent shipping in the zone was calculated for each ship. Therefore, we believe that the results are acceptable.

4.1.4 Auxiliary-engine power data

All auxiliary engines were treated as Category 2 medium-speed diesel (MSD) engines for this analysis. In the Lloyd's database, auxiliary-engine power data are limited. Therefore, these data must be estimated. The estimation approach was to derive

AMTD
5, 5953–5991, 2012

ratios of average auxiliary-engine power to propulsion power based on survey data. For this analysis, California Air Resources Board (ARB) was the principal source of data. Therefore, the results could be considered acceptable because the same procedure has been used by the EPA in the year 2010.

4.1.5 Ship database

The uncertainty of the database of ship specific data used should also be considered as contributing to the total uncertainty. In this study has not been possible to calculate such uncertainty.

4.1.6 Fuel type

Finally, irrespective of ship category (container, passenger, ferry etc.), a ship's engine type and fuel dictate the ship's emissions. Tables 5 and 6 display the relevant data. For passenger ships, ro-ros and ferries, MDO fuels are assumed for both main and auxiliary engines.

4.2 Uncertainties with each method in this study

The most important uncertainty with the first method is the emissions factors that were applied.

The method for applying the emission factors is based on the published sources IVL (Swedish Environmental Research Institute) and Lloyd's Register Engineering Services data. In general, variation within the IVL data is smaller in comparison with the Lloyd's data. For example, the NO_x factors for SSD are 17.4 $g\,kWh^{-1}$ (IVL) and 18.7 (LR). However, the differences in CO, HC and PM are larger. In this study, the ENTEC database has been applied, as in the EPA method (18.1 $g\,kWh^{-1}$ for SSD and 14.0 for MSD). This uncertainty must be taken into account particularly when significant differences are apparent in comparison with other methods, as discussed above.

AMTD
5, 5953–5991, 2012

With the second method, two questions must be considered: the SFOC values and the emission factors used.

First, fuel consumption was estimated based on activity data, not fuel statistics. In the activity-based approach, fuel consumption is estimated for individual ships. The main- and auxiliary-engine fuel consumption of a ship is estimated by multiplying the ME and AE power by the average specific consumption ($g\,kWh^{-1}$) of fuel oil by the main and auxiliary engines.

Activity-based estimates consistently predict fuel-consumption values that are higher than those indicated in fuel statistics. These activity-based estimates share many common inputs and assumptions and are not fully independent. In contrast, statistical data include apparent errors and other inconsistencies that could be expected to cause under-reporting of consumption (Second IMO GHG Study). The SFOC of modern marine engines ranges between 165 $g\,kWh^{-1}$ for the most efficient two-stroke engines to approximately 230 $g\,kWh^{-1}$ for small four-stroke engines The SFOC that was used for SSDs was 195 $g\,kWh^{-1}$, while the BSFC that was used for MSDs was 210 $g\,kWh^{-1}$ based on Lloyd's (1995). However, engines older than 10 yr (engines manufactured before 1993) have been assigned SFOC values 7 % larger than for newer engines (Genesys Engineering Inc., 2003).

In addition, engine type (SSD and MSD) has been considered without distinguishing whether the engine was main or auxiliary.

This uncertainty is important because the differences between the SFOC of new and old engines, average engine age, engine wear, engine maintenance etc. must be considered.

However, the original emission factors are in the unit $g\,kWh^{-1}$. These values have been converted to emissions in $g\,kg^{-1}$ fuel by dividing the SFOC of 206 g fuel/kWh (Corbett and Koehler, 2003). This average value can produce differences from ENTEC values, which are used in the first method.

AMTD
5, 5953–5991, 2012

4.3 Discussion

This research has estimated atmospheric emissions for a precise geographical area: the Strait of Gibraltar and Algeciras Bay. By using a method based on a activity-based model, the results are more realistic and justifiable than other estimates based on the amount of bunker fuels sold over a given time period.

During the research, difficulties were encountered in obtaining reliable data and determining precise emission factors. Overcoming these difficulties will facilitate a finer tuning of the method and more precise estimates.

In addition, it would be interesting to examine the Strait of Gibraltar emission estimates from the perspective of another country (Table 9).

