Port of London Emissions Inventory 2016: Methodology Report

Report to Port of London Authority and Transport for London

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Glossary

AIS	Automatic Identification System
CEF	Correction factors over basic engine emission factors
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CRT	Canal and River Trust
EA	Environment Agency
GIS	Geographic Information System
GLA	Greater London Authority
IMO	International Maritime Organisation
LAEI	London Atmospheric Emissions Inventory
LEGGI	London Energy and Greenhouse Gas Inventory
LEZ	Low Emission Zone
LLI	Lloyds List Intelligence
MCR	Fraction of maximum power output
MMSI	Maritime Mobile Service Identification
NECA	NO_X Emission Control Area
NMVOC	Non-methane volatile organic compounds
N_2O	Nitrous oxide
NO_X	Oxides of nitrogen
NT	National Trust
PLA	Port of London Authority
PM	Particulate matter
PM_{10}	Particulate matter with an aerodynamic size of less than 10 micrometres
$PM_{2.5}$	Particulate matter with an aerodynamic size of less than 2.5 micrometres
RoRo	Roll on, Roll off
TfL	Transport for London
SECA	SO_X Emission Control Area
SFOC	Specific fuel oil consumption
SO_2	Sulphur dioxide
SO_X	Oxides of sulphur
ULEZ	Ultra-Low Emission Zone
VOCs	Volatile organic compound

1 Introduction

The Port of London Authority (PLA) is developing a port-wide air quality strategy and is undertaking data collection activities to support this work. The Port Wide Emissions Inventory exercise was commissioned as part of this programme of work by the PLA, in partnership with Transport for London (TfL), from Aether and TNO, and is the first port wide inventory developed for London. It will also be used to support an update to the London Atmospheric Emissions Inventory (LAEI).

An emissions inventory is an account of pollution releases to the environment from a set of sources. This is used to track changes in emissions over time and to prioritise sources of pollution for potential reductions. This inventory for the Port of London Authority and Transport for London is an inventory of air pollution emissions from the ships that visit and use the whole of the Port of London area.

The GLA and TfL maintain two emissions inventories for London; the LAEI and the London Energy and Greenhouse Gas Inventory (LEGGI). The Mayor supports the continued improvement to the LAEI and LEGGI to ensure that boroughs and other organisations have access to accurate emissions information to help develop effective policies. The inventories are critical to the development, implementation and monitoring of the London Environment Strategy (currently in draft form[1]) and schemes such as London's Low Emission Zone (LEZ) and the Ultra-Low Emission Zone (ULEZ). The current LAEI[2] includes emissions data for the 'base year' 2013, back calculations for 2008, 2010 and projections for years 2020, 2025 and 2030. The current LEGGI is 2013 with an interim update for 2014. The emissions estimates produced through this study will feed into future updates of the LAEI and LEGGI. However, the LAEI does not cover the whole of the area considered in this study and so results have been calculated for the LAEI area and the remainder of the PLA jurisdiction.

The basic process for calculating any emissions inventory is to combine data inputs by multiplying Activity data with Emission Factors for specific sources to calculate emissions. These separate emissions estimates are then aggregated into categories for reporting. Activity data can be sourced from a wide range of different types of datasets, for example could be the amount of fuel consumed by a particular fleet of ships, or the average distance travelled in a year by a type of ship. Emission factors are derived from emissions modelling or emissions measurements and are usually reported in terms of the amount of pollutant emitted per quantity of fuel consumed or per distance travelled. The level of detail chosen for the definition of a source depends on the amount of detail available in the activity data and emission factors.

In many cases in the compilation of an emission inventory there are additional factors that must be taken into account when calculating emissions. Correction factors are therefore applied to the basic function of activity data multiplied by emission factors. For example: fuel quality varies over time and also by location, the size and number of engines in a ship varies within a group of ships. Gaps in data often need to be filled using expert judgement.

[1] https://www.london.gov.uk/sites/default/files/london_environment_strategy-_draft_for_public_consultation.pdf
[2] http://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory-2013

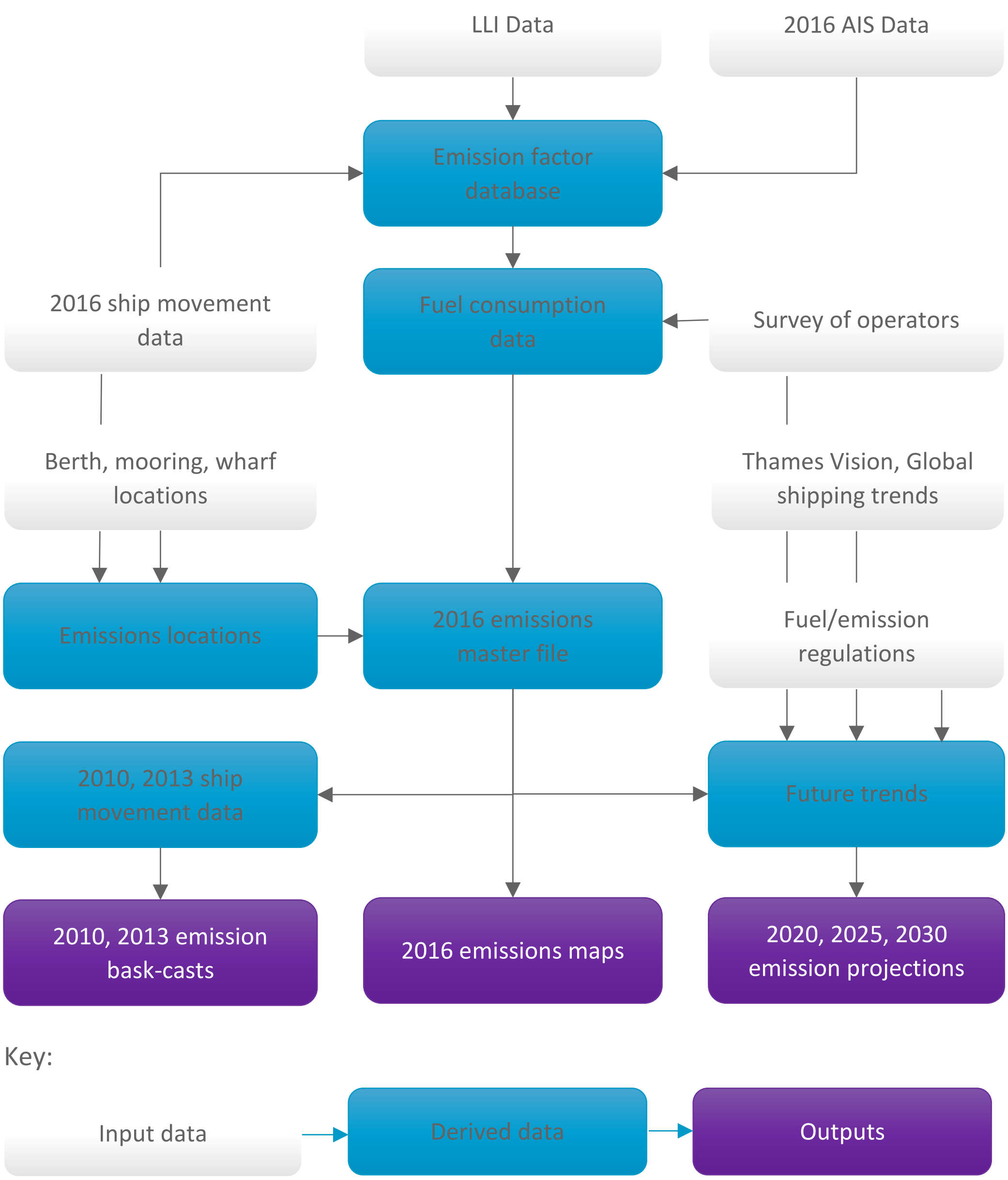
This study provides a higher level of detail than previous emissions estimates for shipping in the Thames, in addition to covering a larger area. The 2013 update of the LAEI used passenger ferry schedules and information on ships at berth, to produce data on ship movements. Using information on individual ships available from Lloyds List Intelligence (LLI), these were used to produce straight line shipping tracks and time at berth for cargo vessels. Emissions factors for nine cargo vessel types and one for passenger ferries were then used to produce the inventory[3].

The methodology for this study, summarised in Figure 1, used detailed information on ships and their movements available through the Automatic Identification System (AIS)[4] data on individual ship movements, alongside the LLI database. Using AIS, individual ship tracks can be plotted and emissions calculated for each using detailed emissions factors for a wide variety of ship types, corrected to take account of engine use and power required for each journey. The totals have been aggregated for categories of ship type. AIS also provides geographical information which allows emissions to be assigned to specific locations and, again, aggregated into the grid cells used in the LAEI. The result is a comprehensive and detailed shipping emission inventory which can be used flexibly to assess the impact of policies and measures.

This report sets out the detailed methodology used to compile the Port of London Emissions Inventory. It accompanies a separate report which presents the emissions inventory data. Emission estimates relating to the LAEI area, including the network of navigable waterways and canals other than the Thames (the blue-ribbon network), have been provided to TfL for inclusion in future updates to the LAEI.

[3] The full methodology is described within the supporting documentation for the LAEI: https://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory-2013
[4] Automatic Identification System (AIS) is an automatic tracking system used on ships and fitted to most commercial vessels. AIS transponders automatically broadcast information, such as ship identification data, position, speed, and navigational status, at regular intervals via a VHF transmitter built into the transponder to (typically) shore based receivers.

Figure 1: Outline methodology for producing the Port Wide Emissions Inventory



2 Scope

The scope of this port wide inventory comprises the Thames, its tributaries and connected waterways, between Teddington and Southend. For administrative purposes, i.e. to ensure data is compatible with the LAEI, the area is split into two main geographical sections and one small additional element considered only for the LAEI. The first section is the area currently covered by the LAEI[5], which approximately equates to the river Thames between the two M25 river crossings. Previous studies have estimated shipping emissions from this part of the Thames, although none have used the detailed methodology described in this report. Shipping emissions within this area will be used as part of a forthcoming update to the LAEI, managed by Transport for London.

The second section is the rest of PLA jurisdiction covering the main port activities for which PLA are responsible, including Tilbury Docks and the London Gateway facility. This area extends east from the M25 orbital motorway crossing at Dartford up to a line extending south from Crow Stone (near Southend) to Yantlet Creek. It excludes activity within the Medway Estuary. Due to the large volume of seagoing ships concentrated in this area, this eastern section accounts for the majority of emissions within the inventory. These areas are shown in **Error! Reference source not found.**.

The third section comprises several London waterways navigable for small private vessels, including the tidal and non-tidal River Thames, the Lee and Wey navigations, and various canals (**Error! Reference source not found.**). These form the remaining part of the "Blue Ribbon" network in London. Although the contribution of such vessels to total emissions from shipping in London is likely to be very small, in locations where activity of other vessels is limited small private vessels may be responsible for most, if not all, of the local emissions from shipping. Note that emissions produced by these boats whilst stationary (e.g. from solid fuel stoves and when engines are used to generate electricity) are outside the scope of the project although emissions at berth for all other river and seagoing vessels are included.

Emissions estimates (tonnes per annum) have been calculated for all relevant pollutants: NO_X, SO_2, PM, CO, CO_2, VOC, NMVOC, CH_4 and some heavy metals. Other pollutants which are covered by the LAEI and LEGGI, e.g. fluorinated gaseous compounds (HFCs, PFCs, SF_6), N_2O, and POPs have not been included as shipping is not a significant source.

These emissions estimates have been provided in disaggregate form in order to show:

- Emissions in each grid square for the study area (and thus totals for the three sections)
- Emissions by vessel type
- Emissions by activity, i.e. whether sailing/manoeuvring or at berth.

The base year for this inventory is 2016. Back calculations for 2010 and 2013 have been made based on aggregated activity data on ship movements within the Thames Estuary, including some AIS data for 2013, combined with adjustments to emission factors based on changes in fuel quality and other sectoral trends.

[5] http://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory-2013

Forward projections for 2020, 2025 and 2030 have been made based on:

- Estimated trends in activity, e.g. cargo tonnages or passenger trips, using data provided by PLA
- Current policy measures, such as changes in fuel quality required in the North Sea SO_x Emissions Control Area and NO_X Emissions Control Area
- Intelligence on global shipping trends, such as changes in seagoing vessel size and efficiency
- Data gathered from operators, such as expected technology changes, use of shore power, other abatement technologies, fleet sizes, etc.

