Emission estimate methodology for maritime navigation

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Summary

- ✔ *The paper reports about the methodology for estimate emissions from navigation, recently updated in the frame of maintenance of the EMEP/EEA air pollutant emission inventory guidebook (the Guidebook)*
- ✔ *The methodology uses both installed capacity and fuel consumption as alternative for estimate emission in cruise (open sea), manoeuvring (approaching harbours) and hotelling (at the dock in port) and take into account both the main and auxiliary engines*

Guidebook

- ✔ The Navigation chapter of the EMEP/EEA air pollutant emission inventory guidebook is the reference for emission estimate at international level
- ✔ The Guidebook is designed to facilitate reporting of emission inventories by countries to the UNECE Convention on Long-range Transboundary Air Pollution and the EU National Emission Ceilings Directive
- ✔ It is also recommended by IPCC Guidelines for the indirect greenhouse gases emissions estimates that Parties report under UNFCCC

Emission estimate methodologies

- ✔ The emissions can be computed:
  - ✔ with fuel related emission factors (EFs) for the different navigation phases where fuel consumptions (FCs) are know
  - ✔ with a methodology based on installed power, where fuel consumptions are not know
- ✔ When installed power is not know specific functions (derived using data on about 100.000 ships from Lloyds register) are proposed to evaluate installed power from gross tonnage
- ✔ Finally simplified methodologies are introduced

World Fleet Characterization

- For the use of the methodologies a world fleet characterization was realized based on an analysis of the available literature on the subject and on statistical analysis of Lloyd's database for 1999 and 2010
- The Lloyd database for 1999 was first analyzed in the frame of MEET project (Methodologies for estimating air pollutant emissions from transport under the transport RTD program of the European Commission fourth framework program)
- The Lloyd database for 2010 was analyzed in the frame of the special project to update EMEP/EEA Guidebook
- In the following slides elaboration of world fleet data from Lloyd's are reported

Emission estimate methodologies

- Where fuel consumptions are known:

$$E_{trip,i} = 10^{-3} \Sigma_e \Sigma_j \Sigma_m \Sigma_p (FC_{e,j,m,p} * EFC_{i,e,j,m,p})$$

- Where fuel consumptions are not known:

$$E_{trip,i} = 10^{-3} \Sigma_p T_p [\Sigma_e \Sigma_j \Sigma_m (P_{e,j} * LF_{e,j} * EFP_{i,p,e,j,m})]$$

i = pollutant

e, engine (main, auxiliary)

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

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

p, phase (cruise, hotelling, manoeuvring)

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

FC, fuel consumption (tonnes)

EFC, fuel consumption based emission factor (kg/tonne)

EFP, power based emission factor (kg/kWh)

T, time (hours), LF, load factor P, engine power

Methodology "fuel based"

This procedure is applicable only where detailed FCs for each ship/engine type combination in the different navigation phases are available

1. Obtain FCs for each individual ship, engine type/fuel class and ship activity (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)
2. Calculate emissions for each ship category and engine type/fuel class multiplying by the EFs (see next slide)

Emission factors

NOx, NMVOC, PM EFs are available as kg/tonn for the individual engine/fuel type combinations. Others pollutants EFs are available as kg/tonn only for fuel type. Also NOx, NMVOC, PM EFs and specific fuel consumptions are available as kg/kWh installed for the individual engine/fuel type combinations. Different NOx EFs are reported for 2000 and 2005. The EFs for 2000 are representative of the fleet before application of IMO NOx Technical Code, while 2005 value are obtained from the year 2000 NOx EFs with a reduction of 3.4% to account for the new engines introduced by 2005

2000 vs 2005 NOx Emission factors

The reduction is obtained starting from 2005 European Commission study that assumed that a new engine meeting the requirements of the NOx Technical Code has roughly 17% lower NOx emissions than a pre-2000 engine. To obtain emission factors for 2005 an average annual rate of replacement for vessels is evaluated to be 4% (the approximate life cycle for a marine engine is assumed to be 25 years), on the basis that the overall fleet size remains constant in each of the 5 years. As 4% of the fleet has new engines with 17% lower NOx the reduction is

$$5 \times 4\% \times 17\% = 3.4\%$$

Emission factors "fuel based" (main pollutants)

