Category		Title
NFR	1.A.3.d.i(i), 1.A.3.d.i(ii), 1.A.3.d.ii, 1.A.4.c.iii, 1.A.5.b	International maritime navigation, international inland navigation, national navigation (shipping), national fishing, military (shipping), and recreational boats
SNAP	080402 080403 080404 080304	National sea traffic within EMEP area National fishing International sea traffic (international bunkers) Inland goods carrying vessels
ISIC		
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Contents

1 Overview

This source category covers all water-borne transport from recreational craft to large ocean-going cargo ships that are driven primarily by high-, slow- and medium-speed diesel engines and occasionally by steam or gas turbines. It includes hovercraft and hydrofoils. Water-borne navigation causes emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), as well as carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), sulphur dioxide (SO_2), particulate matter (PM) and oxides of nitrogen (NO_x). The activities included in this chapter are outlined in Table 1-1 (IPCC, 2006).

Table 1-1 Source category structure referring to NFR nomenclature

Source category	Coverage
1.A.3.d Water-borne navigation	Emissions from fuels used to propel water-borne vessels, including hovercraft and hydrofoils, but excluding fishing vessels. The international/domestic split should be determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship.
1.A.3.d.i International water-borne navigation (International bunkers)	Emissions from fuels used by vessels of all flags that are engaged in international water-borne navigation. The international navigation may take place at sea, on inland lakes and waterways and in coastal waters. Includes emissions from journeys that depart in one country and arrive in a different country. Excludes consumption by fishing vessels (see 1.A.4.c.iii - Fishing). Emissions from international military water-borne navigation can be included as a separate sub-category of international water-borne navigation provided that the same definitional distinction is applied and data are available to support the definition.
1.A.3.d.ii Domestic water-borne navigation	Emissions from fuels used by vessels of all flags that depart and arrive in the same country (excludes fishing, which should be reported under 1.A.4.c.iii, and military, which should be reported under 1.A.5.b). Includes small leisure boats. Note that this may include journeys of considerable length between two ports in a country (e.g. San Francisco to Honolulu).
1.A.4.c.iii Fishing (mobile combustion)	Emissions from fuels combusted for inland, coastal and deep-sea fishing. Fishing should cover vessels of all flags that have refuelled in the country (include international fishing).
1.A.5.b Mobile (water-borne navigation component)	All remaining water-borne mobile emissions from fuel combustion that are not specified elsewhere. Includes military water-borne navigation emissions from fuel delivered to the country's military not otherwise included separately in 1.A.3.d.i, as well as fuel delivered within that country but used by the military of external countries that are not engaged in multilateral operations.
Multi-lateral operations (water-borne navigation component)	Emissions from fuels used for water-borne navigation in multilateral operations pursuant to the Charter of the United Nations. Include emissions from fuel delivered to the military in the country and delivered to the military of other countries.

The importance of this sector ranges from negligible for land-locked countries with no major inland waterways to very significant for some pollutants contribution for many countries. For this latter group, the contribution of emissions from navigation (originating from the combustion of fuel to provide motion or auxiliary power onboard vessels) is sizeable for SO_2, NO_x, CO_2 and CO and of lesser, but still significance importance, for NMVOCs and some metals.

2 Description of sources

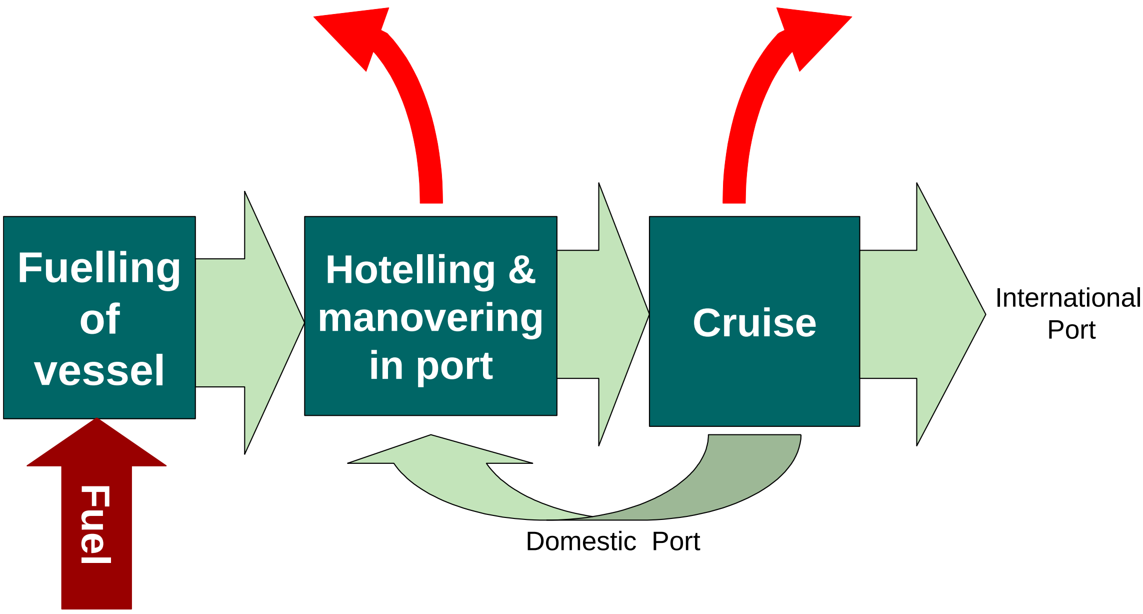
2.1 Process description

Exhaust emissions from navigation arise from:

- engines used as main propulsion engines;
- auxiliary engines used to provide power and services within vessels.

The different types of engines used are discussed in subsection 2.2.

Figure 2-1 Flow diagram for the contribution from navigation to mobile sources combustion emissions



Vessels berth and remain tied up (hotelling) while they unload and load, or whilst they await their next voyage. They then cast off and manoeuvre away from their mooring point before sailing away from the port. Following departure from the despatching port the vessel cruises to its destination, which may be a port in the same country (a domestic voyage, activity within NFR code 1.A.3.d.ii) or in a different country (an international voyage, activity within NFR code 1.A.3.d.i). This simplistic pattern may be complicated by other stopping patterns. The recommended criteria for distinguishing between domestic and international navigation are summarised in Table 2-1. In summary it depends only on the origin and destination of ship for each segment of its voyaging.

Table 2-1 Criteria for defining international or domestic navigation (applies to each segment of a voyage calling at more than two ports)*

Journey type between two ports	Domestic	International
Departs and arrives in same country	Yes	No
Departs from one country and arrives in another	No	Yes

Most shipping movement data are collected on the basis of individual trip segments (from one departure to the next arrival) and do not distinguish between different types of intermediate stops (consistent with the IPCC Good Practice Guidance). Basing the distinction on individual segment data is simpler than looking the complete trip and is likely to reduce uncertainties. It is considered very unlikely that this would make any significant impact to the total emission estimates. This does not change the way that emissions from international journeys are reported under the UNECE LRTAP Convention (i.e. as an additional 'memo-item' that is not included in national totals).

It is important to note that this table relates to all water-borne vessels, whether they operate on the sea, on rivers or lakes. In order to meet the criteria given in Table 2-1, it is necessary to make detailed bottom-up fuel consumption and emission calculations for the individual segments (Tier 3). In order to obtain the most precise estimates for navigation, parties are encouraged to carry out such bottom-up calculations. It is however necessary to meet the general reporting criteria for the party as a whole, and hence if Tier 3 fuel consumption estimates are obtained, parties must subsequently make fuel adjustments in other relevant fuel consuming sectors in order to maintain the grand national energy balance (see e.g. Winther 2008a, Winther 2008b).

The detailed Tier 3 approach, however, requires statistical data which may not be available by the reporting party. The approach therefore can be based on fuel sales reported in national statistics according to the statistical categories: fisheries, national sea traffic and international sea traffic:

National fishing (fisheries): emissions from all national fishing according to fuel sold in the country. By definition, all fuel sold for commercial fishing activities in the reporting party is considered domestic. There is no international bunker fuel category for commercial fishing, regardless of where the fishing occurs.

International sea traffic: emissions from bunker fuel sold for international sea traffic in the country of the reporting party. The emissions are to be reported to both UNFCCC and UNECE for information only.

International inland shipping: emissions from bunker fuel sold for international inland shipping in the country of the reporting party. The emissions are to be reported to UNECE within national totals and to UNFCCC for information only.

Further guidance

In general, the distinction between domestic and international emissions on the basis of the criteria in Table 2-1 should be clear. However, it may be useful to provide some further guidance:

Long distance territories

When part of the territory of a country is at long distance (e.g. for France) and there is no intermediate stop in other countries, the journey is always domestic. For UNFCCC, the allocation is always domestic and included in the national total. Previously for UNECE, only the part of emissions within the European Monitoring and Evaluation Programme (EMEP) area was considered, so that when the location of the overseas territory was outside the EMEP area, a specific allocation rule was necessary. Since the 2002 EMEP Reporting Guidelines there was no longer a reference to the EMEP area with respect to what is included, in order to harmonise with UNFCCC so that the same fuel estimate could be used in both cases. The exception is for parties that have footnotes in their protocols excluding certain areas, in which case the situation is different.

Lack of availability of statistical data

When the necessary statistical data are not available, the reporting party should describe clearly in its National Inventory Report the approach adopted. One possible option would be as follows:

For UNECE as well as UNFCCC, the distinction between domestic and international can be approximated by fuel sales. However, a country is encouraged to verify the definition of bunkers used for this fuel allocation in national statistics (checking that it is similar to the one used for emissions, as it will never be exactly the same). When shipping is a key source, a country should also verify the sales data by performing the ship movement methodology; however this may prove too much to perform on an annual basis.

NB: For UNFCCC, all bunker fuel and related GHG emissions are therefore often considered as ‘international’ (sea ships as well as inland ships).

National grids and ‘international emissions’

The distinction domestic/international is relevant to assess the (future) compliance of a country to its protocol requirements. When reporting, the parties are requested to report their national shipping emissions by grid cell. When emission data are used for modelling purposes by EMEP, it is necessary to also take into account the ‘international’ emissions. International emissions are only reported as memo items, and thus shall not be gridded by the Member States. EMEP thus does not request international maritime emission data by grid cell. For EMEP, the location of maritime emissions is carried out separately including international and transit traffic (prepared by the Lloyds Register). However, Lloyds does not cover the Mediterranean, the Baltic and inland waters, therefore gridding of the emissions from these areas will require a centrally-organised special investigation by EMEP.

