Methodologies for emission inventories for shipping

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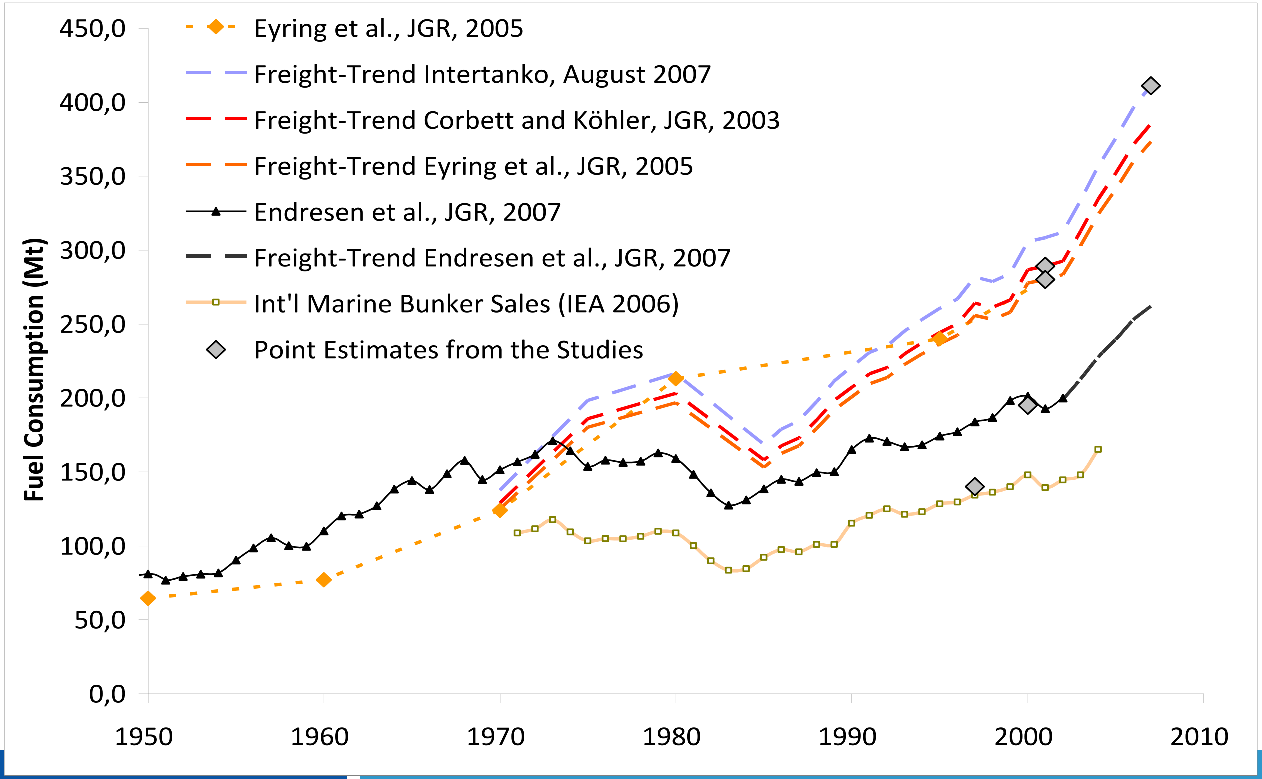
Outline

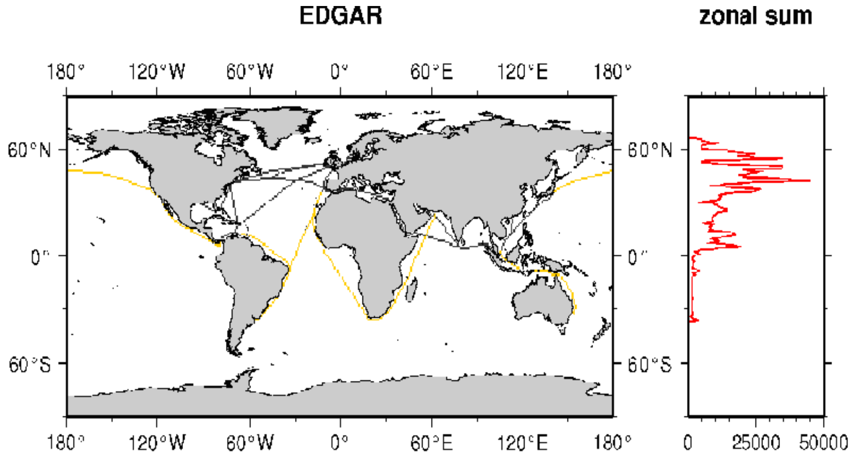
- Shipping activity data (movement, fuel or energy consumption) - examples of top-down & bottom-upp approaches
- Legislation affecting emissions of air pollutants
- Emission factors

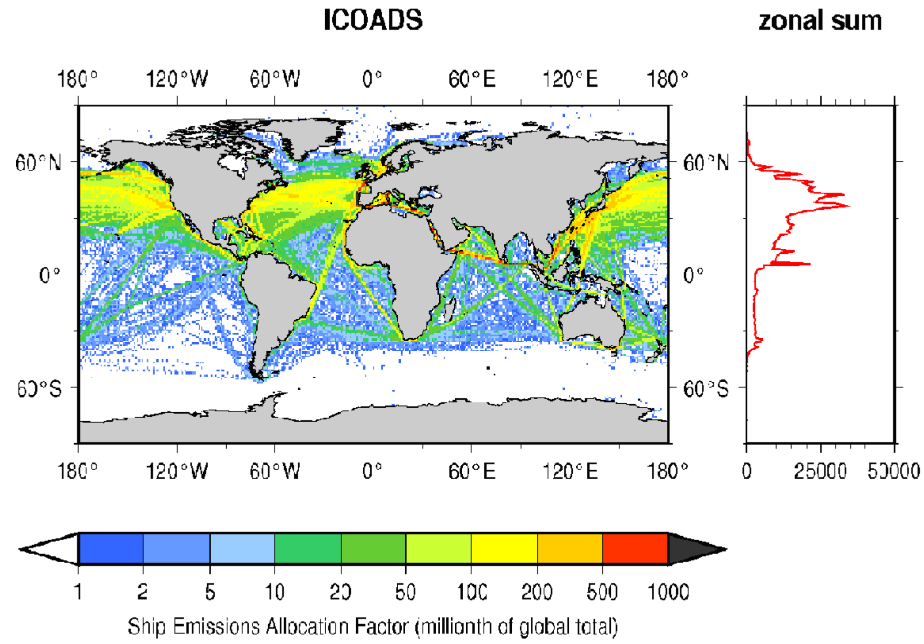
Top-down methodology

- Global shipping emission inventory (Eyring et al., 2010) – top-down fuel based methodology
- Uncertainties - ocean-going ships consumed between 200 and 290 million metric tons (Mt) fuel and emitted around 600 to 900 Tg CO_2 in 2 000
- Around 15% of all global anthropogenic NO_x emissions and 4-9% of SO_2 emissions attributable to ships.



