ARTICLE

Atmospheric emissions of European SECA shipping: long-term projections

Juha Kalli · Jukka-Pekka Jalkanen · Lasse Johansson · Sari Repka

Abstract We modeled the projections of the major atmospheric emissions from shipping of the European sulphur emission control area that includes the Baltic Sea, the North Sea, and the English Channel until 2040. Emission projections were calculated separately for every ship on annual basis, and the model took into account traffic growth, fleet renewal, and the forthcoming regulations. The regulation on sulfur content of ship fuels will drastically decrease the emissions of sulfur oxides and particulate matter ($PM_{2.5}$). As the regulation on nitrogen oxides (NO_x) only affects the new diesel engines, the decrease in emissions will be seen parallel with the fleet renewal. Globally internalized limits will turn NO_x emissions to decrease with moderate traffic growth. However, by designating the Baltic Sea and the North Sea as NO_x emission control areas, more drastic decrease would occur. CO_2 emissions will stay almost constant through the studied timeline. Results show that European Commission's CO_2 target for 2050 will not be reached without implementation of market based measures among the North Sea and the Baltic Sea fleets. Results present new information for decision makers to further develop international regulations of shipping especially in the Baltic Sea and the North Sea.

Keywords Greenhouse gas · Baltic Sea · North Sea · STEAM · $PM_{2.5}$

1 Introduction

Exhaust emissions of shipping are substantial, and they create problems as diminishing air quality and producing unwanted nutrient load on environment (Corbett et al. 2007;

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Dalsøren et al. 2007; Endresen et al. 2003; Corbett et al. 1999; Capaldo et al. 1999; Wang et al. 2007; Georgakaki et al. 2005; Davis et al. 2001; Delft 2006; Kesgin and Vardar 2001; ENTEC 2002; Jalkanen et al. 2009, 2012a, b). Corbett et al. (2007) has estimated that 60,000 premature deaths globally can be contributed to shipping. In Europe, 49,500 deaths in 2000 were estimated to be related to shipping exhaust emissions, and the number of deaths were estimated rise to 53,400 in 2020 (Brandt et al. 2011). The increased concentrations of ultrafine particulate matter (PM) are the main reason for these mortality rates.

International Maritime Organization (IMO) agreed to reduce PM emissions of shipping by regulating the sulfur in ship fuels (IMO 2008). The Baltic Sea, the North Sea, and the English channel were designated as sulfur emission control area (SECA) with stringent limits for sulfur in ship fuels. Most of the sulfur in fuels (95–99 %) will be transformed to sulfur oxides (SO_x) after burning process whereas the rest is converted to particulate sulfate (SO_4), which is one of the key components of the PM. Gaseous SO_2 can eventually be oxidized to SO_3 and sulfuric acid. Therefore, the regulation is seen as an effective way to decrease the negative health effects of ship exhausts.

EC white paper (European Commission 2011) describes the CO_2 targets for maritime transport. CO_2 emissions should be cut by 40 % (if feasible 50 %) by 2050 compared to 2005 levels. Target has been created according to the goal to limit global mean temperature rise to 2 °C. IMO parties adopted mandatory measures in 2011 to reduce emissions of greenhouse gases (GHGs) from international shipping. The amendments to MARPOL Annex VI include measures to improve energy efficiency of ships. Mandatory Energy Efficiency Design Index will be applied only for new ships and the Ship Energy Efficiency Management Plan for all ships. There have also been discussions about market based measures (MBMs) to reduce GHGs of shipping in the IMO. Failure to reduce GHGs from maritime transport would negate efforts made in the other sectors.

Nitrogen oxides (NO_x) deposition from shipping contributes to eutrophication. Atmospheric deposition of nitrogen in total contributes to about 25–30 % of nitrogen input to the Baltic Sea (EMEP 2006). It has been estimated that ship originated NO_x deposition can be over 50 % of the total atmospheric deposition in some Baltic Sea areas and seasons (Stipa et al. 2007), but on annual average about 5 % of the airborne nitrogen comes from shipping. MARPOL Annex VI (IMO 2008) includes a NO_x reduction scheme for new ships. Tier I and tier II limits are global and will be enforced on all new marine diesel engines. However, Tier III will affect only ships sailing inside specified NO_x Emission Control Areas (NECA). So far, only USA and Canadian coastal waters are proposed as NECA in the IMO. Possibility of proposing the Baltic Sea and North Sea are currently under investigation.

In order to further develop international regulation for exhaust emissions from shipping, we need to forecast the future development of the emissions based on the information on shipping and the forthcoming regulation that we have today. This paper presents future scenarios of ship originated atmospheric emissions (CO_2, NO_x, PM, and SO_x) taking into account the forthcoming international regulations of sulfur in ship fuels and possible designation of the North Sea and the Baltic Sea as NECA. Scenarios include assumptions for traffic growth and efficiency increase of vessels.

2 Material and methods

This study presents projections of ship originated atmospheric emissions until 2040. Calculation for scenarios was done with algorithm model programmed with Microsoft Excel. Base year for the future scenarios of the emissions from the North Sea and the Baltic Sea ship traffic was 2009. In 2009, however, the maritime transport was recovering from the economic recession and the emissions may actually be higher than projected in these calculations. Ship Traffic Emission Assessment Model (STEAM2) was used to evaluate the exhaust emissions of the maritime traffic based on the messages provided by the Automatic Identification System (AIS) which enables the identification and location determination of ships (Jalkanen et al. 2009, 2012a). However, only 13 ship types were included in the scenario calculations representing 85 % of the total fuel consumption of shipping in the area. This fleet represents the commercial shipping, and the major part of the ship originated emissions. Categorization of ships was done according to IHS Fairplay (2011) which provides the ship database used in the STEAM2 model.