Harbour emissions

UNECE and EMEP do not require the distinction between emissions in harbours and emissions during cruise. Such information can, however, be relevant for other applications, for example local inventories and for air quality modelling purposes. To determine the location of emissions from seagoing ships it is possible to apply the Tier 3 approach, where several phases in shipping are distinguished (outlined in subsection 3.4).

2.2 Techniques

Marine diesel engines are the predominant form of power unit within the marine industry for both propulsion and auxiliary power generation. In 2010 an analysis of about 100 000 vessels indicated marine diesels powered around 99 % of the world's fleet, with steam turbines powering less than 1 %. The only other type of engine highlighted was gas turbines, used virtually only on passenger vessels, and only used in around 0.1 % of vessels (Trozzi, 2010). Diesel engines can be categorised into slow (around 18% of engines), medium (around 55%), or fast (around 27%), depending on their rated speed.

Emissions are dependent on the type of engine, and therefore these will be reviewed briefly.

Slow speed diesel engines: these have a maximum operating speed of up to 300 rev/min, although most operate at speeds between 80–140 rev/min. They usually operate on a two-stroke cycle, and are cross head engines of 4–12 cylinders. Some current designs are capable of developing in excess of 4 000 kW/cylinder and with brake mean effective pressures of the order of 1.7 MPa. Within the marine industry such engines are exclusively used for main propulsion purposes and comprise the greater proportion of installed power, and hence fuel consumption, within the industry.

Medium speed diesel engines: this term is used to describe marine diesel engines with a maximum operating speed in the range 300–900 rev/min. They generally operate on the four-stroke cycle, are normally trunk piston engines of up to 12 cylinders in line, or 20 cylinders in 'V' formation. Current designs develop power output in the range 100–2000 kW/cylinder and with brake mean effective pressures in the range 1.0–2.5 MPa. Engines of this type may be used for both main propulsion and auxiliary purposes in the marine industry. For propulsion purposes such engines may be used in multi-engine installations and will normally be coupled to the propeller via a gearbox. Engines of this type will also be used in diesel-electric installations.

High speed diesel engines: this title is used to describe marine diesel engines with a maximum operating speed greater than 900 rev/min. They are essentially smaller versions of the medium speed diesel engines or larger versions of road truck vehicle engines; they are used on smaller vessels and are often the source of auxiliary power on board vessels.

Steam turbines: whilst these replaced reciprocating steam engines in the early twentieth century they, themselves, have been replaced by the more efficient diesel engines which are cheaper to run. It is notable that the steam turbine vessels are predominantly fuelled with fuel oil rather than lighter fuels.

Gas turbines: whilst this type of engine is more widely used in warships, they are currently installed in only a very small proportion of the merchant fleet, often in conjunction with diesel engines.

In addition to the categorisation into five types of engines, the marine engines can be further stratified according to their principal fuel: bunker fuel oil (BFO), marine diesel oil (MDO) or marine gas oil (MGO). As is discussed later, some emissions (e.g. of SO_x and heavy metals) are predominantly fuel based rather than dependent on engine type. Consequently a knowledge of the fuel used significantly influences emissions in addition to the engine type using it.

2.3 Emissions

The emissions produced by navigation are a consequence of combusting the fuel in an internal combustion (marine) engine. Consequently, the principal pollutants are those from internal combustion engines. These are CO, VOC, NO_x and PM (including BC[1]) derived from soot which mainly have to do with engine technology, and CO_2, SO_x, PAHs and heavy metals and further PM (mainly sulphate-derived) which originate from the fuel speciation.

On a European scale, SO_2 and NO_x emissions from national shipping can be important with respect to total national emissions (Table 2-2).

Table 2-2 Ranges of contribution of national shipping to total emissions

Pollutant	Contribution to total emissions [%]
SO_x	0-80
NOx	0-30
NMVOC	0-5
CO	0-18
NH_3	-
TSP*	0-3
PM_{10}*	0-4
$PM_{2.5}$*	0-5

Note
* = values from EMEP (https://www.ceip.at/ms/ceip_home1/ceip_home/webdab_emepdatabase/) which correspond to official emissions for 2004, from country submissions in 2006.
0 = emissions are reported, but the exact value is below the rounding limit (0.1 per cent)
- = no emissions reported

2.4 Controls

Pollutant emissions can be controlled by two mechanisms: control of the combustion technology, combined with exhaust gas treatment, and control of the fuel quality. Both these measures are used.

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

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

[1] For the purposes of this guidance, BC emission factors are assumed to equal those for elemental carbon (EC). For further information please refer to Chapter 1.A.1 Energy Industries and Appendix A of this chapter.

The measures in Marpol Annex VI describe the outcomes; they do not stipulate how they are to be achieved. Technology for controlling emissions includes:

- improved engine design, fuel injection systems, electronic timing, etc. to obtain optimum efficiency (optimising CO_2 emissions) reducing PM and VOC emissions;
- exhaust gas recirculation (EGR) where a portion of the exhaust gas is routed back to the engine charge air whereby the physical properties of the charge air are changed. For marine diesel engines, a typical NO_x emission reduction of 10–30 % can be found. This technique has not yet been in regular service for ships;
- selective catalytic reduction (SCR) where a reducing agent is introduced to the exhaust gas across a catalyst. Hereby NO_x is reduced to N_2 and H_2O. However this technology imposes severe constraints on the ship design and operation to be efficient. A reduction of 85–95 % in NO_x can be expected applying this technology. The technology is in use in a few ships and is still being developed;
- selective non catalytic reduction (SNCR) where the exhaust gas is treated as for the SCR exhaust gas treatment technique, except the catalyst is omitted. The process employs a reducing agent, supplied to the exhaust gas at a prescribed rate and temperature upstream of a reduction chamber. Installation is simpler than the SCR, but needs a very high temperature to be efficient. Reductions of 75–95 % can be expected. However, no installations have been applied yet on ships;
- sea water scrubbing. Sea water scrubbing involves removal of SO_2 by sea water scrubbing (Concawe, 1994) and reduction of particulate matters. It allows operation on regular HSFO (high sulphur fuel oil), although it increases 2-3% of the fuel total consumption, but also on low or zero sulphur fuels, such as natugal gas or biofuels. This technique has not yet become widespread due to cost issues but also because this delivers sulphur directly to the oceans which is not considered good practice.

Moreover, EU directives exist which relate to the content of sulphur in marine gas oil (EU-Directive 93/12 and EU-Directive 1999/32) and the content of sulphur in heavy fuel oil used in SECA (EU-Directive 2005/33).

The Marine Environment Protection Committee (MEPC) of IMO has approved amendments to Marpol Annex VI in October 2008 in order to strengthen the emission standards for NO_x and the sulphur contents of heavy fuel oil used by ship engines.

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

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

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

- Tier III (2): diesel engines (> 130 kW) installed on a ship constructed on or after 1 January 2016.

The Tier I–III NO_x legislation values rely on the rated engine speeds (n) given in RPM (revolutions per minute). The emission limit equations are shown in Table 2-3.

Table 2-3 Tier I-III NO_x emission limits for ship engines (amendments to Marpol Annex VI)

Regulation	NO_x limit	Rated engine speeds (revolutions per minute)
Tier I	17 g/kWh $45 \times n^{-0.2}$ g/kWh 9,8 g/kWh	n < 130 130 ≤ n < 2000 n ≥ 2000
Tier II	14.4 g/kWh $44 \times n^{-0.23}$ g/kWh 7.7 g/kWh	n < 130 130 ≤ n < 2000 n ≥ 2000
Tier III	3.4 g/kWh $9 \times n^{-0.2}$ g/kWh 2 g/kWh	n < 130 130 ≤ n < 2000 n ≥ 2000

Tier I limits are to be applied for existing engines with a power output higher than 5 000 kW and a displacement per cylinder at or above 90 litres, installed on a ship constructed on or after 1 January 1990 but prior to 1 January 2000, provided that an Approved Method for that engine has been certified by an Administration of a Party and notification of such certification has been submitted to the Organization by the certifying Administration

In relation to the sulphur content in heavy fuel and marine gas oil used by ship engines, Table 2-4 shows the current legislation in force.

(2) For ships operating in a designated Emission Control Area. Outside a designated Emission Control Area, Tier II limits apply.

Table 2-4 Current legislation in relation to marine fuel quality

Legislation	Region	Heavy fuel oil		Gas oil	
		S-%	Impl. date	S-%	Impl. date
EU-Directive 93/12		None		0.2[1]	1.10.1994
EU-Directive 1999/32		None		0.2	1.1.2000
EU-Directive 2005/33	SECA — Baltic sea	1.5	11.08.2006	0.1	1.1.2008
	SECA — North sea	1.5	11.08.2007	0.1	1.1.2008
	Outside SECA's	None		0.1	1.1.2008
Marpol Annex VI	SECA — Baltic sea	1.5	19.05.2006		
	SECA — North sea	1.5	21.11.2007		
	Outside SECA	4.5	19.05.2006		
Marpol Annex VI amendments	SECA	1	01.03.2010		
	SECA	0.1	01.01.2015		
	Outside SECA	3.5	01.01.2012		
		0.5	01.01.2020[2]		

Notes
1. Sulphur content limit for fuel sold inside EU.
2. Subject to a feasibility review to be completed no later than 2018, to determine the availability of fuel oil to comply with the fuel oil standard set forth in the Amendment. If the conclusion of such a review becomes negative the effective date would default 1 January 2025.

For recreational craft, Directive 2003/44 comprises the emission legislation limits for diesel engines, and for two-stroke and four-stroke gasoline engines, respectively. The CO and VOC emission limits depend on engine size (kW) and the inserted parameters presented in the calculation formulas in Table 2-5. For NO_x, a constant limit value is given for each of the three engine types. For TSP, the constant emission limit regards diesel engines only.