Engine	Phase	Engine type	Fuel type	NOx EF 2000 (kg/tonne)	NOx EF 2005 (kg/tonne)	NMVOC EF (kg/tonne)	TSP PM_{10} $PM_{2,5}$ EF (kg/tonne)
Main	Cruise	Gas turbine	BFO	20.0	19.3	0.3	0.3
			MDO/MGO	19.7	19.0	0.3	0.0
		High-speed diesel	BFO	59.6	57.7	0.9	3.8
			MDO/MGO	59.1	57.1	1.0	1.5
		Medium-speed diesel	BFO	65.7	63.4	2.3	3.8
			MDO/MGO	65.0	63.1	2.4	1.5
		Slow-speed diesel	BFO	92.8	89.7	3.0	8.7
			MDO/MGO	91.9	88.6	3.2	1.6
		Steam turbine	BFO	6.9	6.6	0.3	2.6
			MDO/MGO	6.9	6.6	0.3	1.0
	Manoeuvring Hotelling	Gas turbine	BFO	9.2	8.9	1.5	4.5
			MDO/MGO	9.1	8.8	1.5	1.6
		High-speed diesel	BFO	43.6	42.3	2.5	10.3
			MDO/MGO	43.0	41.7	2.6	4.0
		Medium-speed diesel	BFO	47.9	46.2	6.3	10.3
			MDO/MGO	47.5	45.7	6.6	4.0
		Slow-speed diesel	BFO	67.4	65.1	8.2	11.2
			MDO/MGO	66.7	64.2	8.6	4.4
		Steam turbine	BFO	5.1	4.8	0.9	7.1
			MDO/MGO	5.0	5.0	0.9	2.8
Auxiliary	Cruise Manoeuvring Hotelling	High-speed diesel	BFO	51.1	49.4	1.7	3.5
			MDO/MGO	50.2	48.6	1.8	1.4
		Medium-speed diesel	BFO	64.8	62.5	1.7	3.5
			MDO/MGO	64.1	62.0	1.8	1.4

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

Source: Entec, the emission factors for NMVOC was been derived as 98 % of the original HC emission factors value, based on reported CH4 factors from IPCC.

Emission factors "fuel based" (other pollutants)

Pollutant	BFO	MDO/MGO	Unit	Reference
CO	7.4	7.4	kg/tonne fuel	Lloyd's Register
SO_x	20 * S (1)	20 * S (1)	kg/tonne fuel	Lloyd's Register
Pb	0.18	0.13	g/tonne fuel	Lloyd's Register and Cooper and Gustafsson (average value)
Cd	0.02	0.01	g/tonne fuel	Lloyd's Register and Cooper and Gustafsson (average value)
Hg	0.02	0.03	g/tonne fuel	Lloyd's Register and Cooper and Gustafsson (average value)
As	0.68	0.04	g/tonne fuel	Lloyd's Register and Cooper and Gustafsson (average value)
Cr	0.72	0.05	g/tonne fuel	Lloyd's Register and Cooper and Gustafsson (average value)
Cu	1.25	0.88	g/tonne fuel	Lloyd's Register and Cooper and Gustafsson (average value)
Ni	32	1	g/tonne fuel	Lloyd's Register and Cooper and Gustafsson (average value)
Se	0.21	0.10	g/tonne fuel	Lloyd's Register and Cooper and Gustafsson (average value)
Zn	1.20	1.2	g/tonne fuel	Lloyd's Register and Cooper and Gustafsson (average value)
PCDD/F	0.47	0.13	TEQmg/tonne	Cooper
HCB	0.14	0.08	mg/tonne	Cooper
PCB	0.57	0.38	mg/tonne	Cooper