2.1 Traffic growth

The second GHG study by IMO (2009) addresses the transport demand as the most important driver for ship emissions. The study describes the correlation of gross domestic product (GDP) and maritime transport demand. Annual average growth in world GDP in the study varies between 2.7 % (B2 scenario) and 3.9 % (A1B scenario). Similarly, the total transport demand is estimated to vary from 0.9 % (B2, low bound scenario) to 5.4 % (A1T, high bound scenario). The transport demand also affects the efficiency of transport. When the freight markets change, the demand may increase or decrease. This will lead to shortage or surplus of ships correspondingly. Efficiency will decrease when demand is high and ships need to sail fast. Efficiency increases when there is more time for ships to sail leading to slow steaming. However, this type of change in market stability is difficult to include in the future scenarios and therefore left out of this study.

Algorithm estimating the emissions in this study applies to the growth rates presented in Table 1. Traffic growth is estimated to be moderate except for container traffic that is expected to be more intense. Two percentage higher growth rate for container ships is the same as estimated by the IMO (2009).
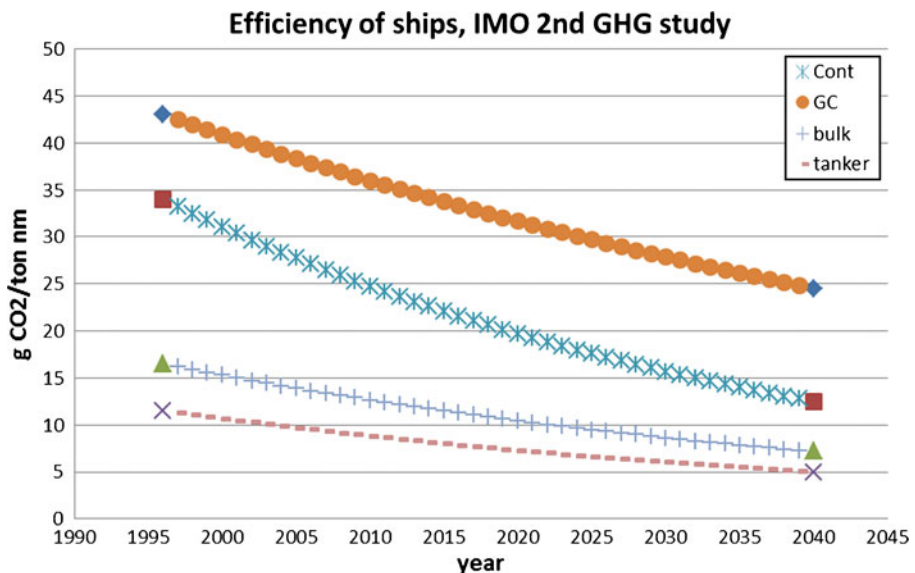
2.2 Efficiency increase

Speed is the key parameter with respect to fuel consumption of a ship and therefore to its emissions. Over time, there has been remarkable development in technology affecting efficiency and speed of ships. Switch from steam turbines to more efficient diesel engines, optimization of ship hull, and propulsion technology development are good examples of this. Technological development is still continuing, and estimates in efficiency increase have been presented by IMO (2009) for four ship types: tankers, general cargo, container, and bulk vessels (Fig. 1). Efficiency rates used in this study are iterated from the IMO (2009) data. Efficiency increase as percentage points per annum of different ship types are presented in Table 1.

Table 1 Ship types of the studied North Sea and Baltic Sea fleet and their average lifetime, traffic growth rate, efficiency increase rate, and number of ships

	Ship type	Average lifetime (years)	Traffic growth (%)	Efficiency increase (%)	Number of ships in the European SECA fleet
1	Reefer ship	26	1.5	2.25	472
2	General cargo ship	26	1.5	1.27	3,350
3	Product tanker	26	1.5	1.90	530
4	Container ship	25	3.5	2.25	1,466
5	Chemical tanker	26	1.5	1.90	1,715
6	Crude oil tanker	26	1.5	1.90	835
7	Liquid natural gas tanker	29	1.5	1.90	61
8	Bulk ship	26	1.5	1.90	2,316
9	Ro-ro ship	27	1.5	2.25	273
10	ROPAX ship	27	1.5	2.25	433
11	Vehicle carrier	27	1.5	2.25	446
12	Liquid petroleum gas tanker	26	1.5	1.90	266
13	Cruise ship	27	1.5	2.25	127
	TOTAL				12,290

2.3 Average lifetime of ships

As NO_x regulations affect differently diesel engines depending their construction year (i.e., ship build year), fleet renewal rate is needed in estimation of NO_x emissions in the future. The algorithm utilizes the STEAM2 internal ship database and compares the

Fig. 1 Efficiency increase of four ship types (container, general cargo, bulk vessel, and tanker) as presented in the second IMO GHG study (IMO 2009)

average lifetime of a ship to the build year of every ship in the Baltic fleet. Average lifetime is assumed separately for the 13 ship types of the study (Table 1).

2.4 CO_2 emissions

The STEAM2 model estimates the fuel consumption of ships based on their movement (AIS) in the studied area. The second IMO GHG study (IMO 2009) presents a factor that can be used to convert heavy fuel oil (HFO) consumption to CO_2 emissions (the factor is 3,130 for HFO kg emitted/ton of fuel). In addition, an estimate for efficiency increase of most common ship types is presented in the study (Table 1, Fig. 1).

Traffic was assumed to increase according to Table 1. Assumptions for traffic growth and efficiency were utilized as annual percentages separately for each ship in the studied fleet. Projections were created until 2040.

