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MARINTEK

Report

Emission factors for CH_4, NO_x, particulates and black carbon for domestic shipping in Norway, revision 1

Klima og forurensningsdirektoratet

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MARINTEK REPORT

TITLE

Emission factors for CH_4, NO_x, particulates and black carbon for domestic shipping in Norway, revision 1

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ABSTRACT

In this report new and updated emission factors for diesel, HFO and gas fuelled ships are presented and discussed as follows:

- NO_x reduction factors from ships with NO_x reduction measures
- NO_x emission factor from gas operated vessels
- Methane emission factors for gas operated vessels
- Updated emission factors for particulate emissions (PM) with a specific factor for the black carbon (BC) fraction of particulate emissions.

A discussion on how low sulfur fuel will affect emissions of PM emissions and the BC fraction of PM is also included.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Shipping	Skipsfart
GROUP 2	Exhaust emissions	Eksosutslipp
SELECTED BY AUTHOR	NO_x, PM and Methane factor	NO_x, PM og metan faktor

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1. Norsk sammendrag

Denne rapporten presenterer og diskuterer følgende oppdaterte og utslippsfaktorer for diesel, tungolje og naturgass (LNG)

- NO_x reduksjonsfaktorer for skip med NO_x reduserende tiltak
- NO_x utslippsfaktor for gassdrevne skip
- Metan utslippsfaktor for gassdrevne skip
- Oppdaterte utslippsfaktorer for partikkelutslipp (PM) med spesifikke faktorer for black carbon (BC) fraksjonen av partikkelutslippet.
- Diskusjon knyttet til hvordan svovelreduksjon i drivstoff vil påvirke utslippene av PM og BC

NO_x reduksjonsfaktorer for NO_x reduserende tiltak

En reduksjonsfaktor er definert for skip med NO_x reduserende tiltak. NO_x reduksjonsfaktoren (RF) er resultatet av å multiplisere vektet reduksjon for tiltaket (WR) med tilgjengeligheten av tiltaket (AV). Reduksjonsfaktoren multiplisert med det opprinnelige NO_x utslippet vil gi reduksjonen av NO_x som oppnås ved å bruke reduksjonstiltaket. Reduksjonsfaktorene er vist i Tabell 1.

Tabell 1 – NO_x reduksjonsfaktorer for NO_x reduserende tiltak

Teknologi	Vektet reduksjon (WR)	Oppetid eller tilgjengelighet (AV)	Reduksjons faktor (RF)	Kommentar
Motor ombygging	0,37	100 %	0,37	Oppdatert med målt NO_x reduksjon
Diesel vann emulsjon	0,15	95 %	0,14	Ikke oppdatert, fremdeles et estimat
Direkte vanninjeksjon (DWI)	0,55	95 %	0,52	Ikke oppdatert, fremdeles et estimat
Fukting av innsugsluft (CAS)	0,55	95 %	0,52	Ikke oppdatert, fremdeles et estimat
Fuktig luft (HAM)	0,55	95 %	0,52	Ikke oppdatert, fremdeles et estimat
Selektiv katalytisk reduksjon (SCR)	0,87	95 %	0,83	Oppdatert med målt NO_x reduksjon

NO_x faktor for gassmoterer

NO_x faktor for gassmotorer er etablert med basis i målte NO_x utslipp fra gassmotorer i drift. Faktoren gir mengde NO_x per mengde drivstoff. Faktorene er gitt i Tabell 2.

Tabell 2 - NO_x faktor for gassmotorer

NO_x faktorer for gassmotorer	5,6 kg NO_x/tonn LNG

Metanutslippsfaktor

Metanutslippsfaktoren er gitt for hver av de tre fartøyskategoriene som bruker gassmotorer i dag.

Metanutslippsfaktoren er oppgitt både i [g CH_4/kWh] og [kg CH_4/ton LNG]. [g CH_4/kWh] faktoren viser hvor mye metan som slippes ut i forhold til arbeidet motoren gjør, mens [kg CH_4/ton LNG] viser hvor mye metan som slippes ut per tonn motoren bruker. I sammenligninger av utslipp er det viktig å ha begge faktorene siden virkningsgraden til motoren gir store utslag på faktorene.

Tabell 3 - Metanutslippsfaktorer

Fartøyskategori (Gass drevet)	**Metan utslippsfaktor, ISO/IMO vektet**	
Ferger (Per dato kun lean burn motorer)	44 [kg CH_4/ton LNG]	8,5 [g CH_4/kWh]
Offshore supply (Per dato kun dual fuel motorer)	80 [kg CH_4/ton LNG]	15,6 [g CH_4/kWh]
Kyst vakt (Per dato kun lean burn motorer)	44[kg CH_4/ton LNG]	8,5 [g CH_4/kWh]

Videreutvikling av gassmotorer for å redusere metanutslippene pågår for fullt hos leverandørene i dag og lean burn SI motorer kan i dag leveres med metanutslippsfaktor som er 50% lavere enn verdiene presentert i Tabell 3.

Datagrunnlaget for metan utslippsfaktor er begrenset og knyttet til et fåtall installasjoner. Samtidig ser en nå en betydelig teknologiutvikling som adresserer disse utfordringene. Det anbefales derfor tett oppfølging med målinger på skip som er i drift og som blir satt i drift i de kommende årene for å bedre datagrunnlaget og for å kunne gi et mest mulig korrekt nivå på metanutslipp fra gassdrevne skip.

Partikkelutslipp

Faktorer for partikkelutslipp (PM) er oppdatert basert på data fra MARINTEK og litteraturen. Egne faktorer for black carbon fraksjonen av PM er også presentert.

Tabell 4 - PM & BC emission factors

Fuel	**Partikkelutslippsfaktorer**
MGO	1,5 [kg PM/tonn MGO]
HFO	5,1 [kg PM/tonn HFO]

Motorkategori	**Black carbon utslippsfaktor [kg BC/tonn fuel]**
Slow speed diesel	0,41±0,27
Medium speed diesel	0,97±0,66
High speed diesel	0,36±0,23

Effekt på partikkelutslipp fra redusering av svovelinnhold i drivstoff

Reduksjon av svovelinnhold i drivstoff vil redusere partikkelmasseutslipp vesentlig. Denne reduksjonen kommer fra en kraftig reduksjon av svovelrelaterte partikler. Hvordan svovelreduksjonen påvirker de resterende partiklene er usikkert. Det er funnet både økning og reduksjon av forksjellige typer partikler som er knyttet til helseeffekter hos mennesker. Hva den resulterende effekten av svovelreduksjonen kommer til å bli er vanskelig å forutse med dagens kunnskap om partikkelutslippene og effekten svovel har på partikkelutslipp. Effekten på klima ser ut til å være hovedsaklig negativ siden reduksjonen av svovel øker levetiden til black carbon i atmosfæren.

I tillegg til effekten av selve svovelreduksjonen vil partikkelutslippene være avhengig av hva slags drivstoff som blir tilgjengelig i fremtiden. Krav om lavere svovelinnhold kan potensielt gi store endringer i drivstoffet som benyttes ombord på skip.

2. Summary and conclusions

In this report new and updated emission factors for diesel, HFO and gas fuelled ships are presented and discussed as follows:

- NO_x reduction factors from ships with NO_x reduction measures
- NO_x emission factor from gas operated vessels
- Methane emission factors for gas operated vessels
- Updated emission factors for particulate emissions (PM) with a specific factor for the black carbon (BC) fraction of particulate emissions.
- A discussion on how low sulfur fuel will affect emissions of PM emissions and the BC fraction of PM is also included.

NO_x reduction factors for NO_x reduction measures

For ships with installed NO_x reduction measures, a NO_x reduction factor has been defined. The NO_x reduction factor is derived by multiplying the weighted reduction with availability. The NO_x reduction factor multiplied with the original NO_x emission gives the reduction of NO_x from a given NO_x reduction measure. Results are shown in Table 5 .