Figure 2: PLA Jurisdiction and LAEI areas for which shipping emissions have been calculated

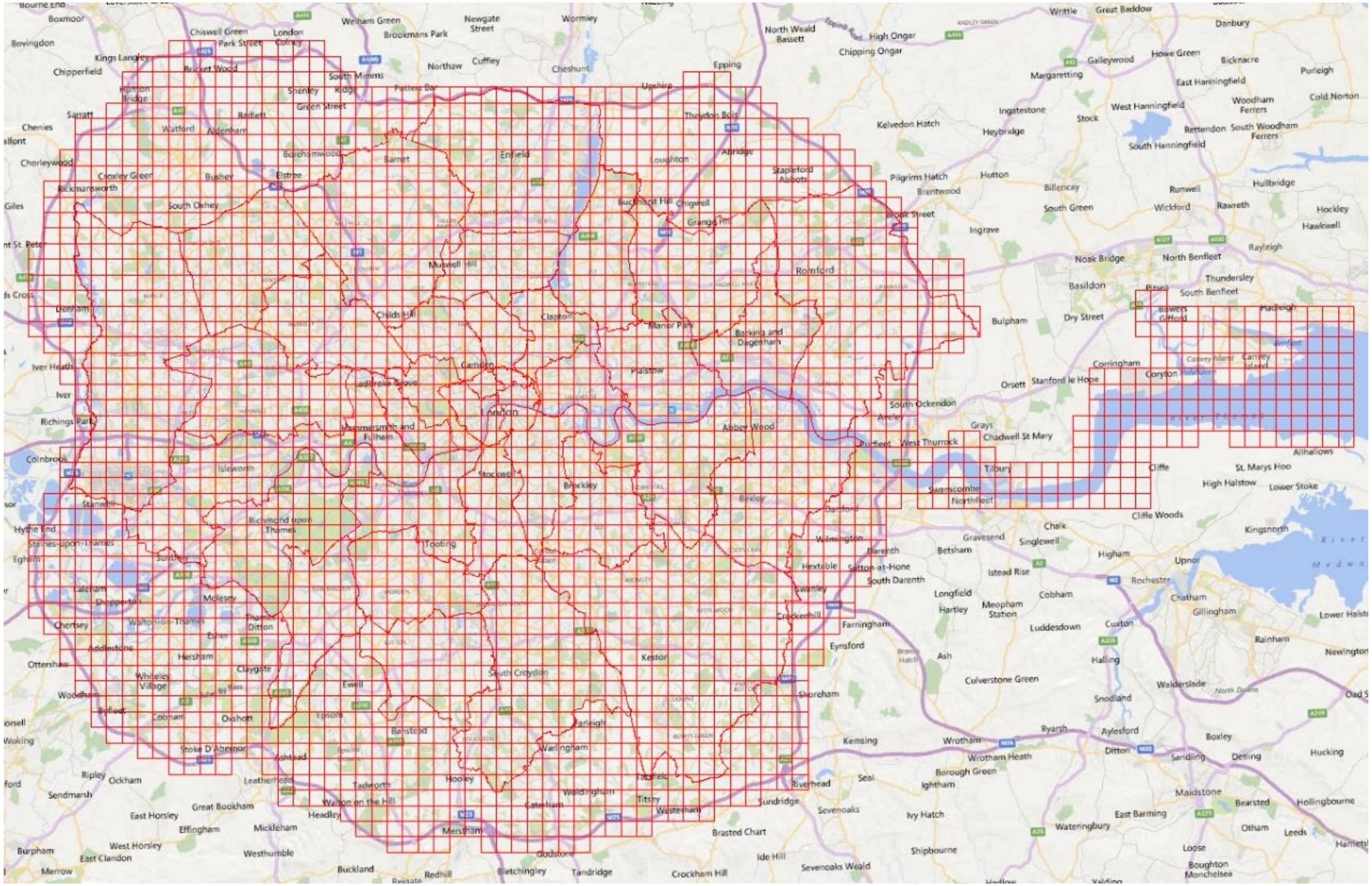
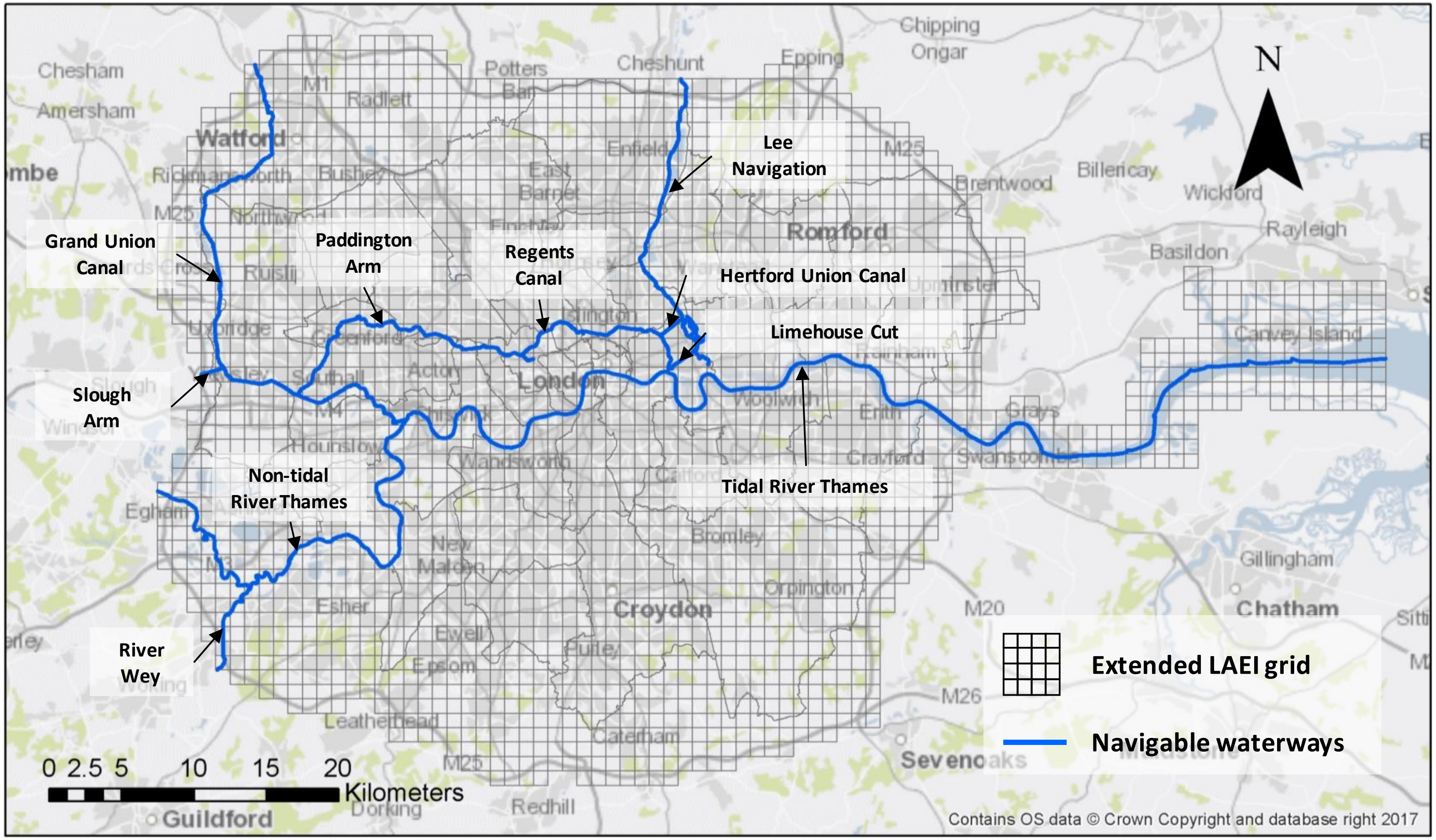


Figure 3: Navigable waterways included in the calculation of emissions from small private vessels



Source: Canal and Rivers Trust Open Data[6]; OS Open Rivers[7]

[6] http://data-canalrivertrust.opendata.arcgis.com/datasets/dab91c04078b4deb890c4381f4a7141a_0
[7] https://www.ordnancesurvey.co.uk/business-and-government/products/os-open-rivers.html

3 Activity Data Sources

Several key datasets were obtained in order to build the overall activity dataset for 2016, which, alongside the emission factors, form the basis for emissions calculation. The main data sources were:

- Automatic Information System (AIS) data on individual ship movements, supplied by PLA. Almost all commercial vessels operating on the Thames have AIS transponders fitted
- Ship berth arrival and departure data, supplied by PLA
- Lloyds List Intelligence (LLI) data on ships for which AIS messages were recorded
- Information gained through a survey of operators
- Projections of port cargo handling and passenger numbers, supplied by PLA[8]
- Locations of berths, wharfs and moorings in GIS format, supplied by PLA
- Data on recreational craft movements, supplied by PLA (including data from the Thames Barrier), Canal and River Trust (CRT) and the Environment Agency.

At its most basic level, data was required on the number and location of vessels operating within the study area. For the great majority of larger vessels, and a significant number of small ones, this was provided by the network of Automatic Identification System (AIS) monitors, shore based receivers which pick up signals from transponders fitted to vessels.

AIS messages provide a significant amount of information about individual vessels, particularly when allied with shipping intelligence data, which in this study was obtained through the LLI database. Each AIS message provides the location, speed and direction of the ship at a given point in time, as well as its name and standard identification numbers. These can be matched to the Lloyds database to provide details on the ship type, dimensions, engine type, number and power, fuel use, year of build, etc. All of these parameters have a significant impact on the emissions produced by that ship.

In more detail:

- Ship dimensions: the larger a ship is, the more power is needed to move it at a given speed and thus the greater the emissions will tend to be. The relationship between the different dimensions, e.g. length, width, draught, is also an important factor
- Engine type: each engine type – reciprocating diesel, gas turbine, steam turbine – will have different emission characteristics and different power profiles
- Engine number: some ships are fitted with multiple engines and, depending on how these are used, this will also affect the emissions profile
- Auxiliary power: larger ships, typically seagoing ships, will have smaller auxiliary power units fitted to provide power, e.g. for onboard services and system, when the ship is at berth
- Fuel use: different fuel grades and types are available, e.g. Marine Diesel, Heavy Fuel Oil, and these can have a profound impact on the type and composition of the ship's emissions. Legislation is in place to control the quality of fuel used in UK inland waterways and in the North Sea

[8] http://www.pla.co.uk/assets/forecasts-consultationdocumentv11december-1.pdf

- Ship (and engine) age: generally, the emissions from an engine increase with age as control systems wear and power output drops. The age of an engine will also affect the level of emission control fitted to it when new.

Data from AIS and LLI were supplemented by a survey sent out to vessel operators using the Port. This provided important information both on vessels not fitted with AIS transponders and on the fuel consumption for those that are; fuel consumption can be calculated but reported figures are an important correlating factor.

The location of berths, wharfs and moorings was supplied by PLA. This provides information both to validate the split between “at berth” and “sailing” calculated from the AIS data and to provide indications of ship movements for non-AIS movements.

For private vessels using the Thames and the other navigable waterways in London, activity data is extremely patchy. There are some basic counts taken at a number of locks in the canal network and on the Thames and these were used to derive total activity data for the “blue ribbon” network.

In addition to estimating emissions for 2016, the project required both back-cast emissions for 2010 and 2013 and emission projections for the years 2020, 2025 and 2030. The process for undertaking this is described in Section 6, below.

The key data sources are described in more detail below.

3.1 Activity Data and Handling

3.1.1 AIS data

Automatic Identification System (AIS) messages are broadcasted from ships and contain information that can be used in the prediction of the ship’s emission. The information in the AIS messages is time and location dependent. Therefore, when AIS messages are collected over a certain time span, e.g. a whole year, a spatial map of shipping emission can be made. Almost all commercial vessels operating on the Thames carry AIS transponders.

Before the actual emission calculation can be carried out, a series of processing steps and quality checks are required:

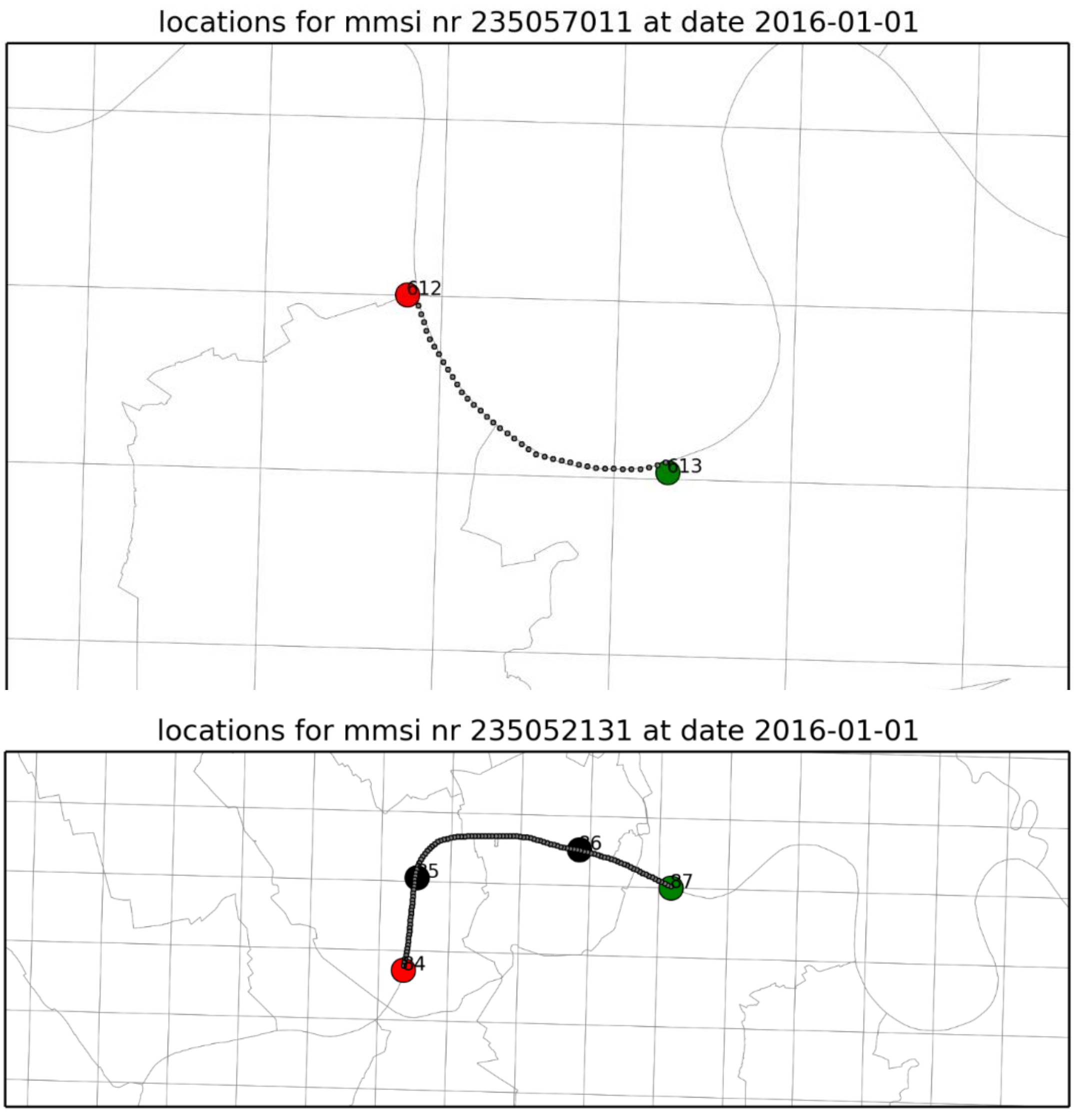
1. Collecting, decoding, selecting and clustering of the AIS messages. AIS messages were collected in encoded files by the PLA. Each file contains messages for a single day from all ships within a domain covered by the study area (Figure 2). A decoding script was applied to these files, which resulted in a series of 365 human readable files for the year 2016. From this collection, 359 files were used in the further process, as 6 files appeared to be corrupt and could not be decoded. The resulting files contained the variables relevant for the emission estimate. These variables are location, speed, time and MMSI (Maritime Mobile Service Identification) number.