The available data sources for applying a detailed method may vary from one country to another. Additionally, the scope of such a study may vary. In this article, only one detailed method for shipping is presented. The method is based on ship movement data, not fuel statistics. In accordance with standard international procedure for gaseous emissions from diesel engines, the base emission factors are presented in terms of the weight of a given pollutant (in grams) divided by the uncorrected work performed by the crankshaft, i.e., $\mathrm{g\,kWh^{-1}}$. Using the specific fuel combustion (grams of fuel consumed per kWh), a simple calculation converts the power-based emission factors from $\mathrm{g\,kWh^{-1}}$ to $\mathrm{g\,t^{-1}}$ of fuel supplied to the engines. The emission factors (derived from the database) for a pollutant have been given specifically for 2 different engine types (MSD and SSD) and two fuels. Therefore, the SO_2 emission factors were based on an ENVIRON formula for converting fuel S content to SO_2 exhaust emission (ENVIRON, 2005). The PM_{10} values were determined from existing engine test data provided by the US Environmental Protection Agency, Docket ID EPA-HQ-OAR–0121-0060, 2007.

The degree of uncertainty for this type of inventory is highly significant. As discussed in Sects. 4.1.1, 4.1.2 and 4.1.3, the results can be considered acceptable. There are other methods (see Sect. 4.1.4) to calculate auxiliary-engine power. For example, Hans Otto Kristensen (DTU, 2009), uses an equation with ±2 % deviation.

AMTD
5, 5953–5991, 2012

However, the deviations obtained for both methods are more important for NO_x and CO, particularly for four-stroke engines. Differences up to 16 % for NO_x have been obtained with both methods, particularly for four-stroke engines. Differences close to 20 % are usually tolerated in emission inventories. However, for CO emissions, certain differences much higher (more than 40 % in many cases) and out of tolerance. The main differences are with four-stroke engines. In this case, the fuel-based emissions-factor method uses a constant emission factor for all engine and fuel types (CORINAIR). However, ENTEC uses different emissions factors for two- and four-stroke engines, respectively (27 % lower value), which cause the large differences in CO emissions.

The fuel consumption of main engines used for propulsion is commonly estimated in the literature as a product of the constant specific fuel oil consumption (SFOC) and instantaneous engine power, which results in a linear relationship between fuel consumption and engine power. Depending on the stroke type, age and power rating of the engine, the base SFOC value typically ranges between 170 $g\,kWh^{-1}$ and 220 $g\,kWh^{-1}$. In this paper, average values of 195 $g\,kWh^{-1}$ for two-stroke engines and 210 $g\,kWh^{-1}$ for four-stroke engines have been applied. These values can be accepted. However, there is a minimum difference in the results for both methods in total emissions (Table 2).

Finally, the largest uncertainty for this inventory type is in the lack of correction factors for engine-maintenance conditions. Maladjustment or a faulty operating system can produce a high uncontrolled emissions percentage for NO_x and CO.

After analysis of the results and the data uncertainties, no large deviations in the results have been observed (2 %). Therefore, the results for both methods may be considered acceptable because the actual uncontrolled deviations appear in the changes in emission factors that occur for a given engine with age. These deviations are often difficult to quantify and depend on individual shipboard service and maintenance routines. Emission factors for CO and NO_x are not constant and depend on engine condition (Durán et al., 2012). For example, when an engine operates under normal in-service conditions, the emissions are within limits. However, with a small fault in injection timing,

AMTD
5, 5953–5991, 2012

the NO_x emission exceeds the limits (30 % higher value in some cases). A fault in the maintenance of the injection nozzles increases the CO emission (15 % higher value in some cases).

5 Conclusions

After analysis, the results for both methods may be considered acceptable but the actual uncontrolled deviations appear in the changes in emission factors that occur for a given engine because the emission factors for CO and NO_x depend on engine condition.

The results of this study and the possible emission reductions that could be obtained if engines were correctly adjusted indicate that emissions monitoring should be continuous and comprehensive for each vessel and the monitoring results should be recorded and analyzed at random by the competent maritime authorities.

Appendix A

The basic equation used to estimate emissions for each engine in each mode is as follows:

$$\text{Emissions}_{(NO_x, CO, HC, CO_2, SO_2)} = \Sigma(P \times \text{LF} \times \text{EF} \times T_{\text{Mode}}) \quad \text{(A1)}$$

where:

P = maximum power output of main or auxiliary engine in kW

LF = Main (Eq. A2) or auxiliary (Tables 5 and 6) engine system load factor as a fraction of maximum rated power output

EF = emission factor (pollutant specific) in grams per kWh engine output for main and auxiliary engines

AMTD
5, 5953–5991, 2012

$T =$ time in mode (here, cruise mode) (h)

Main-engine load factors (LF) were calculated directly from the propeller curve based on the cube of actual speed divided by maximum speed (at 100 % maximum continuous rating, MCR). In addition, cruise-mode activity is based on cruise distance and speed inputs.
Hrs: Cruise Distance (nautical miles)/ Cruising Speed (knots)
Main-engine load factors (LF)

$$LF_{eng} = \left(\frac{AS}{MS}\right)^3 \quad (A2)$$

AS, actual speed.

