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Emission factors for shipping in scenarios

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SMED (Swedish Environmental Emissions Data), is a collaboration between IVL Swedish Environmental Research Institute, Statistics Sweden (SCB), Swedish University of Agricultural Sciences (SLU) and the Swedish Meteorological and Hydrological Institute (SMHI). The collaboration commenced in 2001 with the long-term aim of gathering and developing the competence in Sweden within emission statistics. SMED is, on behalf of the Swedish Environmental Protection Agency and the Swedish Agency for Marine and Water Management, heavily involved in the work related to Sweden's international reporting obligations on emissions within six subject areas (air, water, waste, hazardous substances, noise and measures). A central objective of the SMED collaboration is to develop and operate national emission databases. SMED data also supports national, regional and local governmental authorities for decision making. For more information visit the SMED website www.smed.se (in Swedish).

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Sammanfattning

SMED utgör en förkortning för Svenska MiljöEmissionsData, som är ett samarbete mellan IVL, SCB, SLU och SMHI.

Denna rapport innehåller emissionsfaktorer för nationell och internationell sjöfart i scenarier fram till 2050 för metan, dikväveoxid, svaveldioxid, kväveoxider, volatila organiska föreningar, partiklar och sot. Scenarierna tar hänsyn till beslutat regelverk för sjöfarten avseende svavelhalt i bränsle och emissioner av kväveoxider samt förväntad användning av reningsteknik som skrubbrar och selektiv katalytisk reduktion. Vidare presenteras uppdateringar av emissionsfaktorer för 2019 med fokus på kväveoxider och sot. Uppdateringen omfattar litteraturstudie och analys av främst nya data för partiklar och sot samt nya bränslekvaliteter som introducerats under senare år. Slutligen diskuteras förbättringspotentialen avseende historiska data samt nuvarande emissionsfaktorer.

Summary

SMED is short for Swedish Environmental Emissions Data, which is a collaboration between IVL Swedish Environmental Research Institute, SCB Statistics Sweden, SLU Swedish University of Agricultural Sciences, and SMHI Swedish Meteorological and Hydrological Institute.

This report presents emission factors for domestic and international shipping in scenarios up to 2050 for methane, nitrous oxide, sulphur dioxide, nitrogen oxides, volatile organic compounds, particulate matter and black carbon. The scenario accounts for the decided regulations on fuels’ sulphur content and on emissions of nitrogen oxides as well as the anticipated use of abatement technologies such as scrubbers and selective catalytic reduction. Further, an update of some emission factors for 2019 is included with focus on nitrogen oxides and black carbon as well as recently introduced fuel types. Finally, the potential to review historical data and the improvement potential for existing emission factors are discussed.

Keywords: shipping, emission factors, scenarios, nitrogen oxide, black carbon

Introduction

Background

The methods for calculating emissions in the Swedish emission reporting to the UNFCCC and CLRTAP were developed in two SMED reports by Cooper and Gustafsson (2004a, b), where emission factors are developed that can be used together with fuel sale statistics for domestic and international traffic to calculate emissions. In those reports, emission factors for air pollutants and greenhouse gases for 2002 are presented for different fuel types and engine types. The fuel types are residual oil (RO) and marine diesel oil (MD) (discussed further below) and the engine types are presented in Table 1. Emissions from main and auxiliary engines are considered but emissions from oil-burning boilers are excluded. In a next step the distributions of engine types for ships in both national and international traffic are assessed. For some emission types also the age of the engines (for example for NO_X) is important as well as the use of different abatement measures. Accounting for these parameters effective emission factors are computed which are used in the reporting together with fuel sale data.

Developments since 2004 include the use of automated identification system (AIS) data allowing the identification of all ships which operate in Swedish waters. Such data were used by Segersson and Fridell (2014) to improve the description of the engine mix of the ships for both international and domestic traffic. Further, AIS data are now used to distribute the fuel sale reports on domestic and international traffic (Windmark et al., 2017).

The use of abatement measures in shipping mainly influence the emissions of NO_X through the use of selective catalytic reduction (SCR) to reduce NO_X; further, emissions of ammonia and NMVOC will also be influenced by this. The use of SCR was up to 2018 collected from data from the Swedish Maritime Administration when rebates in the fairway dues where given for low-NO_X ships. From 2018 the system is replaced by using Clean Shipping Index (CSI) and the use of SCR is analyzed from CSI data as described by Fridell and Windmark (2018). For SO_X the emission factors are historically calculated from the fuel sulphur content (FSC). However, the introduction of scrubbers to abate the emissions of SO_2 has made this method unreliable and therefore a method taking into account the use of scrubbers by applying AIS data and information from ship databases (SeaWeb 2020) was developed (Fridell and Widmark 2018).

Table 1. Engine types used by Cooper and Gustafsson (2004a)

Name	Abbreviation	Engine speed range, rpm
Slow speed diesel	SSD	60-300
Medium speed diesel	MSD	300-1000
High speed diesel	HSD	1000-3000
Steam turbines	ST	n/a
Gas turbines	GT	n/a

Aim

The primary aim of this work is to present:

- The expected development of emission factors from present date and every five years until 2050 for the species included in SMED scenarios: methane (CH_4), nitrous oxide (N_2O), sulphur dioxide (SO_2), nitrogen oxides (NO_X), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), particulate matter with an aerodynamic diameter less than 2.5 micrometers ($PM_{2.5}$) and black carbon (BC), for the fuels diesel oil, marine gasoil (MGO) heavy fuel oil (HFO) and liquefied natural gas (LNG), for both domestic and international shipping.
- Review of the presently used emission factors in view of mixed fuel qualities that have entered the market with focus on NO_X and BC.
- An analysis of the need for a review of historical emission factors.
- Point out deficiencies in the data.

This report does not include a review the emission factors for leisure boats.

Marine fuels

The nomenclature and definition of marine fuel oils is rather complicated (Fridell, 2018). There is the ISO-standard 8217 defining marine fuel oils but there are also a number of brand names circulating as well as new fuel mixtures developed as low-cost fuels meeting the sulphur regulations that do not follow the standards. Further, neither the translation to the Swedish system with “eldningsoljor” nor the division in RO and MD is straight forward. In Sweden, light fuel oil is referred to as “Eldningsolja 1”, EO1; heavy fuel oil (including bunker fuel) is referred to as “Eldningsolja 2-6”, Eo2-6. Marine fuel oils are usually characterized by the viscosity and the fuel sulphur content.