- The global emission totals are distributed over the globe using data on ship movement frequencies (EDGAR2.0, COADS, ICOADS, AMVER, PF)

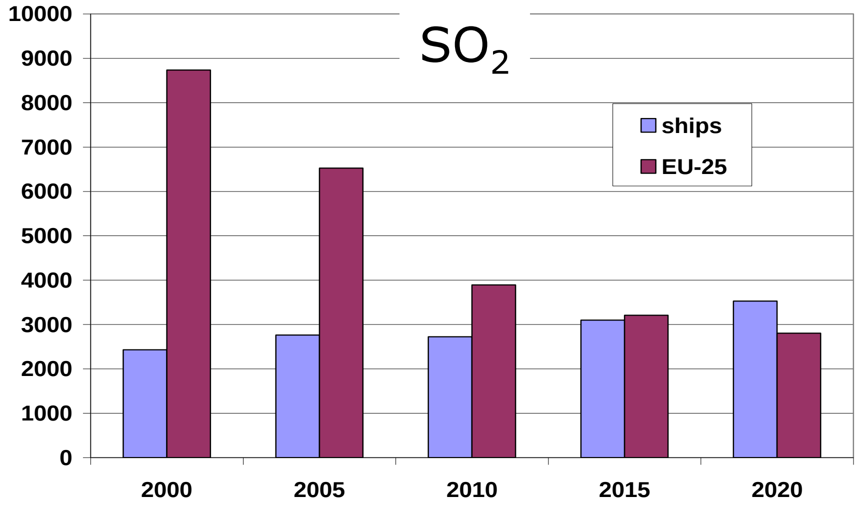


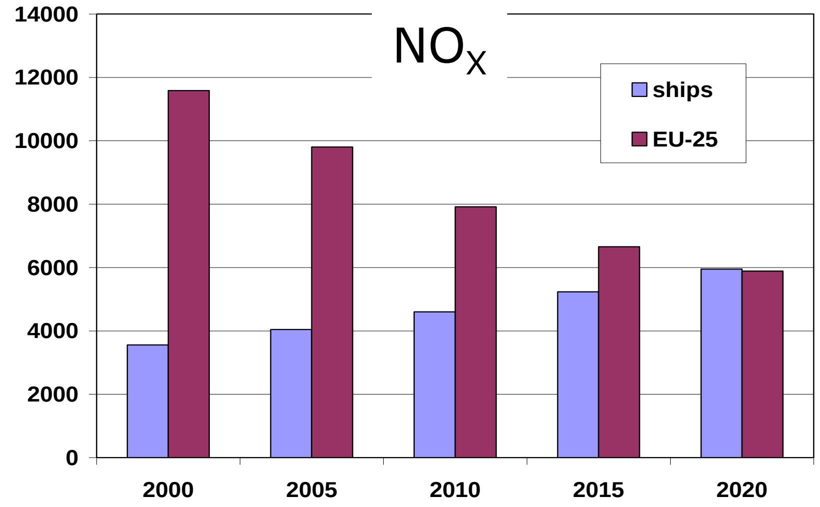


(*Eyring et al., 2009*)

Activity based inventory (bottom-up)

- EMEP – activity based inventory, 50x50 km
- Ship activity data – Lloyd's register
- Emission factors – ENTEC (2005) data





Estimated emissions of SO_2 and NO_X from land sources and shipping in EU25 in 2005-2020 (kton per year) (EMEP, based on 2005-regulations i.e. SECA areas 1.5% S in fuel).

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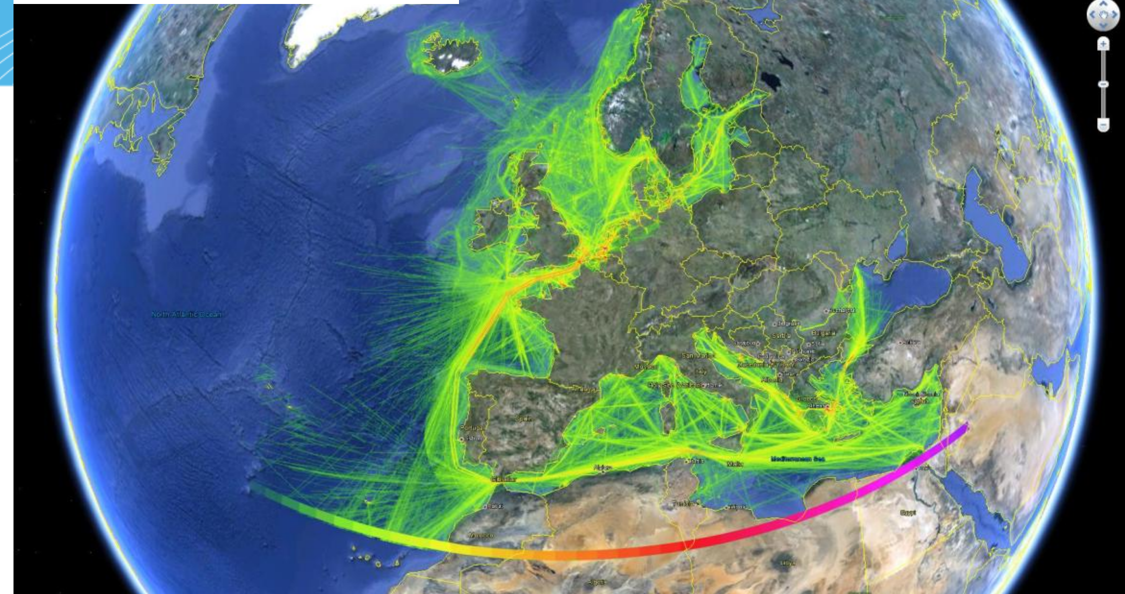
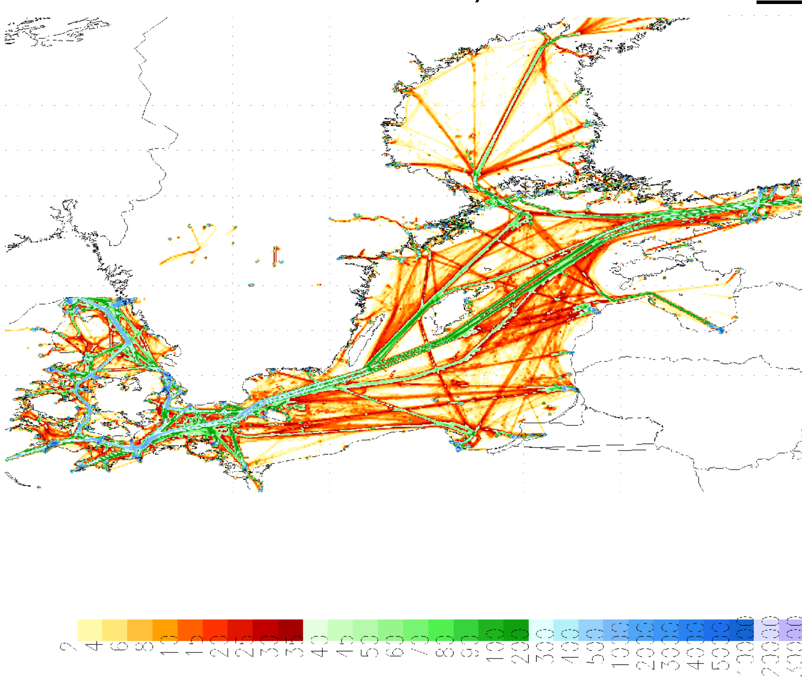
Regional ship emission inventories done at FMI with STEAM