Table 2-5 Overview of the EU Emission Directive 2003/44 for recreational craft

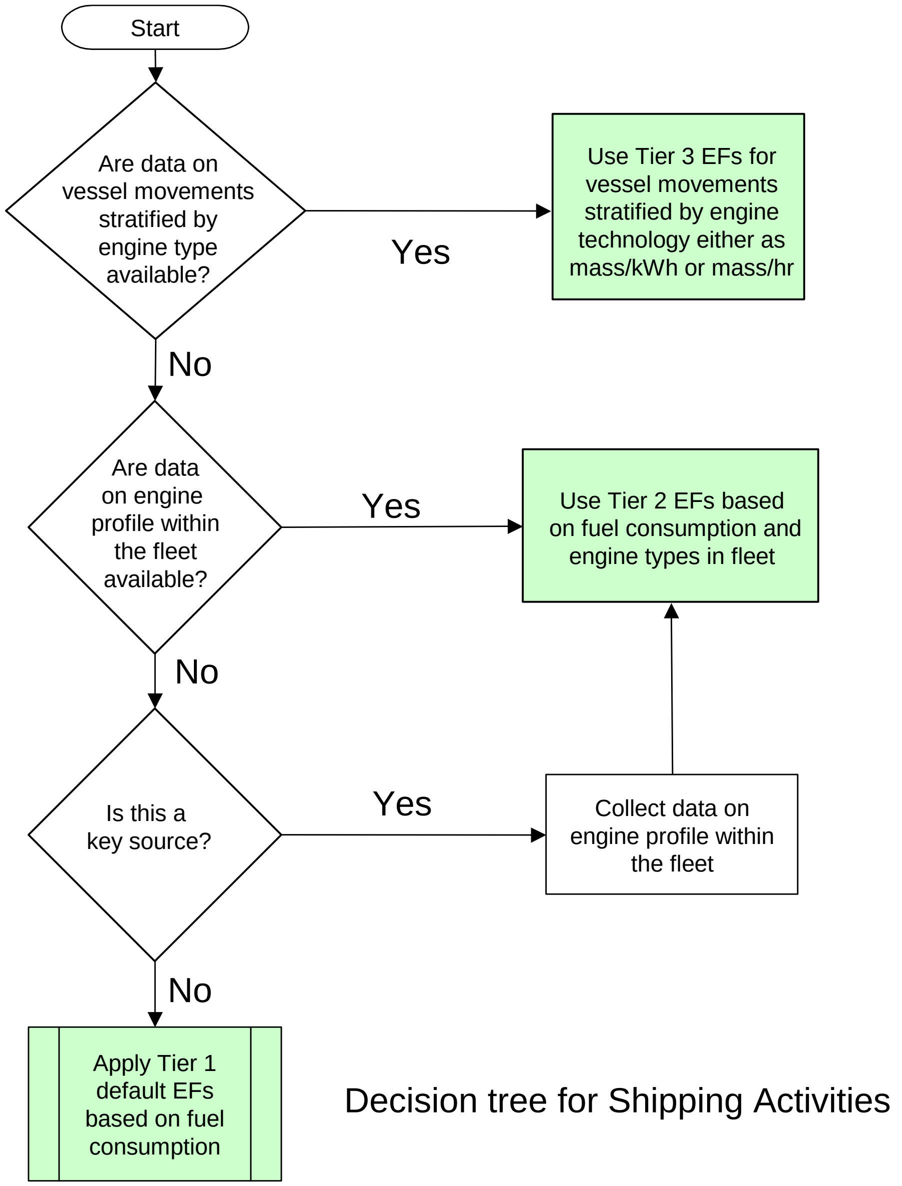
Engine type	Impl. date	$CO=A+B/P^n$			$VOC=A+B/P^n$			NO_x	TSP
		A	B	n	A	B	n		
2-stroke gasoline	1/1 2007	150.0	600.0	1.0	30.0	100.0	0.75	10.0	-
4-stroke gasoline	1/1 2006	150.0	600.0	1.0	6.0	50.0	0.75	15.0	-
Diesel	1/1 2006	5.0	0.0	0	1.5	2.0	0.5	9.8	1.0

3 Methods

3.1 Choice of method

In Figure 3-1 a procedure is presented to select the methods for estimating the emissions from navigation. Emission estimates will need to be separated by NFR code for reporting.

Figure 3-1 Decision tree for emissions from shipping activities



This decision tree is applicable to all parties. Its basic concepts are:

- if detailed information is available then use it as much as possible;
- if this source category is a key source, then a Tier 2 or Tier 3 method must be used for estimating the emissions.

In all cases emissions need to be split by national navigation, international navigation, fishing and military which are usually determined by the available statistics.

3.2 Tier 1 default approach

3.2.1 Algorithm

The Tier 1 approach for navigation uses the general equation to be applied for the different NFR codes:

$$E_i = \sum_m \left(FC_m \times EF_{i,m}\right)$$

where:

E_i = emission of pollutant i in kilograms;

FC_m = mass of fuel type m sold in the country for navigation (tonnes);

$EF_{i,m}$ = fuel consumption-specific emission factor of pollutant i and fuel type m [kg/tonne];

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

The $FC_m \times$ EF product is summed over the four types of fuel used to provide total emissions from navigation. This approach incorporates the relationship between fuel composition and some emissions (notably SO_2 and heavy metals).

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

3.2.2 Default emission factors

The Tier 1 approach uses emission factors for each pollutant for each type of fuel used. Some factors (e.g. SO_2) depend on the fuel quality, which may change from batch to batch, and from year to year, and consequently these emission factors include a 'Sulphur content of fuel' factor. Table 3-1, Table 3-2 and Table 3-3 provide emission factors for ships using bunker fuel oil, marine diesel oil/marine gas oil (MDO/MGO) and gasoline.

3.2.3 Activity data

The Tier 1 approach is based on the premise that the quantities of fuel sold for shipping activities are available by fuel type, from nationally collected data. Fuel data needs to be split by NFR code: national navigation (usually navigation statistics), international (bunkers), fishing (usually available as separate statistics) and military.

Table 3-1 Tier 1 emission factors for ships using bunker fuel oil

Tier 1 default emission factors					
	Code	Name			
NFR Source Category	1.A.3.d.i 1.A.3.d.ii 1.A.4.c.iii 1.A.5.b	International navigation National navigation Agriculture / forestry / fishing: National fishing Other, mobile (including military, land based and recreational boats)			
Fuel	Bunker Fuel Oil				
Not applicable					
Not estimated	NH3, BC				
Pollutant	**Value**	**Unit**	**95% confidence interval**		**Reference**
			Lower	**Upper**	
NOx	79.3	kg/tonne fuel	0	0	Entec (2007). See also note (2)
CO	7.4	kg/tonne fuel	0	0	Lloyd's Register (1995)
NMVOC	2.7	kg/tonne fuel	0	0	Entec (2007). See also note (2)
SOx	20	kg/tonne fuel	0	0	Note value of 20 should read 20*'S'. Lloyd's Register (1995). See also note (1)
TSP	6.2	kg/tonne fuel	0	0	Entec (2007)
PM10	6.2	kg/tonne fuel	0	0	Entec (2007)
PM2.5	5.6	kg/tonne fuel	0	0	Entec (2007)
Benzo(b)fluoranthene	0.03	g/tonne fuel			average value
Benzo(k)fluoranthene	0.02	g/tonne fuel			average value
Benzo(a)pyrene	0.005	g/tonne fuel			average value
Indeno(1,2,3-cd)pyrene	0.009	g/tonne fuel			average value
Pb	0.18	g/tonne fuel	0	0	average value
Cd	0.02	g/tonne fuel	0	0	average value
Hg	0.02	g/tonne fuel	0	0	average value
As	0.05	g/tonne fuel	0	0	average value
Cr	0.72	g/tonne fuel	0	0	average value
Cu	0.2	g/tonne fuel	0	0	average value
Ni	32	g/tonne fuel	0	0	average value
Se	0.04	g/tonne fuel	0	0	average value
Zn	1.2	g/tonne fuel	0	0	average value
PCB	0.57	mg/tonne fuel	0	0	Cooper (2005)
PCDD/F	0.47	ug I-TEQ /tonne fuel	0	0	Cooper (2005)
HCB	0.14	mg/tonne fuel	0	0	Cooper (2005)

Notes

1. S = percentage sulphur content in fuel; pre-2006: 2.7 % wt. [source: Lloyd's Register, 1995]. For European Union as specified in the Directive 2005/33/EC:
   a. 1.5 % wt. from 11 August 2006 for Baltic sea and from 11 August 2007 for the North Sea for all ships;

b. 1.5 % wt. from 11 August 2006 in EU territorial seas, exclusive economic zones and pollution control zones by passenger ships operating on regular services to or from any Community port at least in respect of vessels flying their flag and vessels of all flags while in their ports;
c. 0.1 % by wt. from 1 January 2010 for inland waterway vessels and ships at berth in Community ports.

2. Emission factors for NO_x and NMVOC are the 2000 values in cruise for medium speed engines (see Tier 2).
3. Reference: 'average value' is between Lloyd's Register (1995) and Cooper and Gustafsson (2004).
4. BC fraction of PM (f-BC) = 0.12. *Source: for further information see Appendix A*

Table 3-2 Tier 1 emission factors for ships using marine diesel oil/marine gas oil

Tier 1 emission factor					
	Code	Name			
NFR Source Category	1.A.3.d.i 1.A.3.d.ii 1.A.4.c.iii 1.A.5.b	International navigation National navigation Agriculture / forestry / fishing: National fishing Other, mobile (including military, land based and recreational boats)			
Fuel	Marine diesel oil/marine gas oil (MDO/MGO)				
Not applicable	HCH				
Not estimated	NH3				
Pollutant	**Value**	**Unit**	**95% confidence interval**		**Reference**
			Lower	**Upper**	
NOx	78.5	kg/tonne fuel	0	0	Entec (2007). See also note (2)
CO	7.4	kg/tonne fuel	0	0	Lloyd's Register (1995)
NMVOC	2.8	kg/tonne fuel	0	0	Entec (2007). See also note (2)
SOx	20	kg/tonne fuel	0	0	Note value of 20 should read 20*'S'. Lloyd's Register (1995). See also note (1)
TSP	1.5	kg/tonne fuel	0	0	Entec (2007)
PM10	1.5	kg/tonne fuel	0	0	Entec (2007)
PM2.5	1.4	kg/tonne fuel	0	0	Entec (2007)
Benzo(b)fluoranthene	0.01	g/tonne fuel			average value
Benzo(k)fluoranthene	0.01	g/tonne fuel			average value
Benzo(a)pyrene	0.002	g/tonne fuel			average value
Indeno(1,2,3-cd)pyrene	0.001	g/tonne fuel			average value
Pb	0.13	g/tonne fuel	0	0	average value
Cd	0.01	g/tonne fuel	0	0	average value
Hg	0.03	g/tonne fuel	0	0	average value
As	0.04	g/tonne fuel	0	0	average value
Cr	0.05	g/tonne fuel	0	0	average value
Cu	0.2	g/tonne fuel	0	0	average value
Ni	1	g/tonne fuel	0	0	average value
Se	0.01	g/tonne fuel	0	0	average value
Zn	1.2	g/tonne fuel	0	0	average value
PCB	0.038	mg/tonne fuel	0	0	Cooper (2005)
PCDD/F	0.13	ug I-TEQ/tonne	0	0	Cooper (2005)
HCB	0.08	mg/tonne fuel	0	0	Cooper (2005)

Notes

1. S = percentage sulphur content in fuel; pre-2000 fuels: 0.5 % wt. [source: Lloyd's Register, 1995]. For European Union as specified in the Directive 2005/33/EC:
   a. 0.2 % wt. from 1 July 2000 and 0.1 % wt. from 1 January 2008 for marine diesel oil/marine gas oil used by seagoing ships (except if used by ships crossing a frontier between a third country and a Member State);
   b. 0.1% wt. from 1 January 2010 for inland waterway vessels and ships at berth in Community ports.
2. Emission factor for NO_x and NMVOC are the 2000 values in cruise for medium speed engines (see Tier 2).