The most common fuel used in international shipping since WW2 is HFO or RO which is a high sulphur, high viscosity fuel with varying qualities. Also MGO, which is a distilled product, is used frequently as well as marine diesel oil (MDO), which is a mixture of distilled and residual oils. More recently, the use of LNG has increased. An important regulation for marine fuels is the sulphur standard decided by the international maritime organization (IMO). The maximum allowed FSC can be seen in Figure 1. The SECAs, with the more stringent standard, are the Baltic Sea, the North Sea, the English Channel, the coasts of USA and Canada and around the US Caribbean islands. It should further be noted that fuels with higher FSC can be used if the ship is equipped with scrubbers that limits the SO_2-emissions to levels corresponding to the fuel sulphur limits. Mixed fuels are now sold that meets the fuel limits: very-low sulphur fuel oil (VLSFO), with up to 0.5% FSC, and ultra-low-sulphur fuel oil (ULSFO), with up to 0.1% FSC. In Table 2 some common marine fuel oils are listed.

In order to produce effective emission factor per the required fuel types for Swedish conditions (i.e. diesel, EO1 and EO2-6) it is necessary to assign all fuels to these types. We have assigned MDO to EO2-6. We have also assigned VLSFO and ULSFO to EO2-6 since these products typically are mixture with some residual oil. However, the data for these are very scarce and it is possible that some of these products should be assigned as EO1.

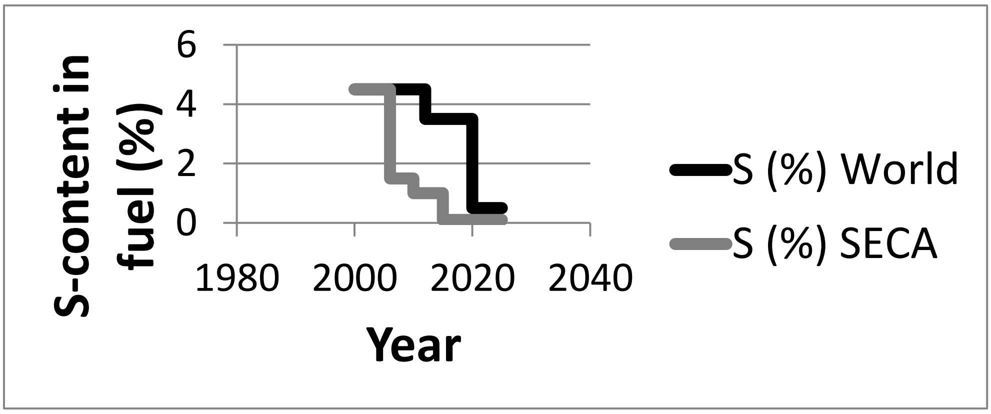

Figure 1. Sulphur regulations for shipping.

Table 2. Marine fuel oils.

Name	ISO 8217 grades	Viscosity (cSt)	FSC	Comment
HFO, RO	RM	10-700	0.5-3.5 %	Used with scrubbers if >0.5% FSC. EO2-6
MDO	DMB, DFB	Max 11	-1.5 %	Mixed product. EO2-6
MGO	DMA, DMX, DMZ	Max 6	Max 0.1%	Distillates. EO1
Diesel	n/a		10 ppm	Road diesel used by ferries trafficking the archipelago, road ferries and commuter traffic.
VLSFO	n/a		0.5%	Meets 2020 world-wide FSC standard. Varying quality. EO1 or EO2-6
ULSFO	n/a		0.1%	Meets 2015 SECA FSC standard. Varying quality.EO1 or EO2-6

The emission factors for LNG fueled ships were recently reviewed by Hult and Winnes (2020). LNG can be used in different types of engines and the most frequent ones are of dual-fuel type where a fraction of MGO is used together with the LNG. This makes it somewhat problematic when allocating emission factors to a specific fuel, for example, even though 95% of the fuel is LNG almost all emissions of SO_2 will originate from sulphur in the MGO.

Methods

The review of emission factors is done through a literature study. The emission factors in scenarios are calculated by taking into account the upcoming regulations and the expected development of engines. Note that only fuel specific emission factors are developed here, the assessment of future fuel mixes are outside the scope of the current report. The historic emission factors (1990-2018) are assessed mainly though investigating if the currently available emission factors and AIS data can be reasons for revision.

For dual fuel LNG engines, the emission factor for SO_2 is calculated from the sulphur content in the respective fuel while emissions that originate from the combustion are reported as emission factors for LNG.

Review of emission factors

The review is here done with emphasis on NO_X and BC. Hult and Winnes (2020) recently reviewed the emission factors for ships using LNG as the main fuel and the results from that study are incorporated here.

Table 3 shows the emission factors used in the Swedish reporting for emissions from 2018 and the LNG emissions factors from Hult and Winnes (2020).

Table 3. Emission factors used for the reporting of Swedish emissions from shipping in 2019 in kg/TJ.

		Diesel	EO1	EO2-6	LNG
Domestic	CH_4	0.38	0.38	0.51	680
	N_2O	4.2	4.2	3.6	n.d.
	SO_2	36.0	36.0	46.0	0.12
	NO_X	830	830	1180	302
	NH_3	0.75	0.75	3.60	n.d.
	NMVOC	19.0	19.0	25.0	42
	$PM_{2.5}$	17.3	17.3	77.0	2.6
	BC	5.76	5.76	10.2	0.77
International	CH_4	0.32	0.32	0.57	680
	N_2O	4.8	4.8	3.9	n.d.
	SO_2	36.0	36.0	570	0.12
	NO_X	660	660	1340	302
	NH_3	0.20	0.20	0.637	n.d.
	NMVOC	16.0	16.0	28.0	42
	$PM_{2.5}$	16.6	16.6	103	2.6
	BC	5.51	5.51	13.8	0.77

Nitrogen oxides

The emissions of nitrogen oxides from ship engines is regulated by the IMO in a tiered system (Figure 2). The allowed emissions depend on the engines' speed and on the year of production. Tier 1 and 2 apply worldwide from year 2000 and 2011, respectively, while Tier III applies in NO_X emission control areas (NECAs): North America and the U.S. Caribbean Sea from 2016, the Baltic and North Seas from 2021. Engines older than from 2000 (sometimes denoted Tier 0) are not addressed by any emission regulation (Cooper and Gustafsson 2004a). An exception is if the engines have undergone a major conversion in which case the engine emissions need to comply with the levels valid at the time of conversion. For Tier 1 and 2 the engines are modified to reach the NO_X-limits which typically has higher fuel consumptions as a consequence. For Tier III oil-fueled diesel engines abatement measures are needed, mainly SCR is used. Thus, the engine setups will be made in such a way that the amount of emitted NO_X is close to the prescribed limit in order to save fuel and, for Tier III, to save urea (urea is used as the reducing agent in SCR-systems).