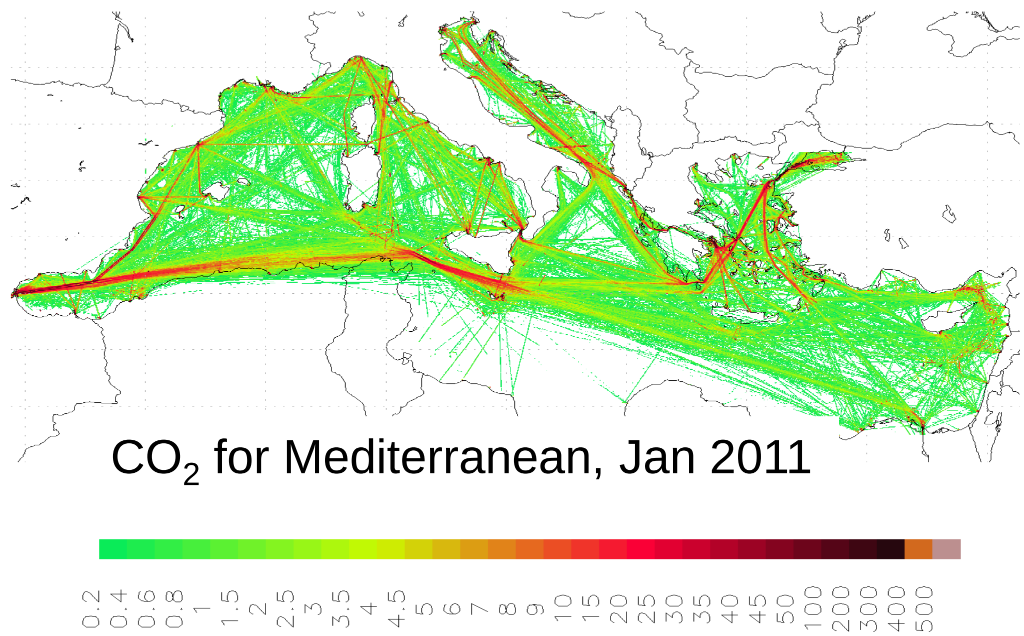
CO_2 for EU waters



AIS data from EMSA, courtesy of EU member states, 2011

CO for the Baltic Sea, Jan 2009

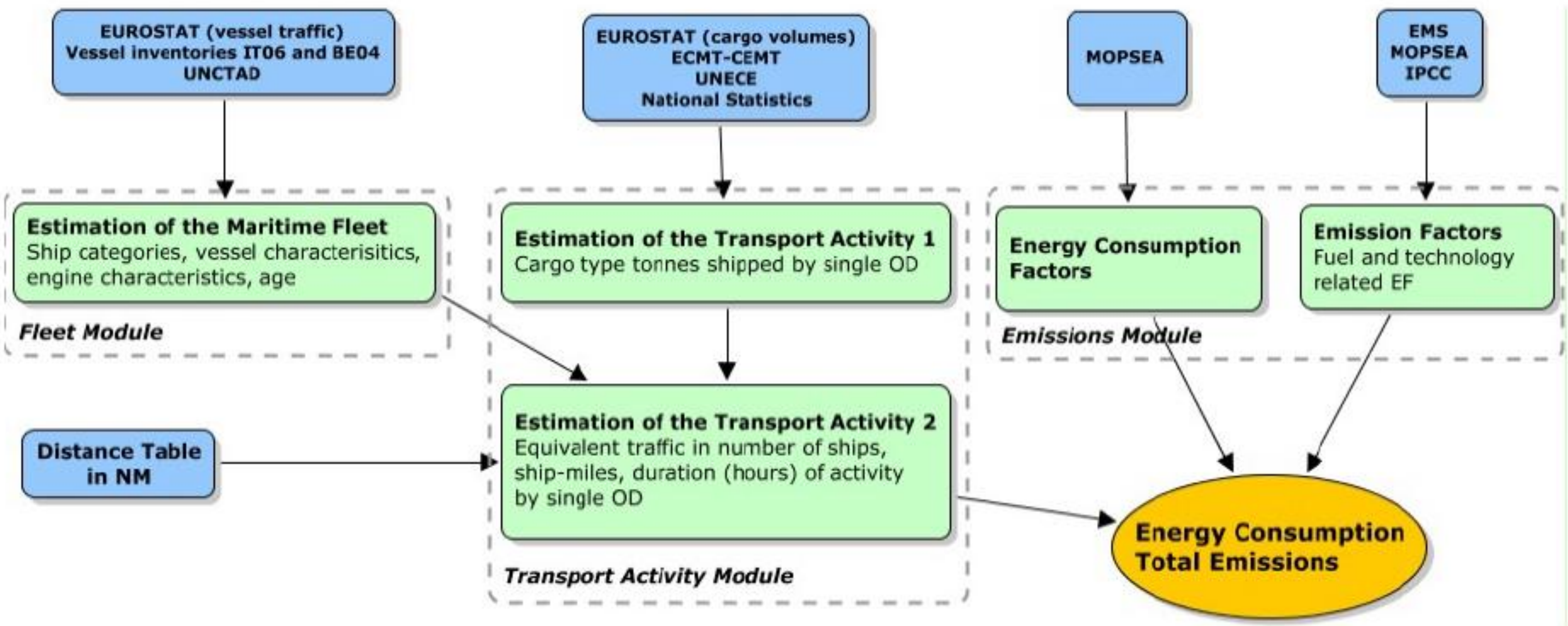




CO_2 for Mediterranean, Jan 2011

Combination of top-down and bottom-up methodologies - Extermis

Fig. 3.1 Flow-chart of the maritime methodology



From Extermis final report, 2008

Emission inventories in ports

- Activity based (bottom-up)
- Most often based on port-call data or AIS data
- Uncertainties in fuel consumption (use of auxiliary power), fuel used (EU legislation) and emission factors

Modeling port emissions with STEAM

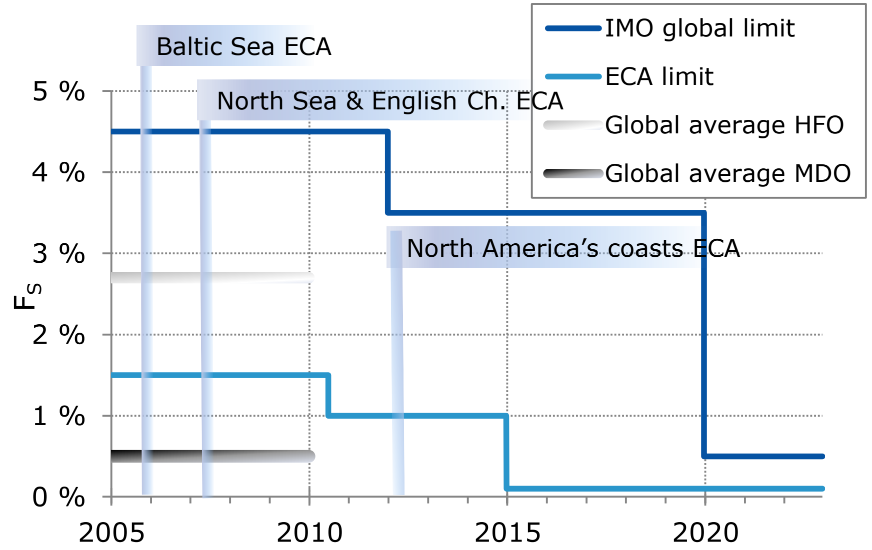
- **Local installations of AIS base stations**
  - Can be repeated anywhere in the world
    - Electricity + network connection required
  - London, Singapore, Shanghai…
- **Istanbul/Bosphorus**
  - This example with 100 x 100 m grid