Table 5 - NO_x reduction factors for NO_x reduction measures

Technology	Weighted Reduction (WR)	Uptime or availability (AV)	Reduction Factor (RF)	Comments
Engine optimization	0.37	100 %	0.37	Updated based on measured NO_x emission reduction
Fuel water emulsification	0.15	95 %	0.14	Not updated, still an estimate
Direct water injection (DWI)	0.55	95 %	0.52	Not updated, still an estimate
Combustion air saturation (CAS)	0.55	95 %	0.52	Not updated, still estimation
Humid air motor (HAM)	0.55	95 %	0.52	Not updated, still an estimate
Selective catalytic reduction (SCR)	0.87	95 %	0.83	Updated based on measured NO_x emission reduction

NO_x factor for gas engines

For gas engines a new NO_x factor is established. The factor is based on the mass of LNG consumed. Results are shown in Table 6.

Table 6 - NO_x factor for gas engines

NO_x factor for gas engines	5.6 kg NO_x/ton LNG

Methane emission factors

The methane emission factors are given for the three vessel categories that use gas engines today.

The methane emissions are given in both [g CH_4/kWh] and [kg CH_4/ton LNG]. When the emissions are given as [g CH_4/kWh], the emission is related to the power production of the engine. The [g CH_4/kWh] is a good indicator of the emissions from the engine since it in cooperates the efficiency of the engine.

When the methane emission is converted into [kg CH_4/ton LNG], it becomes harder to evaluate the level of methane slip from the engine. Depending on the engine efficiency an engine with high methane emission in [g/kWh] might look better than an engine with [g/kWh] emissions. This is caused by dividing the [g CH_4/kWh] by [g fuel/kWh]. If the fuel consumption in [g fuel/kWh] is high the [kg CH_4/ton LNG] factor will be low.

Table 7 - Methane emission factors

Vessel category (Gas operated)	**Methane emission factor, ISO/IMO weighted**	
Ferry (Currently lean burn engines only)	44 [kg CH_4/ton LNG]	8.5 [g CH_4/kWh]
Offshore supply (Currently dual fuel engines only)	80 [kg CH_4/ton LNG]	15.6 [g CH_4/kWh]
Coast guard (Currently lean burn engines only)	44[kg CH_4/ton LNG]	8.5 [g CH_4/kWh]

Further development og gas engines to reduce the methane slip has high priority by engine suppliers, and lean burn SI engines today have 50% lower methane slip than presented in Table 7.

Available data for the methane factor from gas fuelled engines are limited and linked to few installastions only. At the same time a conciderable technology developement is observed where these challenges are addressed. Further work on this issues are recommended which should include full scale measurement on ships which already are in operation and on new ships the next few years to improve statistics and to give correct data of actual methane slip from gas engines.

Particulate emissions

Factors for particulate matter (PM) emissions are updated using MARINTEK data and literature. In addition to PM factors, factors for the black carbon (BC) fraction of PM are also presented.

Table 8 - PM & BC emission factors

Fuel	Particulate matter emission factors
MGO	1.5 [kg PM/ton MGO]
HFO	5.1 [kg PM/ton HFO]

Engine category	Black carbon emission factors [kg BC/ton fuel]
Slow speed diesel	0.41±0.27
Medium speed diesel	0.97±0.66
High speed diesel	0.36±0.23

Effect of low sulfur fuels on PM and BC emissions

Reduced sulfur in fuel will significantly reduce the PM mass emitted. The mass reduction is mainly reduction in sulfur related particles. The effect on the remaining particles which does not contribute significantly to mass emissions is uncertain. Reduced sulfur content in fuel is found to have effect on several different types of particles, and both increasing and decreasing particle emissions from diesel engines may have negative effect on health. What the resulting effect will be is difficult to establish with the current level of knowledge. The effect on climate when reducing sulfur seems to be mostly negative since the black carbon lifetime increases due to longer life time of black carbon particles in the atmosphere.

The effect on PM emissions is not only affected by the sulfur content of the fuel, but also highly affected by the fuel quality resulting from the fuel sulfur reduction.

3. Introduction

Norwegian Pollution Agency has asked MARINTEK to review and update existing exhaust emission factors for the Norwegian domestic maritime sector. The following tasks have been included in the project:

- establish the NO_x emission factor for gas operated vessels
- establish a factor for methane emissions from gas operated vessels
- investigate and update the methane emission factor which exists for diesel engines
- update the particulate emission factors from ship engines

In the project it was requested to allocate the methane emissions to two vessel categories and adjusted for the specific vessel categories operation profiles.

The updated emission factors will be used in the national emissions account/inventory performed by Statistics Norway and the Climate and Pollution Agency.

The work is carried out in the period June –November 2010, and is based on previous work accomplish in 2009.

In this report new and updated factors for NO_x, methane and particulates are presented.

4. Background - Previous work and emissions factors

In the report ”Analysis and NO_x emission factor from ships” (Nielsen and Stenersen 2009), the NO_x emission factor for the domestic Norwegian fleet where updated. The report focused on updating the emission factor for ships powered by conventional diesel engines, and not on establishing a factor for ships with NO_x reduction measures or gas engines. The updated NO_x factor in (Nielsen and Stenersen 2009) was based on measurements performed for the NO_x fund and NO_x factors from EIAPP certificates for engines with building year later than year 2000 in order to establish the emissions before and after NO_x reduction measures. There were very few measurements performed on ships with reduction measures installed before 2009. It was therefore chosen to continue to use estimations from Buhaug (2006) for ships with reduction measures installed.

4.1 Ships with NO_x reduction measures

The original estimations made by Buhaug (2006) are found in Table 9.

Table 9 - Buhaug (2006) Estimated NO_x reduction from ships with reduction measures

Technology	Weighted Reduction (WR)	Uptime or availability (AV)	Reduction Factor (RF)
Engine optimization	0.23	100 %	0.23
Fuel water emulsification	0.15	95 %	0.14
Direct water injection (DWI)	0.55	95 %	0.52
Combustion air saturation (CAS)	0.55	95 %	0.52
Humid air motor (HAM)	0.55	95 %	0.52
Selective catalytic reduction (SCR)	0.80	95 %	0.76
Natural gas fuel	0.85	100 %	0.85

In this report, available data has been used to update the estimation made by Buhaug (2006). Data collected by the NO_x fund from ships with installed NO_x reduction measures forms the basis for the update. Updated factors are presented below.

5. Updated NO_x factors for NO_x reduction measures and gas engines

5.1 Diesel fuelled ships with NO_x reduction measures

When a ship applies for funding by the NO_x fund for economic support to install a NO_x reduction measure, measurements of NO_x before and after system installation is required. These measurements determine how much support is given, dependent on the level of NO_x reduction. Based on these measurements, MARINTEK has been able to update the table established by Buhaug (2006).

The main solutions chosen to reduce NO_x emission by g NO_x/shaft kWh have so far been mainly SCR systems and engine optimization. The NO_x fund does also reward measures that reduce fuel consumption, thereby reducing the total NO_x emissions. In this report, only measures with effect on the NO_x emissions in g NO_x/shaft kWh have been updated. Currently SCR and engine optimization are the only measures with a significant number of installations. Therefore only SCR and engine optimization will be updated in this report. Measures that effect the fuel consumption will be taken into account when the national fuel consumption is used to calculate the total NO_x emission. In Table 10 all the reported installed NO_x reduction systems funded within the NO_X fund are presented.

Table 10 - Distribution of installed Engine rebuilding/optimization and SCR among different vessel categories

Vessel category	**Engine rebulding/optimization**	**SCR**	**Engine rebulding/optimization & SCR**
Fishing vessel	24	14	3
Offshore	15	33	1
Passenger	2		
Bulk	1		
Oil tanker	1	3	
Chemical/Product tanker	2		
LNG tanker	1		
Other	6		
Sum	52	50	4

The number of installed NO_x reduction systems is higher than what is used to calculate the reduction factor. All ships where there are measurements missing and the NO_x reduction has been estimated, or the system is less than three months old, have been removed from the data before establishing the reduction factors. Vessels with engine rebuilding/optimization and SCR installed have also been removed. A total of 32 engine rebuilding/optimizations and 31 engines with SCR where used as a basis to update the NO_x reduction effect on engine rebuilding/optimizations.