Notes
S = percentage sulphur content in fuel

Emission factors "power based" (main pollutants)

Engine	Phase	Engine type	Fuel type	NOx EF 2000 (g/kWh)	NOx EF 2005 (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	0.1	0.1	305.0
			MDO/MGO	5.7	5.5	0.1	0.0	290.0
		High-speed diesel	BFO	12.7	12.3	0.2	0.8	213.0
			MDO/MGO	12.0	11.6	0.2	0.3	203.0
		Medium-speed diesel	BFO	14.0	13.5	0.5	0.8	213.0
			MDO/MGO	13.2	12.8	0.5	0.3	203.0
		Slow-speed diesel	BFO	18.1	17.5	0.6	1.7	195.0
			MDO/MGO	17.0	16.4	0.6	0.3	185.0
		Steam turbine	BFO	2.1	2.0	0.1	0.8	305.0
			MDO/MGO	2.0	1.9	0.1	0.3	290.0
	Manoeuvring Hotelling	Gas turbine	BFO	3.1	3.0	0.5	1.5	336.0
			MDO/MGO	2.9	2.8	0.5	0.5	319.0
		High-speed diesel	BFO	10.2	9.9	0.6	2.4	234.0
			MDO/MGO	9.6	9.3	0.6	0.9	223.0
		Medium-speed diesel	BFO	11.2	10.8	1.5	2.4	234.0
			MDO/MGO	10.6	10.2	1.5	0.9	223.0
		Slow-speed diesel	BFO	14.5	14.0	1.8	2.4	215.0
			MDO/MGO	13.6	13.1	1.8	0.9	204.0
		Steam turbine	BFO	1.7	1.6	0.3	2.4	336.0
			MDO/MGO	1.6	1.6	0.3	0.9	319.0
Auxiliary	Cruise Manoeuvring Hotelling	High-speed diesel	BFO	11.6	11.2	0.4	0.8	227.0
			MDO/MGO	10.9	10.5	0.4	0.3	217.0
		Medium-speed diesel	BFO	14.7	14.2	0.4	0.8	227.0
			MDO/MGO	13.9	13.5	0.4	0.3	217.0

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

Source: Entec, the emission factors for NMVOC was been derived as 98 % of the original HC emission factors value, based on reported CH4 factors from IPCC.

Methodology "power based" (1 of 2)

1. Obtain ship movement data: place of departure, place of arrival, time of departure and time of arrival for each individual ship
2. Determine sailing routes and distances between ports
3. Characterize each ship by ship category and engine type/fuel class (if unknown see default values in LDB slide 1) and record the installed main or auxiliary engine power; if engine power is unknown, and only gross tonnage (GT) is available, installed main engine power can be obtained from default values of LDB slide 2 (with reference to 1997 world fleet, 2010 world fleet and 2006 Mediterranean Sea fleet) and then installed auxiliary engine power from LDB slide 3 (with reference to 2010 world fleet and 2006 Mediterranean Sea fleet; 1997 auxiliary engine data are not available)

Methodology "power based" (2 of 2)

4 Determine the total sailing time for each ship category and engine type/fuel class, either based on the distance and average cruise speed (LDB slide 4) or time of departure and arrival

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 reported in LDB slide 4.

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 LDB slide 5) and emission factors

LDB Slide 1 - Lloyd's data base elaboration
Installed main power vs engine type/fuel class