   Duplicate records were filtered from the collection of data points. To reduce the amount of data to be processed, messages from ships with a speed less the 0.5 knots over a continuous period of over 15 minutes were assumed to be at berth (i.e. not under main engine power) and were clustered.

2. Filling gaps in the data. When a track from an individual ship is distilled from the data collection, discontinuities appear for roughly 10% of the length of the track. This means that data is missing for a particular section of the track. If the gap does not extend over more than a kilometer, i.e. the size of a LAEI grid cell, it will have no consequence and can be ignored. Where gaps extend over more than a kilometer, they will lead to underestimation of emission in the gap and over estimation at the last known location of the ship. Therefore, the gaps were filled by the procedure illustrated by Figure 4. In this procedure, it is assumed that the ship continues its track with its last known speed over the centerline of the river. The resulting emission is divided equally over the gap. This procedure was applied on the complete collection of data.

   Exception handling in this procedure was applied where the gap extends over multiple grid cells and the beginning and end of a gap (as shown in **Error! Reference source not found.**) could not be properly determined. This was the case where (a) the gaps start or end occurred in a corrupted file; or (b) the start or end of the gap is outside the domain, i.e. the ship just entered or just left the domain.

Figure 4: Examples of the gap filling procedure



Note: The gap starts at the red dot and ends at the green dot. The gap is filled with the grey points along the centerline of the river. Top: example of a gap in the track of ship with MMSI 235057011; Bottom: example for MMSI 235052131. In this example, this gap extends over multiple grid cells.

3.1.2 Lloyds List Intelligence

In order to be able to produce time-based emission factors, specific information on ships registering AIS messages was required. A data purchase was made from LLI for all the ships which visited the Port of London in 2016 and 2013 for which AIS messages were received. Table 1 below, provides a list of the data headers requested and the type of information provided by LLI.

Table 1: Data items requested from Lloyds List Intelligence

Lloyds Data Item
LRIMOShipNo
MaritimeMobileServiceIdentityMMSINumber
ShipName
VESSEL_ID
VESSEL_TYPE
VESSEL_TYPE_DECODE
StatCode5
YearOfBuild
ShipStatus
ShipStatusEffectiveDate
GrossTonnage
NetTonnage
Deadweight
TEU
Powerkwmax
Powerkwservice
MainEngineDesigner
MainEngineBuilder
MainEngineModel
ENGINE_DESIGNATION
ENGINE_TYPE
RPM
NumberOfPropulsionUnits
NumberofThrusters
FuelType1First
FuelType1Capacity
FuelType2Second
FuelType2Capacity
Speedservice

Lloyds Data Item
ClassNarrative
CLASS
CLASS_RATING
CLASS_VSL_ID
LastUpdateDate
ConsumptionSpeed1
ConsumptionValue1
MainEngineType
Displacement
PropellerType

The data received from Lloyds List Intelligence were supplemented with data from the fuel survey combined with data from owners and shipbuilders websites concerning important vessels. This covered those vessels with a significant representation within the received AIS-data, which had no IMO-number and so for which no data were available from LLI. Table 2 shows how this information was pre-processed in order to calculate time-based emission factors that ultimately were used in emission calculations.

Table 2: Example of pre-processed data items on behalf of time based emission factors

Data item applied in calculation	Data example	Inferred from	Applied for
Engine_yob	1991	YearOfBuild	to select engine emission factors from Tables 7 to 15
Enginetype_code	MS	RPM	to select engine emission factors from Tables 7 to 15
Engine_yobclass	5	YearOfBuild	to select engine emission factors from Tables 7 to 15
Fuel_ME_code	HFO	RPM and Powerkwmax	to select engine emission factors from Tables 7 to 15
Fuel_AE_code	MDO	RPM and Powerkwmax	to select engine emission factors from Tables 7 to 15
ME_kW_used	2299	Powerkwmax	to calculate time based emission factors
AE_kW_used	340	AUX_IMO_ID and Powerkwmax	to calculate time based emission factors
AUX_IMO_ID	63	VESSELTYPE and Deadweight	to calculate auxiliary engine power
RPM_ME_used	1000	RPM	to calculate NO_x engine emission factor
No_of_main_engines	1	NumberOfPropulsionUnits	to calculate time based emission factors
Speed_used	12.5	Speedservice	to calculate time based emission factors
Size	3	GrossTonnage	to calculate size averaged power if not available

3.1.3 Data Survey

To supplement the data collected through AIS, LLI and other PLA records, a survey was sent to vessel operators. The purpose of the survey was to:

- Gather information on commercial or regular use vessels not fitted with AIS transponders
- Gather information on fuel consumption for AIS equipped vessels (fuel consumption can be inferred but directly reported data provides a very useful calibration)
- Gather intelligence on likely future changes in river traffic and operational practice to support emissions projections.

The survey form is shown in Appendix A. This was sent electronically to the operators as a spreadsheet file, allowing returns to be collated automatically. As these returns were sent on a confidential basis, they are not included in this report, although both the returns and the collated data files have been provided to PLA; 28 completed survey forms were returned. The data provided were very useful in calibrating the calculated emissions using reported fuel consumption data, in particular for passenger ferries where AIS capture was not as high as for other vessel types (see section 7, below).

3.1.4 Private canal and river vessels

In order to calculate emissions from small private vessel movement, activity data is needed in units of total distance travelled by all relevant boats, expressed as boat-km.

After contacting the relevant authorities managing waterways on the blue-ribbon network, including the PLA, Environment Agency and CRT, it became clear that no comprehensive source of movement data is available from which boat-km of small private vessels can be directly inferred, nor are proxies such as fuel usage available.

However, at some locations or during certain time periods the managing authorities do keep records of the number of lock operations occurring (i.e. number of times a lock is emptied or filled) or of the number of boats passing through locks or points on the waterway. For waterways managed by the CRT lockage data were obtained from the 2016 Annual Lockage Report[9]. For the River Wey navigation boat movement data for Thames lock for 2016 were obtained from the National Trust. For the non-tidal Thames boat movement data were obtained for each lock in the study area (during lock keeper's hours) for 2016 from the Environment Agency. For the tidal Thames, numbers of private craft passing through the Thames Barrier between 2010 and 2013 were provided by the PLA, but no other activity data were found. See

[9] https://canalrivertrust.org.uk/media/original/31240-annual-lockage-report-2016.pdf

Table 3 for details of the activity data used.

The numbers of boats passing point locations such as locks or barrages cannot be directly translated into boat-km, but a relationship was assumed between boats passing these points and boats travelling the length of the adjacent waterway sections, then a simple estimate of boat-km was produced by multiplying the number of boats by the length (in km) of each section.

Table 3: Lockage and boat movement data from monitoring points used to estimate boat-km for section of the navigable waterway network in London.

Observation Site	Waterway	Source	BNG Easting	BNG Northing	Observation type	2016 value (annual total)
Lock 90, Hanwell flight	Grand Union	CRT	513600	179300	Lockage	917
Lock 16, Stonebridge	Lee & Stort Navigation	CRT	535100	190400	Lockage	5994
Lock 14, Ponders End 1&2	Lee & Stort Navigation	CRT	536400	195500	Lockage	4534
Lock 10, Waltham Common	Lee & Stort Navigation	CRT	537000	201800	Lockage	2184
Lock 3, Roydon Lock	Lee & Stort Navigation	CRT	541000	210400	Lockage	2191
Lock 4, Stanstead Lock	Lee & Stort Navigation	CRT	538000	212100	Lockage	2176
Lock 6, Sheering Mill	Lee & Stort Navigation	CRT	548800	214400	Lockage	1298
Lock 12, Commercial Road	Regents	CRT	536300	181100	Lockage	1110
Lock 2, Hawley	Regents	CRT	528700	184100	Lockage	2989
Lock 1, Victoria Park Top	Hertford Union	CRT	536700	183900	Lockage	2609
Lock 81, Batchworth	Grand Union	CRT	506200	194000	Lockage	2097
Thames Lock	Grand Union	CRT	517800	177200	Boats	1439
Lock 20, Bow Locks	Lee & Stort Navigation	CRT	538300	182300	Boats	64
Limehouse Basin Lock	Limehouse Basin	CRT	536300	180800	Boats	1447
West India Dock Lock	London Docklands	CRT	538100	179900	Boats	466
Thames barrier (2010 – 2013 average)	Thames	PLA	541644	179510	Boats	8572
Teddington Lock	Thames	EA	516800	171488	Boats	9556
Molesey Lock	Thames	EA	515131	168634	Boats	12991
Sunbury Lock	Thames	EA	510945	168549	Boats	10684
Shepperton Lock	Thames	EA	507369	165907	Boats	13624

Observation Site	Waterway	Source	BNG Easting	BNG Northing	Observation type	2016 value (annual total)
Hook lock	Thames	EA	504353	169432	Boats	11426
Bell Weir Lock	Thames	EA	501733	172057	Boats	12580
Thames Lock	Wey navigation	NT	507251	165540	Boats	1953

3.1.5 Spatial data for private canal and river vessels

To produce a geographical distribution of emissions across the 'Blue ribbon' network a linear representation of all navigable waterways in the study was created as a simple vector map. This was constructed partly from the Ordnance Survey Open Rivers dataset, and partly from a dataset provided by CRT of London navigations. The resulting dataset was made up of many short subsections.

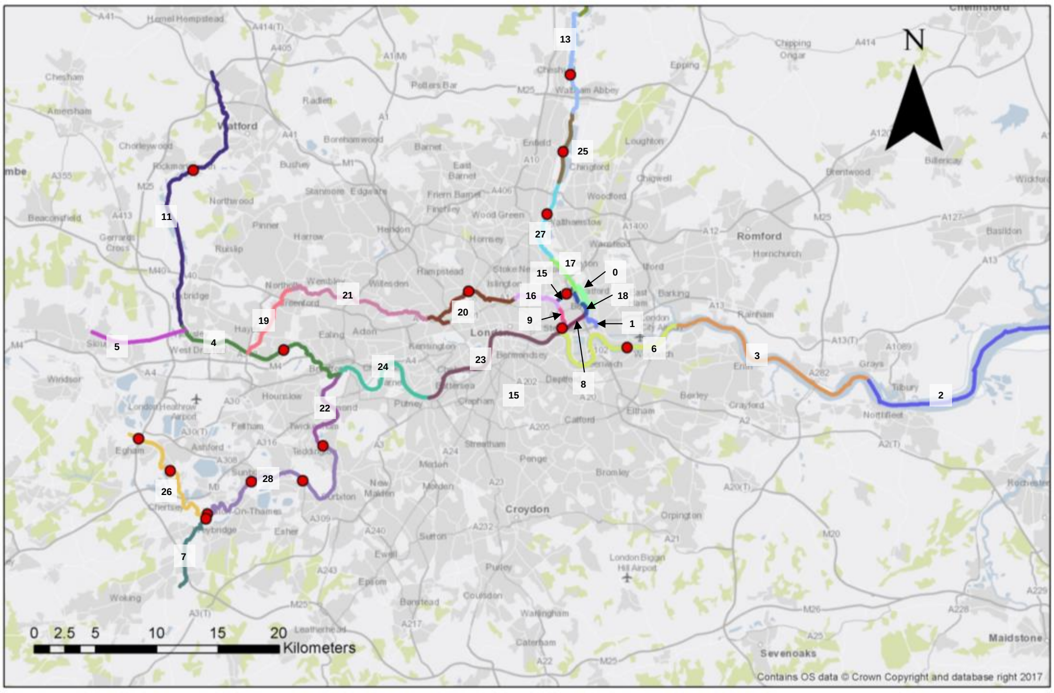
An estimated annual number of boat movements was then assigned to each subsection, based in general on the nearest lockage or boat movement observation point on the same waterway, resulting in 29 lengths of waterway where each subsection was assigned the same level of boat activity. The exceptions to the "nearest observation" rule were the following:

1. The assigned boat activity should change at major junctions between waterways
2. For the non-tidal Thames, observations have a high level of uncertainty as they are only collected on weekdays, during lock keeper's hours. As such, observations from several locks were averaged, and multiplied by 7/5 (to conservatively scale up estimates to include weekends) to give one figure for upstream of the River Wey, and one for downstream.
3. For the tidal Thames, the only observations available were from the Thames barrier (for 2010 – 2013). The average of these observations (8572 boats per year) was deemed to apply to the whole length of the Thames downstream of the barrier. Upstream of the barrier the tidal Thames was divided into 4 sections, at junctions with canals and at Putney in order to break up a very long section (23 and 24 in Figure 5). Boat activity was assumed to gradually decrease section by section between 9557 boats per year at observed at Teddington lock (manned permanently) and 8572 at the barrier.

See

for the locations of all observation data and the definition of all 29 sections of waterway.

Figure 5: Location of lockage or boat movement observation points in London (red points), and the division of London's navigable waterways into sections of equal boat activity (coloured lines)



Note: Each coloured line shows a section of equal boat activity. Numeric labels correspond to the "Waterway section ID" column in Table 4

Where observations were of lockage operations (on CRT waterways), a scaling factor of 1.5 was applied to convert this to boat movements, as between 1 and 4 boats may travel through a lock in the same operation. This scaling factor was based on expert judgement.

Finally, total boat-km was estimated for each section by multiplying the estimate of boats per year by the length of each section in km (Table 4).

Table 4: Number of boat movements, length and activity (boat-km) for each of the 29 sections of navigable waterway defined for small private vessels.