NO_X is mainly formed from N_2 and O_2 in the air via the Zeldovich mechanism taking place at high pressure and temperatures in the cylinders. The rate of NO_X formation increases strongly with increasing temperature and can therefore vary with engine design and fuel characteristics. NO_X can also be formed if nitrogen is present in the fuel which can be the case for HFO.

Summaries of emission factors for NO_X have been presented by Cooper and Gustafsson (2004a). For Tier 0 engines the emission factors presented by Cooper and Gustafsson (2004a) are still valid and for newer engines the Tier limits apply. For the VLSFO and ULSFO fuels there are only few reports publishing measured data. Zetterdahl et al. (2016) measured emissions on a Tier 1 engine using VLSFO with 0.48% FSC at two different engines loads. The measurements indicated that the untreated exhaust exceeded NO_X Tier I levels (the ship was equipped with an SCR to reach lower NO_X-emissions but here we are interested in the engine-out emissions). Specific NO_X emission were 20.8 and 15.6 g/kWh at 50 and 85% of maximum continuous rating (MCR) engine load, respectively. The same engine was also tested for NO_X emissions using an ULSFO with 0.092 % FSC at four different engine loads: 84%, 61%, 38%, and 24%. Specific untreated emissions were 14, 17.7, 19.6, and 21.6 g/kWh in order of decreasing engine load. Winnes et al. 2016, measured NO_X emissions on two different engines using VLSFO with

0.5% FSC. Both engines were Tier I engines, one 2-stroke engine of 105 rpm and one 4-stroke engine of 510 rpm. Fuels were similar in nitrogen content and specific emissions were 9.4 g/kWh at 57% engine load for the medium speed engine and 11.1 g/kWh at 51% engine load for the slow speed engine. Emissions of NO_X from the same engines using MGO were 8.4 g/kWh for the 4-stroke engine and 11.2 g/kWh for the 2-stroke engine. No tests were conducted on other engine loads. Winnes et al. (2020a) measured emissions from a medium speed Tier I engine using 0.1 % FSC fuel oil. Tests were performed at four engine loads: 85%, 75%, 50% and 34%. The specific NO_X emissions were 11.84, 9.73, 11.85, and 15.38 g/kWh in order of decreasing engine loads. Gysel et al. (2017), measured on a medium speed 6300 kW Tier I engine using ULSFO and arrived at a weighted specific NO_X emission of 10.2 g/kWh. Measurements on the same engine using marine gasoil resulted in a slightly higher emission factor, 10.7 g/kWh. The FSCs of the ULSFO and the MGO were 0.009% and 0.005%, respectively. The results from the published measurements of NO_X-emissions with ULSFO and VLSFO are summarized in Table 4. As can be seen from the data it is at present not possible to state that the emissions of NO_X when using ULSFO/VLSFO are different from when using MGO since the results point in different directions.

Table 4 Summary of results from measurement of NO_X on marine engines using mixed fuels. Colours indicate measurements on the same engine.

Engine Tier	Engine speed	Fuel type	FSC (%)	Engine load (% of MCR)	NO_X-emission (g/kWh)	Reference
1	MSD	VLSFO	0.48	50	20.8	Zetterdahl et al. (2016)
1	MSD	VLSFO	0.48	85	15.6	
1	MSD	ULSFO	0.092	84	14	
1	MSD	ULSFO	0.092	61	17.7	
1	MSD	ULSFO	0.092	38	19.6	
1	MSD	ULSFO	0.092	24	21.6	
1	SSD	VLSFO	0.5	51	11.1	Winnes et al. (2016)
1	SSD	MGO	0.5	51	11.2	
1	MSD	VLSFO	0.5	57	9.4	
1	MSD	MGO	0.5	57	8.4	
1	MSD	ULSFO	0.1	85	11.84	

1	MSD	ULSFO	0.1	75	9.73	Winnes et al. (2020)
1	MSD	ULSFO	0.1	50	11.85	
1	MSD	ULSFO	0.1	34	15.38	
1	MSD	ULSFO	0.009	weighted	10.2	Gysel et al. (2017)
1	MSD	MGO	0.005	weighted	10.7	

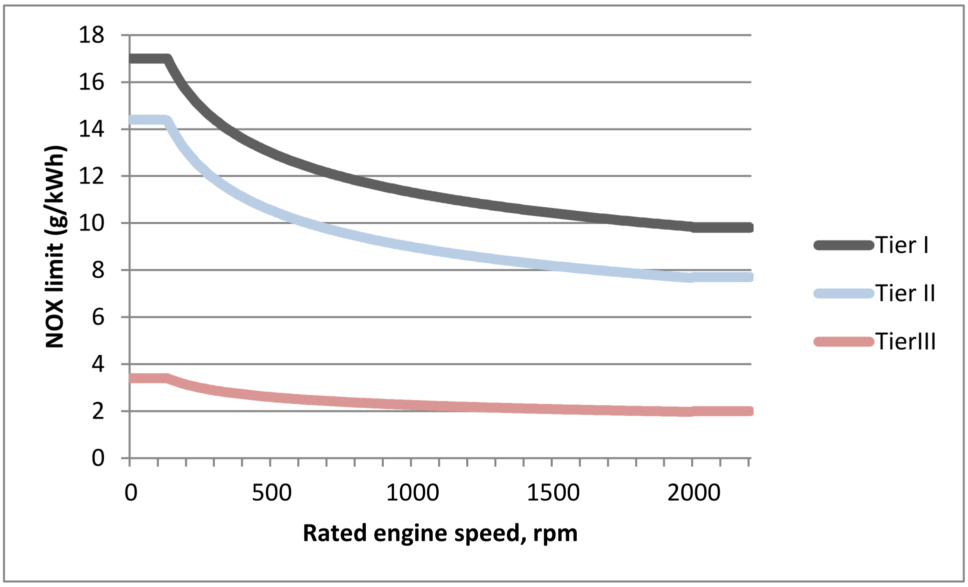

Figure 2. NOx-limits for marine engines

In order to produce effective emission factors for NO_X for Swedish domestic and international traffic the specific emission factors are used together with the following information:

- The distribution of engine types in the fleet, in relation to the fuel consumed, is take from Segersson and Fridell (2012), where the information is based on AIS data in combination with ship database information on engine type. This is the most recent analysis, and long life-time of ships likely means that it is till valid.
- The age distribution of the engines is taken from AIS data for 2018 from Fridell and Windmark (2018) in combination with the ships' ages from a database (SeaWeb 2020). The data is then updated for 2019 by replacing some Tier 0 ships with Tier 2 ships according to historical renewal rates. The distribution in 2018 showed that 27%, 52%, 20% of the ships should follow the NO_x limits for Tier 0, Tier 1 and Tier 2, respectively. The data indicate a renewal rate of 3% giving a distribution for 2019 of 24%, 52%, 23% for the three Tiers.
- The use of abatement methods is taken from list of ships in CSI as described in Fridell and Windmark (2018).