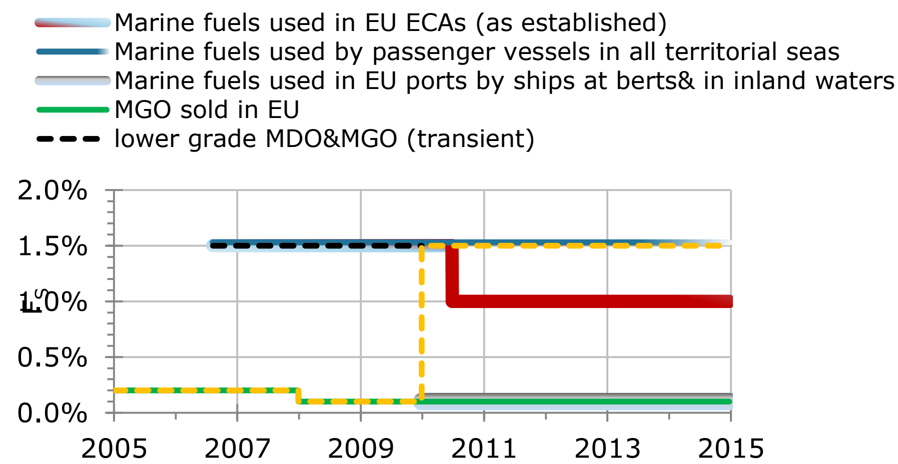
Emissions of NOx from ships in the Bosphorus area, close to Istanbul, Turkey. Image from March 2012

International legislation on shipping emissions

- **IMO Annex VI** of the Marine Pollution Convention (MARPOL) adopted in 1997 by the Marine Environmental Protection Committee (MEPC) came into force in May 2005 (IMO, 2006), amendment in October 2008 - limits on emissions of SO_2 and NO_X globally and provisions for Emission Control Areas (ECA)

- EU – **Fuel directive 2005/33/EC** on the sulphur content of liquid fuels for vessels operating in EU territorial seas which in August 2005 amended directive 1999/32/EC
- In addition: From 11 August 2006 all passenger vessels on regular services in EU territorial seas must comply with the 1.5% sulphur limit
- From 1 January 2010 a 0.1% sulphur limit applies to all marine fuel used by ships at berth in EU ports and by inland waterway vessels.