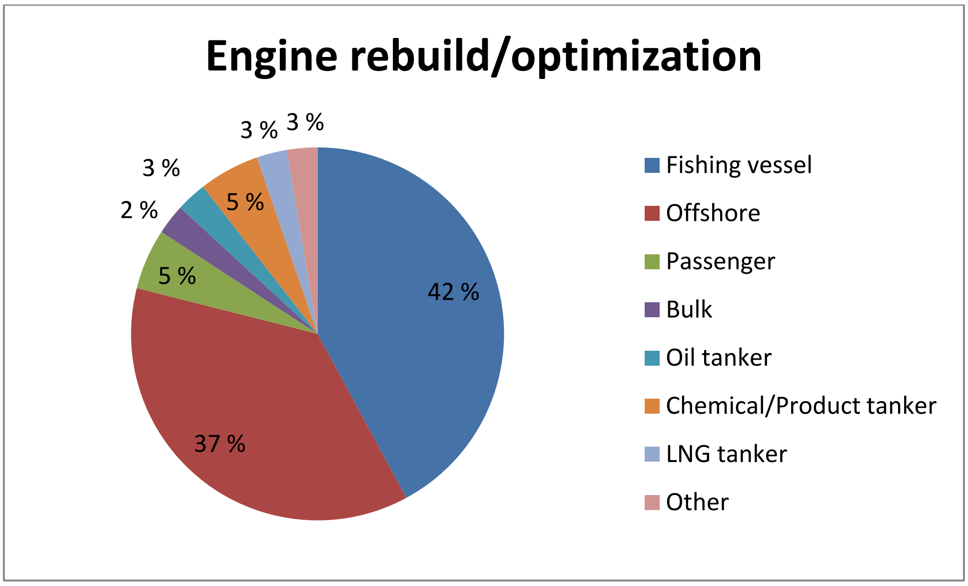

Figure 1 - Distribution of Engine rebuilding/optimization in vessel categories for data used to update the reduction factor

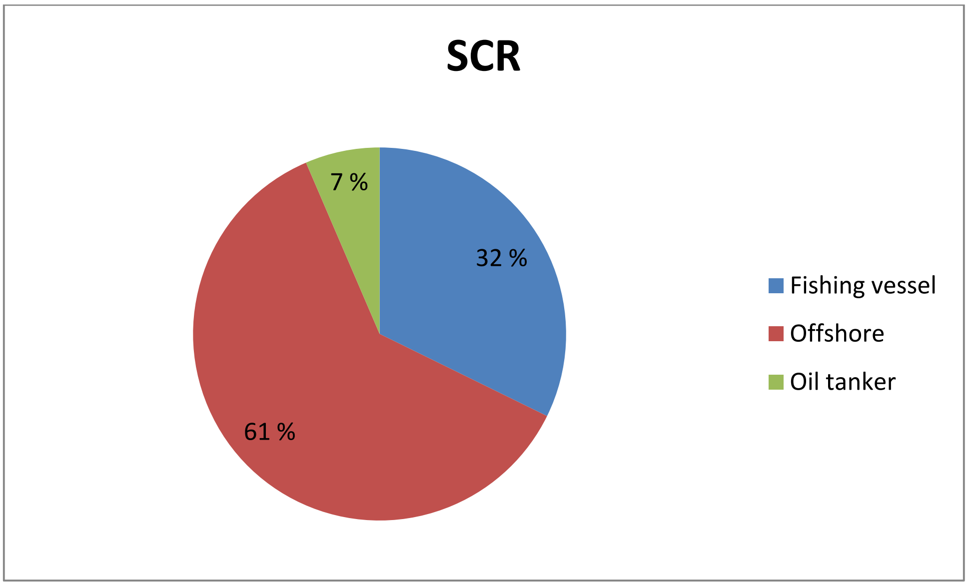

Figure 2 - Distribution of SCR in vessel categories for data used to update the reduction factor

Table 9 is based both on the reduction efficiency (weighted reduction) when the system is operating and the uptime (availability) of the system to establish the reduction factor. Data from the NO_x fund only contain the reduction efficiency in operation and no data on the system uptime. Currently there have been no major system uptime measurements for the different NO_x reduction systems in service on ships in the NO_x fund database. The estimated uptime made by Buhaug (2006) will therefore still be used in this report. However, weighted reduction factor for engine optimization and SCR have been updated based on new measurements. Updated emission reduction factors for NO_x reduction measures are shown in Table 11.

Table 11 - Updated emission reduction factor for NO_x reduction measures

Technology	Weighted Reduction (WR)	Uptime or availability (AV)	Reduction Factor (RF)	
Engine optimization	0.37	100 %	0.37	Updated based on measured NO_x emission reduction
Fuel water emulsification	0.15	95 %	0.14	Not updated, still an estimate
Direct water injection (DWI)	0.55	95 %	0.52	Not updated, still an estimate
Combustion air saturation (CAS)	0.55	95 %	0.52	Not updated, still estimation
Humid air motor (HAM)	0.55	95 %	0.52	Not updated, still an estimate
Selective catalytic reduction (SCR)	0.87	95 %	0.83	Updated based on measured NO_x emission reduction

An example is given to show how to use the NO_x reduction factor:

The case is a ship with original NO_x emission factor of 50 kg NO_x /ton MGO. To reduce the NO_x emission a SCR system is installed. The reduction factor for the SCR system is 0.83.

The new NO_x emission factor for the ship will be 8.5 kg NO_x/ ton MGO:

$$50\ kg\ NOx/ton\ MGO\ \times (1-0.83) = 8.5\ kg\ NOx/ton\ MGO$$

5.2 NO_x factor for gas engines

This report presents a separate NO_x factor for gas engines based on measurements. Through the measurement program of the Norwegian NO_x fund and MARINTEK measurements, five gas engine powered ships have had their NO_x emission measured. Today there are around 20 ships with gas engines operating in Norwegian waters. These ships are offshore supply, ferries and coast guard patrol vessels. Currently only dual fuel and lean burn spark ignited engines are used in Norwegian waters. These engines types operate with a high air excess ratio which lower the combustion temparature in the engine and with a resulting low NO_x production. The measurements are in line with research results and test bed reports for these types of engines, and is valid for various operation modes (high load and low load) of the engines.

If direct gas injection engines are put into service in Norwegian waters a separate factor for this engine principle might be necessary. The direct gas injection engines have higher NO_x emissions than dual fuel and lean burn engines. Direct gas injection will be used for large two stroke engines running on gas.

The NO_x factor for each of the five ships is established according to the NO_x technical code. NO_x emissions varies little over the load range and between vessel categories, therefore an average of the five NO_x factors are used to establish the NO_x factor for gas engines..

Table 12 - NO_x factor for gas engines

NO_x factor for gas engines	5.6 kg NO_x/ton LNG

6. Methane slip

Methane slip from engines is a concern due to methane's properties as a green house gas (GHG). It is 21 times more powerful as a green house gas than CO_2 (IPCC 1995). Although methane used as fuel is less carbon intensive than diesel, methane slip reduces the positive effect due to its high GWP value.

6.1 Natural gas engines

Methane slip from gas engines can be divided in to two categories: operational emissions and engine emissions. Operational emissions can be venting of methane to atmosphere due to certain operation conditions, it may be methane released from refueling or the methane storage on land, etc. Engine emissions are only caused by methane slipping through the combustion chamber unburned. While operational emissions are affected by the design and operation of system surrounding the engine, the engine emissions is caused by the engine concept, design and operation profile. In this report, methane slip is defined to be methane emissions from the engine.