MS, maximum speed from Lloyd's data.

Ninety-five percent of the calls in the input data were directly matched with Lloyd's data. The remaining 5 % were estimated based on the most reliable source of technical data directly linked to individual vessels, as shown in Table 8.

SO_2 *emission factors* were based upon a fuel sulfur to SO_2 conversion formula which was supplied by ENVIRON.

Calculation of SO_2 emission factors, g kWh^{-1}

$$SO_2EF = BSFC \times 64/32 \times 0.97753 \times \text{Fuel Sulfur Fraction} \quad (A3)$$

CO_2 emission factors were calculated from the BSFC assuming a fuel carbon content of 86.7 % by weight 14 and a ratio of molecular weights of CO_2 and C at 3.667.

Calculation of CO_2 emission factors, g kWh^{-1}

$$CO_2EF = BSFC \times 3.667 \times 0.867 \quad (A4)$$

AMTD
5, 5953–5991, 2012

Fuel consumption was calculated from CO_2 emissions based on a 1 : 3.183 ratio.

Approximately 3183 t of CO_2 emissions are assumed produced from one metric ton of fuel.

Calculation of PM_{10} emission factors based on fuel sulfur levels

$$\mathrm{PMEF} = \mathrm{PMNom} + [(\mathrm{SAct} - \mathrm{SNom}) \times \mathrm{BSFC} \times \mathrm{FSC} \times \mathrm{MWR} \times 0.0001] \qquad \text{(A5)}$$

where:

PMEF = PM emission factor adjusted for fuel sulfur.

PMNom = PM emission rate at nominal fuel sulfur level = 0.23 g/kW-hr for distillate fuel, 1.35 g/kW-hr for residual fuel.

SAct = Actual fuel sulfur level (weight percent).

SNom = nominal fuel sulfur level (weight percent) = 0.24 for distillate fuel, 2.46 for residual fuel.

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AMTD

5, 5953–5991, 2012

Emission-factor uncertainties in maritime transport

J. Moreno-Gutiérrez et al.

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AMTD
5, 5953–5991, 2012

Table 1. Comparative results between both methods (t).

Ship type	Engine power-based emission factors			Fuel-based emission factors		
	M.E.	A.E.	Total	M.E.	A.E.	Total
Tankers						
NO_x	3600	159	3759	3300	133.38	3433.38
CO_2	123 560	7580	131 140	121 516	7598	129 114
SO_2	2048	125.8	2173.8	2096	128.6	2224.6
PM_{10}	278.72	16	294.72	260	16	276
CO	278.72	12.4	291.12	287.3	17.7	305
Containers						
NO_x	6320.78	182.85	6503.63	5788	153.6	5941.6
CO_2	216 729.55	8729	225 458.55	213 143	8749	221 892
SO_2	3593.41	134.38	3727.79	3677.2	148.1	3825.3
PM_{10}	489	18.28	507.28	456.2	18.37	474.57
CO	489	14.36	503.36	503.9	20.29	524.19
Reefers						
NO_x	186	20	206	170.7	16.7	187.4
CO_2	6390	950.7	7340	6285	952	7237
SO_2	106	15.8	121.8	108.4	16	124.4
PM_{10}	14.4	2	16.2	13.4	2	15.4
CO	14.4	1.5	15.9	14.8	2.2	17
Ferries						
NO_x	474.6	111.4	586	398.7	93.5	492.2
CO_2	20 230	4745	24 975	22 939.3	5327.6	28 266.9
SO_2	376	88	464	384	90	474
PM_{10}	47	11.6	58.6	47.7	11.2	58.9
CO	37	9	46	52.6	12.4	65
Passengers						
NO_x	15 631	4409	20 040	13 635	3198	16 833
CO_2	746 228	181 474	956 702	747 947	210 960	958 907
SO_2	12 382	3492	15 874	12 661	3571	16 232
PM_{10}	1563	441	2004	1571	443	2014
CO	1228.5	346.5	1575	1734.7	489.3	2224
Ro-Ro						
NO_x	729	63	792	612	53.3	665.3
CO_2	34 787	3025	37 812	34 867	3032	37 899
SO_2	577	50.4	627.4	590	51.5	641.5
PM_{10}	73	6.2	79.2	73.2	6.4	79.6
CO	57.2	5	62.2	81	6.9	87.9
Rest						
NO_x	111	8	119	93	7	100
CO_2	5286	397.5	5683.5	5303.8	399.2	5703
SO_2	88	6.3	94.3	89.7	6.83	96.53
PM_{10}	11	1	12	11.2	1.8	12
CO	8.7	0.65	9.35	12.3	0.92	13.22

AMTD
5, 5953–5991, 2012

Table 2. Total results both methods (t).