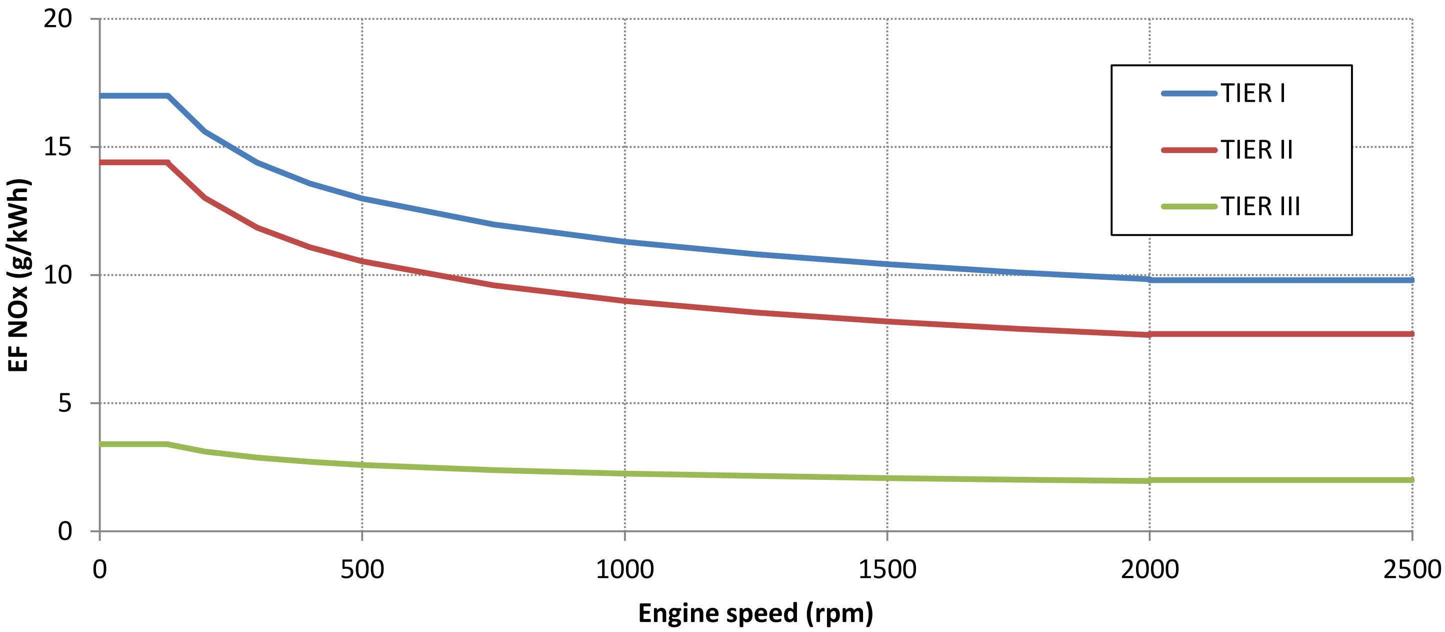
International legislation on shipping emissions

NO_X emission standards – apply on newly built ships or installed engines manufactured after year:

Tier I: After 2000 and prior to 1 January 2011 (& engines built 1 January 1990 - 1 January 2000 with a power output >5,000 kW and cylinder displacement ≥90 litres

Tier II: after 1 January 2011

TIER III: after 1 January 2016 when operating in NO_X-emission control areas



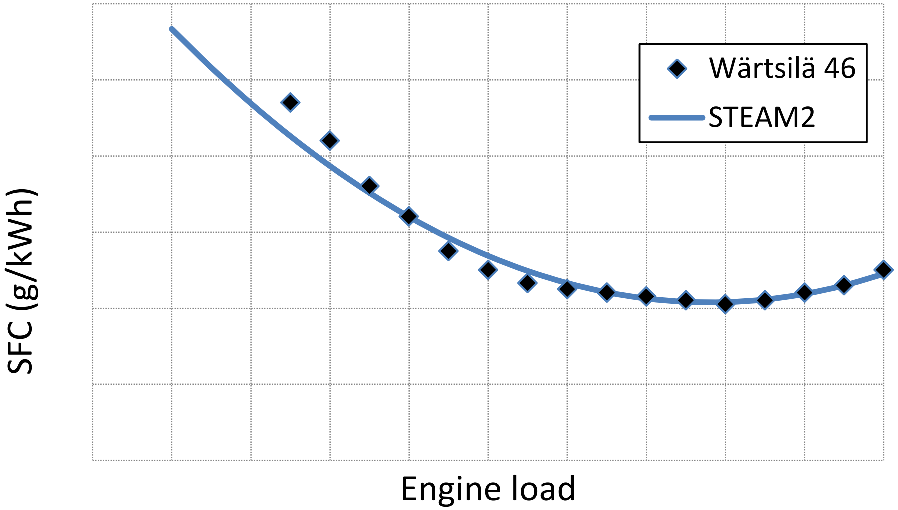
International legislation on shipping emissions

- From July 1st 2010 the more stringent 1% FSC limit of IMO applies in European ECAs while **EC is preparing legislation** that will transpose the 2008-amendment of Annex VI into EU law
- European NOx ECAs (Baltic Sea) not finally agreed yet, application have be submitted by HELCOM but a postpone until 2020 proposed by Norway
- Further reduction options beyond Annex VI discussed in Commission:
  - **ECA in Mediterranean (SECA ±NECA)**
  - **ECA in all European waters (SECA ±NECA)**
  - **1% FSC limit for passenger vessels in all EU waters (optionally 0.1% after 2015)**