Methane slip is a known challenge for natural gas engines. Different engine concepts and designs have large differences in the level of methane slip. The methane slip may also be strongly dependent of the operating profile. To give insight into the problems around methane slip, three different engine concepts will be discussed together with the main sources for the methane slip from these engines:

- Lean burn Otto cycle gas engines (SI gas engines)
- Dual fuel engines
- High pressure natural gas injection diesel cycle

6.1.1 Lean burn Otto cycle gas engines

Lean burn natural gas SI engines use premixed gas which is introduced into the engine through the inlet valve. The gas mixture is ignited by a spark plug. The lean burn natural gas engine operates with high excess air ratio. This means that the combustion is cool creating small amounts of NO_x and maintaining a high efficiency especially at high loads. A typical lean burn natural gas engine has lower efficiency at low and medium load compared to an equivalent diesel engine, and higher efficiency at high loads.

Methane slip from lean burn natural gas engines can be divided in to two main categories: methane slip due to the engine design and slip due to the engine regulation, lambda control in particular. The methane slip due to the engine design is due to wall quenching where the flame dies due to the low temperatures close to the cylinder wall, and crevices where the flame is not able to propagate. Methane slip from regulation is mainly caused by bad lambda control where the natural gas air to mix is not in the range needed to support the flame. Lambda control tends to be poor at low loads. Methane slip from the engine design does also tend to be more significant at low loads, when the temperature in the cylinder is low. This increased methane slip with reduced load implies that the methane slip factor is affected by the operation profile of the engine.

6.1.2 Duel fuel engines

Dual fuel engines are much like lean burn gas engines. The gas is mixed with air before the inlet valve but instead of a spark plug, a diesel pilot flame is used to ignite the gas mixture. A small diesel flame is used to ignite the lean gas mixture which results in a low emission of NO_x and other emission components. The emissions are a little higher than for the lean burn otto cycle engines due to the diesel pilot flame. At lower loads the proportion of energy delivered by the diesel flame increases. This means that the relative emission of NO_x and other emissions components originating from the diesel flame increases with decreased load. The sources for unburned methane are the same in a dual fuel engine as in a lean burn gas engine.

At low loads a dual fuel engine will switch over to only running on diesel. Depending on when this shift occurs, much of the problems with high methane emission at low loads can be avoided in a dual fuel engine. The penalties for switching to diesel are higher emissions of NO_x and other pollutants originating from the diesel combustion.

6.1.3 High pressure natural gas injection diesel cycle

High pressure natural gas injection works on the same principle as a normal diesel engine, with the diesel replaced by natural gas. The natural gas is injected with high pressure close to top dead center and will burn with a diffusion flame. To ignite the natural gas, a diesel pilot flame is needed. The high pressure natural gas injection engine has a higher NO_x emission due to the higher temperatures in the combustion compared to the lean burn engine. The NO_x is still significantly lower than with a normal diesel engine. The efficiency tends to be higher than for an equivalent diesel at low and medium loads, while it drops below the diesel at high loads. Since the gas is burned in a diffusion flame and not as a premixed combustion, the high pressure natural gas injection engine has very low methane emissions. High pressure gas is available on 4 stroke engines and is under development on two stroke engines. High pressure 4-stroke engines are used on some production ships where there is high pressure gas available. Four stroke high pressure gas engines are currently not in operation for shipping. When the high pressure gas becomes an alternative for large two stroke engines a separate methane emission factor is needed for the high pressure gas principle. Establishing this factor should be done when both the market and technology for high pressure gas is more mature.

6.2 Methane emissions factors for gas engines

Currently there are limited data available on methane emissions from gas engines. The few measurements performed are from the first generation of engines, and will not take into account engine development that has been implemented in later engines.

For engine manufacturers the methane slip is data that is not readily sheared, resulting in limited data on new engines to establish the current and future methane emission factor in this report. A prediction on future engine emissions will be based on the limited data from the manufactures and MARINTEK experience on gas engines.

The gas engines are measured according to the E2 cycle. The E2 cycle is a generator cycle where the engine is tested at four load points with constant engine speed.

6.2.1 How to interpret the methane emission factors

The methane emissions are on different engine loads are given in both [g CH_4/kWh] and [kg CH_4/ton LNG]. When the emissions are given as [g CH_4/kWh], the emission is related to the power production of the engine. When the emissions is given in [g CH_4/kWh] the power consumption needed will determine the total emissions. The [g CH_4/kWh] is a good indicator of the emissions from the engine since it incooperates the efficiency of the engine.

When the methane emission is converted into [kg CH_4/ton LNG], it becomes harder to evaluate the level of methane slip from the engine. Depending on the engine efficiency an engine with high methane emission in [g/kWh] might look better than an engine with low methane [g/kWh] emissions. This is caused by dividing the [g CH_4/kWh] by [g fuel/kWh]. If the fuel consumption in [g fuel/kWh] is high the [kg CH_4/ton LNG] factor will be low.

6.2.2 Lean burn SI gas engine

The current methane emissions from lean burn engines are based on measurements performed by MARINTEK and input from gas engine manufactures. The two numbers in Table 13 shows the span in emissions from engines installed on ships operating in Norwegian waters.

Table 13 - Methane emissions from lean burn SI gas engines

Lean burn engines E2 cycle, specific fuel consumption: 9320 – 7850 kJ/kWh				
Load	25 %	50 %	75 %	100 %
Methane emissions [g CH_4/kWh]	41.3 – 22.6	9.05 – 7.8	7.34 – 6.9	6.17 - 6
Methane emission [kg CH_4/ton LNG]	134 – 110	41 – 47	37 – 45	32 – 41

6.2.3 Dual fuel engine

Methane emissions from dual fuel engines have been measured by MARINTEK on one offshore supply vessel.

Table 14 - Methane emissions from dual fuel engines

Dual fuel engine E2 cycle, specific fuel consumption: 8048 kJ/kWh				
Load	25 %	50 %	75 %	100 %
Methane emissions [g CH_4/kWh]	40.40	21.95	13.36	12.70
Methane emission [kg CH_4/ton LNG]	154	105	74	69

6.2.4 Methane emission factors according to ISO/IMO weighting

Based on the measurements presented above a weighted methane emission factor has been calculated based on ISO 8178/ IMO NO_x Technical Code weighting.

For lean burn engines the distribution of different engines gives the average methane emission for each load point and total emission factor.

Table 15 - Methane factors ISO/IMO weighted Lean burn SI engine

Load E2 cycle	**25 %**	**50 %**	**75 %**	**100 %**	**ISO/IMO corrected methane factor**
Weight	0.15	0.15	0.5	0.2	
Lean burn engine [g CH_4/kWh]	34.1	8.6	7.2	6.1	8.5
Lean burn engine [kg CH_4/ton LNG]	124	43	40	36	**44**

Table 16 - Methane factors ISO weighted Dual fuel engines

Load E2 cycle	**25 %**	**50 %**	**75 %**	**100 %**	**ISO/IMO corrected methane factor**
Weight	0.15	0.15	0.5	0.2	
Dual fuel [g CH_4/kWh]	40.4	22	13.4	12.7	15.6
Dual fuel [kg CH_4/ton LNG]	154	105	74	69	**80**

6.3 Methane emission factor for different ship types

Currently there are around 20 ships divided in to three ship categories using gas engines in Norway, ferries, offshore supply vessels and coast guard patrol ships. Offshore supply vessels currently use dual fuel engines, while ferries and the coast guard uses lean burn gas engines. This split in engine types between ship categories can be used to establish a methane emission factor for each ship segment by using the methane factor for each engine type.

Since methane slip is dependent on the operation profile of the ship, modification of the ISO/IMO weighting to account for the specific operation profile of ships using LNG as fuel, may give a better estimate of the methane emission factor.

6.3.1 Methane emission factor for ferries

Ferries have a very distinctive operation profile with high load during the crossing, changing load from low to medium during maneuvering and low load when pushing against the ramp. To estimate a general operation profile of a ferry, a typical timetable for a ferry connection and onboard measurements carried out by MARINTEK is used as basis.

The time used for a crossing and at quay is based on time tables for different ferry connections, while the time needed for maneuvering is based on measurements of power consumption of different crossings performed by MARINTEK. The power needed for crossing, maneuvering and at the ramp is also based on power measurements.

Table 17 - Typical time used at different operation modes for ferries

Operation mode	Time
At ramp	8 min
Crossing	20 min
Maneuvering	3 min

The new weighting is based on the amount of fuel consumed in the different load points. This is calculated by using measured power and the time spent in the three operation modes and the fuel consumption in each load point.