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

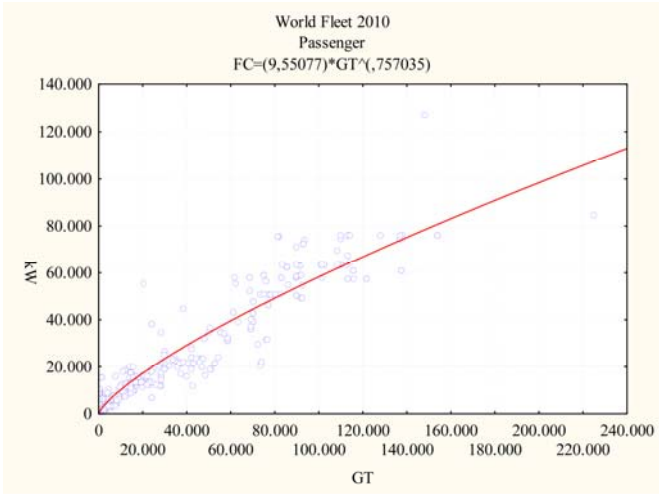
LDB Slide 2 - Lloyd's data base elaboration
Installed main engine power vs gross tonnage

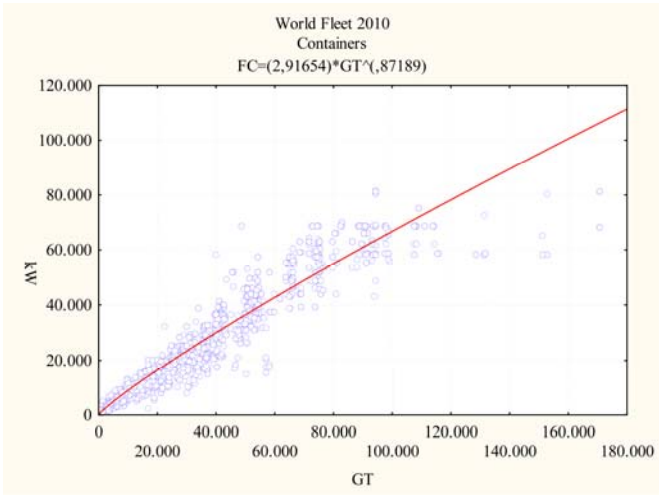
Installed main engine power as a function of gross tonnage (GT)

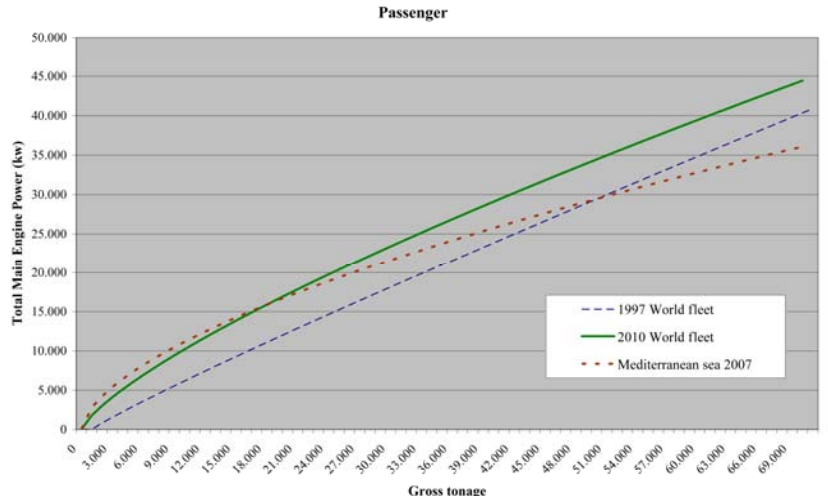
Ship categories	2010 World fleet	1997 World fleet	Mediterranean Sea fleet (2006)
Liquid bulk ships	$14.755*GT^{0.6082}$	$29.821*GT^{0.5552}$	$14.602*GT^{0.6278}$
Dry bulk carriers	$35.912*GT^{0.5276}$	$89.571*GT^{0.4446}$	$47.115*GT^{0.504}$
Container	$2.9165*GT^{0.8719}$	$1.3284*GT^{0.9303}$	$1.0839*GT^{0.9617}$
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	$54.2171*GT^{0.6420}$	$27.303*GT^{0.7014}$	