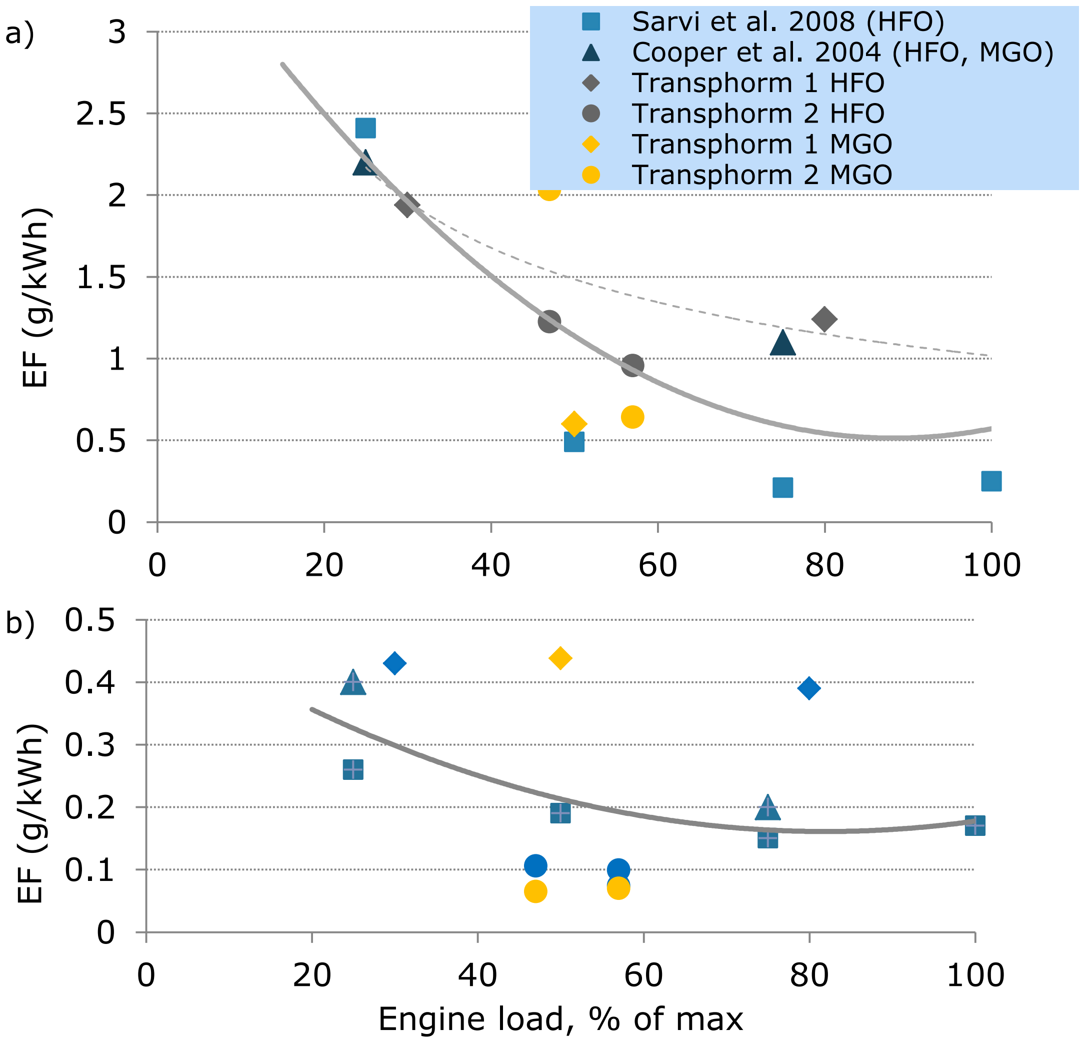
Emission factors

- Emission per fuel consumed or per energy produced by the ship engines
- Fuel or energy consumption for different ship categories available eg. in Entec (2005), some models calculate fuel consumption based on information from ship register, account for speed, waves e.t.c. (Jalkanen et al., 2010)
- Emission factors often used for typical (full) load operation of vessels; employment of load-dependent emission factors in some AIS emission inventories

Engine type	Fuel type	SFC (g/kWh)
Slow speed	Residual oil	195
	Marine distillates	185
Medium speed	Residual oil	215
	Marine distillates	205
High speed	Residual oil	215
	Marine distillates	205

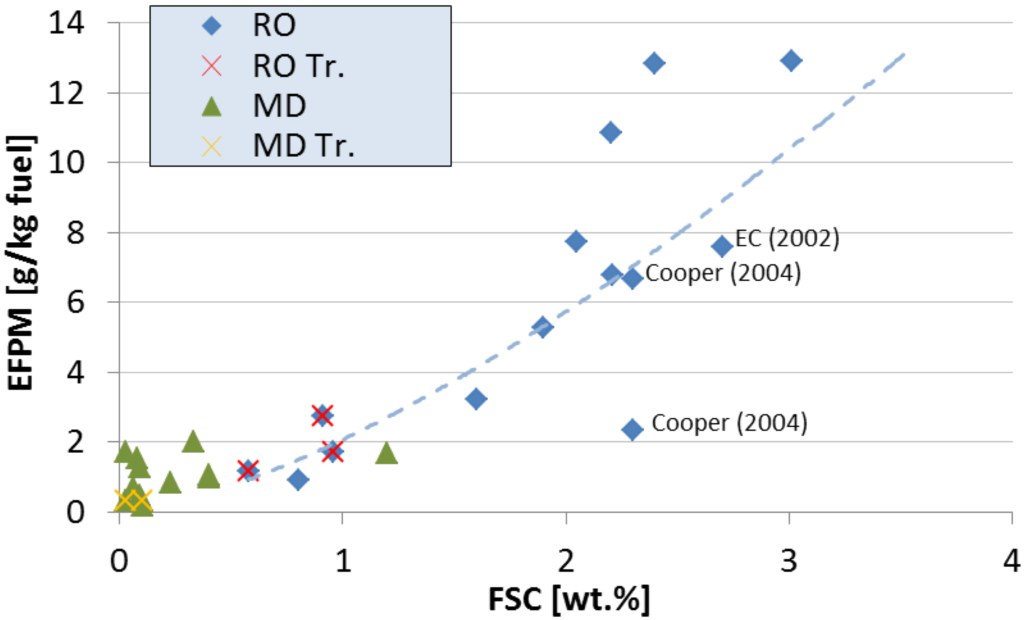


CO (a) and HC (b)



a)
b)
Sarvi et al. 2008 (HFO)
Cooper et al. 2004 (HFO, MGO)
Transphorm 1 HFO
Transphorm 2 HFO
Transphorm 1 MGO
Transphorm 2 MGO
EF (g/kWh)
Engine load, % of max
0
0.5
1
1.5
2
2.5
3
0.1
0.2
0.3
0.4
20
40
60
80
100

Emission factors for PM – effect of fuel sulphur content



Emission factors for particle mass EFPM as a function of FSC (in wt. %). EF(PM) for RO is plotted in blue, EFPM for MD is plotted in green. Datapoints with crosses (Tr.) are from the Transphorm measurement campaigns.

The various abatement techniques and their evaluated emission reduction efficiencies.

Abatement technique	EF_{NOx}	EF_{SOx}	EF_{CO}	EF_{VOC}	EF_{PM}	EF_{NH3}
Low NO_X engine technologies[1]	−20%		0*	0†	0†	
Exhaust gas recirculation[1]	−30 - −40%					
Direct Water Injection[1]	−50 - −60%			0	0	0
Humid Air Motor[1]	−70 - −85%		0	0	0	
Selective Catalytic Reduction[1]	−91%		0	0	0	+0.1 g/kWh
SCR + oxidation catalyst[2]	−90%		−70%	−80%		
Sea Water Scrubber[3]	0	−95%			0-80%‡	
Fuel Emulsifier[3]	−10%					
Wetpac[3]	−50%					

* Some increase possible
† Unconfirmed up to 50 % reduction
‡ Value from Jalkanen et al. (2011). According to Corbett (2010) reductions range from -98% to -45%, largest fractions of PM are reduced more effectively than the small ones.
[1] Lövblad and Fridell, 2006
[2] Cooper and Gustafsson, 2004
[3] Jalkanen et al., 2009