Table 18 - Modified ISO/IMO weighting to fit with ferry operation

Load	25 %	50 %	75 %	100 %
Weight	0.18	0.04	0.70	0.08

The methane emission factor for ferries with modified weighting is given in Table 19.

Table 19 - Methane emission factor for ferries (modified weighting)

Load	25 %	50 %	75 %	100 %	ISO/ IMO corrected methane factor
Weight	0.18	0.04	0.70	0.08	
Lean burn engine [kg CH_4/ton LNG]	125	43	40	35	**45**

Compared to the ISO/IMO weighting, the ferry factor with modified weighting due to operational profile is approxemately the equal.

6.3.2 Methane emission factor for offshore supply

The operation profile of an offshore supply vessel is characterized by steaming from shore out to the offshore installation, maneuvering to the installation and laying on DP while loading and offloading. Offshore supply ships often have diesel or in this case gas electric propulsion, where multiple engines turns generators which again power electric motors to propel the ship. The idea is to run as few engines as possible at high loads allowing for high efficiency at more operation modes. This means that low total load does not necessary mean low engine load.

Table 20 - Modified ISO/IMO weighting to fit with offshore supply operation (modified weighting)

Load	25 %	50 %	75 %	100 %
Weight	0.20	0.21	0.51	0.08

Table 21 - Methane emission factor for offshore supply with modified weighting factor

Load	25 %	50 %	75 %	100 %	ISO/IMO corrected methane factor
Weight	0.20	0.21	0.51	0.08	
Dual fuel [kg CH_4/ton fuel]	154	105	74	69	**85**

Compared with the standard ISO/IMO weighting, the offshore supply factor is approximately 6 % higher. The uncertainty for offshore supply is higher than for ferries since the possibilities to combine several engines at different loads makes estimating the modified weighting more challenging.

6.3.3 Methane emission factor for coast guard patrol ship

For coast guard patrol ships MARINTEK does not have any data on operation profile. Therefore it is assumed that the normal ISO/IMO weighting fits with the operation profile of these ships. The coast guard patrol ships use lean burn gas engines.

Table 22 - Methane emission factor coast guard patrol ships

Load	25 %	50 %	75 %	100 %	ISO/IMO corrected methane factor
Weight	0.15	0.15	0.5	0.2	
Lean burn engine [kg CH_4/ton LNG]	124	43	40	36	**44**

6.3.4 Evaluation of methane emission factors for gas engines

The methane emission factors presented are based on a very limited number of independent measurements. The measurements where performed on some of the first gas engines put in operation onboard ships in Norwegian waters and do not reflect the progress made to reduce methane slip. To get better basis for estimation of the methane emissions from ships with gas engines more measurements are needed.

The modification to the ISO/IMO weighting to better fit the operation profiles of ferries and offshore supply vessels gives a small increase in the emission factor. The main reason for this increase is the high methane slip at low loads. Since the methane emission factor based on adapted operation profile is very close to the ISO/IMO based weighting MARINTEK recommends that the ISO/IMO weighting is used. The difference in CH_4 factor between adapted weighting and ISO/IMO weighting does not justify the uncertainty introduced when establishing a new weighting. By using the standard ISO/IMO weighting there is no room to discuss if the correct weighting has been used.

Table 23 - Recommended methane emission factors for gas fuelled ships

Vessel category (Gas operated)	ISO/IMO corrected methane factor	
Ferry	44 [kg CH_4/ton LNG]	8.5 [g CH_4/kWh]
Offshore supply	80 [kg CH_4/ton LNG]	15.6 [g CH_4/kWh]
Coast guard	44[kg CH_4/ton LNG]	8.5 [g CH_4/kWh]

6.3.5 Methane emission from new gas engines

As the focus on methane slip has increased, engine makers have increased their efforts to reduce the methane slip. There are currently no independent measurements that can be used to establish a factor for newer engines. Instead of a factor, emissions from newer engines will be discussed and estimated based on the data received from engine manufactures and MARINTEK experience.

One reason for the high methane slip for gas engines is that the old gas engines are based on diesel engine designs. This leaves limited room for improving the methane slip. The primary use of the first engines was also onshore power generation where the engines run on high load where methane slip is low. The new gas engines are designed as gas engines from the start. Designing the engine from the start as a gas engines enables designs that takes into account causes for methane slip. These engines are also designed for operation onboard ships.

For the dual fuel engine concept one paper presented at CIMAC congress 2010 in Bergen shows different techniques to reduce the methane slip from dual fuel engines (Arto 2010). These techniques together with optimized design for gas operation will significantly reduce the methane slip.

MARINTEK received data on one of the newest lean burn engine designs available today.

Table 24 Methane factors for new lean burn gas engine designs

Load E2 cycle	**ISO/IMO corrected methane factor**
Lean burn engine [g CH_4/kWh]	**3.9**
Lean burn engine [kg CH_4/ton LNG]	**25**

6.4 Methane slip during refueling of ship

During refueling of ships some methane slip may be expected. In principle two refueling solutions are possible, i.e. refueling from an LNG truck or refueling from a fixed bunkering station.
The methane slip is related to safety issues where operational procedures includes purging of hoses and pipes in advance and after the ship has been refueled. This methane slip is not included in the proposed methane emission factors.

6.5 Methane slip factor for diesel engines

Statistics Norway (SSB) uses a methane emission factor of 0.23 kg/ton for diesel engines. This is equivalent to 0.040 to 0.044 g/kWh for engines with specific consumption of between 175 g/kWh and 195 g/kWh. This is equivalent to between 1 and 3 ppm methane in the exhaust from a diesel engine.

MARINTEK does not find any theoretic basis to why there should be methane in diesel exhaust. There is no reason to believe that there is methane in the diesel fuel and it is very unlikely that methane is produced during the combustion.

To investigate if it is possible to measure any methane in the exhaust a test was performed on an engine installed in the MARINTEK machinery laboratory. This engine is a Scania heavy duty six cylinder truck engine. The test was performed with marine gas oil (MGO) as fuel. The exhaust was measured with an instrument able to measure total hydrocarbon emission (THC) and methane (CH_4). The load points where tested, 500 Nm, 800 Nm and 1100 Nm, all three at 1200 rpm. First THC was measured at all load points. The instrument was calibrated following normal instrument procedures, delivering calibration gas at 1 bar through the calibration inlet. Then all load point where repeated while measuring CH_4. The instrument was calibrated in the same manner with methane. The results are presented in the following table:

Table 25 - Methane emissions from diesel, instrument calibrated through the calibration inlet at 1 bar

RPM	**Torque [Nm]**	**THC (C1) [ppm]**	**CH_4(C1) [ppm]**	**Fuel**
1200	500	55.59	0.72	MGO
1200	800	69.36	1.09	MGO
1200	1100	78.18	1.90	MGO

This measurement fits well to the emission factor used by Statistics Norway. It is reason to be skeptical to these results since the ppm value is very low, and the instrument is sensitive to the exhaust pressure. To investigate if the exhaust pressure could cause the instrument to show methane values it was decided to do another test where the instrument is calibrated through the sample inlet at the same pressure as the exhaust. This was only done on one load point due to the time it takes to calibrate and measure in this way. The result is presented in the following table:

Table 26 - Methane emission form diesel, instrument calibrated through sample inlet at exhaust pressure

RPM	**Torque [Nm]**	**THC (C1) [ppm]**	**CH_4(C1) [ppm]**	**Fuel**
1353	940	99.8	0	MGO

The result shows that there is no methane in exhaust from diesel engines, and that the current factor is based in measurement errors most likely caused by instrument sensitivity to exhaust pressure. These measurements should not be used to update the emission factor for methane from diesel engines. The measurement must be repeated by others before it is accepted. Currently the results can be used to start questioning the methane slip factor for diesel engines and to initiate more rigorous measurements.