Equations 1 and 2 present the logic of calculating the fuel consumption and CO_2 emissions for a ship in particular year. Annual fuel consumption and emission inventories for the SECA fleet were created by summarizing the ship specific results.

Equation 1, estimating a fuel consumption of vessel X in year a+1

$$
\begin{aligned}
\text{Fuel consumption of vessel X in year } a+1 \, [\text{tons}] = {} & \text{Fuel consumption of vessel X in year } a \, [\text{tons}] \quad (1) \\
& \times \ (1 + \text{traffic increase of ship X } [\%]/100\%) \\
& \times \ (1 - \text{efficiency increase of ship X } [\%]/100\%)
\end{aligned}
$$

Equation 2 shows conversion of fuel consumption into CO_2 emissions

$$
CO_2 \text{ emissions of vessel X in year } a\,[\text{tons}] = 3.130 \times \text{fuel consumption of vessel X in year } a\,[\text{tons}]
$$
$$(2)$$

2.5 SO_x emissions

Almost all sulfur in ship fuel will oxidize to SO_x in the burning process of diesel engine, but a small fraction (1–5 %) will be emitted as particulate matter. Therefore, in order to estimate SO_x and PM emissions, we need to know the fuel consumption and the sulphur content of the fuel. STEAM2 model assumes that all main engines are using fuel with the maximum sulfur content allowed by the current legislation. In 2009, the maximum allowed sulphur content in ship fuels was 1.5 wt% (IMO 2008). The sulfur limit in SECA decreased to 1.0 wt% from January 7, 2010 onwards, and it will be further limited to 0.1 w% from January 1, 2015 onwards. The EU directive 2005/33/EC limited ship fuels at berth to 0.1 w% from January 1, 2010 onwards. Future scenarios take these decreasing limits into account. Auxiliary engine fuel sulfur content is 0.5 % by default.

The base year 2009 emissions were estimated by the STEAM2 model. Some ships have voluntarily used low sulphur fuels for several years. STEAM2 utilizes a ship database developed for the model. Database includes data from IHS Fairplay, but supplements it with manually collected information about fuel qualities used in the ships, specific fuel oil consumption data obtained from engine manufacturers, other

classification societies, experimentally determined emission factors, and installed abatement techniques. Therefore, the SO_x emissions produced by the model are more reliable than converting the SO_x emissions from the annual fuel consumption of the fleet. Calculation of future SO_x emissions are based on Eq. 1, except that the fuel consumption is replaced with the SO_x emissions of the ship (Eq. 3).

Equation 3, estimating SO_x emissions of vessel × in year a+1

$$\text{SO}_x \text{ emissions of vessel X in year a} + 1 = \text{SO}_x \text{ emissions of vessel X in year a[tons]} \times \quad (3)$$

$$(1 + \text{traffic increase of ship X } [\%]/100\%) \times (1 - \text{efficiency increase of ship X } [\%]/100\%)$$

The STEAM2 model estimates the SO_x emissions separately for the main and the auxiliary engines including assumptions for the sulfur content of the fuel. If a vessel is using 1.0 % S fuel in main engines and 0.1 % S in the auxiliaries in 2014, the SO_x calculation follows the Eq. 4. SO_x emissions of the main engines are cut to one tenth due to the same sulfur content drop in the fuel. However, the factor for SO_x emissions of the auxiliaries is one because the fuel quality is not changing. SO_x emissions are practically linearly dependent on the sulfur content in the fuel.

Equation 4 shows an example of 0.1 % S effect in 2015 when calculating the vessel's SO_x emissions. A vessel is assumed to use 1.0 % S in main engines and 0.1 % S in auxiliary engines in 2014.

$$\text{SO}_x \text{ emissions of vessel X in year 2015} = \text{SO}_x \text{ emissions of vessel X}_{\text{main engines}} \text{ in year 2014[tons]} \times$$

$$(1 + \text{traffic increase of ship X } [\%]/100\%) \times (1 - \text{efficiency increase of ship X } [\%]/100\%) \times 0.1 +$$

$$\text{SO}_x \text{ emissions of vessel X}_{\text{auxiliaries}} \text{ in year 2014[tons]} \times (1 + \text{traffic increase of ship X } [\%]/100\%) \times$$

$$(1 - \text{efficiency increase of ship X } [\%]/100\%) \times 1$$

$$(4)$$

2.6 Fine particle (PM$_{2.5}$) emissions

In STEAM2 model (Jalkanen et al. 2012a), $PM_{2.5}$ emissions are divided into elementary carbon (EC), organic carbon, ash, sulfate (SO_4), and associated water (H_2O). These five components together represent the PM emissions in the scenarios of this paper. PM emissions are highly dependent on the fuel quality and the engine load (Buhaug et al. 2009; Agrawal et al. 2008) (Fig. 2). STEAM2 model takes these into account in the year 2009 PM emissions, but does not include the load dependent conversion efficiency of fuel sulfur to SO_4 as described by Petzold et al. (2010). According to Petzold et al. (2010), the conversion of fuel sulfur to PM SO_4 increases with increasing engine load (from 1 to 5 %), which is not currently taken into account in the STEAM2 model. However, when creating future scenarios and utilizing percentile changes per annum, we assume that the nature of traffic will remain constant and changes concerning engine load are not included in the calculations. PM scenarios of this paper take into account the effect of sulfur in ship fuels as described in IMO (2009) and as presented in Fig. 2 and Table 2.