Waterway section ID	Estimated boats per year	Section length (km)	Estimated activity (Boat-km)
0	750	5.9	4431
1	225	2.5	565
2	8572	30.0	256817
3	8572	19.3	165358
4	1376	16.1	22090
5	1376	1.7	2304
6	8572	15.0	129006
7	1953	7.3	14215
8	1665	2.5	4163
9	1665	2.5	4193
11	3146	24.8	78082
13	3276	2.6	8528

Waterway section ID	Estimated boats per year	Section length (km)	Estimated activity (Boat-km)
15	3914	2.0	7957
16	3914	4.1	15961
17	3914	3.9	15130
18	39134	2.3	8977
19	4484	7.1	31733
20	4484	9.9	44566
21	4484	13.1	58629
22	9556	8.9	84763
23	8900	14.6	130382
24	9200	11.5	106140
25	6801	6.1	41323
26	15555	13.0	202642
27	8991	7.1	63678
28	15508	18.8	291362

Note: Waterway section IDs correspond to the numeric labels in Table 5.

4 Emission Factors

4.1 Overview

Previous attempts to estimate shipping emissions for the Thames have tended to use either surrogate statistics, e.g. fuel sales, or have used generic factors for ship types, i.e. they have started at an aggregated level. This study uses a more complex process for vessels carrying AIS transponders. Standard emissions factors are adjusted according to ship and journey characteristics to produce near unique factors for each individual AIS message. The outputs from these calculations are then aggregated according to vessel type. This allows, in theory, a far more detailed inventory to be produced, although it also places greater demands in terms of data needs.

The initial step is to split activity, as represented by AIS messages, into “sailing and manoeuvring” and “at berth”. Vessels with a speed of less than 0.5 knots over a continuous period of over 15 minutes were assumed to be at berth.

For sailing and manoeuvring, AIS data is used to calculate the speed of each ship and, from this, the amount of power required to move the ship at that speed. Calculations were based on key parameters obtained from AIS and LLI data sources. Both speed and power use are key variables in the emission calculation. A correction to the assumed engine load is made based on the number of main propulsion engines fitted to the ship. Multiple engines tend to result in more optimal (i.e. higher) load at low speeds compared to single engine vessels because one or more engines can be switched off at very low speeds.

As a result, an emission is calculated using an emission factor based on the power required to attain the actual speed, using a correction factor corresponding with the power rating on each engine for each ship as it moves through the Port of London. This is then aggregated by ship type to give emissions for that type for the specific year. Ship types are based on information obtained from LLI. Further aggregation to a more generalised set of ship types has been undertaken to give aggregated outputs.

For ships at berth, where auxiliary engines and boilers are used, emissions factors based on survey work undertaken within the Clean North Sea Shipping (CNSS) project, adopted by the Dutch national inventory, were used. These vary according to ship type and volume (gross tonnage), both of which have a bearing on the amount of work auxiliary engines are required to undertake. For example, for tankers, fuel usage and thus emissions at berth tend to be high relative to other ship types because they need to power cargo pumps and produce inert gas.

Data resulting from the survey of operators (Section 3.1.3) was used to validate the outputs and, where necessary, make further corrections.

4.2 Sailing and Manoeuvring

During sailing and manoeuvring, the main engine(s) are used to propel/manoeuvre the ship. Their emission factors per ship, in g per kWh, were determined according to Dutch inventory methodologies called Emission registration and Monitoring Shipping (EMS) protocols[10] [11]. An English language report[12] is available, which covers the emission calculations in accordance with the EMS protocols.

In the emission factor calculation for each ship, the nominal engine power and speed are used. For this study these parameters were taken from the LLI database of September 2015 as far as new valid data were available. In the case that only one single main engine is present, it is assumed that a vessel requires 85% of its maximum continuous rating power (MCR) to attain the design speed (its service speed). When multiple main engines are present some more assumptions have to be made in order to calculate the required power of the main engines. This is described below. The following formula is used to calculate the emission factor per second.

Formula 1:

$$EF' = EF * CEF * \frac{P * fMCR}{3600}$$

where:

EF' Actual emission factor expressed as kg per second

EF Basic engine emission factor expressed as kg per KWh (Table 7/Table 15)

CEF Correction factors of basic engine emission factors (

[10] J. Hulskotte (TMO-MEP), E. Bolt (RWS-AVV), D. Broekhuizen (RWS-AVV); EMS-protocol Emissies door verbrandingsmotoren van varende en manoeuvrerende zeeschepen op het Nederlands grondgebied; Versie 1, 22 november 2003

[11] J. Hulskotte (TMO-MEP), E. Bolt (RWS-AVV), D. Broekhuizen (RWS-AVV); EMS-protocol Verbrandingsemissies door stilliggende zeeschepen in havens; Versie 2, 22 november 2003

[12] H. Denier van der Gon, J. Hulskotte, Methodologies for estimating shipping emissions in the Netherlands; A documentation of currently used emission factors and related activity data; PBL report 500099012, ISSN: 1875-2322 (print) ISSN: 1875-2314 (on line), April 2010

Table 17/Table 19)

P Engine power [KiloWatts]

fMCR Actual fraction of the MCR

The emission for each valid AIS-message was calculated by multiplication of the EF' with the time period (between the actual and last AIS-message).

The correction factors of basic engine emission factors (CEF) reflect the phenomena that cause the emission factors to change when engines are active in sub-optimal power ranges.

Besides this change in emission factors, ships do not always sail at their designed speed. As such, the actual power use has to be corrected for the actual speed. The power requirements are approximately proportionate to the ship's speed to the power of three. For very low speeds this approximation would underestimate the required power, since manoeuvring in restricted waters increases the required power. Furthermore, engines are not capable of running below a certain load (minimal fuel consumption of 10% compared to full load). To account for this, the relationship between speed and power is adjusted slightly as shown in Formula 2:

Formula 2:

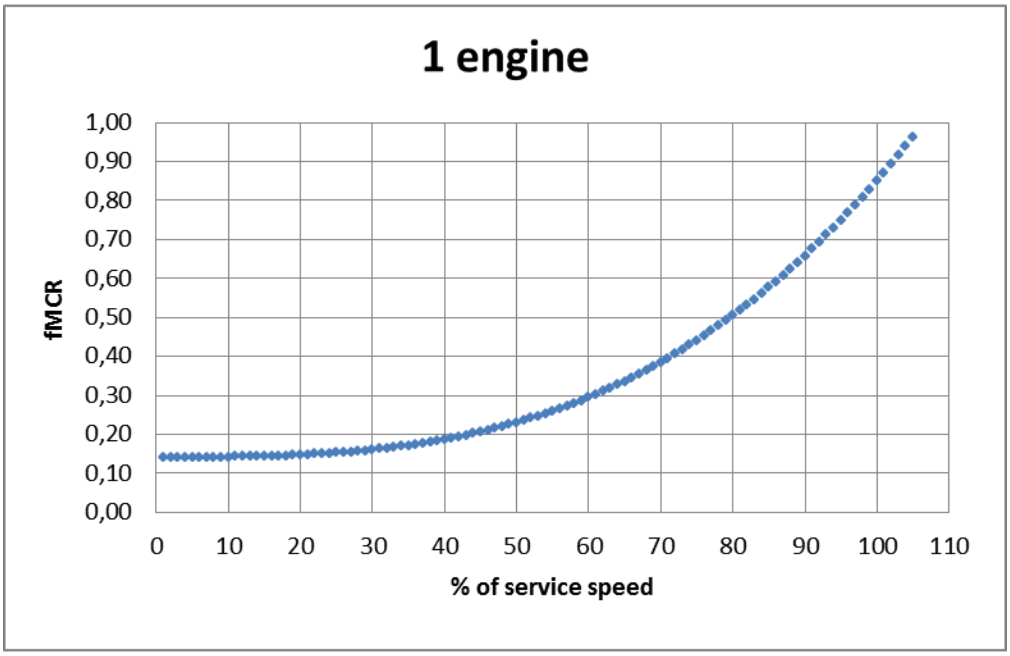
$$fMCR = CRS_{cor} * 0.85 = \frac{\left[\left(V_{actual} / V_{design}\right)^{3} + 0.1\right]}{1.1} * 0.85$$

where:

V Actual vessel speed [knots]

Note that the Correction Reduced Speed factor CRScor has to be capped at a maximum of 1.176 (a value of 1.2 has been used in calculations), since this is the value for which 100% engine power is reached. In **Error! Reference source not found.** the relationship is shown between the speed relative to the service speed and the power relative to the rated power of the ships single propulsion engine as implied in Formula 2.

Figure 6: The relationship between service speed and fraction of maximum power (fMCR) at ships with one single propulsion engine used in emission calculations



4.2.1 Correcting for Multiple Propulsion Engines

When a ship has multiple main propulsion engines, probably not all of these engines will be used in all situations. For instance, many specialised ships have specialised installations that are only used when these ships are performing their specialised tasks (dredgers, supply ships, icebreakers, tugs etc.). Other ships may have redundant engine capacity for safety and other reasons (passenger ships, roro-ships). It is difficult to account for the usage of multiple engines within emission calculations, since many differences will exist between individual ship designs. All kinds of possible situations which are not known from the AIS-data may have different influence on emissions from different ships types. Nevertheless, ignoring the existence of multiple engines is not realistic. The presence of multiple engines on some ship types (i.e. passenger and roro-ships) could lead to a significant underestimation of total emissions where only the power of the largest engine is taken into account.

Before going into an analysis of the usage of main engines when multiple engines are present, it is useful to analyse which number of engines occur so frequently as to have a significant influence on total emissions.

Table 5 shows that for ships with more than 1 engine, only ships with 2 and 4 engines contribute significantly to the total installed power of the whole seagoing fleet (17.1% in total). The same conclusion will probably hold with respect to the contribution to total emissions. Therefore, it is reasonable to concentrate the analysis of emission factors for ships with multiple engines on ships with 2 and 4 propulsion engines.

Table 5: World seagoing fleet with number of installed main engines and their total installed power and average installed power per ship [13]

[13] Data from IHS elaborated and presented in Brake M.C. ter, Hulskotte J.H.J., Sea shipping emissions 2015, Netherlands continental shelf, 12-mile zone and port areas, MARIN report 29555-1-MSCN-rev.2, 16 June 2017

Main Engine count	Ships count	Total power installed MW	Average power installed per ship MW	% of total power installed
1	109,489	534,901	4.9	80.9%
2	24,011	87,343	3.6	13.2%
3	926	4,459	4.8	0.7%
4	1,912	25,822	13.5	3.9%
5	89	1,551	17.4	0.23%
6	177	5,992	33.9	0.91%
7	4	139	34.8	0.02%
8	31	1,017	32.8	0.15%
9	6	261	43.5	0.04%
10	1	3.0	3.0	0.00%
12	2	15.6	7.8	0.00%
	136,648	**661,504**	**4.8**	**100.0%**

4.2.2 Calculating fuel consumption for multiple engines

As a data source for daily fuel usage of ships, the ship characteristic database-item FUEL_CONSUMPTION of the LLI database was analysed. Daily fuel consumption is given for only about 10,000 ships. By far the majority of these 10,000 are ships with a single main engine; fuel consumption serves as a very good proxy for engine emissions.

To estimate the daily fuel consumption of a ship (ton/day) a very simple formula was applied:

Formula 3:

$$FC = \frac{Active\ Engines\ \times MCRss\ \times Power\ \times SFOC \times 24}{1000}$$

Where:

FC = Daily fuel oil consumption (ton/day)

Active_Engines = number of active engines involved in normal propulsion (-)

MCR_{ss} = fraction of power to reach service speed (0.85 for single engine ships, for more engines see

Table 6)
Power = power of a single engine (MW)
SFOC = specific fuel oil consumption (kg/MWh)
24/1000 = 24 hours/day;1000 kg/ton

Note that the calculation of fuel consumptions is completely parallel to the calculation of emissions. Instead of selected SFOC from Table 7 to Table 10, approximate values of the SFOC are used. Because (in the LLI database) the service speed is assumed, the values of CEF (Correction factors over basic engine emission factors) in the calculation can be ignored because the values will be very close to 1.The SFOC (specific fuel oil consumption) applied is 0.175 (kg/kWh) for engines above 3 MW and 0.200 (kg/kWh) for engines equal to and below 3 MW. As a reference for these values, see Table 7 to Table 10.

As a reference for ships with multiple engines, the fuel consumption of ships with 1 main engine is shown. So far, a power setting of 85% MCR is assumed in modelling ship's emissions. It can be seen in **Error! Reference source not found.** that this assumption gives rather accurate results for the majority of ships (but not all ships) with one main engine. The 7918 ships of which data on fuel consumption was available had an average calculated fuel consumption of 24.8 ton/day by the main engine while the average specified fuel consumption was 26.1 ton/day. This implies that calculated fuel consumption (on average) on the service speed seems to be 5% lower than the specified fuel consumption. Given the number of possible uncertainties this does not seem to be a major difference.

For ships with two main engines, two active engines were assumed and 75% MCR (instead of the standard of 85%[14]) to reach the service speed. It can be seen in **Error! Reference source not found.** that these assumptions give accurate results for the majority of ships with two main engines. The 546 ships of which data on fuel consumption are available show an average calculated fuel consumption of 35.7 ton/day while the average specified fuel consumption is 35.6 ton/day.

For ships with four main engines four active engines were assumed and also 75% MCR (instead of the standard of 85%) to reach the service speed. As can be seen in much less data is available for four engine ships which causes more scatter in the data. The 29 ships of which data are available show an average calculated fuel consumption of 39.2 ton/day while the average specified fuel consumption is 32.8 ton/day.