- Convert to mass of emission per fuel heat content by using the specific heat values for the fuels and specific fuel consumption from Cooper and Gustafsson (2004a).

The effective NO_X emission factors are presented in Table 5. The difference in emission factors between the fuel types only influences the emissions of Tier 0 engines since Tier 1 and 2 engines are assumed to closely follow the emission limits (Figure 2). For EO2-6 we do not have data on the distribution of the sold fuel on the different qualities but since the emissions factors do not vary significantly, and only 24% of the ships belong to Tier 0, this uncertainty will not be important.

Table 5. NO_X emission factors for 2019 in kg/TJ.

Fuel	**Domestic**	**International**
Diesel	830	660
EO1	830	660
EO2-6	1180	1340
LNG	160	160

SCR will also have influence on other emissions. The NH_3 content in the exhaust is about 15 ppm which translates to an emission factor of about 0.1 g/kWh (Cooper and Gustafsson 2004a). The emission factor for NMVOC is decreased by about 25% by using SCR (Winnes et al. 2020b).

Black carbon

Black carbon emission factors depend on both engine and fuel characteristics. Further, different instrument types used for measurements have been shown to give different results (Jiang, 2018; ICCT, 2016; Timonen et al., 2017). Emission factors from some available studies are summarized in Table 6 and Figure 3.:

Table 6. BC emission factors from literature for oil-fuelled marine engines.

Engine type	**Fuel type**	**Engine load**	**Aftertreatment**	**BC (g/kg)**	**BC (g/kWh)**	**Study**
2-stroke, HSD	DMA	75%		0.07-0.28	-	Jiang et al., 2018
2-stroke, HSD	RMB-30	75%		0.10-0.40	-	Jiang et al., 2018
2-stroke, HSD	RMG-380	75%		0.03-0.22	-	Jiang et al., 2018
2-stroke, HSD	DMA	25%		0.50-1.1	-	Jiang et al., 2018
2-stroke, HSD	RMB-30	25%		1.1-2.5	-	Jiang et al., 2018
2-stroke, HSD	RMG-380	25%		0.7-1.6	-	Jiang et al., 2018
4-stroke	HFO (S = 0.65%)	40%	EGCS		0.022	Lehtoranta et al., 2019
4-stroke	HFO (S = 0.65%)	75%	EGCS		0.018	Lehtoranta et al., 2019
4-stroke	HFO (S = 0.65%)	40%	EGCS + SCR		0.016	Timonen et al . 2017
4-stroke	HFO (S = 0.65%)	75%	EGCS + SCR		0.014	Timonen et al . 2017
4-stroke	HFO (S = 1.9%)	65%	DOC + EGCS		0.013	Lehtoranta et al., 2019
2-stroke	HFO (S = 2.3%)	51%	EGCS		0.0012	Fridell and Salo, 2014
2-stroke	HFO (S = 2.3%)	51%			0.011	Fridell and Salo, 2014
4-stroke	HFO (S = 2.7%)	76%			0.022	Winnes et al., 2020
4-stroke	HFO (S = 2.7%)	49%			0.035	Winnes et al., 2020
4-stroke	HFO (S = 2.7%)	32%			0.065	Winnes et al., 2020
4-stroke	HFO (S = 2.7%)	76%	EGCS		0.022	Winnes et al., 2020
4-stroke	HFO (S = 2.7%)	48%	EGCS		0.022	Winnes et al., 2020
4-stroke	HFO (S = 2.7%)	41%	EGCS		0.028	Winnes et al., 2020
2-stroke and 4-stroke	HFO (S = 1.89%)	weighted			0.086	ICCT (Johnson et al.), 2016
2-stroke and 4-stroke	HFO (S = 1.89%)	weighted	EGCS		0.0062	ICCT (Johnson et al.), 2016
2-stroke	HFO (S = 1.89%)	94%			0.0041	ICCT (Johnson et al.), 2016
2-stroke	HFO (S = 1.89%)	93%	EGCS		0.0034	ICCT (Johnson et al.), 2016
4-stroke	LSFO (S = 0.1%)	85%	EGCS		0.006	Winnes et al., 2020
4-stroke	LSFO (S = 0.1%)	75%	EGCS		0.004	Winnes et al., 2020
4-stroke	LSFO (S = 0.1%)	50%	EGCS		0.01	Winnes et al., 2020
4-stroke	LSFO (S = 0.1%)	34%	EGCS		0.012	Winnes et al., 2020
2-stroke, SSD	MGO (S = 0.03%)	57%		0.002		ICCT (Johnson et al.), 2016
2-stroke, SSD	MGO (S = 0.03%)	41%		0.009		ICCT (Johnson et al.), 2016
2-stroke, SSD	MGO (S = 0.03%)	28%		0.051		ICCT (Johnson et al.), 2016
2-stroke, SSD	MGO (S = 0.03%)	9%		0.019		ICCT (Johnson et al.), 2016