Equation 3 was used also for the PM calculations. Conversion factors (Table 2) were used with fuel quality changes. For example, a ship using heavy fuel oil of
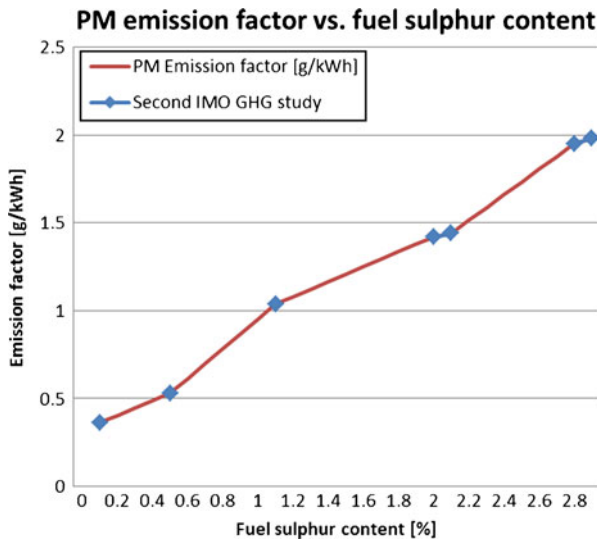
Fig. 2 Change of $PM_{2.5}$ emission factor [g/kWh] as the function of sulfur content in ship fuels as presented by Buhaug et al. 2009 in the Second IMO GHG study

1.0 % S in the main engines in 2014 will have to start using fuel oil with 0.1 % S in 2015. Then, its $PM_{2.5}$ emissions from the main engines will be multiplied with a factor 0.38 in addition with percentile changes of traffic growth and efficiency increase (Eq. 5). If it was assumed that the ship was already using 0.1 % S in the main or auxiliary engines, the $PM_{2.5}$ emissions will have a conversion factor of one.

Equation 5 shows the effect of switching to 0.1 % S fuel in 2015 for SO_x emissions. A vessel is assumed to use 1.0 % S fuel in main engines and 0.1 % S in auxiliary engines in 2014.

$$PM_{2.5} \text{ emissions of vessel X in year } 2015 = PM_{2.5} \text{ emissions of vessel X}_{\text{main engines}} \text{ in year } 2014 \text{ [tons]} \times$$

$$(1 + \text{traffic increase of ship X } [\%]/100\%) \times (1 - \text{efficiency increase of ship X } [\%]/100\%) \times 0.38 +$$

$$PM2.5 \text{ emissions of vessel X auxiliaries in year } 2014 \text{ [tons]} \times (1 + \text{traffic increase of ship X } [\%]/100\%)$$

$$\times (1 - \text{efficiency increase of ship X } [\%]/100\%) \times 1$$

$$(5)$$

Table 2 Conversion factor for $PM_{2.5}$ in different cases of fuel quality change

Fuel quality change	$PM_{2.5}$ conversion factor
1.5S% to 1.0S%	0.79
1.0S% to 0.1S%	0.38
1.5S% to 0.1S%	0.30
0.5S% to 0.1S%	0.68
1.5S% to 0.5S%	0.44
1.0S% to 0.5S%	0.56

2.7 NO$_x$ emissions

Because the regulations concerning NO$_x$ emissions will affect ships built after a specific date, age of a ship and fleet renewal rate must be known and defined when defining future scenarios. Age of a ship is included in the STEAM2 internal ship database and can be used in scenario calculations. Renewal rate is an assumption made for the scenario calculations of this paper, and it is utilized as an average ship lifetime. Average ship lifetimes are presented in Table 1 and given separately for each studied ship type.

STEAM2 model assumes that all ships in 2009 were following the tier I standard. Illustration of the IMO's three tier scheme is presented in Fig. 3. Projection calculation assumes that when a ship reaches an average maximum lifetime of its category, it will be replaced with an otherwise similar ship (size, type, engines, fuel consumption, emissions, etc.) except that it is complying the current regulation valid in that year. For example, if a ship will be replaced in 2013, its NO$_x$ emissions of 2012 will be multiplied with traffic growth and efficiency increase factors and in addition with the tier II factor of 20 % from the tier I level.

Equation 6 shows an example of estimating year 2013 NO$_x$ emissions for a new vessel x. A tier I vessel by reaching its maximum lifetime is replaced by new tier II vessel.

$$NO_x \text{ emissions of vessel X in year } 2013 = NO_x \text{ emissions of vessel in year } 2012 \text{[tons]} \times (1 + \text{traffic increase of ship X [\%]}/100\%) \times (1 - \text{efficiency increase of ship X [\%]}/100\%) \times [(100\% + \text{Tier II factor } (-20\%))/100\%]$$

$$(6)$$

There are two NO$_x$ projections produced to investigate the effect of possible designation of the Baltic Sea and the North Sea as NECA. In the NECA scenario ships renewed after January 1, 2016 will be assumed to be tier III compliant.
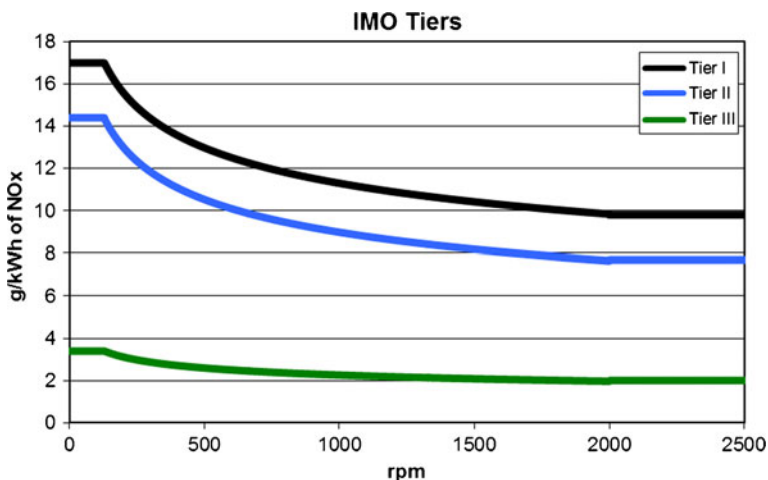