3. Reference: 'average value' is between Lloyd's Register (1995) and Cooper and Gustafsson (2004)
4. BC fraction of PM (f-BC) = 0.31. *Source: for further information see Appendix A*

Table 3-3 Tier 1 emission factors for ships using gasoline

Tier 1 emission factor					
	Code	Name			
NFR Source Category	1.A.3.d.ii	National navigation			
Fuel	Gasoline				
Not applicable	HCH, PCB, HCB				
Not estimated	NH3, Pb, Cd, Hg, As, Cr, Cu, Ni, Se, Zn, PCDD/F, Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Indeno(1,2,3-cd)pyrene				
Pollutant	**Value**	**Unit**	**95% confidence interval**		**Reference**
			Lower	**Upper**	
NOx	9.4	kg/tonne fuel	0	0	Winther & Nielsen (2006)
CO	573.9	kg/tonne fuel	0	0	Winther & Nielsen (2006)
NMVOC	181.5	kg/tonne fuel	0	0	Winther & Nielsen (2006)
SOx	20	kg/tonne fuel	0	0	Winther & Nielsen (2006)
TSP	9.5	kg/tonne fuel	0	0	Winther & Nielsen (2006)
PM10	9.5	kg/tonne fuel	0	0	Winther & Nielsen (2006)
PM2.5	9.5	kg/tonne fuel	0	0	Winther & Nielsen (2006)

Notes: The table contains averaged figures between 2-stroke and 4-stroke engines, assuming a share of 75% 2-stroke and 25% 4-stroke ones. If more detailed data are available the Tier 2 method should be used.
BC fraction of PM (f-BC) = 0.05. *Source: for further information see Appendix A*

3.3 Tier 2 technology specific approach

3.3.1 Algorithm

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

For this approach the algorithm used is:

$$E_i = \sum_m \left(\sum_j FC_{m,j} \times EF_{i,m,j} \right)$$

where:

E = annual emission (tonnes),

$FC_{m,j}$ = mass of fuel type m used by vessels with engine type j (tonnes),

$EF_{i,m,j}$ = average emission factor for pollutant i by vessels with engine type j using fuel type m,

i = pollutant

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

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

3.3.2 Tier 2 engine and fuel-specific emission factors

For all pollutants except NO_x, NMVOC and PM (TSP, PM_{10} and $PM_{2,5}$), the Tier 2 emission factors for a specific fuel type are the same as Tier 1 emission factors, for each of the different types of fuel (Table 3-1 to Table 3-3). Tier 2 emission factors for NO_x, NMVOC and PM together with specific fuel consumption (g_{fuel}/kWh) are presented in Table 3-4.

In the table different NO_x emissions factors are reported for 2000, 2005 and 2010. The emission factors for 2000 (Entec, 2002) are representative of the fleet before application of IMO NO_x Technical Code (see section 2.4) while 2005 and 2010 values (according to Entec, 2007) are obtained from the year 2000 NO_x emission factors with a reduction of 3.4% and 6.8% to account for the new engines introduced by 2005 and 2010.

This reductions are obtained starting from 2005 European Commission study (Entec, 2005) that assumed that a new engine meeting the requirements of the NO_x Technical Code has roughly 17% lower NO_x emissions than a pre-2000 engine. To obtain emission factors for 2005 and 2010 fleets, as is not possible to establish the number of annual engine replacements within the fleet, the number of new low NO_x engines in the fleet is assumed only to coincide with new vessels. Between 2000 and 2010 the average annual rate of replacement for vessels is evaluated (based on data for 2000 to 2005 in Entec, 2007) to be 4%, on the basis that the overall fleet size remains constant (the approximate life cycle for a marine engine is assumed to be 25 years, which is equivalent to an annual replacement rate of 4%) [3].

Table 3-4 Tier 2 emission factors for NO_x, NMVOC, PM and specific fuel consumption for different engine types/fuel combinations

Tier 2 default emission factors							
Engine type	**Fuel type**	**NO_x 2000** (kg/tonne)	**NO_x 2005** (kg/tonne)	**NO_x 2010** (kg/tonne)	**TSP - PM_{10}** (kg/tonne)	**$PM_{2,5}$** (kg/tonne)	**Specific fuel consumption** (g fuel/kWh)
Gas turbine	BFO	20.0	19.3	18.6	0.3	0.3	305
	MDO/MGO	19.7	19.0	18.3	0.0	0.0	290
High-speed diesel	BFO	59.6	57.7	55.6	3.8	3.4	213
	MDO/MGO	59.1	57.1	55.1	1.5	1.3	203
Medium-speed diesel	BFO	65.7	63.4	61.3	3.8	3.4	213
	MDO/MGO	65.0	63.1	60.6	1.5	1.3	203
Slow-speed diesel	BFO	92.8	89.7	86.5	8.7	7.8	195
	MDO/MGO	91.9	88.6	86.5	1.6	1.5	185
Steam turbine	BFO	6.9	6.6	6.4	2.6	2.4	305
	MDO/MGO	6.9	6.6	6.4	1.0	0.9	290

([3]) In each of the 5 and 10 years, 4% of the fleet has new engines (17% lower NO_x): 5 x 4% x 17% = 3.4% and 10 x 4% x 17% = 6.8%

Source: Entec (2002), Entec (2007), emission factors calculated in kg/tonne of fuel using specific fuel consumption.

BFO –Bunker Fuel Oil, MDO –Marine Diesel Oil, MGO –Marine Gas Oil
BC fraction of PM (f-BC); BFO: 0.12, MDO/MGO: 0.31. Source: for further information see Appendix A

NMVOC factors were derived as being 98 % of the original HC value (based on reported CH_4 factors from IPCC (1997)). As outlined by Entec, emissions largely depend on the installed engine type on board a ship and the fuel used, rather than the type of vessel (container, passenger ferry, etc.).

For small pleasure boats and service boats, Tier 2 emission factors are listed in Table 3-5.

Table 3-5 Tier 2 emission factors for recreational boats (NFR 1A3dii-Small Boats)

Tier 2 default emission factors				
Fuel	**Pollutant**	**Units**	**Conventional**	**2003/44/EC**
Diesel	NO_x	kg/tonne fuel	38.4	32.8
	CO	kg/tonne fuel	19.8	18.6
	NMVOC	kg/tonne fuel	7.45	6.18
	TSP	kg/tonne fuel	4.60	3.71
	PM_{10}	kg/tonne fuel	4.60	3.71
	$PM_{2,5}$	kg/tonne fuel	4.60	3.71
	NH_3	g/tonne fuel	7.00	7.00
Gasoline: 2-stroke	NO_x	kg/tonne fuel	3.27	
	CO	kg/tonne fuel	481	
	NMVOC	kg/tonne fuel	233	
	TSP	kg/tonne fuel	12.6	
	PM_{10}	kg/tonne fuel	12.6	
	$PM_{2,5}$	kg/tonne fuel	12.6	
	NH_3	g/tonne fuel	3	
Gasoline: 4-stroke	NO_x	kg/tonne fuel	26.8	25.8
	CO	kg/tonne fuel	851	348
	NMVOC	kg/tonne fuel	26.7	29.2
	TSP	g/tonne fuel	188	188
	PM_{10}	g/tonne fuel	188	188
	$PM_{2,5}$	g/tonne fuel	188	188
	NH_3	g/tonne fuel	5	5

Source: Winther & Nielsen, 2006
BC fraction of PM (f-BC); Diesel: 0.55, Gasoline: 0.05. Source: for further information see Appendix A

3.3.3 Activity data

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

National statistical port arrivals data for the EU are collected and provided to Eurostat by all Member States according to the Maritime Statistics Directive (Council Directive 96/64/EC). Quarterly statistics both for movements, passengers and goods spilt by direction, partner entity and type of cargo are available from the Eurostat Newcronos Maritime Database. These data refers for main ports only (but 90 % of the total traffic).

Detailed analysis of vessel profiles can be found in Entec (2002), Appendix D Breakdown of vessel profiles.

The following steps are required to estimate emissions:

1. obtain national statistical port arrivals data by type of vessel as in Table 3-6.
2. compute total power installed by type of vessel referring to Table 3-6.
3. split total power installed for each type of vessel by engine speed/fuel class using Table 3-7.
4. compute total power installed by engine speed/fuel class as sum of figures derived in step 3.
5. assume that fuel usage is proportional to total power installed to assign statistical fuel consumption (from Table 3-4) to different engine speed/fuel class.
6. estimate national emissions with emission factors in Table 3-4.