Figure 7: Calculated daily fuel usage of one engine ships compared with specifications

[14] J.H.J.Hulskotte, E. Bolt, D. Broekhuizen; EMS-protocol Emissies door Verbrandingsmotoren van Zeeschepen op het Nederlands Continentaal Plat; versie 2, 22 November 2003

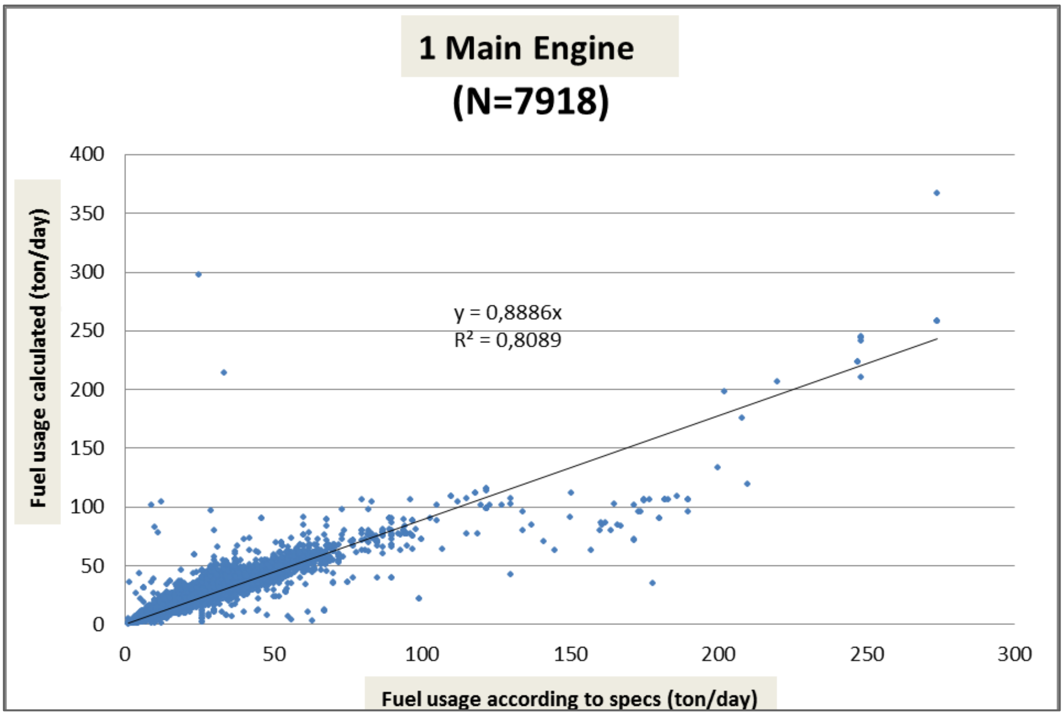


Figure 8: Calculated daily fuel usage of two engine ships compared with specifications

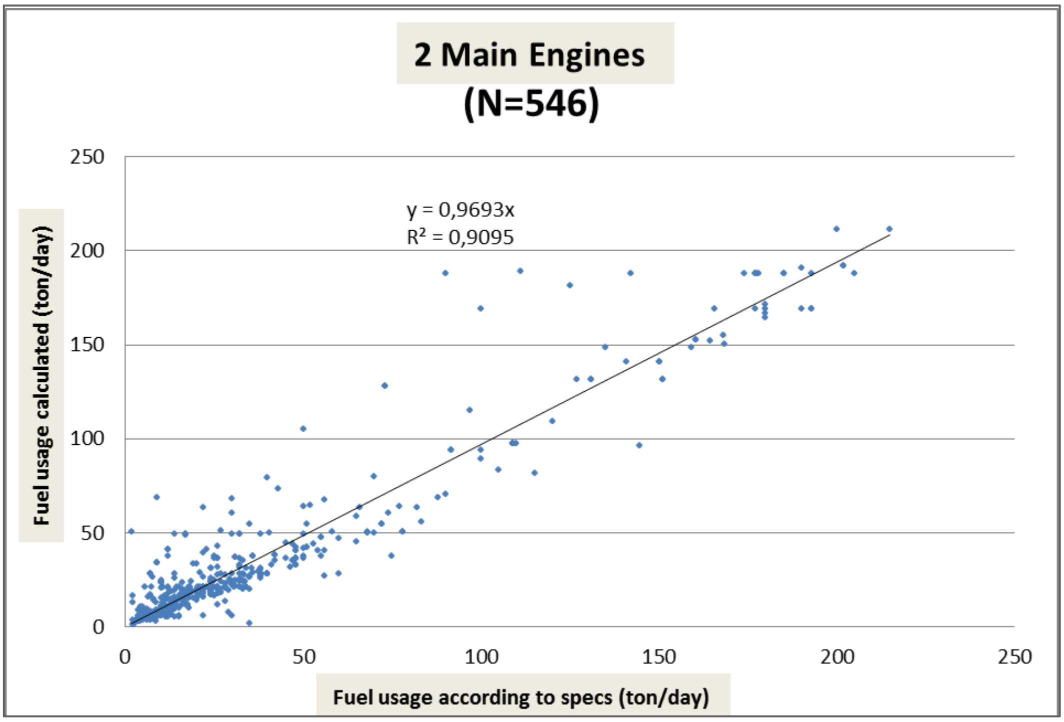
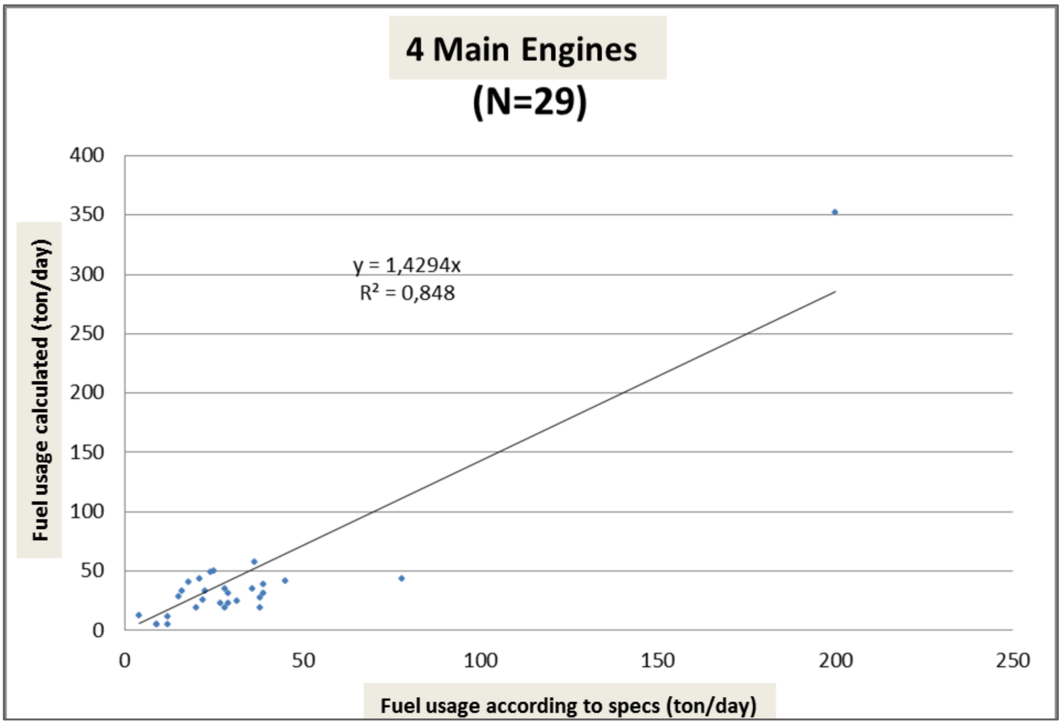


Figure 9: Calculated daily fuel usage of four engine ships compared with specifications



Some data filtering was applied to four engine ships. Excluded in the analysis are special cases such as high-speed ferries, supply and service vessels, tugs and fishing ships and one ship mainly propelled by LNG.

It can be argued that energy consumption of four engine ships seems to be overestimated by the assumptions that are applied, but with such a small dataset it is hard to determine whether the assumptions on ships with four main engines are correct or not. Even if there is an overestimation, this will probably not lead to big differences in total emissions, since the contribution of four engine ships in total installed power is below 4% (Table 5).

For ships with other numbers of main engines the available data did not allow any check of possible assumptions on the fuel consumption.

Apart from the check of fuel consumption of two and four engine ships as presented above, for ships with three or five to twelve engines additional assumptions had to made in order to enable calculation of emissions of these ships. These assumptions are shown in

Table 6 are rather uncertain. However, the total installed power is only 2% and therefore, the influence on total emissions will be minimal.

Table 6: Maximum number of engines assumed to be operational for propulsion with multiple engines present and the fraction of MCR assumed (MCR_{ss}) to attain the service speed

Ship type	Engines Present → / Engines Operational ↓	2	3	4	5	6	7	8	9	10	12
Oil tanker	2	0.75	0.85								
	4			0.75							
Chemical/ LNG/LPG tanker	2	0.75	0.85								
	4			0.75		0.75					
	6								0.75		
Bulk carrier	2	0.75	0.85								
	4			0.75	0.75	0.75					
Container ship	2	0.75	0.85								
	4			0.75	0.75	0.75	0.75	0.75			
	6								0.75	0.75	
General Dry Cargo	2	0.75	0.85								
	4			0.75	0.75	0.75		0.75			
RoRo Cargo/ Vehicle	2	0.75	0.85								
	4			0.75	0.75	0.75		0.75			
Reefer	2	0.75	0.85								
	4			0.75	0.75						
Passenger	2	0.5	0.85	0.75		0.75			0.75		
Miscellaneous	2	0.75									
	4			0.75							
Tug/Supply	2	0.5	0.85	0.75	0.75	0.75	0.75	0.75	0.75		0.75
Non Merchant	2	0.5	0.85	0.75	0.75	0.75	0.75	0.75			0.75

4.2.3 Calculating emissions for multiple engines

The calculation of emissions with multiple engines becomes more complicated because the number of active engines has to be calculated separately. For this reason, the calculation of EF' is slightly different from Formula 1.

Formula 4:

$$EF' = EF * CEF * \frac{NoEA * P * fMCR}{3600}$$

EF’ Actual emission factor expressed as kg per nautical mile

EF Basic engine emission factor expressed as kg per KWh (Table 7/Table 15

CEF Correction factors of basic engine emission factors (

Table 17/Table 19)

NoEA	Number of active engines (engines that actually are working on a certain moment)
P	Engine power of one single engine [Watts]
fMCR	Actual fraction the MCR of active engines
V	Actual vessel speed [knots]

Formula 5:

$$NoEA = minimum\ (Engines\ Operational, round\ (CRScor * Engines\ Operational * MCRss) + 1)$$

Note that the Number of active engines depends on the level of CRScor, which depends on the ships speed, and that the maximum number of active engines is equal to Engines Operational.

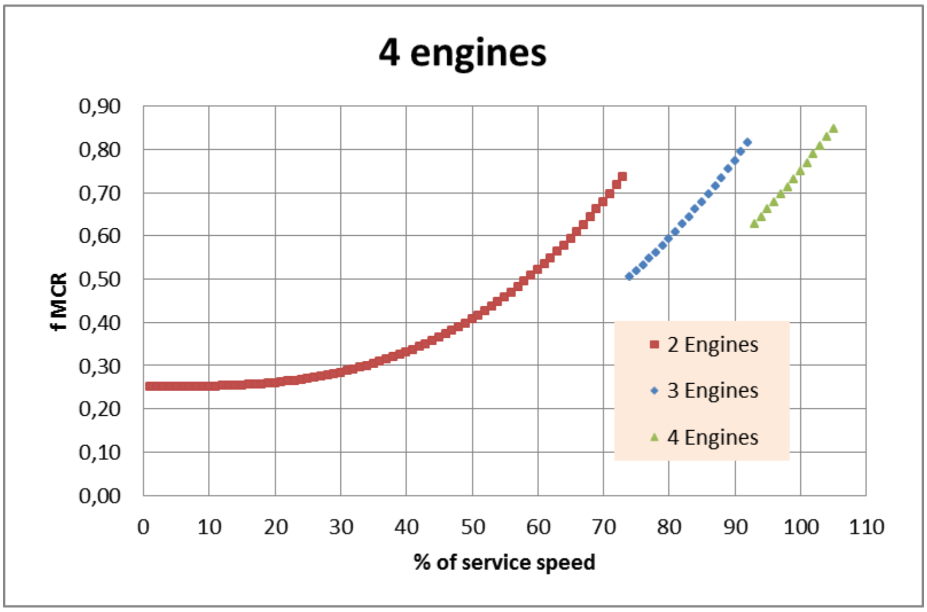
Formula 6:

fMCR= [Engines Operational]/NoEA * CRScor * MCR_{ss}

The fMCR for individual ship engines is linear inversely related to the Number of active engines (more engines active give lighter work for individual engines). In essence Formula 4 is the same as Formula 1 except the accounting of Engines Active in the available total Engine power and the application of modified fMCR in the selection of the CEF-values (Formula 5).

In **Error! Reference source not found.** the relationship is shown between the speed relative to the service speed and the power relative to the rated power of the ships propulsion engines at ships with 4 propulsion engines as implied in Formula 4 and 5.

Figure 10: The relationship between service speed and fMCR at ships with four propulsion engines as used in emission calculations (Formula 4 and 5)



4.2.4 Auxiliary Engines and Equipment

Aside from the main engines, most vessels have auxiliary engines and equipment that provide (electrical) power to the ship's systems. There is very little information available on the use of auxiliary engines. Perhaps the best estimate to date has been made in the *Updated 2000 Study on Greenhouse Gas Emissions from Ships report*[15] (Table 14 from that report)., to which many ship experts contributed. The percentage taken from that report was multiplied with the main power of each individual ship. This is explained in detail in section 4.4, below.

4.3 Engine Emission Factors

Table 7 to Table 15 show the engine emission factors[16/17] per engine type and fuel type expressed in grams per unit of mechanical energy delivered by ships engines (g/kWh). Partial implementation of the SO_X Emission Control Area (SECA) according to the MARPOL Annex VI in 2015 has been assumed. As a consequence, the sulphur percentage in heavy fuel oil is set on 0.2% m/m and the sulphur percentage in marine diesel oil is assumed to be 0.2% m/m in the NCP part of the SECA.

Linear relations exist between SFOC and SO_2 and CO_2 depending on fuel quality. SFOC values as such are not used in emission calculations.

PM reduction is associated with sulphur reduction because a certain fraction of oxidised sulphur is emitted as sulphuric acid which easily condenses to sulphuric acid particles (PM) in exhaust gases. Based on the sulphur reductions, additional PM reductions were estimated applying a linear relationship between sulphur and PM[18].