Fig. 3 Three tier scheme of IMO for NO$_x$ emissions of diesel engines. Tier II represents 20 % decrease from the tier I level and tier III 80 % decrease from the tier I level

Traffic growth and efficiency increase in the NO_x scenarios are inferred from the NO_x emissions of current year fleet. In other words, the traffic growth include as much tier I, II, and III traffic as in the current fleet. This assumption does not take into account the possibility that traffic increase can result from ships with varying age arriving to the NECA area.

2.8 European SECA fleet and its emissions in the base year 2009

Table 3 presents the emission inventory for the total European SECA fleet in 2009 and that of the fleet chosen for this study. We can see how filtrating smaller ship types out decrease the emissions (Table 3). Number of ships in the studied European SECA commercial fleet per ship type is presented in Table 1.

3 Results

3.1 CO_2 emissions

According to the projections, CO_2 emissions stay almost constant until 2040 (Fig. 4). It can be seen how efficiency increase is overriding the traffic growth rate preventing CO_2 emissions to increase.

Highest fuel consumption and therefore CO_2 emissions are produced by container, ROPAX, and general cargo vessels (Table 4). Container and general cargo vessels are the only ship types of which CO_2 emissions continue to grow in the future. Reason for this is the higher traffic growth rate of container vessels and smaller efficiency increase rate of general cargo vessels compared to other ship types.

Table 3 Comparison of base year (2009) emissions of total European SECA fleet (STEAM2) and European SECA commercial fleet (13 ship types of this study, all identified by their IMO number). Total fleet includes all ships equipped with an AIS transponder but not necessarily an IMO number, i.e., ice breakers, tugs, barges, yachts, etc.

	TOTAL 2009[a]	This study 2009, commercial fleet, 13 ship types all identified by their IMO number	Difference, %
Fuel consumption [megatons]	15.3	13.0	−15
CO_2 [megatons]	47.3	40.8	−14
NO_x [kilotons]	1 003	878	−12
SO_x [kilotons]	332	278	−16
$PM_{2.5}$ [kilotons]	76.5	64.5	−16
Number of ships	31,407[a] (21,038)[b]	12,290	−61[a] (−42)[b]

The number of ships in parenthesis represents the vessels with an IMO number. Thus, the difference of −61 % represents the difference in number of ships between the commercial fleet and all vessels regardless of their size

[a] Including the small vessels with no IMO number

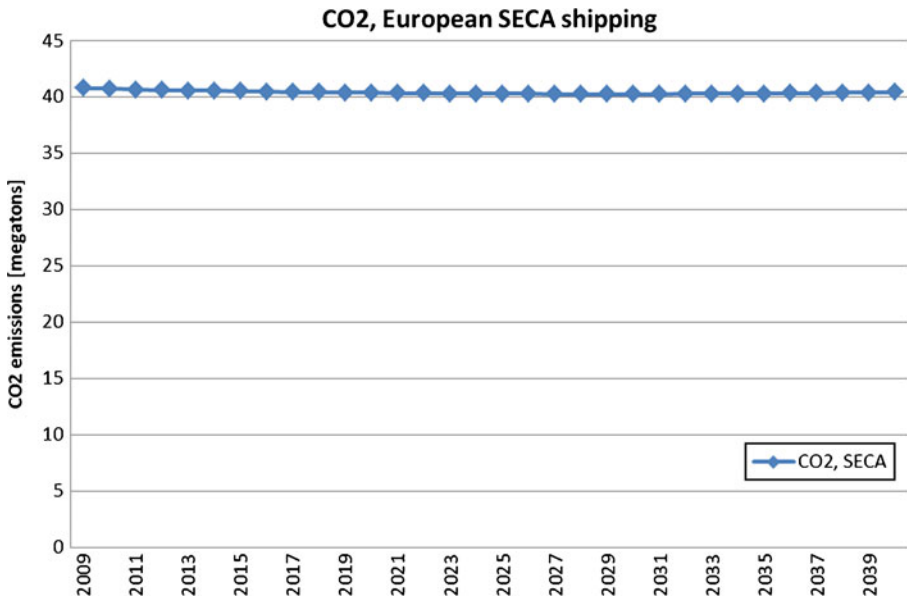[b] Excluding the small vessels with no IMO number

Fig. 4 CO_2 emissions of the European SECA commercial fleet until 2040

3.2 SO_x emissions

SO_x emissions will decrease step by step (Fig. 5) when the regulation on sulphur in ship fuels enters into force. The first drop can be seen in 2010 when sulphur limit drops from 1.5 to 1.0 % as described in IMO (2008). At the same time, EU directive 2005/33/EC on sulfur in ship fuels at berth enters into force also affecting the results