7. Particle emissions $PM_{2.5}$

7.1 Evaluating and updating the current $PM_{2.5}$ emission factor

Today's emission factors for $PM_{2.5}$ used in the Norwegian national inventory are 0.475 kg/ton $PM_{2.5}$ for ships below 500 gross tons and 0.855 kg/ton for ships above 500 gross tons. To update the PM emission factors, both measurements performed by MARINTEK and literature are used. Findings in the literature and measurements performed by MARINTEK gives the following emission factors:

Table 27 - $PM_{2.5}$ emission factors from literature and MARINTEK

$PM_{2.5}$		(Agrawal, Welch et al. 2008)	Lloyds Service data	(Cooper 2003)	US EPA	CARB*	MARINTEK
Auxiliary (MGO) PM	g $PM_{2.5}$/kWh	0.141±0.005	0.3	0.26	0.42	0.25	0.47
Main (HFO) PM	g $PM_{2.5}$/kWh	1.60±0.08	1.23		1.08	1.5	0.9

* Californian air Resource Board

To calculate the emission factor, an assumed specific consumption is used: 195 g/kWh for auxiliary engines and 175 g/kWh for main engines. The MARINTEK factor is calculated based on the consumption data collected together with the particle measurement:

Table 28 - $PM_{2.5}$ emission factor in kg/ton fuel

$PM_{2.5}$		(Agrawal, Welch et al. 2008)	Lloyds Service data	(Cooper 2003)	US EPA	CARB*	MARINTEK
MGO PM	Kg $PM_{2.5}$/ton MGO	0.7	1.5	1.3	2.2	1.3	1.7
HFO PM	Kg $PM_{2.5}$/ton HFO	9.1	7.0		6.2	8.6	5.1

* Californian air Resource Board

The big difference in PM emission factor between auxiliary engines and main engines is caused by different sulfur levels in marine gas oil (MGO) and heavy fuel oil (HFO). Although the literature gives the impression that auxiliary engines run on MGO and main engines run on HFO, this is not always the case. Since the fuel quality is the main cause of the big difference in PM emissions between HFO and MGO, a split between HFO and MGO instead of splitting between main engines and auxiliary engines will better reflect the effect of fuel quality on PM emissions. Having one emission factor for MGO and one for HFO also makes calculating the national PM emissions in Norwegian waters much easier since you only need the total consumption of HFO and MGO and not the total kW produced by auxiliary and main engines.

The split between small and large ships is also inefficient since the main influence on emission factor is fuel quality not the size of the ship. MARINTEK recommends using an average of all emission factors found in the literature for MGO fuel, since this is a low sulfur fuel. For HFO, MARINTEK recommend to use the MARINTEK measurements since these are performed on ships operated in Norwegian waters using the HFO available for ships operating in Norwegian waters. The low sulfur regulation of the North Sea will makes measurements performed other places in the world less relevant since the amount of sulfur will greatly affect the emission factor. There is still uncertainty around the PM emission factor for HFO, since the number of measurements done on HFO is low. It is also recommended that more PM measurements are performed on ships operating in Norwegian waters, both inside the SECA area and outside.

Table 29 - Recommended $PM_{2.5}$ emission factors

Fuel	$PM_{2.5}$ Emission factor
MGO	1.5 [kg $PM_{2.5}$/ton MGO]
HFO	5.1 [kg $PM_{2.5}$/ton HFO]

In today’s calculation of the national emission inventory, $PM_{2.5}$, PM_{10} and total suspended particles (TSP) are used. The relation used are TSP = PM_{10} and $PM_{2.5} = PM_{10}*0.95$. MARINTEK recommends continued use of these realitions.

7.2 Black carbon emission factor

Black carbon (BC) emissions are in focus because of their ability to absorb radiation from the sun and turn it in to heat. Black carbon is part of the elemental carbon fraction of PM. Black carbon is a part of particle mass emission and is collected on the filters when measuring according to the ISO 8178 standard.

There are currently uncertainties regarding black carbon emissions. There are no standard definitions, no standard measurement technique or method. Black carbon measurements are therefore of uncertain quality (Novakov and Kirchetter 2007). The black carbon definition varies from study to study, some treats all EC or soot emissions as BC (Schneider, Krischner et al. 2008), while others have more stringent definitions of BC. This makes it difficult to compare different studies. Still there have been some attempts to come up with a BC emission factor. Lack et al. (2009) have presented the following BC emission factors. For EC and BC emissions it seems that engine category has the greatest influence on BC emission factors, where fuel quality had the greatest influence on the total PM mass factor.

Table 30 - Black carbon emission factors (Lack, Corbett et al. 2009)

Engine category	Black carbon emission factors [kg BC/ton fuel]
Slow speed diesel	0.41±0.27
Medium speed diesel	0.97±0.66
High speed diesel	0.36±0.23

7.3 Effect of fuel sulfur reduction on PM emissions

7.3.1 PM in general

PM emission is a complicated topic, which is not fully understood. New knowledge is constantly being developed. Based on the current knowledge, MARINTEK will evaluate likely changes in PM emissions, and effects on health and climate due to the regulation of sulfur content in fuel. First an introduction to particulates will be given so that the reader can follow the evaluation.

7.3.1.1 Particle composition

Particulate matter is a collection of a very large number of complex solid and volatile particles which are suspended in the exhaust. These particles can be divided into two main groups, soluble and solid particles. The soluble and solid particles can again be divided into soluble organic fraction and soluble inorganic fraction. Soluble inorganic fraction consists mainly of sulfur originating from the fuel and water while the soluble organic fraction consists mainly of unburned hydrocarbon from the fuel or the lubrication oil. The solid organic fraction mainly consist of solid carbonaceous particles originating from partly combusted fuel and lubrication oil, while the inorganic consist of metals and ash originating from the fuel and lubrication oil (Hellen and Ristimaeki 2007). The solid carbonaceous particles are sometimes called soot, elemental carbon (EC), black carbon (BC) etc.

7.3.1.2 Particle measurement

Today there are two standards for particulate measurements: ISO 8178 and ISO 9096. Both standards measures particle mass by collecting particles on a filter and weighing the mass of particles collected. The difference between the methods is that ISO 8178 cools and dilutes the exhaust before it reaches the filter, while ISO 9096 collects particles from undiluted hot exhaust.

I addition to mass which has a measurement standard, there are many other particulate properties which may be of interest. Among others there are: particulate number, diameter, volume, surface, light absorption/reflection and chemical composition. Many of these properties are interesting to measure with a particulate size resolution. There are many instruments and methods that are able to measure many of these properties, but as long as there are no standard regulating methodology and principle, it will always be difficult to compare results from different studies.

7.3.1.3 Fuel

The fuel quality is a major factor affecting the amount of particles and their composition. Fuel used onboard ships can be divided in to two main categories: heavy fuel oil (HFO) and marine distillates (MGO). HFO is mainly used in two stroke slow speed engines and medium speed engines, while MGO is mainly used in medium speed and high speed engines.

Table 31 - Typical fuel data for MGO

MGO		
Property		Limit value
Viscosity at/40°C	Average	3.0 cSt
Viscosity at/50°C	Average	2.5 cSt
Density at/15°C	Average	845 kg/m^3
Higher heating value pr. kg	Average	45870 kJ/kg
Higher heating value pr. liter	Average	38760 kJ/liter
Lower heating value pr. kg	Average	43060 kJ/kg
Lower heating value pr. liter	Average	36386 kJ/kg
Flame point	Min.	62°C
Pour point	Average	-15°C
	Max.	-12°C
Fog point	Max.	0°C
Blocking point (CFPP)	Max.	-11°C
Sulfur content	Average	0.10 % weight / 0.05 % weight
	Max.	0.20 % weight
Cetan index	Min.	47
Cetan number	Average	51.5
Sediment content	Max.	0.01 % weight
Water content	Max.	0.01 % volume