Emission factors for PAH

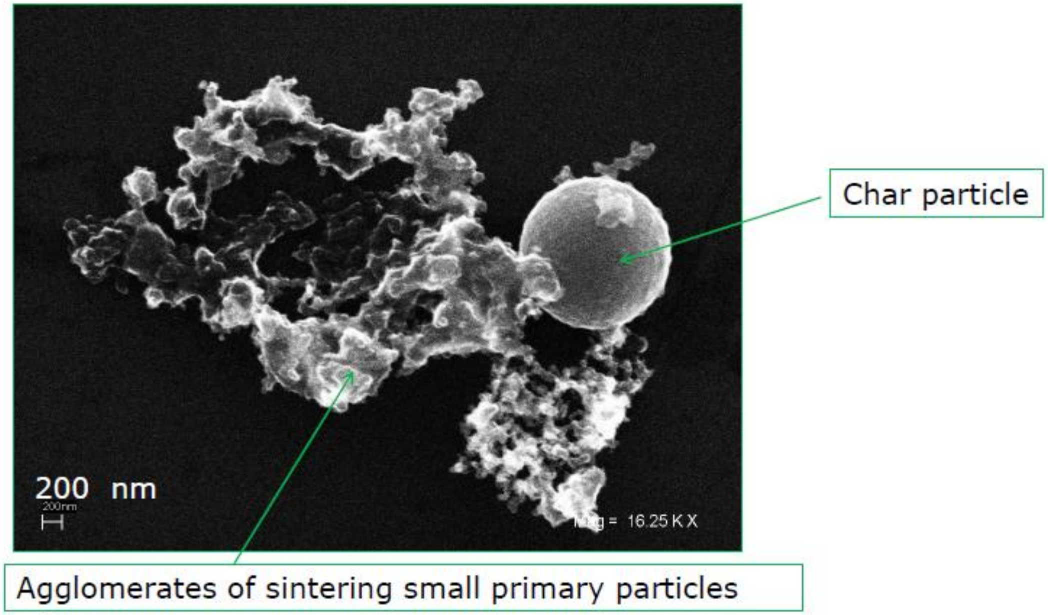
Emission factors for PAH (Total PAH-4, EC, 2000) and benzo(a)pyrene. *st.dev.* is standard deviation of the data.

Engine type	Fuel type	Cooper and Gustafsson (2004)			Agrawal et al., 2008 75-85% load		Agrawal et al., 2010 75-90% load	
		at sea		manoeuvring				
		g/kg_{fuel}	g/kWh	g/kWh	g/kWh	st.dev	g/kWh	st.dev
Total PAH-4								
SSD	MD	3.2×10^{-5}	5.92×10^{-6}	5.37×10^{-6}				
SSD	RO	3.1×10^{-5}	6.05×10^{-6}	5.46×10^{-6}	1.5×10^{-4}	1.4×10^{-4}	1.3×10^{-3}	3.8×10^{-4}
MSD&SSD	MD	2.9×10^{-5}	5.95×10^{-6}	5.54×10^{-6}	5.3×10^{-6}	7.9×10^{-7}		
MSD&SSD	RO	2.8×10^{-5}	6.02×10^{-6}	5.38×10^{-6}				
Benzo(a)pyrene								
SSD	MD	5.4×10^{-6}	9.99×10^{-7}	9.07×10^{-7}				
SSD	RO	5.1×10^{-6}	9.90×10^{-7}	9.17×10^{-7}	1.2×10^{-4}	1.2×10^{-4}	2.0×10^{-4}	1.2×10^{-4}
MSD&SSD	MD	4.9×10^{-6}	1.00×10^{-6}	9.02×10^{-7}				
MSD&SSD	RO	4.7×10^{-6}	1.01×10^{-6}	9.03×10^{-7}	1.7×10^{-6}	2.5×10^{-7}		

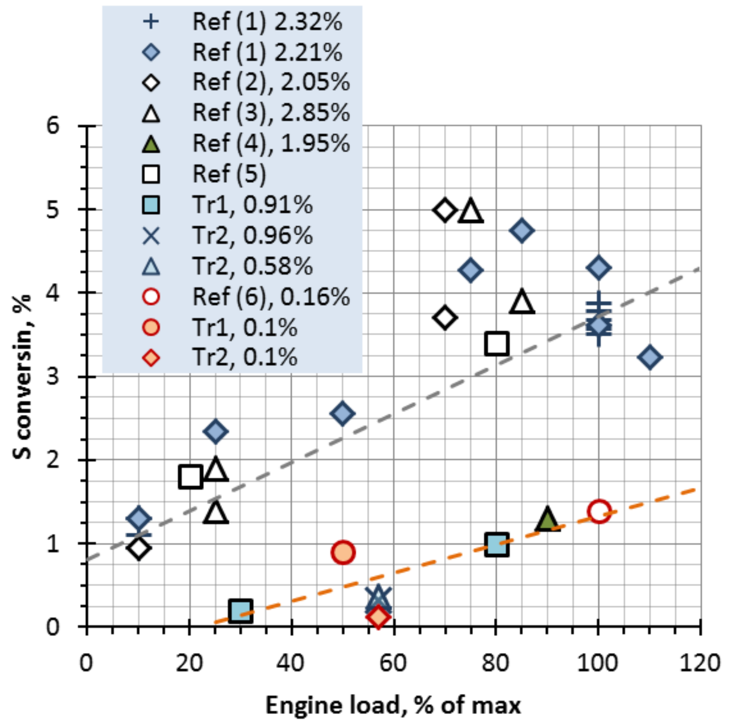
Primary PM from shipping

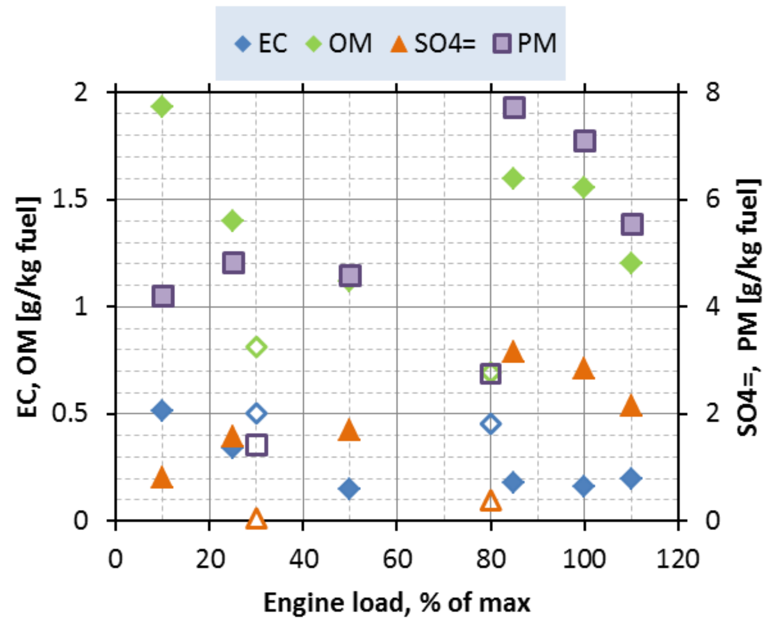
- 35-60% non-volatile, 40-65% volatile PM
- Non-volatile: EC, mineral species containing Ca, V, Ni, S,
- Volatile: $SO_4^{=}$, OC, H_2O