Table 4 Estimated CO_2 emissions [kilotons] of different ship types until 2015

|	2009	2010	2011	2012	2013	2014	2015
Crude oil tanker	2,779	2,761	2,743	2,732	2,720	2,708	2,697
LPG tanker	689	685	681	678	675	672	669
Chemical tanker	4,348	4,320	4,292	4,274	4,255	4,237	4,219
Product tanker	1,196	1,188	1,180	1,175	1,170	1,165	1,160
Bulk ship	2,518	2,502	2,486	2,475	2,465	2,454	2,444
Container	9,102	9,264	9,426	9,536	9,648	9,761	9,875
LNG tanker	114	114	113	112	112	111	111
Ropax	8,237	8,141	8,045	7,982	7,919	7,857	7,795
Ro-ro	3,408	3,368	3,328	3,302	3,276	3,250	3,225
Vehicle carrier	1,274	1,259	1,244	1,234	1,224	1,215	1,205
General cargo	5,032	5,048	5,064	5,074	5,085	5,096	5,106
Cruise ship	1,159	1,145	1,132	1,123	1,114	1,105	1,097
Reefer	958	947	935	928	921	914	906
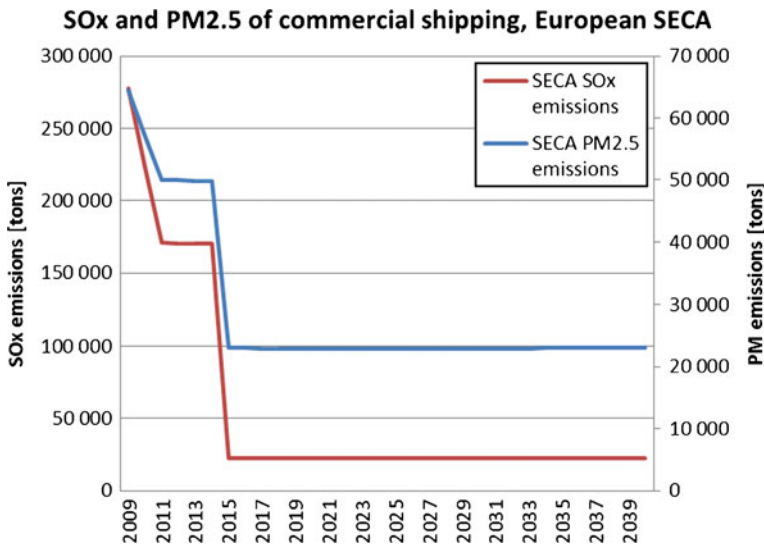
Fig. 5 SO_x and $PM_{2.5}$. emissions of the European SECA commercial fleet until 2040

even if its effect is minor compared to Marpol Annex VI regulation. SO_x and $PM_{2.5}$ emissions stay almost constant after 2015 until 2040, and they are both at the same level (around 23 kt/year).

Year 2011 is the first full calendar year when we can see the real effect of the 1.0 % S limit. SO_x emissions will drop 39 % in 2011 from the 2009 level and 87 % in 2015 from the 2014 level as the ships are assumed to switch from 1.0S% fuel to 0.1S%. The total decrease is 92 % in 2015 from the 2009 level (Table 5).

Container and ROPAX vessels were the ship types with the highest SO_x emissions in 2009 (Table 6). They produced 43 % of emissions even though they represent only 15 % of the fleet. This is because their traffic amount and fuel consumption in the area is high. General cargo vessels, chemical tankers, and ro-ro vessels were three next highest SO_x emitters.

3.3 $PM_{2.5}$ emissions

$PM_{2.5}$ emissions are decreasing in similar fashion as SO_x emissions, but not as drastically (Fig. 5). This is due to the fact that there will still be PM emissions even

Table 5 Effect of MARPOL Annex VI to SO_x and $PM_{2.5}$ emissions (%)

Pollutant	Decrease between 2009 and 2011	Decrease between 2014 and 2015	Total decrease between 2009 and 2015
Change in sulphur content of ship fuels inside SECA	1.5%S to 1.0%S (including 0.1%S at berth in Baltic/EU ports)	1.0 to 0.1%S	1.5 to 0.1%S
SO_x	−39 %	−87 %	−92 %
$PM_{2.5}$	−23 %	−54 %	−64 %

Table 6 Estimated SO$_x$ emissions of different ship types [ton] until 2015

	2009	2010	2011	2012	2013	2014	2015
Crude oil tanker	18,428	14,754	11,397	11,348	11,299	11,251	1,375
LPG tanker	4,155	3,279	2,466	2,456	2,445	2,435	340
Chemical tanker	27,792	21,986	16,605	16,534	16,463	16,392	2,245
Product tanker	7,604	6,017	4,546	4,526	4,507	4,488	616
Bulk ship	17,310	13,748	10,465	10,420	10,375	10,331	1,361
Container	62,793	51,196	38,987	39,443	39,905	40,373	5,492
LNG tanker	758	614	483	481	479	477	52
Ropax	58,461	46,810	36,452	36,166	35,882	35,601	4,582
Ro-ro	24,940	20,081	15,764	15,640	15,518	15,396	1,894
Vehicle carrier	9,165	7,292	5,632	5,587	5,544	5,500	668
General cargo	31,650	25,127	18,737	18,776	18,816	18,856	2,774
Cruise ship	8,951	7,212	5,632	5,588	5,544	5,500	615
Reefer	5,945	4,683	3,547	3,520	3,492	3,465	463

if the fuel would be completely sulfur free. PM$_{2.5}$ emissions will drop 23 % in 2011 from the 2009 level and 54 % in 2015 from 2014 level. The total decrease is 64 % in 2015 from the 2009 level (Table 5). Division of PM$_{2.5}$ emissions between ship types is very similar compared to the SO$_x$ emissions (Table 7).

3.4 NO$_x$ emissions

Two scenarios were developed for NO$_x$ emissions. Scenario 1 is calculated assuming designation of the Baltic Sea, North Sea, and English channel as NECA (Fig. 6).