Table 3-6 Estimated average main engine power (total power of all engines) by ship category

Ship category	Main engine power (kW)	
	1997 fleet	2010 fleet
Liquid bulk ships	6.695	6.543
Dry bulk carriers	8.032	4.397
Container	22.929	14.871
General cargo	2.657	2.555
Ro Ro Cargo	7.898	4.194
Passenger	3.885	10.196
Fishing	837	734
Other	2.778	2.469
Tug	2.059	2.033

Source: Trozzi, 2010

Table 3-7 Percentage of installed Main Engine power by engine type/fuel class (2010 fleet)

Ship category	SSD MDO /MGO	SSD BFO	MSD MDO /MGO	MSD BFO	HSD MDO /MGO	HSD BFO	GT MDO /MGO	GT BFO	ST MDO /MGO	ST BFO
Liquid bulk ships	0.87	74.08	3.17	20.47	0.52	0.75	0.00	0.14	0.00	0.00
Dry bulk carriers	0.37	91.63	0.63	7.29	0.06	0.02	0.00	0.00	0.00	0.00
Container	1.23	92.98	0.11	5.56	0.03	0.09	0.00	0.00	0.00	0.00
General cargo	0.36	44.59	8.48	41.71	4.30	0.45	0.00	0.10	0.00	0.00
Ro Ro Cargo	0.17	20.09	9.86	59.82	5.57	2.23	2.27	0.00	0.00	0.00

Passenger	0.00	3.81	5.68	76.98	3.68	1.76	4.79	3.29	0.00	0.02
Fishing	0.00	0.00	84.42	3.82	11.76	0.00	0.00	0.00	0.00	0.00
Others	0.48	30.14	29.54	19.63	16.67	2.96	0.38	0.20	0.00	0.00
Tugs	0.00	0.00	39.99	6.14	52.80	0.78	0.28	0.00	0.00	0.00

SSD - Slow Speed Diesel, MSD – Medium Speed Diesel, HSD - High Speed Diesel, GT – Gas Turbine,
ST – Steam Turbine; MDO –Marine Diesel Oil, MGO –Marine Gas Oil, BFO –Bunker Fuel Oil

Source: Trozzi, 2010

For recreational craft, Tier 2 uses fuel sales split into technology layers as an input for the emission calculations.

For diesel-fuelled boat engines, a first-order approximation (in the absence of more detailed data) is to assume for any given inventory year, that all engine ages have the same share of total fuel consumption. For Denmark as an example, this gives a 6.67 % fuel consumption share for the engines of 0 to 14 years of age (diesel engine lifetime: 15 years). Furthermore, it is known that from 2006 new sold diesel boat engines must comply with the EU emission directive 2003/44. This enables the distribution of fuel consumption shares into technology layers for the relevant inventory years.

In case of gasoline boat engines, there has been an increase in new sales of four-stroke engines lately, and a corresponding decrease in the number of new sold two-stroke engines. The assumption behind the Danish inventory is that from 1998 the number of new sales has been decreasing, and from 2006 no new sales of two-stroke engines occurs.

Table 3-8 shows the change of fuel consumption for 2-stroke and 4-stroke engines from 1997 to 2015, all engines being of the conventional type. In order to find the absolute fuel consumption figure for 2-stroke and 4-stroke engines for inventory years 1998 and later, a rational approach is to use the 1997 figure for fuel consumption and then apply the index changes from Table 3-8 per engine category. In this table, both 2-stroke and 4-stroke fuel consumption receives an index value of 100 in year 1997. By reading Table 3-8 this means that the 2-stroke fuel consumption in e.g. 2010 is only 17.3% of the 1997 value while the 4-stroke consumption is double as much as it was in 1997 in absolute terms.

For estimating emissions from small boats, where separate national activity statistics are not collected, activity data (in tonnes of fuel by fuel type and engine standard) will need to be derived from data on the population of these vessels.

Table 3-8 Fuel consumption index numbers for small boats based on the Danish Inventory

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
2 stroke	100	100	98.8	96.4	92.8	87.9	81.6	73.9	63.5	51.9	41.5	32.3	24.2	17.3	11.5	6.92	3.46	1.15	0
4 stroke	100	105	111	118	126	135	145	156	164	173	181	188	195	200	205	208	211	213	214

Source: Winther & Nielsen, 2006

A further split into technology layers is only relevant in the case of four-stroke engines, since all two-stroke engines are of the conventional type. All engines can be assumed to have the same share of fuel consumption, which in the case of Denmark amounts to a 10 % fuel consumption share for engines between 0 and 9 years of age (gasoline engine lifetime: 10 years). From 2007 new sold gasoline boat engines must comply with Directive 2003/44/EC, and based on this, the fuel consumption for four-stroke engines can be split into the engine types conventional and technology layer 2003/44/EC.

3.4 Tier 3 Ship movement methodology

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

The ship movement methodology is recommended when detailed ship movement data as well as technical information on the ships (e.g. engine size and technology, power installed or fuel use, hours in different activities) are available. It is suited for estimating national and international emissions. The methodology may be quite time consuming to perform. In order to meet the general reporting criteria for the country as a whole, a country must subsequently make fuel adjustments in other relevant fuel consuming sectors in order to maintain the grand national energy balance.

The methodologies may be used to calculate the emissions following the UNECE/EMEP definition of national and international shipping, as well as other definitions (flag, ownership, geographical area etc.).

3.4.1 Algorithm

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

$$E_{Trip} = E_{Hotelling} + E_{Manouvering} + E_{Cruising}$$

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

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

$$E_{Trip,i,j,m} = \sum_{p} \left(FC_{j,m,p} \times EF_{i,j,m,p} \right)$$

where:

E_{Trip} = emission over a complete trip (tonnes),

FC = fuel consumption (tonnes),

EF = emission factor (kg/tonne) from Table 3-9,

i = pollutant (NO_x, NMVOC, PM)

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

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

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

Emissions of other pollutants than those in Table 3-9 can be calculated using the Tier 1 method with the emission factors included in Table 3-1 through Table 3-3, depending on the type of fuel.

When fuel consumption per trip phase is not known, then a different methodology is proposed for computing emissions, based on installed power and time spent in the different navigation phases. Emissions can be calculated from a detailed knowledge of the installed main and auxiliary engine power, load factor and total time spent, in hours, for each phase using the following equation.

$$E_{Trip,i,j,m} = \sum_{p} \left[T_P \sum_{e} \left(P_e \times LF_e \times EF_{e,i,j,m,p} \right) \right]$$

where:

E_{Trip} = emission over a complete trip (tonnes),
EF = emission factor (kg/tonne) from Table 3-10, depending on type of vessel,
LF = engine load factor (%)
P = engine nominal power (kW)
T = time (hours),
e = engine category (main, auxiliary)
i = pollutant (NO_x, NMVOC, PM)
j = engine type (slow-, medium-, and high-speed diesel, gas turbine and steam turbine).
m = fuel type (bunker fuel oil, marine diesel oil/marine gas oil, gasoline),
p = the different phase of trip (cruise, hotelling, manoeuvring).

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

$$T_{\text{Cruising}}(\,hours\,) = \frac{\text{Distance Cruised(km)}}{\text{Average Cruising Speed(km/hr)}}$$

Where the installed power of the main or auxiliary engines is not known, this can be estimated with the methodology described in chapter 0.

Emissions of other pollutants than those in Table 3-10 can be calculated using the Tier 1 method and the emission factors included in Table 3-1 and Table 3-2, depending on the type of vessel.

For estimating emissions from small boats, where separate national activity statistics are not collected, activity data need to be derived from data on the population of these crafts, by boat type, fuel type, engine type, technology layer, and activity data for engine load factors and the estimated annual hours of use. The fuel consumption and emissions per fuel type are estimated as follows:

$$E_{i,m} = \sum_{b} \sum_{e} \sum_{z} \left(N_{b,e,z} \times T_{b,e,z} \times P_{b,e,z} \times LF_{b,e,z} \times EF_{b,e,z} \right)$$

where

E = emissions by small boats per year (tonnes)
N = number of vessels (vessels)
T = average duration of operation of each vessel per year (hours/vessel)
P = nominal engine power (kW)

LF = engine load factor (%)
EF = emission factor (g/kWh)
b = vessel type (yawl, cabin boat, sailing, …)
e = engine type (inboard, onboard, 2S, 4S)
i = pollutant (NMVOC, NH_3, NOx, PM) or fuel consumption
m = fuel type (gasoline, diesel)
z = technology layer (conventional, 2003/44/EC)

Generally, if the calculations for navigation are based on samples, the results must be scaled to get an annual total. A Geographical Information System (GIS) can be used to spatially disaggregate the data.

3.4.2 Tier 3 engine, fuel and activity specific emission factors

NO_x, NMVOC and PM emission factors for the individual engine/fuel type combinations are provided in Table 3-9 in units of mass of pollutant per tonne of fuel and in Table 3-10 in units of mass of pollutant per kWh. In this table, the specific fuel consumption is also given. For an explanation of factors separated for 2000, 2005 and 2010 see Tier 2 (section 3.3.2).

For the other pollutants, emission factors of Tier 1 can be used (Table 3-1 and Table 3-2).

For small recreational and service vessels, emission factors are listed in Table 3-11, taken from Winther and Nielsen (2006).

Table 3-9 Tier 3 emission factors for NO_x , NMVOC, PM for different engine types/fuel combinations and vessel trip phases (cruising, hotelling, manoeuvring)

Engine	Phase	Engine type	Fuel type	NO_x EF 2000 (kg/tonne)	NO_x EF 2005 (kg/tonne)	NO_x EF 2010 (kg/tonne)	NMVOC EF (kg/tonne)	TSP PM_{10} $PM_{2.5}$ EF (kg/tonne)
Main	Cruise	Gas turbine	BFO	20.0	19.3	18.6	0.3	0.3
			MDO/MGO	19.7	19.0	18.3	0.3	0.0
		High-speed diesel	BFO	59.6	57.7	55.6	0.9	3.8
			MDO/MGO	59.1	57.1	55.1	1.0	1.5
		Medium-speed diesel	BFO	65.7	63.4	61.3	2.3	3.8
			MDO/MGO	65.0	63.1	60.6	2.4	1.5
		Slow-speed diesel	BFO	92.8	89.7	86.5	3.0	8.7
			MDO/MGO	91.9	88.6	86.5	3.2	1.6
		Steam turbine	BFO	6.9	6.6	6.4	0.3	2.6
			MDO/MGO	6.9	6.6	6.4	0.3	1.0
	Manoeuvring Hotelling	Gas turbine	BFO	9.2	8.9	8.6	1.5	4.5
			MDO/MGO	9.1	8.8	8.5	1.5	1.6
		High-speed diesel	BFO	43.6	42.3	40.6	2.5	10.3
			MDO/MGO	43.0	41.7	40.1	2.6	4.0
		Medium-speed diesel	BFO	47.9	46.2	44.6	6.3	10.3
			MDO/MGO	47.5	45.7	44.3	6.6	4.0
		Slow-speed diesel	BFO	67.4	65.1	62.9	8.2	11.2
			MDO/MGO	66.7	64.2	62.1	8.6	4.4

		Steam turbine	BFO	5.1	4.8	4.7	0.9	7.1
			MDO/MGO	5.0	5.0	4.7	0.9	2.8
Auxiliary	Cruise Manoeuvring Hotelling	High-speed diesel	BFO	51.1	49.4	47.6	1.7	3.5
			MDO/MGO	50.2	48.6	46.8	1.8	1.4
		Medium-speed diesel	BFO	64.8	62.5	60.4	1.7	3.5
			MDO/MGO	64.1	62.0	59.7	1.8	1.4