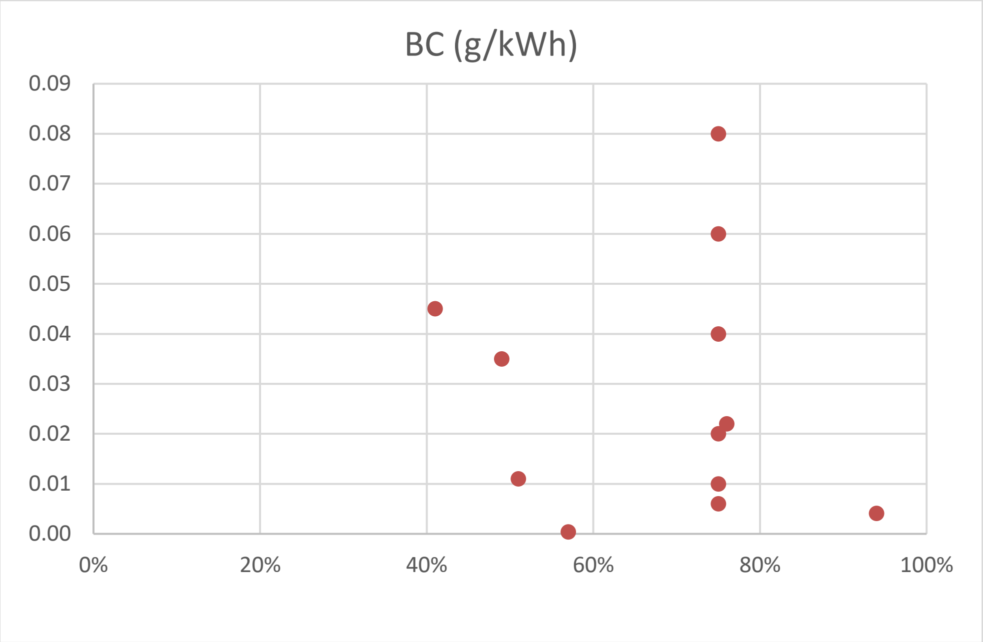

Figure 3. BC emission factors for oil-fuelled marine engines as a function of engine load.

An analysis of the data and the references considered indicate that straightforward correlations between fuel sulphur contents and BC emission factors are difficult to establish (Jiang et al., 2018; Lack and Corbett 2012). Lack and Corbett (2012) reasons that improvements to fuel quality (from residual to distillate fuels) can reduce BC emissions by an average of 30% and potentially up to 80%.

Many measurement studies focus on the elemental carbon emissions which are comparable to black carbon emissions. Differences between EC and BC emission factors can relate to differences in analytical methods, see e.g. Moldanová et al. (2013).

Corbett et al. (2010) suggest an EC emission factor span 0.03-0.17 g/kWh with a best value of 0.07 g/kWh based on results from two plume measurement campaigns and one on-board measurement. Gysel et al. (2017) measured EC from a medium speed engine and the results indicated emission factors of 0.01 g/kWh for MGO and LSHFO. Khan et al. (2012), measured EC emission factors for a marine engine using MGO to be 0.0023 -0.0087 g/kWh at 12-24% engine load and to be 0.0039-0.0057 g/kWh with HFO on engine loads 24-90%. The EC emission factors increased with decreasing engine loads. The test engine was a marine slow speed diesel. Moldanova et al. (2009) measured EC emissions to be 0.02 g/kWh for a slow speed engine on 84% engine load.

Moldanova et al. (2013), presents EC emission factors from three different engines. A 4-stroke engine using HFO emitted approximately 0.5 and 0.8 g EC/kg fuel on 80 and 30% engine load, respectively. Another 4-stroke engine, also using HFO, had emissions of between 0.3 and 0.55 g/kg at 57% engine load. The study also measured on a medium speed auxiliary engine that had an EC emission factor of 0.25 g/kg at 47% engine load using MGO. Assuming a specific fuel consumption (SFC) of 200 g/kWh, the specific EC emissions were 0.06-0.2 g/kWh for the 4-strokes using HFO and 0.05 for the auxiliary engine on MGO. Lack et al. (2011) determined EC emission factors from in plume measurements for a 2-stroke engine to 0.22 g/kg when using HFO and 0.13 g/kg when using MGO. At an SFC of 200 g/kWh the corresponding specific emissions of EC are 0.04 g/kWh at HFO combustion and 0.03 g/kWh at MGO combustion.

Combined, the measurement studies on BC and EC emissions indicate a plausible range from 0.01 g/kWh to 0.1 g/kWh although one measurement indicate emissions as low as 0.4 mg/kWh. Excluding the results from measurements on very low engine loads, which are not very representative for ships in daily operation, an emission factor for BC of 0.03 g/kWh seems representative for the selection of engines that have appeared in the measurement studies. Emissions of BC from MGO combustion in diesel engines appear to be lower than those from HFO combustion. The BC emissions from hybrid fuels, VLSFO and LSFO, are more difficult to determine. The sulphur content of a fuel is not a parameter that determine BC emissions. Comer et al. (2017), conclude from a literature review: *"Researchers have found that (a) distillate fuels emit less BC than HFO; (b) desulfurized residual fuels emit more BC than HFO at typical engine operating loads; and (c) with few exceptions, 0.5% sulfur residual fuel blends seem to emit as much or more BC as HFO. Specifically, Johnson et al. (2016) tested the effects of fuel switching on BC emissions and found that distillate fuel had the lowest BC EF and that a desulfurized residual fuel (RMB-30) had the highest BC EF at typical engine operating loads of 25% to 75%, higher even than HFO."*

Comer et al. (2017) considers measurement studies by Euromot, UCR, and Finnish researchers, and arrive at the emission factors for black carbon based on functions derived from measurement values. The emission factors in Table 7 are weighted according to the E2 test cycle of ISO 8178, and based on emission factors for the respective engine loads from Comer et al. (2017).

Table 7. BC Emission factors (g/kg) from Comer et al. 2017, for 2-stroke and 4-stroke engines using HFO and MGO at different engine loads, and a weighted emissions factor per combination of engine type and fuel type. Weighted according to ISO 8178 E2. Assuming specific fuel consumption of 200 g/kWh.

	Engine load 100% (g/kg)	Engine load 75% (g/kg)	Engine load 50% (g/kg)	Engine load 25% (g/kg)	**WEIGHTED EF ISO 8178 E2 test cycle (g/kg)**	**WEIGHTED EF ISO 8178 E2 test cycle (g/kWh)**
	Weight assigned by ISO 8178 (E2)				-	-
	0.2	*0.5*	*0.15*	*0.15*		
BC EF 2-stroke HFO	0.15	0.17	0.2	0.26	**0.18**	**0.04**
BC EF 4-stroke HFO	0.2	0.26	0.39	0.78	**0.35**	**0.07**
BC EF 2-stroke MGO	0.03	0.03	0.04	0.06	**0.036**	**0.007**
BC EF 4-stroke MGO	0.1	0.14	0.21	0.48	**0.19**	**0.04**

The reason for the significantly lower BC emissions from 2-stroke engines, especially in combination with MGO, are not fully explained and therefore difficult to include in a recommendation for scenario calculations. The average emission factor for HFO combustion is 0.05 g/kWh and for MGO 0.02 g/kWh, using the values in Table 7. Average emission factors for the two engine types are 0.02 g/kWh for slow speed diesels (2-stroke engines) and 0.05 g/kWh for medium speed diesels (4-stroke engines).

For practical reason, the use of emission factors based on fuel types is recommended here; this is also what is recommended in the EMEP Guidebook.