Table 7 Estimated PM$_{2.5}$ emissions [ton] of different ship types until 2015

|	2009	2010	2011	2012	2013	2014	2015
Crude oil tanker	4,447	3,909	3,429	3,414	3,399	3,385	1,480
LPG tanker	1,087	952	830	826	823	819	390
Chemical tanker	6,729	5,899	5,148	5,126	5,104	5,082	2,391
Product tanker	1,845	1,617	1,411	1,405	1,399	1,393	660
Bulk ship	4,098	3,596	3,145	3,131	3,118	3,104	1,419
Container	15,383	13,899	12,171	12,313	12,457	12,603	5,917
LNG tanker	203	179	158	157	156	156	63
Ropax	12,557	11,019	9,722	9,646	9,570	9,495	4,346
Ro-ro	5,392	4,725	4,165	4,132	4,100	4,067	1,773
Vehicle carrier	2,167	1,892	1,660	1,647	1,634	1,621	703
General cargo	7,329	6,488	5,649	5,661	5,673	5,685	2,806
Cruise ship	1,862	1,633	1,434	1,423	1,412	1,401	578
Reefer	1,419	1,236	1,080	1,071	1,063	1,055	485
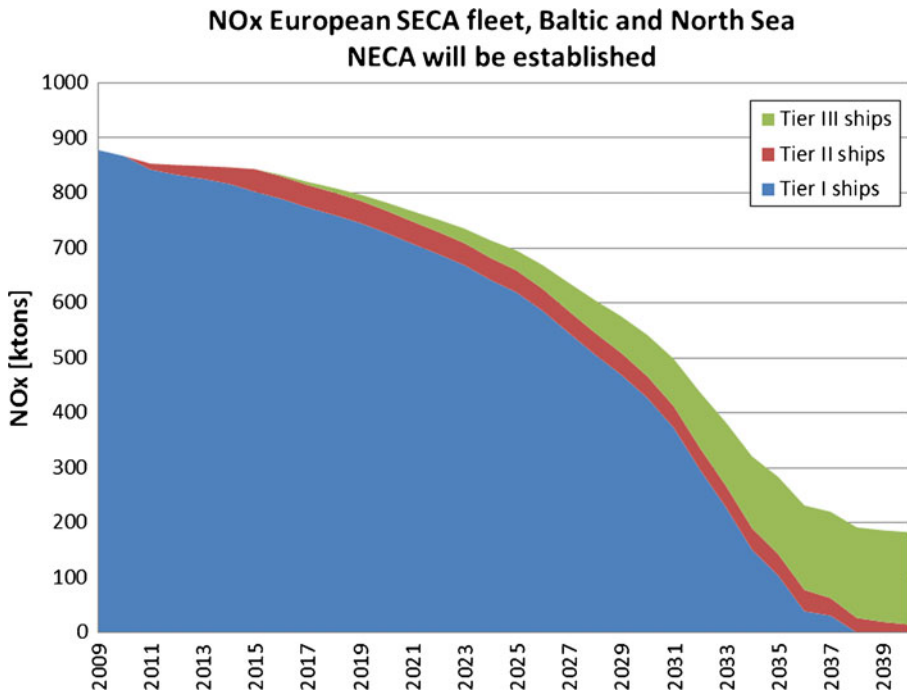
Fig. 6 Scenario 1. NO$_x$ emissions of the European SECA commercial fleet until 2040. Emissions are presented as they are produced by tier I, tier II, and tier III ships

Emissions were estimated to drop 11 % in 2020 and 79 % in 2040 compared to base year 2009 (Table 8).

Scenario 2 presents estimations for NO$_x$ if the Baltic Sea, North Sea, and English channel NECA will not be established (Fig. 7). Emissions in this case were estimated to decrease 6 % in 2020 and 22 % in 2040 compared to base year 2009 (Table 8).

Figures 6 and 7 present the share of NO$_x$ emissions produced by tier I, tier II, and tier III ships in scenario 1 and scenario 2, respectively. Figures show how tier I ships will be removed from the fleet before 2037.

Table 8 NO$_x$ emissions of the Baltic commercial fleet in 2009, 2020, and 2040 and their estimated decrease (%) compared to base year 2009. Scenario 1: Baltic Sea will be designed as NECA. Scenario 2: Baltic NECA will not be established

NO$_x$ emission of the Baltic commercial fleet	2009	2020, decrease from 2009 level		2040, decrease from 2009 level	
Scenario 1, Baltic and North Sea NECA	878 kt	783 kt	−11 %	183 kt	−79 %
Scenario 2, no Baltic and North Sea NECA	878 kt	827 kt	−6 %	686 kt	−22 %

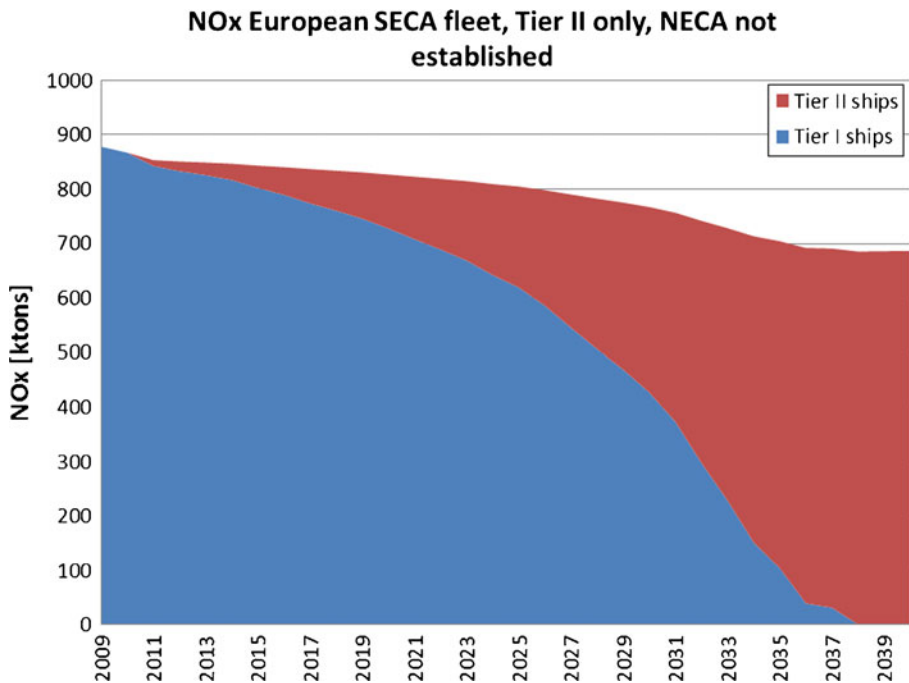## NOx European SECA fleet, Tier II only, NECA not established