ME88% MITEX T16 filter



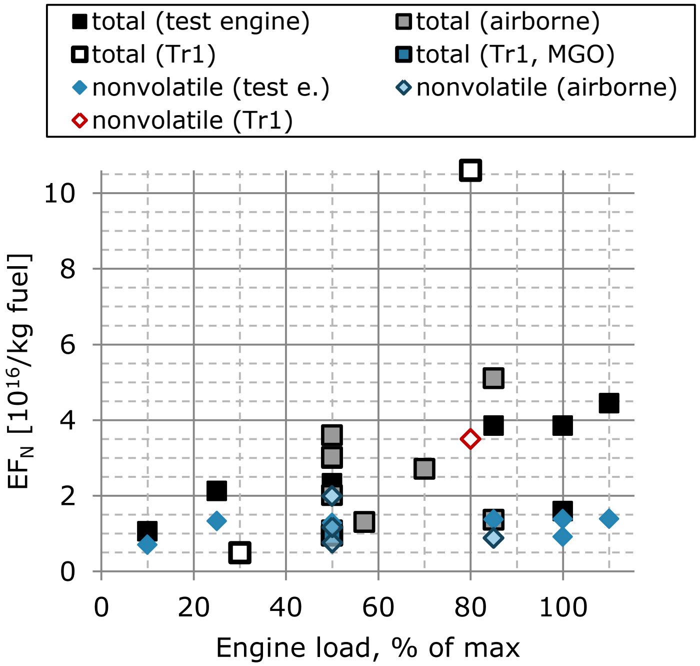
Emission factors for PM – effect of engine load

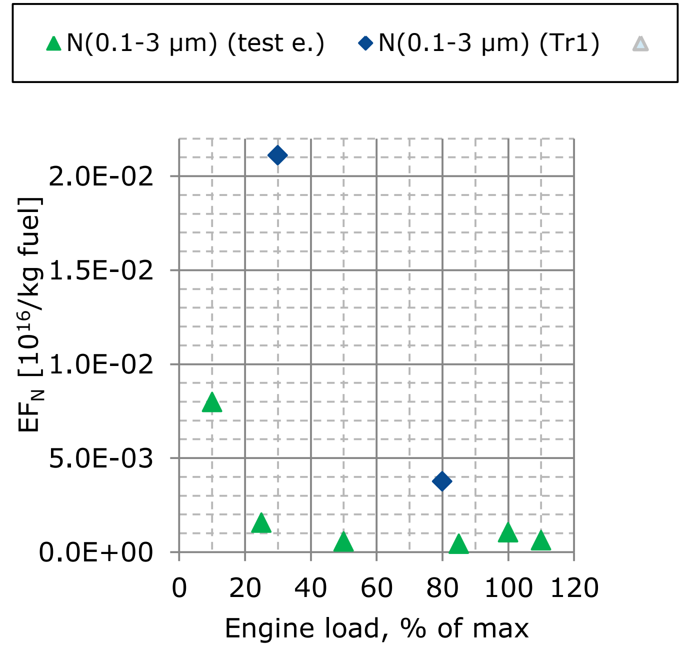




a) Ref (1): Kasper et al., 2007; Ref (2): Agrawal et al., 2008a; Ref (3): Agrawal et al., 2008b; Ref (4): Moldanová et al., 2009; Ref (5) Petzold et al., 2010).
b) FSC 2.40wt-% , from Petzold et al., data in their Table 1).

Emission factors for PN – effect of engine load





EF(PN) measured on test engine burning RO with FSC 2.21 (test engine), and 0.91 (Tr1) and in airborne measurements in ship plumes. a – total and non-volatile particles, b – particles in accumulation mode. (from Petzold et al., 2010, D2.1.4 and Jonsson et al., 2011)

EF - conclusions

- EF(PM) for engines using RO 1 - 13 g/kg fuel, mean around 7 (RO with low S content ~2g/kg), and for engines using MD 0.2 -1 g/kg fuel.
- For EC the recommended EFs are for HFO 0.5 g/kg fuel at low engine load and 0.2 g/kg-fuel for high engine load and for MGO 0.3 g/kg-fuel at low and 0.1 g/kg fuel at high engine loads.
- Emission factors for metals are dependent on fuel composition, in case of Ca and Zn on composition and consumption of the lubricant. Some variability of metal EF with engine load has also been observed.
- Emission factors for particle number concentrations are in the order of magnitude of 10^{16} #/kg-fuel with a positive correlation between EF(PN) and the engine load. Between 1/3 and 2/3 of particles have been found to be volatile.
- Emissions of PAH and some other HC species are also dependent on their concentration in the fuel. Available EF(PAH-4) for RO vary between 6 and 11300 g/kWh, with most of the values between 6 and 100 g/kg fuel.

EF – inland shipping

- Emission factors of S, CO, HC, NO_X and PM for inland shipping are affected by **Directives 97/68/EG and 97/70/EG**.
  - EF(CO_2), CO, HC will be about the same as for marine gasoil
  - EF(NO_X) of newer engines are limited by 97/68/EG, for engines older than 2007 or 2009 EFs for MGO can be used
  - PM and PAHs EF(PAH) no data are available. From correlation between FSC and EF(PM) one can extrapolate for the new FSC limit EF(PM) = 1.5g/kg-fuel.
  - EF(EC) and EF(OC) parts in PM-mass can be approximated by PM composition of large pre-Euro and Euro-I road diesel engines which is 51% for EC/PM-mass and 35% for OC/PM-mass. For EF(PN) use of EF 0.3×10^{16} #/kg-fuel is recommended and for EF(PAH) use of EF for MGO is recommended.