Exhaust gas cleaning systems (EGCS), “scrubbers”, reduce BC emissions. The average emission factor from available measurement studies is 0.02 g/kWh. This correspond to removal of approximately 1/3 of the BC in the exhaust. The data are few, literature estimates are 40% reduction (Corbett et al., 2010), and 30% reduction (Comer et al., 2017) of BC at the use of scrubbers. Four measurement studies have considered removal of BC and/or EC across the scrubber at different engine loads. The average reduction from these measurements is 45% (ICCT, 2016; Timonen et al., 2017; Winnes et al., 2020; Fridell och Salo, 2014). We recommend calculating a reduction of BC emissions over scrubber of 40%.

The suggested BC emission factors are summarised in Table 8.

Table 8. BC emission factors

Fuel	EGCS	BC emission factor g/kWh
MGO	No	0.02
HFO	No	0.05
VLSFO/ULSFO	No	0.05
HFO	Scrubber	0.03

From these effective emission factors per fuel (as energy content) can be calculated with a similar method as outlined for NO_X. The suggested emission factors for the reporting can be found in Table 9.

Table 9. BC emission factors for 2019 for reporting.

Fuel		BC emission factor (kg/TJ)
Diesel	Domestic	2.5
Eo1	Domestic	2.5
Eo2-6	Domestic	5.4
LNG	Domestic	0.77
Diesel	International	2.5
Eo1	International	2.5
Eo2-6	International	5.4
LNG	International	0.77

Other emissions

In this section emission factors for CH_4, N_2O. NH3, NMVOC, PM and SO_2 are discussed. The suggested emission factors can be found in Table 13 and Table 14.

The emission factor for CH_4 is low for fuel oil, and there are no indications of a change with time, while it is significant for LNG as described in Hult and Winnes (2020).

The emissions of N_2O are also low and we have not found any updated emission factors.

The use of SCR is the main factor influencing the emissions of NH_3. For the earlier system in Sweden for SCR there was a limit of 20 ppm in the exhaust for SCR engines, this still applies for CSI. Thus, the emission factor for NH_3 is strongly correlated to the use of SCR. The emission factors in Table 10 takes into account the use of SCR and the NH_3 content in the exhaust is about 15 ppm which translates to an emission factor of about 0.1 g/kWh (Cooper and Gustafsson 2004a).

Table 10. NH3 emission factors for 2019 in kg/TJ

Int.	MD	0.21
Int.	RO	0.74
Nat.	MD	0.41
Nat.	RO	1.21.

NMVOC is also influenced by the use of SCR since some hydrocarbons can be oxidized over the SCR catalyst. The used emission factors are updated to account for this.

For PM there is a strong correlation between fuel and engine types and the emissions. The emission factors were updated in Fridell and Windmark (2018). An average $PM_{2.5}$ emission factor for MGO is calculated to 0.22 g/kWh based on several measurement studies. For HFO with sulphur content less than 0.5%, an EF is 0.43 g/kWh.

In another analysis of emission factors for PM at combustion of low sulphur fuel (Winnes et al. 2019) it was concluded that from available measurements it was not reasonable to distinguish emission factors for different engine loads, engine types, or fuel types. For fuels with less than 0.5% S, an average emission factor for PM was calculated to 0.2 g/kWh, results from individual measurements are presented in Figure 4.

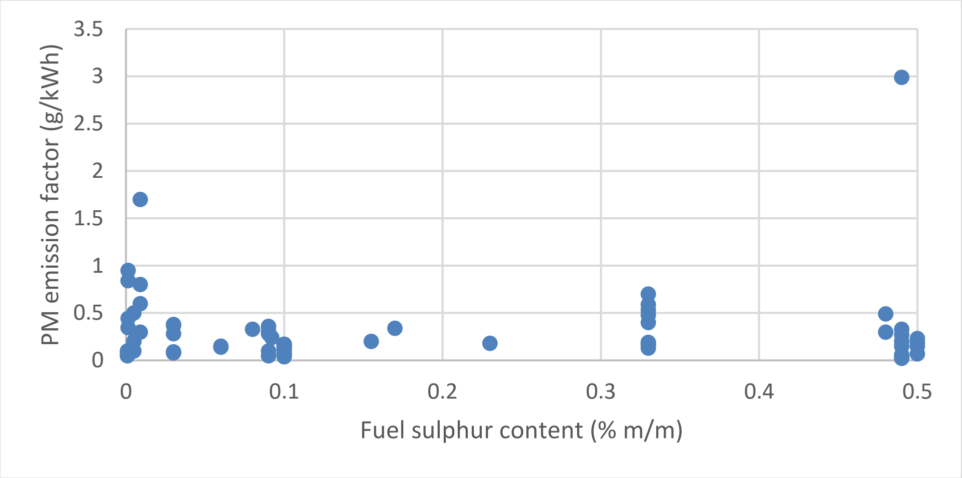

Figure 4. PM emission factors from measurement studies on marine engines using fuels with less than 0.5% sulphur content (Lehtoranta et al. 2019; ICCT, 2016; Gysel et al., 2017; Winnes and Fridell, 2009; Agrawal et al., 2008b; Cooper, 2003; Cooper, 2001; Winnes et al., 2016; Zetterdahl et al., 2016; Winnes et al., 2020; Moldanova et al., 2013; Kasper et al-., 2007; Khan et al., 2019; Fridell et al., 2008).

IMO's 4th GHG report presents formulas for calculating specific PM10 emissions factors, from marine engines based on fuel sulphur content (IMO, 2020). Different formulas are applied for HFO and MDO/MGO. The equation for HFO is:

$$EF = 1.35 + SFC \times 7 \times 0.02247 \times (S - 0.0246)$$

And the equation for MGO/MDO is

$$EF = 0.23 + SFC \times 7 \times 0.02247 \times (S - 0.0024)$$

An HFO with 2.7% sulphur content would thus cause PM emissions of 1.4 g/kWh, regardless of engine type and engine load. An MGO with 0.1% sulphur would cause PM emissions of 0.19 g/kWh. Both estimates use an assumption that the specific fuel consumption (SFC) is 200 g/kWh.

The emissions of SO_2 is as discussed related to the FSC in the sold fuel and the use of scrubbers. The emission factors have already incorporating these aspects.