Table 7: Emission factors and specific fuel oil consumption (SFOC) applied on slow speed engines (SP) operated on heavy fuel oil (HFO), (g/kWh)

Year of build	NO_x	PM-HFO 2010-2014	PM-HFO 2015	SO_2 2010-2014	SO_2 2015	VOC	CO	CO_2	SFOC
1900–1973	16	0.74	0.43	4.2	0.42	0.6	3	666	210
1974–1979	18	0.72	0.43	4	0.40	0.6	3	635	200
1980–1984	19	0.70	0.43	3.8	0.38	0.6	3	603	190
1985–1989	20	0.69	0.43	3.6	0.36	0.6	2.5	571	180
1990–1994	18	0.68	0.43	3.5	0.35	0.5	2	555	175
1995–1999	15	0.57	0.33	3.4	0.34	0.4	2	539	170
2000–2010	~rpm	0.57	0.33	3.36	0.34	0.3	2	533	168
2011–2015		0.46	0.23	3.3	0.33	0.3	2	524	165

[15] Buhaug, Ø., Corbett, J. J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D. S., Lee, D., Lindstad, H., Mjelde, A., Pålsson, C., Wanquing, W., Winebrake, J. J., Yoshida, K.; Updated Study on Greenhouse Gas Emissions from Ships: Phase I Report; International Maritime Organization (IMO) London, UK, 1 September, 2008
[16] J. Hulskotte (TMO-MEP), E. Bolt (RWS-AVV), D. Broekhuizen (RWS-AVV); EMS-protocol Emissies door verbrandingsmotoren van varende en manoeuvrerende zeeschepen op het Nederlands grondgebied; Versie 1, 22 november 2003
[17] J. Hulskotte (TMO-MEP), E. Bolt (RWS-AVV), D. Broekhuizen (RWS-AVV); EMS-protocol Verbrandingsemissies door stilliggende zeeschepen in havens; Versie 2, 22 november 2003
[18] Hulskotte J.H.J.; Voorstel voor aanpassing van PM2,5 en PM_{10}-fracties van emissies van de zeescheepvaart; TNO-060-UT-2011-02190, 20 december 2011

Table 8: Emission factors and specific fuel oil consumption (SFOC) applied on slow speed engines (SP) operated on marine diesel oil (MDO), (g/kWh)

Year of build	NO_x	PM 2010-2014	PM 2015	SO_2 2010-2014	SO_2 2015	VOC	CO	CO_2	SFOC
1900–1973	16	0.64	0.33	4.2	0.42	0.6	3	666	210
1974–1979	18	0.62	0.33	4	0.40	0.6	3	635	200
1980–1984	19	0.60	0.33	3.8	0.38	0.6	3	603	190
1985–1989	20	0.59	0.33	3.6	0.36	0.6	2.5	571	180
1990–1994	18	0.58	0.33	3.5	0.35	0.5	2	555	175
1995–1999	15	0.47	0.23	3.4	0.34	0.4	2	539	170
2000–2010	~rpm1	0.47	0.23	3.36	0.34	0.3	2	533	168
2011–2015		0.46	0.23	3.3	0.33	0.3	2	523	165

Notes: 1 calculated by formulas provided in Table 11

Table 9: Emission factors and specific fuel oil consumption (SFOC) applied on medium/high speed engines (MS) operated on Heavy fuel oil (HFO), (g/kWh)

Year of build	NO_x	PM-HFO 2010-2014	PM-HFO 2015-	SO_2 2010-2014	SO_2 2015-	VOC	CO	CO_2	SFOC
1900–1973	12	0.96	0.64	4.5	0.45	0.6	3	714	225
1974–1979	14	0.94	0.63	4.3	0.43	0.6	3	682	215
1980–1984	15	0.93	0.63	4.1	0.41	0.6	3	651	205
1985–1989	16	0.91	0.63	3.9	0.39	0.6	2.5	619	195
1990–1994	14	0.90	0.63	3.8	0.38	0.5	2	603	190
1995–1999	11	0.80	0.53	3.7	0.37	0.4	2	587	185
2000–2010	~rpm1 92	0.79	0.53	3.66	0.37	0.3	2	581	183
2011–2015	~rpm 72	0.79	0.53	3.6	0.36	0.3	2	571	180

Table 10: Emission factors and specific fuel oil consumption (SFOC) applied on medium/high speed engines (MS) operated on marine diesel oil (MDO), (g/kWh)

Year of build	NO_x	PM-MDO 2010-2014	PM-MDO 2015-	SO_2 2010-2014	SO_2 2015-	VOC	CO	CO2	SFOC
1900–1973	12	0.66	0.34	4.5	0.45	0.6	3	714	225
1974–1979	14	0.64	0.33	4.3	0.43	0.6	3	682	215
1980–1984	15	0.63	0.33	4.1	0.41	0.6	3	650	205
1985–1989	16	0.61	0.33	3.9	0.39	0.6	2.5	619	195
1990–1994	14	0.55	0.28	3.8	0.38	0.5	2	603	190
1995–1999	11	0.50	0.23	3.7	0.37	0.4	2	587	185
2000–2010	~rpm1 92	0.49	0.23	3.66	0.37	0.3	2	581	183
2011–2015	~rpm1 72	0.49	0.23	3.6	0.36	0.3	2	571	180

Notes: 1) Calculated by formulas provided in Table 11
2) Fixed number applied on auxiliary engines only

Table 11: Emission factors of NO_X dependant on engines RPM

Year of build	RPM range	IMO-limits (g/kWh)	Emission factor NO_X (g/kWh)
2000–2010	< 130 RPM	17.0	0.85 x 17.0
	Between 130 and 2000 RPM	45 x n-0.2	0.85 x 45 x n-0.2
	> 2000 RPM	9.8	0.85 x 9.8
2011–2015	< 130 RPM	14.4	0.85 x 17.0
	Between 130 and 2000 RPM	44 x n-0.23	0.85 x 44 x n-0.23
	> 2000 RPM	7.7	0.85 x 7.7

ESI NO_X-scores were received from the PLA in order to check the ratio of the applied NO_X emission factors of individual vessels (as given in Table 11) with the measured values as implied in the NO_X-scores. Emission factors of individual vessels were derived using the engines RPM and the age of the vessels. An overview of the corrections as applied on individual vessels is provided in Table 12.

Table 12: Correction factors on original emission factors

applicable IMO standard	#vessels (N)	Average correctionfactor	Standard deviation of correctionfactor	% of IMO standard
tier I	423	1.02	0.10	87%
tier II	163	1.10	0.08	93%

From Table 12 it can be concluded that the assumption about the emission factor lying at 85% of the applicable standard limit value seems to be rather accurate for tier I engines. However, emission factors of tier II engines seem to be higher lying slightly below 95% of the standard limit value. These conclusions have not been applied on vessels without ESI NO_x-scores. This might have resulted in a slight underestimation of NO_x emissions.

Emission factors of gas turbines were adjusted according to Cooper[19].

Table 13: Emission factors and specific fuel oil consumption (SFOC) of gas turbines (TB) operated on marine diesel oil (MDO), (g/kWh)

Fuel	NO_X	PM-MDO NCP	PM-MDO Other	SO_2 NCP	SO_2 Other	VOC	CO	CO_2	SFOC
MDO	5.7	0.140	0.065	1.55	0.62	0.1	0.32	984	310

Emission factors of steam turbines were partially adjusted according to Cooper.

Table 14: Emission factors and specific fuel oil consumption (SFOC) of steam turbines (ST) operated on LNG, HFO or MDO, (g/kWh)

Fuel	NO_X	PM NCP	PM Other	SO_2 NCP	SO_2 Other	CH_4	VOC	CO	CO_2	SFOC
LNG	1.94	0.01	0.01	0.0	0.0	0.045		0.06	688	250
HFO	2.0	0.495	0.300	3.06	0.61		0.1	0.15	971	306
MDO	2.0	0.490	0.295	1.45	0.58		0.1	0.15	923	291

[19] Cooper D., Representative emission factors for use in "Quantification of emissions from ships associated with ship movements between port in the European Community" (ENV.C.1/ETU/2001/0090), 2002

Emissions of more modern LNG tanker propelled mostly propelled by medium speed diesel engines fuelled by LNG were calculated by means of emission factors as shown in Table 15 below.

Table 15: Emission factors and specific fuel oil consumption (SFOC) of medium speed engines (MS) operated on LNG, (g/kWh)

Fuel	NO_X	PM	SO_2	CH_4	CO	CO_2	SFOC
LNG	2.0	0.02	0.0	2.43	0.2	450	162

The change-over from fuels at LNG-tankers in the model calculations is assumed dependent on the speed of the ships expressed as CRScor. Below a value of CRScor of 0.2 LNG-tankers switch from gaseous LNG to liquid fuel used by main engines according to the scheme presented in Table 16 below. The fuels assumed to be used by auxiliary engines are also presented in Table 16.

Table 16: Fuel switch scheme of LNG-tankers in dependence of operational speed

Engine type	Main engines		Auxiliary engines	
	0.2 <= CRScor < 1.2	0 <= CRScor < 0.2	0.2 <= CRScor < 1.2	0 <= CRScor < 0.2
MS	LNG	MDO	MDO	MDO
MS	LNG	HFO	HFO	MDO
ST	LNG	MDO	MDO	MDO
ST	LNG	HFO	HFO	MDO

4.3.1 Correction Factors for Engine Emission Factors

At speeds around the design speed, the emissions are directly proportional to the engine's energy consumption. However, in light load conditions, the engine runs less efficiently. This phenomenon leads to a relative increase in emissions compared to the normal operating conditions. Depending on the engine load, correction factors specified per substance can be adopted according to the EMS protocols. The correction factors were extended by distinction of different engine types in order to get more accurate calculations. Three engine groups were discerned: reciprocating engines, steam turbines and gas turbines.

The correction factors used are shown in

Table 17 to Table 19. The list was extended by some values provided in the documentation of the EXTREMIS model[20].

[20] F. Chiffi, Schrooten E., De Vlieger I., EX-TREMIS - Exploring non road Transport; Emissions in Europe – Final Report; IPTS - Institute for Prospective Technological Studies. DG-JRC, 2007

Table 17: Correction factors for reciprocating diesel engines

Power % of MCR	CO_2, SO_2 SP	CO_2, SO_2 S	NO_X	PM-HFO/ PM-MDO	VOC, CH_4	CO
10	1.2	1.21	1.34	1.63	4.46	5.22
15	1.15	1.18	1.17	1.32	2.74	3.51
20	1.1	1.15	1.1	1.19	2.02	2.66
25	1.07	1.13	1.06	1.12	1.65	2.14
30	1.06	1.11	1.04	1.08	1.42	1.8
35	1.05	1.09	1.03	1.05	1.27	1.56
40	1.045	1.07	1.02	1.03	1.16	1.38
45	1.035	1.05	1.01	1.01	1.09	1.23
50	1.03	1.04	1.00	1.01	1.03	1.12
55	1.025	1.03	1.00	1.00	1.00	1.06
60	1.015	1.02	0.99	1.00	0.98	1.00
65	1.01	1.01	0.99	0.99	0.95	0.94
70	1.00	1.01	0.98	0.99	0.92	0.88
75	1.00	1.00	0.98	0.98	0.89	0.82
80	1.01	1.00	0.97	0.98	0.87	0.76
85	1.02	1.00	0.97	0.97	0.84	0.7
90	1.03	1.01	0.97	0.97	0.85	0.7
95	1.04	1.02	0.97	0.97	0.86	0.7
100	1.05	1.02	0.97	0.97	0.87	0.7

The correction factors for CO_2 and SO_2 are assumed to be equal. These newly added factors for CO_2 and SO_2 were derived from two recent publications[21/22] by taking interpolated values. A distinction was made for slow-speed engines (referred as SP) and medium and high-speed engines (referred as MS). Although correction factors for other substances may differ by engine type also, a numerical distinction was not possible.

Since steam turbines are predominantly used by LNG carriers, two types of fuels were assumed to be consumed: LNG and HFO. It was assumed that at lower engine loads (up to CRScor = 0.2) steam turbines are operated by HFO. On higher loads (from CRScor = 0.2) usage of LNG (boil-off gas) is assumed. The source of the correction factors of steam turbines, in

[21] Jalkanen J.-P.,Johansson L., Kukkonen J., Brink A., Kalli J., Stipa T.; Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide; Atmos.Chem.Phys.,12,2641-2659, 2012
[22] MAN Diesel&Turbo; SFOC Optimisation Methods For MAN B&W Two-stroke IMO Tier II Engines; document 5510-0099-00ppr, Augustus 2012

Table 18, was the EXTREMIS model.

Table 18: Correction factors for steam turbines

Power % of MCR	CO_2	SO_2	NO_X	PM-HFO	VOC, CH_4	CO
10	1.4	3.04	0.3	3	5.44	11.65
15	1.4	3.04	0.34	2.8	5.11	10.83
20	1.4	3.04	0.37	2.8	4.72	9.96
25	1.4	3.04	0.41	2.8	4.39	9.09
30	1.2	2.02	0.44	1.5	4.00	8.26
35	1.00	1.00	0.47	1.00	3.61	7.39
40	1.00	1.00	0.51	1.00	3.28	6.57
45	1.00	1.00	0.54	1.00	2.89	5.7
50	1.00	1.00	0.57	1.00	2.56	4.83
55	1.00	1.00	0.61	1.00	2.17	4
60	1.00	1.00	0.64	1.00	1.83	3.13
65	1.00	1.00	0.68	1.00	1.44	2.26
70	1.00	1.00	0.76	1.00	1.33	1.96
75	1.00	1.00	0.84	1.00	1.22	1.65
80	1.00	1.00	0.92	1.00	1.11	1.30
85	1.00	1.00	1.00	1.00	1.00	1.00
90	1.00	1.00	1.00	1.00	1.00	1.00
95	1.00	1.00	1.00	1.00	1.00	1.00
100	1.00	1.00	1.00	1.00	1.00	1.00

Correction factors for gas turbines, shown in Table 19, were estimated with data from the ICAO Aircraft Engine Emissions Databank[23]. The emission behaviour of the GE CF6-6D (marine derivative: GE LM2500) and the Allison 501 (AN 501) was taken as representative for the two most occurring gas turbines in marine applications. CEF values in low power ranges have been changed since the 2011 calculation because an adapted interpolation scheme has been applied.