Totals	NO_x	SO_2	CO	CO_2	PM_{10}
Method 1	32 005.63	23 083.09	2502.93	1 389 111.05	2972
Method 2	27 652.88	23 618.33	3236.31	1 389 198.9	2930.47

AMTD
5, 5953–5991, 2012

Table 3. Auxiliary to propulsion ratio. All the auxiliary engines are medium speed. REST ship types were not provided in the ARB methodology, so values from the Starcrest Vessel Boarding Program were used. Starcrest Consulting Group, Port-Wide Baseline Air Emissions Inventory, prepared for the Port of Los Angeles, 2004.

Ship type	Average propulsion engines (kW)	Numbers	Power each (kW)	Total auxiliary power (kW)	Auxiliary/ propulsion ratio
Auto carrier	10 700	2.9	983	2850	0.266
Bulk carrier	8000	2.9	612	1776	0.222
General cargo	9300	2.9	612	1776	0.191
Tankers	9400	2.7	735	1985	0.211
Containers	30 900	3.6	1889	6800	0.220
Reefers	9600	4.0	975	3900	0.406
Passengers	39 600	4.7	2340	11 000	0.278
Ro-ro	11 000	2.9	983	2850	0.259
Rest	6250	2.9	580	1680	0.269

AMTD
5, 5953–5991, 2012

Table 4. Auxiliary engine load factor assumptions.

Ship type	Cruise	RSZ	Maneuvering	Hotel
Auto carrier	0.13	0.30	0.67	0.24
Bulk carrier	0.17	0.27	0.45	0.22
General cargo	0.17	0.27	0.45	0.22
Tankers	0.13	0.27	0.45	0.67
Containers	0.13	0.25	0.50	0.17
Reefers	0.20	0.34	0.67	0.34
Passengers	0.80	0.80	0.80	0.64
Ro-ro	0.15	0.30	0.45	0.30
Rest	0.17	0.27	0.45	0.22

AMTD
5, 5953–5991, 2012

Table 5. Emission factors for main engines using RM, $g\,kWh^{-1}$.

Engine	NO_x	CO	CO_2	PM_{10}	SO_2
SSD	18.1	1.40	620.62	1.4	10.29
MSD	14.0	1.10	668.36	1.4	11.09

AMTD
5, 5953–5991, 2012

Table 6. Auxiliary engine emission factors.

Engine fuel	NO_x	CO	CO_2	PM_{10}	SO_2
RM	14.70	1.10	668.36	1.4	11.09
MDO	13.9	1.10	668.36	0.6	6.16

AMTD
5, 5953–5991, 2012

Table 7. Fuel-based exhaust gas emission factors used in the 2007 inventory.

Emission		Emission factor (kg emitted/t of fuel)	Guideline reference
CO		7.4	CORINAIR
CO_2	Residual fuel oil	3130	IPPC, 2006
	Marine diesel oil	3190	IPPC, 2006
SO_2	Residual fuel oil (2.7 % S)	54	CORINAIR
	Marine diesel oil (0.5 % S)	10	CORINAIR
NO_x	Slow-speed diesel engines	85	
	Medium-speed diesel engines	56	
PM_{10}	Residual fuel oil	6.7	CORINAIR
	Marine diesel oil	1.1	CORINAIR

NO_x Emission factors: non-regulated/subject to IMO NO_x regulation (2007 average emission factor).

AMTD
5, 5953–5991, 2012

Emission-factor uncertainties in maritime transport

J. Moreno-Gutiérrez et al.

Table 8. Speed-power relations in the model. Kristensen, H. O.: Unpublished data material provided by Senior researcher, Dep. of Mechanical Engineering, Section of Coastal, Maritime and Structural Engineering, DTU, 2009.

Ship category	AS as a function of Peng
Container ships	AS = 3.7 × Ln(Peng) – 14.8
Tankers	AS = 1.12 × Ln(Peng) + 4.6
Bulk carriers	AS = 1.31 × Ln(Peng) + 2.8
Ro-ro Cargo ships	AS = 3.82 × Ln(Peng) – 15.9
Ro-ro Passenger ships	AS = 0.00037 × Peng + 14.5

AMTD
5, 5953–5991, 2012

Table 9. Comparative analysis from the perspective of other countries.