Fig. 7 Scenario 2. NO_x emissions of the European SECA commercial fleet until 2040. Emissions presented as they are produced by tier I and tier II ships

4 Conclusions

MARPOL Annex VI regulating the sulfur in ship fuels is an efficient method to decrease SO_x and $PM_{2.5}$ emissions of shipping. Especially in the case of European SECA, a drastic decrease of SO_x and $PM_{2.5}$ (92 % and 64 %, respectively, from the 2009 level) in 2015 will occur. However, the cost of the fuel switch may be high; our most recent estimate is in the range of 3.3–4.6 billion USD per year (Jalkanen et al. 2012b).

Ship originated NO_x emissions will turn to slow decrease due to MARPOL Annex VI's three tier reduction scheme. This will happen even if the Baltic Sea, North Sea, and English channel would not be designated as NO_x Emission Control Area. Results show how the efficiency increase, and tier II NO_x limit together outweigh the moderate traffic growth. NO_x emissions are estimated to decrease 6 % in 2020 and 22 % in 2040 from the 2009 level. If the Baltic Sea, North Sea, and English channel will be designated as NO_x Emission Control Area, more drastic decrease in NO_x emissions will occur. NO_x emissions are estimated to decrease 11 % in 2020 and 79 % in 2040 from the 2009 level.

Container vessels, different tankers, ro-ro/passenger and general cargo ships are generating the most of ship originated atmospheric emissions in the SECA areas. Even if the number of container, RoPax, and ro-ro vessels is low compared to other ship types, they represent the major share of the total fuel consumption in the area.

CO_2 emissions of the European SECA commercial fleet will stay almost constant in the future if the moderate traffic growth and efficiency increase assumptions used in this study will come true. Container and general cargo vessels are the only ship

types the CO_2 emissions of which continue to grow in the future. The reason for this is the higher traffic growth rate of container vessels and smaller efficiency increase rate of general cargo vessels compared to other ship types.

EC white paper (European Commission 2011) describes the CO_2 targets for maritime transport. CO_2 emissions from maritime transport should be cut by 40 % (if feasible 50 %) by 2050 compared to 2005 levels. The white paper does not define a fleet or an area for the target, but from the results of this study, we can see that the Baltic Sea and the North Sea will not be able to reach this target with the current policies.

There are several methods how CO_2 emissions can be cut. Technical methods have been taken into account in this study by the assumption of efficiency increase. Liquiefied natural gas (LNG) and other alternative fuels are a long-term solution for both CO_2 and NO_x emissions and therefore probably will not alone lead to reaching of the EC targets.

Slow steaming can remarkably reduce fuel consumption of specific ships. According to Cariou (2011), slow steaming has reduced emissions by approximately 11 % over the past 2 years. In containerships, up to 70 % decrease in emissions can be achieved when the speed is halved (Corbett et al. 2009). Multiengine vessels are able to shut down engines when reducing their speed, but for ships with one main engine, it would mean lowering of the engine load. This can lead to increase of PM and NO_x emissions and higher specific fuel consumption because the engine is not running on its optimal engine load. Larger number of ships is also needed to reach the same annual cargo turnover as without the slow steaming. This will increase the need for additional container capacity because the rotation of cargo containers will also slow down. There is overcapacity of ships in the market in time of economic recession which leads to slow steaming of ships. When additional ships are added to maintain scheduled frequency, lower speeds still provide CO_2 reduction on most routes, although cost efficiency varies among routes (Corbett et al. 2009). The base year 2009 of this study could be an example of it. According to Cariou (2011), slow steaming is sustainable in the long run only if the bunker prices remain rather high ($350–400) or if powerful market-based solutions are implemented to sustain bunker prices.

Currently, there is a debate in IMO about the MBMs. Some of the presented MBMs have an out of sector influences. The Global Emission Trading System and the International Fund for GHG emissions include out of sector reductions mechanisms and a possibility to compensate the CO_2 emissions. Based on the results of this study, we can conclude that without implementation of new mechanisms to reduce CO_2 emissions, i.e., the market based measures, the EC target for the year 2050 will not be reached.

The newest emission estimates show a 9 % increase in CO_2 emissions between 2009 and 2010 as the maritime transport is recovering from the economic recession. Therefore, the emissions may even be higher than projected because year 2009 may not represent a normal year of traffic activity in the area. In future studies, it would be advisable to change the base year to 2010 or 2011 and to include an estimate of market penetration of LNG as ship fuel to improve the precision of emission projections.

the Baltic Sea region. This publication reflects the author's views and the Managing Authority of Central Baltic INTERREG IV A program 2007–2013 cannot be held liable for the information published by project partners. This publication cannot be taken to reflect the views of the European Union.

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