Table 19: Correction factors for gas turbines

Power % of MCR	CO_2, SO_2	NO_X	PM-MDO	VOC	CO
10	1.26	0.23	0.98	48.71	64.4
15	1.17	0.3	0.95	37.73	51.15
20	1.04	0.41	0.9	22.35	32.6
25	0.96	0.48	0.88	13.02	21.34
30	0.87	0.55	0.85	2.58	8.75
35	0.88	0.58	0.84	2.46	7.98
40	0.89	0.61	0.84	2.33	7.2
45	0.91	0.64	0.83	2.21	6.42

[23] I. Grose and J. Flaherty, LNG Carrier Benchmarking, LNG15 2007; Shell Global Solutions International BV, 2007

Power % of MCR	CO_2, SO_2	NO_X	PM-MDO	VOC	CO
50	0.92	0.67	0.82	2.08	5.65
55	0.93	0.7	0.81	1.96	4.88
60	0.94	0.74	0.8	1.83	4.1
65	0.95	0.77	0.8	1.71	3.32
70	0.96	0.8	0.79	1.58	2.55
75	0.97	0.83	0.78	1.46	1.77
80	0.98	0.86	0.78	1.33	1
85	0.99	0.93	0.89	1.17	1
90	0.99	0.95	0.92	1.1	1
95	1	0.98	0.96	1.05	1
100	1	1	1	1	1

4.4 Ships at Berth

When a ship is berthed, in most cases the main engines are stopped. The auxiliary engines and equipment will be kept in service to provide (electrical) power to the ship's systems, on board cargo handling systems and accommodations.

The procedure for the calculation of emissions from ships at berth is derived from the EMS protocol with some minor modifications. The methodology was published in Atmospheric Environment[24].

For each individual vessel time-based emission factors were derived dependent on vessel type, vessel year of build and vessel size expressed in Gross ton.

Formula 7:

EF-auxiliary engines/boiler =

Fuel rate * GT/1000 * Fuel% in auxiliary engines * Emission factor/3600

Wherein:

EF-auxiliary engines/boiler	=	time based emission factor (gram/second)
GT	=	Size of the vessel expressed in gross ton
Fuel rate	=	Fuel consumption (kg/1000GT.hour), Table 20
Fuel% in aux/boiler	=	100% Low sulphur fuel (0.1 % S) assumed since 2010 (./.),Table 21
Emission factor	=	emission factor per substance dependent on year of build (g/kg fuel), Table 23

Emissions were calculated by multiplying the time at berth of each individual vessel with the emission factors of individual vessels as has been calculated with Formula 7. For the London Port Wide Emissions Inventory, the length of time at berth was derived for each individual event for each ship on the basis of AIS data. Ships with a speed less the 0.5

[24] Hulskotte J.H.J, H.A.C. Denier van der Gon, Emissions From Seagoing Ships At Berth Derived From An On-Board Survey; Atmospheric Environment, Doi: 10.1016/j.atmosenv.2009.10.018, 2009

knots over a continuous period of over 15 minutes were assumed to be at berth. Since the year of build of each ship was known, emission factors per amount of fuel dependant on the classification of year of build were applied. The amount of fuel used was calculated from the length of time at berth, ship type and volume in gross tonnage. The amount of fuel used at berth is more accurately determined in two reports on behalf of the CNSS project[25/26].

Table 20: Fuel rate of ships at berth, (kg/1000 GT.hour)

Vessel type	Fuel rate
Bulk carrier	2.4
Container ship	6
General Cargo	6.1
Other passenger vessels	8.9
Cruise vessels	32.4
RoRo Cargo	6.1
Oil Tanker	19.3
Other Tanker	14.5
Reefer	19.6
Other	9.2
Tug/Supply	15.6

Since January 1st 2010, the sulphur content of marine fuels used for ships at berth is regulated to a maximum of 0.1 percent. This implies that only marine gas oil with a sulphur content below 0.1 percent is allowed in harbours. The specification of fuel types at berth is adapted according to this new regulation (Table 21).

Table 21: Specification of fuel types of ships at berth per ship type (%)

Vessel type	HFO	MDO	MGO/ULMF
Bulk carrier	0	0	100
Container ship	0	0	100
General Cargo	0	0	100
Passenger	0	0	100
RoRo Cargo	0	0	100
Oil Tanker	0	0	100
Other Tanker	0	0	100
Fishing	0	0	100
Reefer	0	0	100
Other	0	0	100
Tug/Supply	0	0	100

[25] J.H.J Hulskotte, B. Wester, A.M. Snijder, V. Matthias; International survey of fuel consumption of seagoing ships at berth; TNO 2013 R10472, 18 December 2013
[26] J.H.J., Hulskotte, V. Matthias; Survey of fuel consumption of seagoing tankers at berth in Rotterdam; TNO 2013 R11287, 27 August 2013

Table 22 gives figures about allocation of fuel amount over engine types and apparatus during berth as is indicated by Formula 7.

Table 22: Allocation of fuels usage in engine types and apparatus per ship type (%)

Vessel type	Power (MS)	Boiler
Bulk carrier	90	10
Container ship	70	30
General Cargo	90	10
Passenger	70	30
RoRo Cargo	70	30
Oil Tanker	20	80
Other Tanker	50	50
Reefer	90	10
Other	100	0
Tug/Supply	100	0

In following tables, the emission factors used for emissions at berth are presented.

Table 23: Emission factors of medium/high speed engines (MS) at berth, (g/kg fuel)

Year of build	NO_X	PM-MDO	VOC	CO
Fuel	all	MGO/ULMF	all	all
1900 – 1973	53	1.4	2.7	13
1974 – 1979	65	1.5	2.8	14
1980 – 1984	73	1.6	2.9	15
1985 – 1989	82	1.8	3.1	13
1990 – 1994	74	1.3	2.6	11
1995 – 1999	59	0.8	2.2	11
2000 – 2010	49	0.8	1.6	11
2011 – 2015	39	0.8	1.6	11

At berth usage of medium speed engines was assumed.

Table 24: Emission factors of boilers at berth, (g/kg fuel)

Fuel	NO_X	PM-MDO	VOC	CO
MGO/ULMF	3.5	0.7	0.8	1.6

Table 25: Emission factors of all engines and apparatus, (g/kg fuel)

Fuel	SO_2	CO_2
MGO/ULMF	4	3150

In tanker ships a reduction factor for boilers (50% for PM and 90% for SO_2) is applied to the emission factors, because gas scrubbers are often applied in order to protect ship internal spaces for corrosion by inert gases produced by boilers.

4.5 Canal Boats

In contrast to the approach taken for larger ships described above, for small private vessels it was not possible to estimate emissions factor for individual boats, due to limited data availability.

Instead, emissions factors were used corresponding to five categories of vessel - short, medium and long narrowboats, cabin cruisers and “wide beam barge” vessels - representing the main types of boats operating on canals and rivers in the UK. These emission factors were calculated as part of a project undertaken by Aether and TNO for the CRT.

The key differences between these classes of vessel affecting emissions are their differing sizes (which affects the engine size and power required to sail each km), different fuel types (cabin cruisers are predominantly petrol powered whereas the other classes are mostly diesel powered), and engine age. The emissions factors calculated are typical of vessels with average size and engine characteristics for each category, considering all boats registered with CRT in England and Wales. Using such average values is sufficiently accurate for producing aggregate, provided that the characteristics of vessels operating in London do not differ systematically from those in the rest of England and Wales.

The emissions factors also vary depending on the dimensions of the waterway on which vessels are travelling and the speed of the vessel. Emission factors have been provided for three types of waterway: narrow canals (width 2.5m, depth 1.3m), wide canals (width 4.5m, depth 1.3m) and very wide canals or rivers (width 46m, depth 3m). Narrowboats are assumed to travel 5km/h on narrow canals, 7km/h on wide canals and 10km/h on very wide canals or rivers. For cabin cruisers and “wide beam barge style” vessels, emissions factors have been calculated for speeds of 6, 8, 10 and 12km/h.

The pollutants covered by the emission factors are CO_2, CO, NO_x, PM_{10}, SO_2 and “Hydrocarbons”. The precise emissions factors used, expressed in units of grams per km, are provided in Table 26 below

Table 26: Emissions factors used in the calculation of emissions from small private vessels

Boat type	Waterway type/speed	Emission factor (g/km)					
		CO_2	SO_2	NO_x	PM_{10}	Hydrocarbons	CO
Short Narrowboat	Narrow Canal (2.5m wide, 1.3m deep, 5km/h)	1858	0.0117	23.2	1.3	1.6	7.3
Medium narrowboat		1962	0.0124	24.0	1.2	1.5	6.9
Long Narrowboat		2089	0.0132	25.4	1.0	1.4	7.5
Short Narrowboat	Wide Canal (4.5m wide,1.3m deep, 7km/h)	1780	0.0112	21.8	1.1	1.3	4.8
Medium narrowboat		1814	0.0114	22.4	1.0	1.2	5.1
Long Narrowboat		1910	0.0120	23.4	0.8	1.0	5.0

Boat type	Waterway type/speed	Emission factor (g/km)					
		CO_2	SO_2	NO_x	PM_{10}	Hydrocarbons	CO
Short Narrowboat	River (46m wide, 3m deep, 10km/h)	1637	0.0103	20.0	1.1	1.4	5.0
Medium narrowboat		1633	0.0103	20.2	1.0	1.1	4.1
Long Narrowboat		1701	0.0107	21.0	0.8	1.0	4.1
Cabin cruiser	6 km/h	202	0.0013	1.8	0.1	1.5	26.1
	8 km/h	355	0.0022	2.9	0.1	2.2	45.3
	10 km/h	551	0.0035	4.4	0.2	3.4	70.3
	12 km/h	794	0.0050	6.3	0.4	4.8	101.1
Wide beam barge style	6 km/h	682	0.0043	9.5	0.4	1.3	7.1
	8 km/h	1105	0.0070	13.1	0.4	0.8	4.3
	10 km/h	1622	0.0102	19.7	0.6	0.9	4.2
	12 km/h	2298	0.0145	27.8	0.9	1.0	3.8

5 Inventory Development and Mapping

LLI provided 67 ship types, each of which have emissions totals calculated for each of the pollutants, for ease or presentation, these have been aggregated further into 14 main types, with the relationship between the two shown in Table 27, below.

Following the gap filling procedure described in section 3.1.1, the emissions calculation was carried out for all points within the data selection. This resulted in a point set with the emission, corresponding to these points. This emission point set was spatially aggregated to 1km cells, corresponding to the LAEI grid. Some of the LAEI grid cells are intersected by multiple boroughs. The emission for the distinct boroughs was estimated as well. This was done by first making a spatial aggregation of the emission points towards 100m cells and next clustering the emission in these 100m cells per borough.

Table 27: Aggregated ship types

Lloyds Registry Class	Aggregated Class
crude oil tanker	Oil tanker
Combined chemical and oil tanker	Oil tanker
Liquefied Natural Gas Carrier	Chemical/LNG/LPG tanker
Liquefied Petroleum Gas Carrier	Chemical/LNG/LPG tanker
tank barge	Chemical/LNG/LPG tanker
asphalt tanker	Chemical/LNG/LPG tanker
bunkering tanker	Chemical/LNG/LPG tanker
chemical tanker	Chemical/LNG/LPG tanker
edible oil tanker	Chemical/LNG/LPG tanker
product tanker	Chemical/LNG/LPG tanker
Tanker (unspecified)	Chemical/LNG/LPG tanker
water tanker	Chemical/LNG/LPG tanker
bulk carrier	Bulk carrier
bulk carrier with container capacity	Bulk carrier
bulk cement carrier	Bulk carrier
wood-chip carrier	Bulk carrier
fully cellular containership	Container ship
fully cellular refrigerated	Container ship
cargo/training	General Dry Cargo
general cargo	General Dry Cargo
general cargo with container capacity	General Dry Cargo
livestock	General Dry Cargo
barge	General Dry Cargo
hopper barge	General Dry Cargo
vehicle carrier	RoRo Cargo/Vehicle
roll on roll off with container capacity	RoRo Cargo/Vehicle
Roll on Roll off (RoRo)	RoRo Cargo/Vehicle
reefer	Reefer

Lloyds Registry Class	Aggregated Class
passenger RoRo	Passenger (cruise)
passenger (cruise)	Passenger (cruise)
ferry	Passenger (ferry)
cutter suction dredger	Dredger
dredger	Dredger
hopper dredger	Dredger
suction hopper dredger	Dredger
sand suction dredger	Dredger
trailing suction dredger	Dredger
trailing suction hopper dredger	Dredger
cable ship	Miscellaneous
diving support	Miscellaneous
exhibition ship	Miscellaneous
semi-sub HL vessel	Miscellaneous
landing craft	Miscellaneous
lighthouse/tender	Miscellaneous
maintenance	Miscellaneous
patrol ship	Miscellaneous
pontoon	Miscellaneous
repair ship	Miscellaneous
support	Miscellaneous
salvage	Miscellaneous
training	Miscellaneous
work ship	Miscellaneous
research	Miscellaneous
seismographic research	Miscellaneous
supply	Tug/Supply
anchor handling tug/supply	Tug/Supply
anchor handling tug	Tug/Supply
fire fighting tug	Tug/Supply
pusher tug	Tug/Supply
salvage tug	Tug/Supply
tug	Tug/Supply
tractor tug	Tug/Supply
tug/supply	Tug/Supply
fishing (general)	Fishing
trawler (All types)	Fishing
Naval Vessel	Non Merchant
yacht	Non Merchant

6 Back-Casting and Projections

Emissions estimates for the year 2016 were used as the base year for emission back-casting and projections. To provide emissions estimates for previous years, i.e. back casting, activity data for 2010 and 2013 were calibrated against 2016, and emissions factors developed using real data on ship movements and characteristics. To estimate future years, i.e. projections, the emissions were scaled using projected trends in ship activity and characteristics, such as size and type, as well as know changes in regulation. These processes are described in more detail, below.