Country (year 2007)	NO_x (kt)	SO_x (kt)	CO_2 (kt)	PM_{10} (kt)
Puerto Rico e Islas Vírgenes (EPA-420-R-10-013)	36.95	29.56	1798	3.79
Demark (NERI)	78.11	38.21	3482	6.46
Norway (Dalsøren et al.)	15.85	9.08	653	0.87
UK (ENTEC)	929	397	40 401	35.6
Strait of Gibraltar	32.005	23.0083	1389.111	2.972

AMTD
5, 5953–5991, 2012

Table 10. Total average fuel consumption. Average BSFC 195 $g\,kWh^{-1}$ (2 strokes) and 210 $g\,kWh^{-1}$ (4 strokes).

Ship Type	M.E. Power (MW)	A.E. Power (MW)	Fuel consumption (t) M.E.	A.E.	Total
Tankers	62 216	3544.4	38 822	2381.8	41 203.8
Containers	176 371	(6596.3)	68 096.8	(2742.74)	(70 839.54)
Ferries	13 070	2906	7191	1599	8790
Passengers	893 885	198 800	245 908	54 690	300 598
Ro-ro	19 515	1516.3	11 024	856.6	11 880.6
Reefers	4419	610	2007.8	298.4	2306.2
Rest	3171.5	230	1667	120.75	1787.75
Total	1 172 647.5	214 203	374 716.6	62 689.29	437 405.84

AMTD

5, 5953–5991, 2012

AMTD
5, 5953–5991, 2012

Emission-factor uncertainties in maritime transport

J. Moreno-Gutiérrez et al.

Table 11. Total emissions based in the first method (t).

Ship type	NO_x	SO_2	CO	CO_2	PM_{10}
Tankers	3759	2173.8	291.12	131 140	294.72
Containers	6503.63	3727.79	503.36	225 458.55	507.28
Reefers	206	121.8	15.9	7340	16.2
Ferries	586	464	46	24 975	58.6
Passengers	20 040	15 874	1575	956 702	2004
Ro-ro	792	627.4	62.2	37 812	79.2
Rest	119	94.3	9.35	5683.5	12
Total	32 005.63	23 083.09	2502.93	1 389 111.05	2972

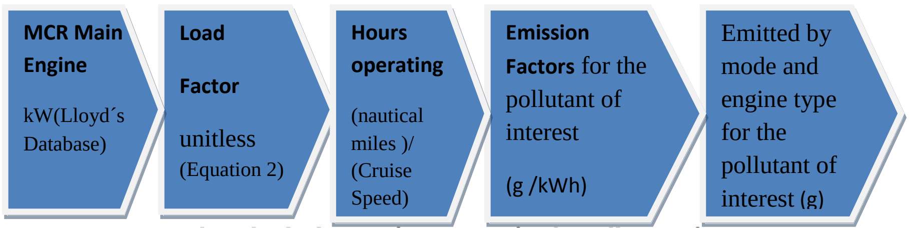

Fig. 1. Activity-based calculation of emissions for the pollutant of interest.

AMTD
5, 5953–5991, 2012

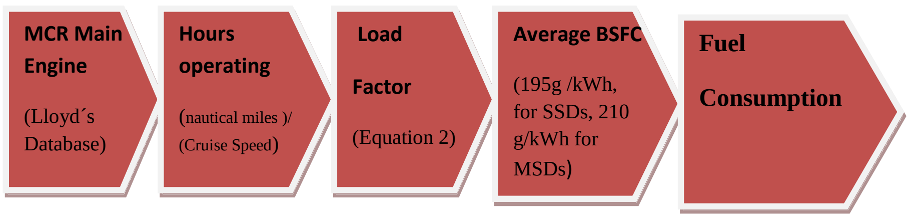

Fig. 2. Activity-based calculation of fuel consumption.

AMTD
5, 5953–5991, 2012

Emission-factor uncertainties in maritime transport

J. Moreno-Gutiérrez et al.

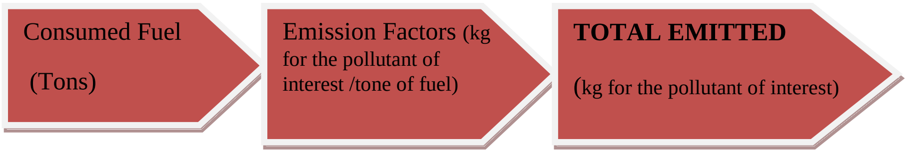

Fig. 3. Activity-based calculation of total emissions.