Scrubbers significantly influence the levels of SO_2 in the exhaust gases Lehtoranta et al, 2019a; Winnes et al., 2020; Fridell and Salo, 2014; ICCT, 2016; Zhou et al., 2017). Further, the technology reduces the levels of hydrocarbon compounds and has also been reported to give minor reduction of contents of NO_X and CO_2. Significant effects can be seen for hydrocarbon emissions and particles (Lehtoranta et al., 2019a; Winnes et al., 2020; Fridell and Salo, 2014) although at least one study have shown increased PM emissions (ICCT, 2016). This is explained as formation of sulphate particles downstream the scrubber and salt particles originating from the salt in the sea water. Measurement studies on emissions for ships with scrubbers converge towards particle mass reduction efficiencies around 30%, see Table 11.

Table 11. Measured reduction potentials over scrubbers of emissions of SO_X, HC and PM. Data from Emerge D1.1 (Winnes et al., 2020b).

	SOX	HC	PM
Reduction potential	98.8±1.09%	36.3±14.7	30.2±21.6
Sources	Lehtoranta et al., 2019a; Winnes et al., 2020; Fridell and Salo, 2014; ICCT, 2016; Zhou et al., 2017	Winnes et al., 2020; Fridell and Salo, 2014	Lehtoranta et al., 2019a; Winnes et al., 2020; Fridell and Salo, 2014; ICCT, 2016

From the published studies it is not possible to draw conclusions on differences in emission reduction potential between open and closed loop scrubber systems.

The recommended $PM_{2.5}$ emission factors from this analysis are summarised in Table 12.

Table 12. Recommended emission factors for 2019 for PM2.5.

Fuel	FSC (%)	EGCS	Emission factor g/kWh
MGO/ULSFO	0.1	No	0.22
HFO	2.7	No	1.4
VLSFO	0.5	No	0.43
HFO	2.7	Scrubber	0.98

Emission factors in scenarios

The scenario-emission factors are made by considering known changes in regulation and anticipated development in technology. It should again be emphasized that the main driver when it comes to changing emissions from shipping up to 2050 is not changes in emission factors but move from fossil fuels to other fuels caused by the problems with global warming and in order to meet the IMO target of a 50% reduction in GHG-emissions from international shipping by 2050 in relation to 2008. In order to produce emission factors up to 2050 the following are considered:

The FSC limit is set worldwide to 0.5% from 2020. The limit in SECAs is 0.1%. We do not anticipate any further changes in the FSC-limits. The use of scrubbers is anticipated to continue and increase. The HFO that is used worldwide from 2020 is either VLSFO (ULSFO in SECAs) or high sulphur fuel used in ships with scrubbers. The fraction of the fuel that will be used in scrubbers in the future is difficult to assess. The decision by ship-owners and operators to invest in scrubbers is made based on the investment costs and the anticipated cost difference between VSLFO and HFO. In 2019 we found that about 50% of the high FSC HFO sold was used in scrubber ships (the rest was used outside SECA) and about 20% of the EO2-6 was ULSFO. We assume that the use of scrubbers will increase up to 2050 reaching 60% of the EO2-6 sold in Sweden with 20% being ULSFO and 20% VLSFO. It should be noted that the use of scrubbers will not have an impact on the emission factor for SO_2 but will impact the $PM_{2.5}$ and BC emission factors. However, the use of scrubbers will significantly influence the amount of pollutants emitted to water which is outside the scope of this report.

New engines in the North and Baltic Seas will have to follow the Tier 3 NO_X-limits for ships keel-laid after 2021. In practice this means that ships in operation by ca 2022 will follow these rules due to the delay between the dates for a new ship being keel-laid and being in operation. The most frequently used abatement method today to reach Tier 3 is SCR and we have assumed that new ships from 2022 will use SCR. The emission factor for NO_X will thus decrease in the future as old ships are replace by new ones. We have assumed a replacement fraction of 3% per year, first replacing Tier 0 ships, then Tier1 ships and finally Tier 2 ships. The increased use of SCR also influences the emission factors for NH_3 and NMVOC as discussed above.

As discussed by Hult and Winnes (2020) and Stenersen and Thonstad (2017) there are different types of LNG engines with different emission factors. We here assume that dual-fuel engines will dominate in relation to the LNG sold to ships in Sweden. For these engines the emissions of mainly CH_4 and NO_X varies between types and model year. The methane slip is lower for newer engines than for older ones and significantly lower for the high-pressure type engines than for the other types. The emissions of NO_X, on the other hand, is higher for the high-pressure engines and these are expected to use SCR to reach Tier 3. Thus, in order to assess the future emission factors for shipping it is necessary to assess how the engine mixture will develop. We have here assumed that the fraction of high-pressure engines in traffic to and from Sweden will remain the same as today, meaning that about 10% of the LNG is consumed in such engines. Further, we assume that new engines have CH_4 emissions representative for the latest technology (for low-pressure engines) which means that the CH_4-emission factor will decrease with time. Finally, it is assumed that new high-pressure engines will use exhaust gas after-treatment to follow the Tier 3 NO_X-limit. This also means that we assume a certain increase in NH3-emissions as the use of SCR increases.

The emission factors or $PM_{2.5}$ and BC are not expected to change. It is possible that the IMO will introduce limits for emissions of BC, but this is not decided, nor is it possible to anticipate the details of such restrictions. Thus, the most reasonable assumption is that the emission factors will remain the same, with the exception that the assumed increase in use of scrubbers will have a small influence.

The resulting emission factors up to 2050 can be found in Table 13 and Table 14. The data for LNG are from Hult and Winnes (2020).

Table 13. Emission factors in scenarios for Domestic shipping (in g/GJ)

Fuel	**Year**	**CH_4**	**N_2O**	**SO_2**	**NO_X**	**NH_3**	**NMVOC**	**$PM_{2.5}$**	**BC**
Diesel	2019	0.38	4.2	0.47	830	0.41	19	27	2.5
	2025	0.38	4.2	0.47	764	0.41	19	27	2.5
	2030	0.38	4.2	0.47	703	1.1	18.7	27	2.5
	2035	0.38	4.2	0.47	567	3.8	17.7	27	2.5
	2040	0.38	4.2	0.47	474	5.6	17.0	27	2.5
	2045	0.38	4.2	0.47	380	7.4	16.3	27	2.5
	2050	0.38	4.2	0.47	259	10.2	15.2	27	2.5
EO1	2019	0.38	4.2	36	830	0.4	19	27	2.5
	2025	0.38	4.2	36	764	0.4	19	27	2.5
	2030	0.38	4.2	36	703	1.1	19	27	2.5
	2035	0.38	4.2	36	567	3.8	18	27	2.5
	2040	0.38	4.2	36	474	5.6	17	27	2.5
	2045	0.38	4.2	36	380	7.4	16	27	2.5
	2050	0.38	4.2	36	259	10.2	15	27	2.5
EO2-6	2019	0.51	3.6	46	1180	1.2	25	67	5.4
	2025	0.51	3.6	46	1086	1.2	25	70	5.3
	2030	0.51	3.6	46	1000	1.9	24.6	74	5.2