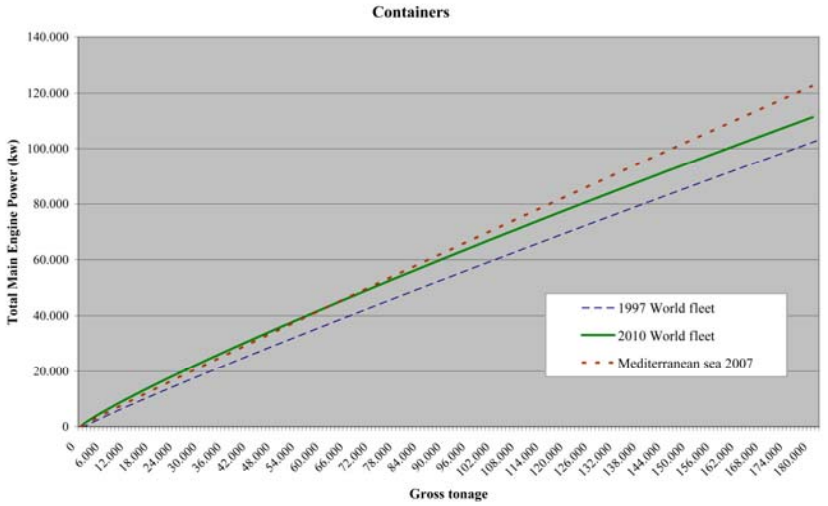
Source: Trozzi for 2010 and 1997 world fleets, Entec, for 2006 Mediterranean Sea fleet (for 1997 fleet was used the conversion 1 GT = 1.875 GRT)

Main Power vs GT for 1997 world, 2010 world, and 2007 Mediterranean sea fleets









LDB Slide 3 - Lloyd's data base elaboration
Average ratio of Auxiliary vs Main engine

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 for 2010 world feet Entec for 2006 Mediterranean Sea fleet

LDB Slide 4 - Lloyd's data base elaboration
Average cruise speed and duration of in-port activities

Average cruise speed and average duration of in-port activities

Ship Type	Ave.Cruise Speed (km/h)	Manouvering 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

LDB Slide 5 - Lloyd's data base elaboration
Load and operating time

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

Simpler methodology (Tier 2)

1. Obtain national statistical Fuel Consumptions by fuel and port arrivals data by type of vessel
2. Compute total power installed by type of vessel using data elaborated from Lloyds (LDB slide 6)
3. Split total power installed for type of vessel by engine speed/fuel class (ES/FC) using Lloyds data (LDB slide 7)
4. Compute total power installed by ES/FC as sum of figures derived in step 3
5. Assume fuel usage proportional to total power installed to assign consumption to ES/FC
6. Estimate national emissions with EFs for main engine in cruise

LDB Slide 6 - Lloyd's data base elaboration
Average main engine power

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

LDB Slide 7 - Lloyd's data base elaboration
Main engine power by engine type/fuel class

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

Very simpler methodology (Tier 3)

When only statistical information about fuel consumption are known, a very simplified methodology (Tier 1) can be used, computing the emissions as the product of fuel consumptions and:

- for NOx , NMVOC, PM the 2000 fuel based emission factors in cruise for medium speed engines
- for the other pollutants, fuel based emission factors

Conclusions

- The paper reports emission estimate methodologies developed in the frame of maintenance of the EMEP/EEA air pollutant emission inventory guidebook
- Emissions can be estimated at different levels that are expressed in three tiers of increasing complexity
- A detailed "ship movement" methodology has been described (the methodology is quoted as Tier 3 in EMEP/EEA air pollutant emission inventory guidebook) that must be used 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

Conclusions

- Emission factors, specific fuel consumptions and all other data useful to the estimates have been discussed. Emission factors derive from literature review while all other relevant functions and parameters are derived utilizing Lloyd's database (years 1997 and 2010) for world fleet
- Simplified methodologies has been introduce to use when only statistical information about fuel consumption are known (Tier 1) or when also information about port arrivals by type of vessel are available (Tier 2)