Source: Entec (2002), Entec (2007), the emission factors for NMVOC was been derived as 98 % of the original HC emission factors value, based on reported CH4 factors from IPCC (1997).
Note
See Table 3-1 and Table 3-2 for emission factors for other pollutants.
BC fraction of PM (f-BC); BFO: 0.12, MDO/MGO: 0.31. Source: for further information see Appendix A

Table 3-10 Tier 3 emission factors for NO_x, NMVOC, PM and Specific Fuel Consumption for different engine types/fuel combinations and vessel trip phases (cruising, hotelling, manoeuvring) in g/kWh

Engine	Phase	Engine type	Fuel type	NO_x EF 2000 (g/kWh)	NO_x EF 2005 (g/kWh)	NO_x EF 2010 (g/kWh)	NMVOC EF (g/kWh)	TSP PM_{10} $PM_{2.5}$ EF (g/kWh)	Specific fuel consumption (g fuel/kWh)
Main	Cruise	Gas turbine	BFO	6.1	5.9	5.7	0.1	0.1	305.0
			MDO/MGO	5.7	5.5	5.3	0.1	0.0	290.0
		High-speed diesel	BFO	12.7	12.3	11.8	0.2	0.8	213.0
			MDO/MGO	12.0	11.6	11.2	0.2	0.3	203.0
		Medium-speed diesel	BFO	14.0	13.5	13.0	0.5	0.8	213.0
			MDO/MGO	13.2	12.8	12.3	0.5	0.3	203.0
		Slow-speed diesel	BFO	18.1	17.5	16.9	0.6	1.7	195.0
			MDO/MGO	17.0	16.4	15.8	0.6	0.3	185.0
		Steam turbine	BFO	2.1	2.0	2.0	0.1	0.8	305.0
			MDO/MGO	2.0	1.9	1.9	0.1	0.3	290.0
	Manoeuv ring Hotelling	Gas turbine	BFO	3.1	3.0	2.9	0.5	1.5	336.0
			MDO/MGO	2.9	2.8	2.7	0.5	0.5	319.0
		High-speed diesel	BFO	10.2	9.9	9.5	0.6	2.4	234.0
			MDO/MGO	9.6	9.3	8.9	0.6	0.9	223.0
		Medium-speed diesel	BFO	11.2	10.8	10.4	1.5	2.4	234.0
			MDO/MGO	10.6	10.2	9.9	1.5	0.9	223.0
		Slow-speed diesel	BFO	14.5	14.0	13.5	1.8	2.4	215.0
			MDO/MGO	13.6	13.1	12.7	1.8	0.9	204.0
		Steam turbine	BFO	1.7	1.6	1.6	0.3	2.4	336.0
			MDO/MGO	1.6	1.6	1.5	0.3	0.9	319.0
Auxi-liary	Cruise Manoeuv ring Hotelling	High-speed diesel	BFO	11.6	11.2	10.8	0.4	0.8	227.0
			MDO/MGO	10.9	10.5	10.2	0.4	0.3	217.0
		Medium-speed diesel	BFO	14.7	14.2	13.7	0.4	0.8	227.0
			MDO/MGO	13.9	13.5	13.0	0.4	0.3	217.0

BFO –Bunker Fuel Oil, MDO –Marine Diesel Oil, MGO –Marine Gas Oil
Source: Entec (2002), Entec (2007), the emission factors for NMVOC was been derived as 98 % of the original HC emission factors value, based on reported CH4 factors from IPCC (1997).
Note. See Table 3-1 and Table 3-2 for emission factors for other pollutants.
BC fraction of PM (f-BC); BFO: 0.12, MDO/MGO: 0.31. Source: for further information see Appendix A

Table 3-11 Tier 3 emission factors for recreational vessels

Fuel type	Vessel type	Engine Type		Technology Layer	Nominal power	NMVOC	NH_3	NO_x	TSP PM_{10} $PM_{2.5}$	Fuel
					[kW]	[g/kWh]				
Gasoline	Other boats (< 20 ft)	Out board	2S	2003/44	8	45.49	0.002	2	10	791
				Conv.	8	254.69	0.002	2	10	791
			4S	2003/44	8	21.60	0.002	7	0.08	426
				Conv.	8	21.60	0.002	7	0.08	426
	Yawls and cabin boats	Out board	2S	2003/44	20	36.17	0.002	3	10	791
				Conv.	20	170.45	0.002	3	10	791
			4S	2003/44	20	12.60	0.002	10	0.08	426
				Conv.	20	12.60	0.002	10	0.08	426
	Sailing boats (< 26 ft)	Out board	2S	2003/44	10	42.61	0.002	2	10	791
				Conv.	10	254.69	0.002	2	10	791
			4S	2003/44	10	21.60	0.002	7	0.08	426
				Conv.	10	21.60	0.002	7	0.08	426
	Speed boats	In board	4S	2003/44	90	9.00	0.002	12	0.08	426
				Conv.	90	9.00	0.002	12	0.08	426
		Out board	2S	2003/44	50	31.51	0.002	3	10	791
				Conv.	50	170.45	0.002	3	10	791
			4S	2003/44	50	12.60	0.002	10	0.08	426
				Conv.	50	12.60	0.002	10	0.08	426
	Water scooters	Out board	2S	2003/44	45	31.91	0.002	3	10	791
				Conv.	45	170.45	0.002	3	10	791
			4S	2003/44	45	12.60	0.002	10	0.08	426
				Conv.	45	12.60	0.002	10	0.08	426
Diesel	Motor boats (27–34 ft)	In board		2003/44	150	1.67	0.002	8.6	1	275
				Conv.	150	1.97	0.002	8.6	1.2	275
	Motor boats (> 34 ft)			2003/44	250	1.58	0.002	8.6	1	275
				Conv.	250	1.97	0.002	8.6	1.2	275
	Motor boats (< 27 ft)			2003/44	40	1.77	0.002	9.8	1	281
				Conv.	40	2.17	0.002	18	1.4	281
	Motor sailors			2003/44	30	1.87	0.002	9.8	1	281
				Conv.	30	2.17	0.002	18	1.4	281
	Sailing boats (> 26 ft)			2003/44	30	1.87	0.002	9.8	1	281
				Conv.	30	2.17	0.002	18	1.4	281

Source: Winther & Nielsen, 2006
BC fraction of PM (f-BC); Diesel: 0.55, Gasoline: 0.05. Source: for further information see Appendix A

Activity data

The LMIS (Lloyd's Maritime Information Service) database records all ship movements world-wide. The database includes ship size, destination, approximate time of arrival and departure, engine type and number, etc. The data are available in computerised form. The database covers all ships greater than 250–500 gross tonnes. Ferries and fishing vessels are typically not included. Smaller ports are also excluded. A week or a whole year may be chosen. A selection may also be made on area or on ship nationality. The dataset will have to be purchased.

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

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

For ferries, ship movement data will be available from timetables giving the departures and destinations. International timetables include all main ferry routes in Europe, but more detailed information (covering smaller ferries) will be available from national sources. Such information must be supplemented with engine information. It should be distinguished between summer and winter when applying timetables.

The International Council for the Exploration of the Seas collects information on fishing deliveries (catch area and port of landing) which gives an indication of the vessel movements. The data here are confidential, but are based on national reporting which may be available. The information must be linked to a vessel register. Additional information must be collected on the time spent fishing, as fishing vessels will not move in straight lines when operating. Fishing vessels may also be used for other activities than fishing. Factory ships and trawlers may have significant fuel use connected to trawling, processing and refrigeration, in addition to the vessel movement.

The customs or coast guard authorities may keep records of the international ship traffic in national territorial waters.

Two different procedures are available in Tier 3 starting on a basis of either fuel consumption or engine power.

a. Estimating emissions based on fuel consumption

This procedure is applicable only where detailed information about fuel consumptions for each ship/engine type combination in the different navigation phases is available; otherwise use the alternative engine power based procedure below.

1. Obtain fuel consumption for each individual ship, engine type/fuel class and ship activity. This may be done for the whole year or a representative sample of the year, for all ships or for a representative sample of the ships for each ship category and engine type/fuel class. This choice will depend on the resources available and the required accuracy of the study.
2. Calculate emissions for each ship category and engine type/fuel class multiplying by the emission factors from Table 3-9.

b. Estimating emissions based on engine power

1. Obtain ship movement data: place of departure, place of arrival, time of departure and time of arrival for each individual ship. This may be done for the whole year or a representative sample of the year, for all ships or for a representative sample of the ships. This choice will depend on the resources available and the required accuracy of the study.
2. Determine the sailing routes and distances between ports. This may be done individually or fitted into the main shipping lanes. A GIS (Geographical Information System) is useful, but not necessary, for this task. If a GIS is not available, there are standard distance tables for distances between main ports (Thomas Reed Publications, 1992). The main shipping routes are given in the IMO publication 'Ships' Routing' (International Maritime Organization, 1987). Distances are given in Reed's Marine Distance Table (Thomas Reed Publications, 1992).
3. Characterise each ship by ship category (as in Table 3-6) and engine type/fuel class (if unknown use Table 3-7) and record the installed main or auxiliary engine power. A ship register, giving the size and engine type of individual ships, is useful for this. Such a register of the national fleet should be available in most countries but usually only covering national ships. Lloyds Register's Register of Ships will provide details of national and international shipping greater than 100 GT. If engine power is unknown, and only gross tonnage (GT) is available, installed main engine power can be obtained from Table 3-12 (with reference to 1997 world fleet, 2010 world fleet and 2006 Mediterranean Sea fleet) and then installed auxiliary engine power from Table 3-13 (with reference to 2010 world fleet and 2006 Mediterranean Sea fleet while 1997 world fleet data are not available).
4. Determine the total sailing time for each ship category and engine type/fuel class, either based on the distance and average cruise speed (Table 3-14) or time of departure and arrival. The choice should be based on an assessment of the quality of the data.
5. Determine total hotelling and manoeuvring time for each ship category and engine type/fuel class by port survey or on the basis of average time spent values provided (Table 3-14).
6. Calculate emissions for each ship category and engine type/fuel class multiplying total time spent in each phases, as determined in previous steps 4 and 5, by the installed main and auxiliary engine power, for each ship category, calculated as determined in step 3, load factors (and for main engine % time of operation) from Table 3-15 and emission factors from Table 3-10.