Table 32 - Typical data marine heavy fuel oil

Marine heavy fuel oil			
Properties	Test method	Max / min	Limit value
Viscosity at/50°C	ISO 3104	Max.	380 cSt
Density at/15°C	ISO 3675	Max.	991 kg/m^3
Flame point	ISO 2919(B)	Min.	60°C
Pour point	ISO 3016	Max.	30°C
Carbon residue	ISO 10370	Max.	18 % weight
Ash content	ISO 6245	Max.	0.15 % weight
Water content	ISO 3733	Max.	0.5 % volume
Sulfur content	ISO 8754	Max.	4.5 % weight
		Low sulfur Max.	1.0 % weight
Vanadium	ISO 1497	Max.	300 mg/kg
Aluminum plus silisium (silicate?)	ISO 10478	Max.	80 mg/kg
Sink	IP 501	Max.	15 mg/kg
Phosphor	IP 501	Max.	15 mg/kg
Calcium	IP501	Max.	30 mg/kg

7.3.1.4 PM and health

One of the current main reasons for the interest and regulation of PM emissions are the health effects caused by PM emissions. PM regulation started with mass emissions limits of particles smaller than 10 micrometer (PM_{10}). Then it was found that there where a better correlation between particles smaller than 2.5 micrometer ($PM_{2.5}$) and health effects, now $PM_{0.1}$are evaluated since in has better correlation to health effect than PM_{10} and $PM_{2.5.}$ The challenge with $PM_{0.1}$ is the lack of sensitivity of current mass measuring instruments and standards. The current regulation of PM emissions is therefore based on mass of particles smaller than 2.5 micrometer. Currently there are concerns regarding using PM mass as the only metrics to regulate PM emissions (Oberdörster, Finkelstein et al. 2000; Brown, Wilson et al. 2001; Somers, McCarry et al. 2004; Brutscher 2005). Due to the complex nature of particles and medical science, there is no clear recommendation regarding the metric which is best correlated against health effect.

Figure 3 (Kittelson, Watts et al. 2004) shows particle deposition plotted against the particle size, together with typical diesel distributions of number, mass and surface.

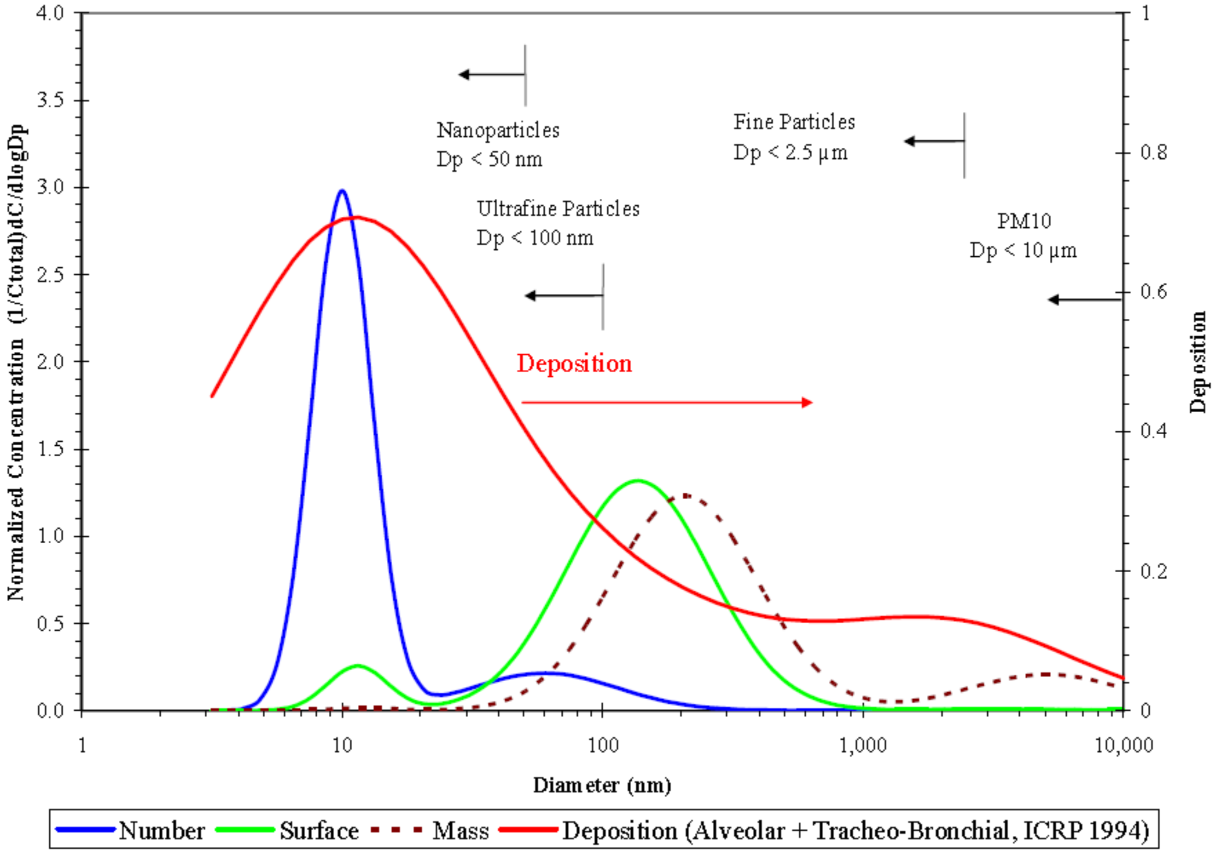

Figure 3 - Typical particle distributions and deposition (Kittelson, Watts et al. 2004)

When looking at the health effects caused by particle emissions it is reasonable to look at solid and volatile particles separate. These two types of particles are likely to have different ways of affecting the human health. Volatile particles do most likely dissolve on the surface of the lungs. The health effect will probably be best correlated to the amount of toxic material in the volatile particles, and the toxicity of the material. Solid particles have been found to penetrate and affect the tissue as single particles. It is suspected that solid particles are toxic just from their mere existence, independent of their composition (Kasper 2004).

7.3.2 Typical PM emissions from ships

The composition of particles varies with both fuel quality and engine design and principle. Typical particle compositions are presented in the next two figures (Hellen and Ristimaeki 2007):

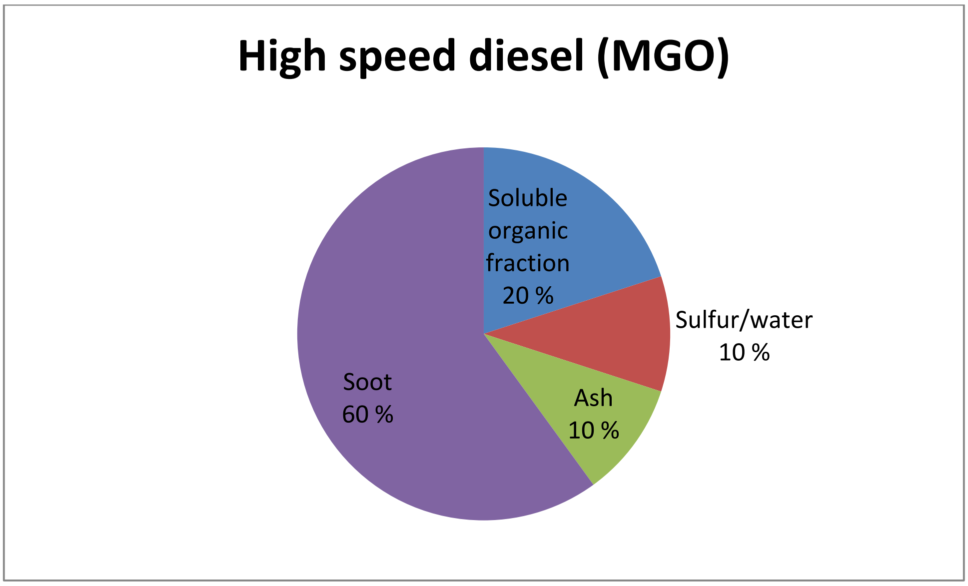

Figure 4 - Typical content of PM from MGO % mass (Hellen and Ristimaeki 2007)