	2035	0.51	3.6	46	806	4.3	23.3	77	5.1
	2040	0.51	3.6	46	673	6.1	22.4	80	5.0
	2045	0.51	3.6	46	540	7.8	21.4	83	5.0
	2050	0.51	3.6	46	368	10.3	20.0	86	4.9
LNG	2019	680	n.d.	0.13	302	n.d	43	2.6	0.77
	2025	680	n.d.	0.13	294	0.11	43	2.6	0.77
	2030	680	n.d.	0.13	281	0.30	43	2.6	0.77
	2035	680	n.d.	0.13	268	0.49	43	2.6	0.77
	2040	680	n.d.	0.13	255	0.68	43	2.6	0.77
	2045	680	n.d.	0.13	242	0.87	43	2.6	0.77
	2050	680	n.d.	0.13	229	1.06	43	2.6	0.77

Table 14 Emission factors in scenarios for International shipping (in g/GJ)

Fuel	**Year**	**CH_4**	**N_2O**	**SO_2**	**NO_X**	**NH_3**	**NMVOC**	**$PM_{2.5}$**	**BC**
Diesel	2019	0.32	4.8	0.47	660	0.21	16	27	2.5
	2025	0.32	4.8	0.47	607	0.21	16	27	2.5
	2030	0.32	4.8	0.47	559	1.0	16	27	2.5
	2035	0.32	4.8	0.47	451	3.6	15	27	2.5
	2040	0.32	4.8	0.47	377	5.5	14	27	2.5
	2045	0.32	4.8	0.47	302	7.3	14	27	2.5
	2050	0.32	4.8	0.47	206	10.1	13	27	2.5
EO1	2019	0.32	4.8	36	660	0.21	16	27	2.5
	2025	0.32	4.8	36	607	0.21	16	27	2.5
	2030	0.32	4.8	36	559	0.96	16	27	2.5
	2035	0.32	4.8	36	451	3.61	15	27	2.5
	2040	0.32	4.8	36	377	5.48	14	27	2.5
	2045	0.32	4.8	36	302	7.35	14	27	2.5
	2050	0.32	4.8	36	206	10.1	13	27	2.5
EO2-6	2019	0.57	3.9	570	1340	0.74	28.0	67	5.4
	2025	0.57	3.9	124	1233	0.74	28.0	70	5.3
	2030	0.57	3.9	124	1135	1.46	27.6	74	5.2
	2035	0.57	3.9	124	916	4.00	26.1	77	5.1
	2040	0.57	3.9	124	765	5.78	25.0	80	5.0
	2045	0.57	3.9	124	613	7.57	24.0	83	5.0
	2050	0.57	3.9	124	418	10.23	22.4	86	4.9
LNG	2019	680	n.d	0.13	302	n.d	43	2.6	0.77
	2025	680	n.d	0.13	294	0.11	43	2.6	0.77

	2030	680	n.d	0.13	281	0.30	43	2.6	0.77
	2035	680	n.d	0.13	268	0.49	43	2.6	0.77
	2040	680	n.d	0.13	255	0.68	43	2.6	0.77
	2045	680	n.d	0.13	242	0.87	43	2.6	0.77
	2050	680	n.d	0.13	229	1.06	43	2.6	0.77

Review of historical emission factors

For CH_4, N_2O and NMVOC there are no new data indicating that the EFs should be updated. The EF for NMVOC has through the years been updated in respect to the varying use of SCR (this has a very marginal influence).

For NH_3 we suggest a small update to reflect the use of SCR.

For SO_2 the EFs have been developed from fuel sale statistics including the FSC and there is no need for update. The use of scrubbers became significant only recently and this is reflected in the EF for SO_2 for 2018 and 2019.
For $PM_{2.5}$ and BC we suggest updates in view of the new data on emission factors (compare

Table 3 with Table 13 and Table 14).

For NO_X we suggest an update for the more recent years (2012-2018). For the emission factors for 2019 we have used AIS data from Fridell and Windmark (2018) giving the distribution between ships of different Tiers as described above. The emission factors for the other years have not been calculated.

Some emission factors for diesel should be updated. The reason is that it has recently been clear that the diesel sold to shipping is similar to road diesel. The emission factors for SO_2 and PM should therefore reflect that this fuel have a much lower sulphur content. For emission factors more related to combustion (e.g. NO_X) it is reasonable to keep the same emission factors as for EO1.

Improvement potential in data for emission factors

Here are listed some remaining points for improvement of emission factors for shipping.

For NO_X the emission factors have been updated mainly by using detailed data on the age distribution of ships in waters around Sweden. Further improvement could be obtained by analyzing fuel consumption in ships of different age (and thus different Tier standard). More important will be to follow the development of Tier III ships coming from 2021, and also the existing ships that reach this standard. The assumption that the NO_X-emissions follow the regulated level may not be valid for several reasons; for example, if the ships run frequently at low engine loads where SCR systems cannot be operated. There is likely also a discrepancy between the test cycle emissions and real operation emissions. Further, the slip of NH_3 from SCR systems are uncertain since this is not specifically regulated for Tier III ships.

For scrubbers the emissions of particulate matter remain uncertain. More data on PM and BC emissions would be needed. Further, it is also possible that scrubbers of different design show different emission profiles.

For the relatively new mixed fuels, ULSFO and VLSFO, there is a lack of measurement data. These fuels do today not follow a specific ISO standard and a future standardization will make the analysis more straight forward. The division into Eo1 and Eo2-6 for these fuels also remain uncertain.

There will be a range of new fuels coming into the sector, such as FAME, LBG, alcohols, NH_3 and H_2 where emission measurements will be called for.

The LNG engines of today show high slip of methane but this should be monitored since improvements with lower methane slip in the future are likely.

The AIS data is an excellent tool to collect information on ship movements and the details about the ships is accessed from databases. However, there is currently no information on the type of fuel used onboard which limits the accuracy in the calculations of emissions.

Specific fuel consumption of marine engines has improved during the years which is currently not accounted for in the emission inventories.

Finally, the Swedish emission inventory does not take into account emissions from oil-fueled boilers. These are mainly used in ports (exhaust boilers are used at sea) but can for some cases contribute significantly to emissions.

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