Table 3-12 Installed main engine power as a function of gross tonnage (GT)

Ship categories	2010 world fleet	1997 world fleet	Mediterranean Sea fleet (2006)
Liquid bulk ships	$14.755*GT^{0.6082}$	$29.821*GT^{0.5552}$	$14.602*GT^{0.6278}$
Dry bulk carriers	$35.912*GT^{0.5276}$	$89.571*GT^{0.4446}$	$47.115*GT^{0.504}$
Container	$2.9165*GT^{0.8719}$	$1.3284*GT^{0.9303}$	$1.0839*GT^{0.9617}$
General Cargo	$5.56482*GT^{0.7425}$	$10.539*GT^{0.6760}$	$1.2763*GT^{0.9154}$
Ro Ro Cargo	$164.578*GT^{0.4350}$	$35.93*GT^{0.5885}$	$45.7*GT^{0.5237}$
Passenger	$9.55078*GT^{0.7570}$	$1.39129*GT^{0.9222}$	$42.966*GT^{0.6035}$
Fishing	$9.75891*GT^{0.7527}$	$10.259*GT^{0.6919}$	$24.222*GT^{0.5916}$
Other	$59.049*GT^{0.5485}$	$44.324*GT^{0.5300}$	$183.18*GT^{0.4028}$
Tugs	$54.2171*GT^{0.6420}$	$27.303*GT^{0.7014}$	

Source: Trozzi (2010) for 2010 and 1997 world fleets; Entec (2007) for 2006 Mediterranean Sea fleet; (for 1997 fleet a conversion 1 GT = 1.875 GRT was used)

Table 3-13: Estimated average vessel ratio of Auxiliary Engines / Main Engines by ship type

Ship categories	2010 world fleet	Mediterranean Sea fleet (2006)
Liquid bulk ships	0.30	0.35
Dry bulk carriers	0.30	0.39
Container	0.25	0.27
General Cargo	0.23	0.35
Ro Ro Cargo	0.24	0.39
Passenger	0.16	0.27
Fishing	0.39	0.47
Other	0.35	0.18
Tugs	0.10	

Source: Trozzi (2010) for 2010 world fleet; Entec (2007) for 2006 Mediterranean Sea fleet

Table 3-14 Assumptions for the average cruise speed and average duration of in-port activities

Ship Type	Ave.Cruise Speed (km/h)	Manoeuvring time (hours)	Hotelling time (hours)
Liquid bulk ships	26	1.0	38
Dry bulk carriers	26	1.0	52
Container	36	1.0	14
General Cargo	23	1.0	39
Ro-Ro Cargo	27	1.0	15
Passenger	39	0.8	14
Fishing	25	0.7	60
Other	20	1.0	27

Source: Elaboration from Entec (2002)

Table 3-15 Estimated % load of MCR (Maximum Continuous Rating) of Main and Auxiliary Engine for different ship activity

Phase	% load of MCR Main Engine	% time all Main Engine operating	% load of MCR Auxiliary Engine
Cruise	80	100	30
Manoeuvring	20	100	50
Hotelling (except tankers)	20	5	40
Hotelling (tankers)	20	100	60

Source: Entec (2002)

Table 3-16 lists the activity data for diesel, two-stroke and four-stroke gasoline-fuelled recreational craft typically being used, derived from the Danish emission inventory (Winther and Nielsen, 2006).

Table 3-16 Activity data for recreational craft in Denmark

Fuel type	Engine type	Vessel type	Engine	Engine size (kW)	Ann, Hours (hours)	Load factor	Lifetime (years)
Gasoline	2-stroke	Yawls and cabin boats	Out-board	20	50	0.5	10
		Sailing boats (< 26 ft)	Out-board	10	5	0.5	10
		Speed boats	Out-board	50	50	0.5	10
		Other boats (< 20 ft)	Out-board	8	30	0.5	10
		Water scooters	Built-in	45	10	0.5	10
	4-stroke	Yawls and cabin boats	Out-board	20	50	0.5	10
		Sailing boats (< 26 ft)	Out-board	10	5	0.5	10
		Speed boats	In-board	90	75	0.5	10
		Speed boats	Out-board	50	50	0.5	10
		Other boats (< 20 ft)	Out-board	8	30	0.5	10
		Water scooters	Built in	45	10	0.5	10
Diesel		Motor boats (27–34 ft)	In-board	150	150	0.5	15
		Motor boats (> 34 ft)	In-board	250	100	0.5	15
		Motor boats (< 27 ft)	In-board	40	75	0.5	15
		Motor sailors	In-board	30	75	0.5	15
		Sailing boats (< 26 ft)	In-board	30	25	0.5	15

Source: Winther & Nielsen, 2006

3.5 Species profile

The speciation of PAHs as determined by Lloyd's Register (1995) is given in Table 3-13. Cooper et al, (1996) has measured the C_2-C_6 and C_6-C_{12} hydrocarbon concentrations in exhaust from two ferries given in Table 3-16.

Table 3-17 PAH emissions, distribution by species

Species	Average (%)	Range (%)
Phenanthrene	37	32-54
Anthracene	1	0-2
Fluoranthene	11	9-15
Pyrene	14	12-20
3,6-dimethylphenanthrene	4	3-5
Triphenylene	12	9
Benxo(b)-fluorene	6	2-19
Benzo(a)anthracene	2	0-2
Chrysene	5	3-9
Benzo(e)-pyrene	2	0
Benzo(j)fluoranthene	0	0
Perylene	0	0-3
Benzo(b)-fluoranthene	1	0-2
Benzo(k)-fluoranthene	0	0
Benzo(a)pyrene	0	0
Dibenzo(a,j)anthracene	0	0-1
Dibenzo(a,l)pyrene	0	0
Benzo(g,h,i)perylene	1	0-2
Dibenzo(a,h)anthracene	1	0-6
Ideno(1,2,3-c,d)pyrene	0	0-1
3-methyl-cholanthrene	0	0
Anthanthrene	0	0

Source: Lloyd's Register, 1995

Table 3-18 Exhaust hydrocarbon concentrations (%)

Species	Ferry 1	Ferry 2
Ethane	0	0
Ethene	5	20
Propane	0	0
Propene	2	6
Ethyne	0	0
Propadiene	0	0
Butane	0	0
trans-2-Butene	0	0
1-Butene	0	1
Isobutene	1	18
cis-2-butene	0	0
Pentane	0	0
Propyne	0	0
3-Methyl-1-butene	0	0
trans-2-Pentene	0	0
1-Pentene	0	1
cis-2-Pentene	0	0
Hexane	0	0
Other C_6 alkenes	0	0
1-Hexene	0	0
Nonane	10	0
Decane	25	0
Undedecane	19	0
Dodecane	14	0
Benzene	4	35
Toluene	5	15
Ethylbenzene	1	0
o-Xylene	2	0
m Plus p-Xylene	4	4
1,3,5-Trimethylbenzene	2	0
1,2,4-Trimethylbenzene	2	0
1,2,3-Trimethylbenzene	3	0

Source: Cooper et.al, 1996.

3.6 Military shipping activities

Emissions from military water-borne fuel use can be estimated using the same algorithm as is used for the Tier 1 approach (see subsection 3.2). Due to the special characteristics of the operations, situations, and technologies (e.g. .aircraft carriers, very large auxiliary power plants, and unusual engine types) associated with military water-borne navigation, a more detailed method of data analysis is encouraged when data are available. Inventory compilers should therefore consult military experts to determine the most appropriate emission factors for the country's military water-borne navigation.

Due to confidentiality issues (see completeness and reporting); many inventory compilers may have difficulty obtaining data for the quantity of military fuel use. Military activity is defined here as those activities using fuel purchased by or supplied to military authorities in the country. It is good practice to apply the rules defining civilian domestic and international operations in water-borne navigation to military operations when the data necessary to apply those rules are comparable and available. Data on military fuel use should be obtained from government military institutions or fuel suppliers.

If data on fuel split are unavailable, all the fuel sold for military activities should be treated as domestic.

Emissions resulting from multilateral operations pursuant to the Charter of the United Nations should not be included in national totals; other emissions related to operations shall be included in the national emissions totals of one or more parties involved. The national calculations should take into account fuel delivered to the country's military, as well as fuel delivered within that country but used by the military of other countries. Other emissions related to operations (e.g. off-road ground support equipment) should be included in the national emissions totals in the appropriate source category.

4 Data quality

4.1 Completeness

If Tier 3 approach is used to calculate the fuel consumption and emissions for navigation, it is necessary to make fuel adjustments in other relevant fuel consuming sectors in order to maintain the grand national energy balance. The latter point is essential if the general reporting criteria for the country as a whole is to be followed.

If Tier 1 and 2 estimates are calculated, the methods should be reconciled to total fuel use. Since countries generally have effective accounting systems to measure total fuel consumption. The largest area of possible incomplete coverage of this source category is likely to be associated with misallocation of navigation emissions in another source category. For instance, for small watercraft powered by gasoline engines, it may be difficult to obtain complete fuel use records and some of the emissions may be reported as industrial (when industrial companies use small watercraft), other off-road mobile or stationary power production. Estimates of water-borne emissions should include not only fuel for marine shipping, but also for passenger vessels, ferries, recreational watercraft, other inland watercraft, and other gasoline-fuelled watercraft.

Fugitive emissions from transport of fossil fuels should be estimated and reported under the NFR category 1.B.2.a.v Distribution of oil products. Most fugitive emissions occur during loading and unloading and are therefore accounted under that category. Emissions during travel are considered insignificant.

Completeness may also be an issue where military data are confidential, unless military fuel use is aggregated with another source category.

There are additional challenges in distinguishing between domestic and international emissions. As each country's data sources are unique for this category, it is not possible to formulate a general rule regarding how to make an assignment in the absence of clear data. It is good practice to specify clearly the assumptions made so that the issue of completeness can be evaluated.

4.2 Verification

It is good practice to conduct quality control checks. Specific procedures of relevance to this source category are outlined below.

Comparison of emissions using alternative approaches

If possible, the inventory compiler should compare estimates determined for water-borne navigation using both Tier 1 and Tier 2 approaches. The inventory compiler should investigate and explain any anomaly between the emission estimates. The results of such comparisons should be recorded.

Review of emission factors

The inventory compiler should ensure that the original data source for national factors is applicable to each category and that accuracy checks on data acquisition and calculations have been performed. If national emission factors are available, they should be used, provided that they are well documented. For the default factors, the inventory compiler should ensure that the factors are applicable and relevant to the category.