6.1 Back casting

The emissions of 2013 were calculated by using AIS-data of the last half year of 2013. To adjust for the total activity to represent the whole of 2013, the emissions calculations had to be corrected. In **Error! Reference source not found.**, the observed ratio between activity data in 2016 and the last half year in 2013 (both from AIS data) is presented. Depending on vessel type the ratios of sailing vessels (expressed in vessel kilometre) differ in several cases considerably from the ratios of vessels at berth (expressed in hours spent at berth). This observation lead to the conclusion that AIS-data of 2013 probably were not of the same quality as AIS-data from 2016. Therefore, the pattern of activity was corrected using 2016 activity data. This correction was carried out through the multiplication of emissions for 2013 (as calculated from 2013 last half year AIS-data) with multiplication factors as shown in **Error! Reference source not found.**. The emissions were corrected by the assumption that the distances travelled, and the time spent at berth per vessel type, did not change between 2013 and 2016. Through the application of this calculation procedure, the resulting 2013 emission data are based on emission factors that are applicable for 2013 and with a spatial pattern of activity as observed within 2013 AIS-data. However total activity of 2013, derived from 2013 AIS data, has been “normalised” to 2016 activity.

Table 28: Multiplication factors for correction of incomplete AIS-data in 2013

Vessel type	Sailing	At berth
Oil tanker	2.2	2.7
Chemical/LNG/LPG tanker	1.8	1.4
Bulk carrier	3.8	3.8
Container ship	3.7	1.8
General Dry Cargo	1.2	1.5
RoRo Cargo/Vehicle	5.7	2.5
Reefer1	n/a	n/a
Passenger	1.6	1.8
Miscellaneous	1.5	3.0
Tug/Supply	2.1	2.3
Non Merchant	1.8	5.4
Cruise ship	2.5	1.3
Dredger	1.9	1.5

For 2010, it was assumed that emission factors in the period between 2010 and 2013 did not change significantly as no new regulatory measures came into effect in that period.

The results for 2010 were derived by applying indices on arrivals of the reported vessel types in 2010 and 2013. The indices (multipliers) Calculated from the number of arrivals were taken from the POLARIS gate data as received from PLA (**Error! Reference source not found.**). Trends were corrected to 1.00 (i.e. no change between the years) for vessel types that showed unrealistic trends within available data.

Table 29: Activity per vessel type of all voyages registered in POLARIS, total Gross ton (GT)

Vesseltype	Sum of Gross Tonnage 2013 (kT)	Sum of Gross Tonnage 2010 (mT	Index (multiplier), 2013 to 2010
Bulk carrier	9,130	9,200	1.01
Chemical/LNG/LPG tanker	5,070	15,500	3.06
Container ship	75,200	86,000	1.14
Cruise ship	1,930	2,240	1.16
Dredger	15,200	16,200	1.06
General Dry Cargo	16,200	15,200	0.93
Miscellaneous	200	90	1.00*
Non Merchant	20	9	1.00*
Oil tanker	25,300	41,200	1.63
Passenger	0+	4	1.00*
Reefer	940	2,480	2.64
RoRo Cargo/Vehicle	134.000	142,000	1.06
Tug/Supply	1,040	1,200	1.16

** Corrected to 1.00*

+ No data recorded

6.2 Projections

The projections were calculated by multiplication with a pollutant-specific multiplication factor. The multiplication factor is calculated by taking the product of the expected development of cargo and passenger transport (as index on the 2016 volume) with the expected development of emission factors per substance (as index on the 2016 emission factors). Cargo and passenger transport projections were taken from the work supporting the Thames Vision and are summarised in Table 30. The development of the emission factors was taken as result from calculations with the POSEIDON model. This can be expressed by the following formula:

Formula 8:

Emission y, c, s = Emission 2016,c,s * MFy,c,s , (ton/year)

Where:

Emission y, c, s = Emission in future year(y) for cargo (c) and substance (s), (ton/year)

Emission 2016,c,s = Emission in 2016 for cargo (c) and substance (s) as calculated with AIS-data, (ton/year)

MFy,c,s = Multiplication factor for future year (y), cargo (c) and substance (s), (index)

The multiplication factors are calculated by the following formula:

Formula 9:

$$MF_{y,c,s} = Cargo_{c,y} / Cargo_{c,2016} * EF_{s,y} / EF_{s,2016}$$

Where:

Cargo c,y = Cargo (c) amount in future year (y), (Million ton or Million passengers)
Cargo c,2016 = Cargo (c) amount in historical year 2016, (Million ton or Million passengers)
EF s,y = Average emission factor of substance (s) for future year (y), (g/kWh)
EF s,2016 = Average emission factor of substance (s) in historical year 2016, (g/kWh)

Table 30: Cargo[27] and passenger[28] projections as used in emission projections

Cargo group	2020	2025	2030	2035	Unit
Unitised	29.7	37.3	42.5	48.3	MT
Petroleum	12.9	12.1	11.4	10.7	MT
Aggregates	10.9	11.5	11.7	12.4	MT
Other cargos	6.4	6.8	7.1	7.6	MT
Intra Port	5	5.2	5.4	5.7	MT
Passengers	12	14	17	20	MPAX

MT = 1 million tonne, MP = 1 million passengers

Projections of average emission factors per substance as presented in **Error! Reference source not found.** were derived from the POSEIDON model. Within this model fleet renewal on global scale is represented with a special correction with respect to fleet renewal in the North Sea area. Fleet renewal in the North Sea area is faster than globally. This makes that the average emission factors are gradually dominated by lower emission factors of most modern vessels with approved engine energy efficiency causing lower CO_2 emission factors. In addition, the implementation of the North Sea as a NO_x control area (from 2021) has been derived from the fleet renewal as strict NO_x emission regulation is applied to vessels produced from 2021 and thereafter.

Table 31: Projections of average emission factors, g/kWh

Substance	2016	2020	2025	2030	2040
CO_2	587	580	568	554	542
NO_x	11.7	10.6	8.6	6.7	4.5
PM_{10}	0.35	0.33	0.31	0.28	0.27
SO_2	0.37	0.36	0.36	0.34	0.34
VOC	0.37	0.42	0.27	0.38	0.13
CO	2.04	2.00	1.70	1.50	1.06

[27] http://www.pla.co.uk/assets/forecasts-consultationdocumentv11december-1.pdf
[28] http://www.pla.co.uk/About-Us/The-Thames-Vision, based on expert stakeholder input

7 Key Assumptions and Uncertainties

As with any study of this type, there are uncertainties and assumptions in the estimation process which could impact on the final outputs. The table below summarises the key uncertainties alongside the potential impact they could have on the final emission estimates.

Table 32: Key assumptions and uncertainties

Assumption or uncertainty		Potential impact on emission totals
AIS data	AIS data does not provide complete coverage for all ship journeys. Interference with transponder messages may result in either messages not being received by shore stations or being assigned incorrect locations. This issue was far more significant for vessels in the central London area, notably passenger vessels. A tested methodology was used to fill in gaps in reported journeys but there is the possibility of under-reporting for certain vessel types.	Small overall; potentially larger for certain ship types such as passenger vessels.
Non-AIS vessels	For vessels without AIS transponders, less accurate movement data was used, e.g. reported movements through control points, e.g. locks or the Thames Barrier.	Small as non-AIS vessels tend to be much smaller and non-commercial craft
Fuel consumption	Fuel consumption is a key correcting factor for the emission factors. For some vessel classes, notably passenger vessels, reported fuel consumption was significantly different from the calculated fuel consumption based on AIS data. Expert judgment was used to define a realistic figure.	Small overall, potentially larger for certain ship types such as passenger vessels
Auxiliary engines	Emissions at berth are the result of auxiliary engines being used to power onboard activities and services and a ship moving less than 0.5 knots for more than 15 minutes was assumed to be at berth and making use of the auxiliary engine. However, information on the auxiliary engines fitted to specific ships is incomplete, even within high quality data sources such as LLI. The assumptions used in study (see section 4.4) are based on an internationally recognised methodology[29], which included extensive surveys of ship emissions at berth. Using this methodology, individual vessel time-based emission factors were derived dependent on vessel type, year of build and size expressed in gross tonnes. While it is conceivable that ships in the Port of London differ significantly from those in other ports, any such differences are likely to be minor	Small to medium

[29] Hulskotte J.H.J, H.A.C. Denier van der Gon, Emissions From Seagoing Ships At Berth Derived From An On-Board Survey; Atmospheric Environment, Doi: 10.1016/j.atmosenv.2009.10.018, 2009

Assumption or uncertainty		Potential impact on emission totals
Sulphur content of fuel	Emissions of SO_2 are closely related to the amount of sulphur in the fuel used. The sulphur content of fuels is controlled by EU and UK law. In the North Sea and English Channel, fuel not exceeding 0.1% was required to be used from 2015 (previously 1%). The same limit applies to ships at berth. Vessels on inland waterways and leisure craft must use fuel not exceeding 0.001% sulphur. In this study, 100% compliance with the relevant standards at sea and for inland navigation have been assumed. However, surveys in the Netherlands undertaken since the fuel quality regulations were introduced have shown that ships at berth are, on average, 90% compliant. Therefore, it has been assumed that 10% of seagoing ships at berth use 1% sulphur fuel for their auxiliary operations.	Medium to large for sea-going vessels at berth, increasing sulphur emissions by around 50%. However, no evidence on compliance levels of ships in the inventory area was available at the time of the study.
Future trends	In projecting emissions to future years, the inventory estimates rely on the forecasts of several other organisations and studies. Each of these contain uncertainties and often include ranges, whereas the inventory compilation has only used a central estimate. Some of the future trends, such as the increase in ferry passenger numbers, were based on expert stakeholder input. While this remains a valid method of information gathering, it is more difficult to analyse for uncertainty. In addition, intelligence on future trends which could not be quantified has not been taken into account.	Small in the short term but increasing over time.

8 Conclusions and Potential Future Improvements

This study represents the first comprehensive emissions inventory to include port wide emissions . The methodology draws very heavily from similar inventories in The Netherlands and is consistent with international practice. As such, it provides a level of detail well beyond what was previously available. However, and as with any inventory, there is scope for improvement. Key priorities for a subsequent update to the inventory are to increase data capture for both AIS and non-AIS vessels and to develop a port specific evidence base to support the inventory (current and projections) to reduce reliance on assumptions derived from studies elsewhere. The key areas for improvement are as follows:

- Run sensitivity tests on the key assumptions used in this inventory to allow better quantification of uncertainties and a more targeted improvement programme. Emissions estimates have only been produced for a single, “central scenario”, e.g. the projected cargo throughput of the port. Assumptions used in developing the inventory, and the projections, could have a significant impact on the estimates. Understanding these sensitivities will help to direct improvement work to reduce uncertainty and increase confidence in the emissions outputs.
- Improve AIS data capture in central London, particularly for passenger vessels. AIS data capture for passenger vessels was relatively low with the result that fuel consumption calculated though captured journeys falling some way short of the reported fuel consumption. Analysis of the AIS data also showed significant gaps where continuous journeys would be expected. The reasons for this low rate of data capture should be investigated.
- Develop the evidence base for London on issues such as auxiliary power and fuel used at berth. A number of rich data sources were used to develop this inventory. However, two key areas where a supportive evidence base for London was not available was the number, type and use of auxiliary engines fitted to ships visiting the Port of London and the type of fuels used while at berth.
- Develop geographically specific activity data for future years. There are a number of significant developments in train along the Thames which could impact both the distribution and magnitude of emissions in future years, such as changes to passenger ferry services and the development of a new London cruise terminal. At the time of study, quantifiable data on such developments was not available and so they have not been taken into account in the projections;
- Develop more detailed activity data for the blue ribbon network. While not a significant source of emissions in the context of the whole inventory, vessels using the non-tidal Thames, Thames tributaries and the canal network have the potential to be locally relevant sources. Moreover, the emissions are generally closer to receptors (people) than other shipping and thus potentially more significant in terms of exposure. However, activity data on the blue ribbon network is sparse; improving activity data for recreational vessels on the blue ribbon network would greatly improve emissions estimates for such craft. This could include stationary, i.e. emissions from heating or battery charging while moored, as well as moving vessels

Operator Survey

PLA Port Emissions Inventory - Data Survey

Please complete all questions in the 'Survey' sheet to the best of your knowledge, as free text unless instructed to select an option from a drop down list.
If you have any questions, or require assistance in completing this survey, please contact Tim Williamson: tim.williamson@aether-uk.com

Part 1: General Information

1.a. Operator Name

b. Address

c. Phone number

d. Email address

2. Business Type

Part 2: Current Activities

3. Please provide the following information. Note that if your vessels are fitted with AIS transponders, you do not need to complete columns 3-9 (shaded)

Vessel Name	IMO No. (if applicable)	Max load capacity (t)	LOA (m)	Beam (m)	Draft (m)	Annual distance travelled (km, approx.)	Which river reaches do these vessels operate in? Please use the list shown in the "reaches" tab, below, as a check	Average cruising speed (knots, km/h*) *please specify
Right click on the row label (number on left of screen) and 'insert' more rows if required								

(table continued)

Average engine running time (hours per day)	Engine capacity (cc)	Engine power (BHP)	Year of engine build	Fuel type	Annual fuel consumption	Fuel units	Other comments

4. Do your engines comply with any recognised emission standard, such as IMO I or II, and if so, which?

5. How and where do you source your fuel?

6. Do you have the most recent fuel specification note? If so, what was the sulphur content?

Part 3: Future activity

7. Considering the timeframes of 2016-2020 and then 2021-2030, please give your estimates of changes in your vessel fleet:

a. Do you have planned engine changes for existing vessels?

2016-2020:

2021-2030:

If yes (or likely), what kind of changes will you make? Like for like replacement or will the engine/propulsion system be different?

b. Do you plan to acquire new vessels

2016-2020:

2021-2030:

If yes (or likely), will they be additional or replacement? Please provide other details if you can.

c. In your view, will your activity on the Thames: increase, remain stable or decrease?

2016-2020:

2021-2030:

d. In your view, what other changes could happen with regard to Thames river traffic?

2016-2020:

2021-2030:

e. Do your vessels currently have the capacity to use shoreside electrical power?

f. If shoreside power were available along the Thames, would you consider using it?

2016-2020:

2021-2030

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