If emissions from military use were developed using data other than default factors, the inventory compiler should check the accuracy of the calculations and the applicability and relevance of the data.

Check of activity data

The source of the activity data should be reviewed to ensure applicability and relevance to the category. Where possible, the data should be compared to historical activity data or model outputs to look for anomalies. Data could be checked with productivity indicators such as fuel per unit of water-borne navigation traffic performance compared with other countries. For example, the previous European Topic Centre on Air and Climate Change (ETC/ACC) of the Environment Agency (EEA) provided a useful dataset from 2003, http://air-climate.eionet.eu.int/databases/TRENDS/TRENDS_EU15_data_Sep03.xls, which presents emissions and passenger/freight volume for each transportation mode for Europe. The information for shipping is very detailed. Examples of such indicators include: for ships with less than 3 000 GT the CO_2-index range from 0.09 to 0.16 kg CO_2/tonne-km; for larger ships between 0.04 and 0.14 kg CO_2/tonne-km; and for passenger ferries, the factors range from 0.1–0.5 kg CO_2/passenger-km.

External review

The inventory compiler should perform an independent, objective review of calculations, assumptions or documentation of the emissions inventory to assess the effectiveness of the QC programme. The peer review should be performed by expert(s) (e.g. transport authorities, shipping companies, and military staff) who are familiar with the source category and who understand inventory requirements.

4.3 Developing a consistent time series and recalculation

It is good practice to determine fuel use using the same method for all years. If this is not possible, data collection should overlap sufficiently in order to check for consistency in the methods employed.

Emissions of NO_x, PM, NMVOC and CO will depend on engine type and technology. Unless technology-specific emission factors have been developed, it is good practice to use the same fuel-specific set of emission factors for all years.

Mitigation activities resulting in changes in overall fuel consumption will be readily reflected in emission estimates if actual fuel activity data are collected. Mitigation options that affect emission factors, however, can only be captured by using engine-specific emission factors, or by developing control technology assumptions. Changes in emission factors over time should be well documented.

Marine diesel oil and bunker fuel oil are the fuels used primarily for large sources within water-borne navigation. As the sulphur and metals contents of these fuels may vary over the time series, the source of sulphur content should be explicitly stated, as well as the dates the fuels were tested.

4.3.1 Uncertainties

Entec (2002) provides estimates of uncertainties for emission factors as indicated in the table below.

Table 4-1: Estimated uncertainties given as percentage related to the emission factors

Parameter	at sea	manoeuvring	in port
NO_x	±20%	±40%	±30%
SO_x	±10%	±30%	±20%
NMVOC	±25%	±50%	±40%
PM	±25%	±50%	±40%
Fuel Consumption	±10%	±30%	±20%

Note: Estimated uncertainties at the 95% confidence interval given as a relative percent of the emission factors (in g/kWh or kg/tonne fuel). For example the NO_x emission factor at sea has a 20 % relative uncertainty assigned, which means that 95 % of ships' emissions will lie within ± 20 % of the assigned factors. Source: Entec (2002)

Much of the uncertainty in the activity data for water-borne navigation emission estimates is related to the difficulty of distinguishing between domestic and international fuel consumption. With complete survey data, the uncertainty may be low (say ±5 percent), while for estimations or incomplete surveys the uncertainties may be considerable (say ±50 percent). The uncertainty will vary widely from country to country and is difficult to generalise. Global data sets may be helpful in this area, and it is expected that reporting will improve for this category in the future.

4.4 Gridding

The EMEP modelling centres do not need very detailed and exact data since the EMEP grids are quite large (50*50 sq km) and therefore an approach using lesser detail may be sufficient. One approach may be to use harbour statistics to get time in dock, multiply by a dock fuel consumption factor per ship category (if appropriate), see where the ship goes from (sample) transport statistics and multiply by a consumption factor per nm (nautical mile). The emissions are then distributed by a straight line going from departure to destination.

4.5 Reporting and documentation

No specific issues.

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6 Point of enquiry

Enquiries concerning this chapter should be directed to the relevant leader(s) of the Task Force on Emission Inventories and Projection's expert panel on Transport. Please refer to the TFEIP website (www.tfeip-secretariat.org/) for the contact details of the current expert panel leaders.

Appendix A: Black carbon (BC) fractions of PM emissions from navigation

In order to maintain consistency throughout the guidebook, it should be noted that the literature emission factor values used here directly represent elemental carbon (EC), and these values are assumed to be equal to BC.

Table A1 presents an overview of the nine studies which have been regarded relevant as sources for BC fractions of PM emissions (f-BC) for navigation. All studies report emission results from single engine measurements, except one study for which the results are obtained from plume measurements of a large number of vessels. Apart from f-BC fractions, for each study the vessel type, fuel type and engine characteristics such as engine speed class, stroke and engine size is listed, as well as the PM emission sampling conditions as far as information is available. Some of the following references also report figures for OC which can be input for the further assessment of OC fractions of PM (f-OC).

Agrawal (2010) reports PM measurement results (including hydrated sulphate), EC and OC, from this specific study and previous measurements documented in Agrawal (2008a and 2008b). Agrawal et al. (2010) interpret EC as BC for all three studies.

Petzold (2010) reports own PM measurement results (including hydrated sulphate) as well as EC, BC, OM and SO_4^{2-}. In addition, Petzold show a result summary table for other measurement studies with corresponding PM and BC measurements, and hence f-BC to be derived from these measurements. The PM results from Murphy et al. (2009) are listed including hydrated sulphate. The PM results from Lack et al. (2009) based on plume measurements are listed excluding hydrated sulphate. The latter explains why BC shares become very high in the Lack et al. (2009) case, as shown in Table A1.

In more details, the above mentioned study Murphy et al. (2009) reports measurements of total PM (including hydrated sulphate), EC, OC, and sulphate (SO_4). Calculated hydrated sulphate (H_2SO_4*$6.5H_2O$) figure is also shown. The EC results obtained by Murphy et al. (2009) are interpreted as BC by Petzold et al. (2010).

Lack et al. (2009 and 2011) report plume measurements of total PM excluding SO_4 bound water or ash, and also reports SO_4, POM and BC. As previously mentioned, the BC shares of PM derived from Lack et al. (2009, 2011) are generally high compared to other measurements studies. The high BC emission shares can be explained by the fact that the related PM emissions does not include water bound SO_4. Lack et al. (2009) obtain emission results from the plume of 211 commercial vessels during an extensive measurement campaign. In Lack et al. (2011), the emissions are measured from one vessel before and after fuel switch between low sulphur and high sulphur fuel.

Lack et al (2009) reports f-BC figures derived from measurements made by Petzold et al. (2004) and Kasper et al. (2007).

A comprehensive literature review has been made by Lack and Corbett (2012) assessing the emission impact of engine load, fuel quality and exhaust after treatment systems for engines used by navigation. Although the work made by Lack and Corbett (2012) contain a lot of detailed information of BC emissions from ship engines, data on total PM emissions are excluded from the literature review. Hence, it is not possible to derive consistent f-BC fractions of PM from this source.

The derived f-BC fractions as well as vessel, fuel, engine characteristics and sampling conditions from the above mentioned studies are listed in the following Table A1.

Table A1. BC fractions of PM emissions from relevant studies

Reference	Vessel	Fuel[a]	Engine[b]	Stroke	Size (kW)	Sampling	f-BC
Petzold et al. (2004)	-	HFO	SS				0.07
Kasper et al. (2007)	Tanker	HFO	SS	2-stroke	8500	-	0.17
	Tanker	MDO	SS	2-stroke	8500	-	0.17
Lack et al. (2009)		HFO	SS			Plume	0.12
		MDO	MS			Plume	0.40
		MDO	HS			Plume	0.22
		MDO, avg				Plume	0.31
Lack et al. (2011)		HFO	SS			Plume	0.06
		MDO	SS			Plume	0.33
Agrawal et al. (2008a)	Container	HFO	SS	2-stroke	50270	8178-1	0.013
Agrawal et al. (2008b)	Tanker	HFO	SS	2-stroke	15750	8178-1	0.011
Agrawal et al. (2010)	Container	HFO	SS	2-stroke	54840	8178-4	0.003
Murphy et al. (2009)	Container	HFO	SS	2-stroke	54840	8178-1	0.003
Petzold et al. (2010)	-	HFO	MS	4-stroke	10000		0.026

a: HFO: heavy fuel oil; MDO: marine diesel oil
b: SS: Slow speed; MS: Medium speed; HS: High speed

Conclusion

It is proposed to use the f-BC fractions derived from the plume measurements made by Lack et al. (2009) and to distinguish only between fuel types. The main reason for selecting the data from Lack et al. (2009) is that the latter study is very comprehensive having measured the emissions from 211 commercial vessels. In opposition, the remaining studies referenced above are single engine experiments. The data for slow speed engines from Lack et al. (2009) is used to represent HFO (f-BC = 0.12) in the guidebook chapter for navigation, whereas the average of the emissions from medium and high speed engines is used to represent MDO (f-BC = 0.31). A +/- uncertainty range of 20 % for the BC emission factor is stated by Lack et al. (2009), and this emission factor uncertainty range is adopted for the Guidebook as well.

Table A2 lists the tables in the guidebook chapter for navigation which contain f-BC fraction information. These fractions must then be combined with the existing PM factors in the Guidebook in order to establish the final BC emission factor in each case.

Table A2 Guidebook tables which contain f-BC fraction data

Table no.	Tier	Detail	BC:PM data source
3-1	1	HFO	Present note; f-BC = 0.12
3-2	1	MGO	Present note; f-BC = 0.31
3-3	1	Gasoline (boats)	Winther et al. (2011); f-BC = 0.05
3-4	2	Engine type x Fuel type	Present note; HFO: 0.12, MGO: 0.31
3-5	2	Boats (D/G2/G4) x Fuel type	Winther et al. (2011); diesel: 0.55, gasoline: 0.05
3-9	3	Phase x Engine type x Fuel type	Present note; HFO: 0.12, MGO: 0.31
3-10	3	Phase x Engine type x Fuel type	Present note; HFO: 0.12, MGO: 0.31
3-11	3	Boats (D/G2/G4) x Vessel type x Fuel type	Winther et al. (2011); diesel: 0.55, gasoline: 0.05

For diesel fuelled boats, f-BC = 0.55 are taken from road transport conventional car engines available from the COPERT model. For gasoline fuelled boats, f-BC = 0.05 are taken from Winther and Nielsen (2011) based on information from Kupiainen and Klimont (2004).

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