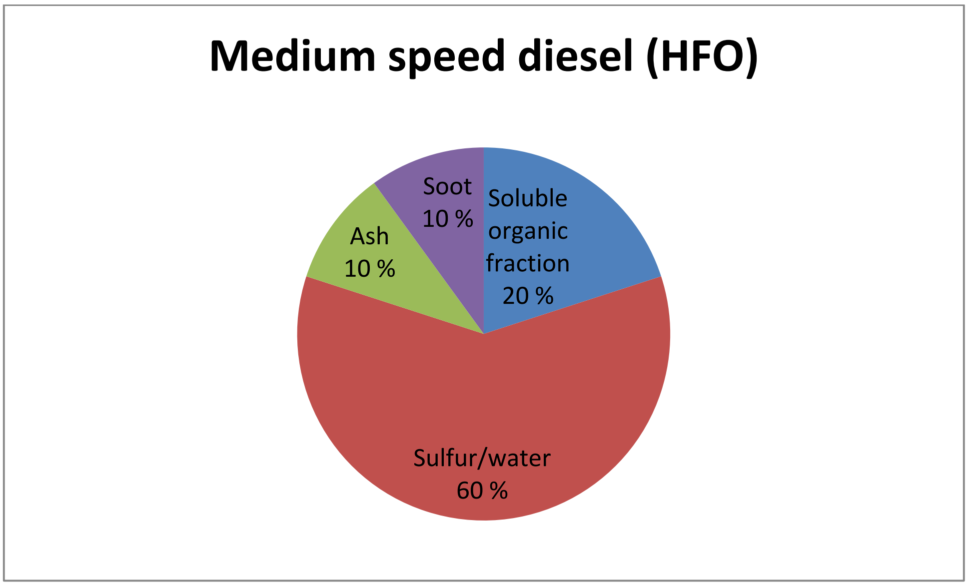

Figure 5 - Typical content of PM from HFO % mass (Hellen and Ristimaeki 2007)

7.3.3 Measurement of PM according to the ISO 8178 standard

The measurements presented in Figure 4 and in Figure 5 are measured according to the ISO 8178 standard. The filters have been analyzed for chemical composition after the measurement. One big weakness with the ISO 8178 standard is that it does not set any demands on the dilution ratio or temperature beyond a limited set of requirements. It is one requirement to the velocity on the filter surface, the temperature of the exhaust must be 47°C +-5°C and the dilution ratio must be higher than 4. The amount of mass collected from the volatile fraction is very sensitive to the temperature and dilution ratio. A small change in dilution ratio may give large changes in mass, especially if the fuel sulfur content is high. Since the solid fraction is not sensitive to the dilution ratio and temperature it is possible to alter the composition of the PM emission by changing the dilution ratio and temperature. This means that the ISO 8178 standard is not well suited to measure particle emissions from ships, especially from ships which uses a fuel with high sulfur content (Ristimaeki, Hellen et al. 2010).

7.3.4 Effect of fuel sulfur reduction on PM emissions

Reduction of fuel sulfur content will reduce mass emissions measured with ISO 8178 and ISO 9096. For measurements performed by the ISO 8178 standard this reduction is dependent on the dilution ratio and temperature. How large the expected reduction will be is difficult to establish due to the limited information regarding dilution ratio and temperature given in studies investigating PM emissions from ships.

Lack et al.(2009) have performed measurements on ship exhaust. Their measurement suggest that a change from fuel with an average fuel sulfur content of more than 0.5% to fuel with less than 0.5% will give a reduction of the sulfur mass fraction of total PM mass from 50 % down to 3 %. The PM mass factor will also be reduced from 4.2 kg/ton to 2.1 kg/ton. Even though there are uncertainties attached with these numbers, they still provide a clue on how PM emissions will change due to lower sulfur content in fuels.

7.3.5 Effect of fuel quality changes to meet low sulfur regulations

Changes in PM emissions due to fuel sulfur regulation will also depend on changes in the fuel quality. Changes in fuel quality may be a consequence of the demand for low sulfur fuel. The regulation may also make ship owners change fuel quality from HFO to MGO or to LNG depending of the fuel prizes

Today, low sulfur crude oil is used to produce low sulfur heavy fuel oil for use in SECA areas. Meeting the demand for low sulfur HFO fuels have been fairly straight forward. Still there have been some incidents where heavy fuel oil with a high amount of cycle oil has been sold. A large fraction of cycle oil will reduce the fuel quality, which again may lead to higher emissions of particulate. How the demand for low sulfur oil will be covered in the future is uncertain. There will probably not be enough low sulfur crude oil available to meet the demands, and the average quality of heavy fuel oil might suffer. This might lead to higher emissions of particles, originating from the combustion process.

Ship owner might also choose to switch to distillate qualities or even LNG for new buildings and retrofits if applicable. A switch to distillate fuel qualities will reduce the emissions of sulfur metal compounds and ash. On the other hand the emission of elemental carbon (EC) might increase. Metals in heavy fuel oil reduce the oxidation temperature for carbon compounds by acting as oxidation catalyst. Higher EC emission for MGO compared to HFO have been found on high loads, while the opposite have been found on low loads (Ristimaeki, Hellen et al. 2010).

7.3.6 Reduced fuel sulfur content effect on health

It has been estimated that the number of deaths caused by $PM_{2.5}$ emissions might be reduced by as much as 50 % dependent on the resulting average fuel sulfur reduction on a global scale after 2015 (Winebrake, Corbett et al. 2009).

Although sulfur is part of $PM_{2.5}$, it might not be the largest contributor to adverse health effects, making estimations on health effects of reduced fuel sulfur difficult. To estimate the effect of PM reduction on health it is needed to look at how the different components of PM affect health. Since PM consist of a large amount of different components it is unlikely that all these components affect the health in the same way or to the same degree. It is therefore necessary to look at the different PM components individually to see the health effect of different PM reduction measures which targets specific PM components.

Even though reduced fuel sulfur content will significantly reduce emission of $PM_{2.5}$ particle mass, there are studies suggesting that this reduction won’t necessary give significant positive health effect. Sulfates which make up the significant part of sulfur content in PM seams to have no significant health effect. On the other hand compound consisting of sulfur and metals seems to have a significant health effect. Combustion of heavy fuel oil is believed to be a significant source of sulfur metal compounds. There are also uncertainty regarding different chemical reactions including sulfur and the health effect of these unknown compounds. (Gelein and Schlesinger 2005; Grahame and Schlesinger 2007). If the metal content of the fuel together with sulfur is a larger health hazard than the sulfates, questions whether reducing the sulfur and not doing anything with the metal content of fuel will achieve a significant reduction of health problems caused by PM from HFO combustion should be investigated. Reducing the sulfur to a lower level might not do significant difference since there still are sulfur and metals left in the fuel.

A possible positive effect of reduced fuel sulfur has been presented by Lack et al. (2009). Their study shows a linear relation between the amount of organic compounds in PM emissions and the amount of sulfur in the fuel. This relationship is explained by the lubrication oil consumption is reduced when the fuel sulfur is reduced. The lubrication oil is consumed to neutralize the acid caused by the fuel sulfur. According to Garhame and Schelisinger (2007), there will be a positive health effect of reduced organic compounds emissions.

7.3.7 Effect of low sulfur fuels on black carbon emissions

The hygroscopicity of BC particles is a major factor determining the particle lifetime in the atmosphere. If BC particles have a long atmospheric lifetime, it will absorb more radiation from the sun. This means that the effect of BC emission is determined by the amount of BC emitted and for how long the BC is suspended in the atmosphere.

Reduction of sulfur content in fuels seems to increase the lifetime of BC particles emitted from ships. The sulfur increases the hygroscopicity of the BC particles, which increases the amount of water binding to the particle, reducing the time before the particle is washed out of the atmosphere. The carbonaceous particles are by themselves not hydroscopic, which means that their lifetime in the atmosphere is long. Reducing the fuel sulfur content may therefore increase the effect of BC on global warming, and increase the human exposure to elemental carbon particles due to the longer lifetime in the atmosphere (Lack, Corbett et al. 2009).

7.4 Particle emissions - conclusion

Due to the complex nature of particulate matter it is reasonable to assume that not all particulates pose the same health risk or act as a global warming agent. To execute effective measures to reduce the health effect caused by particles and the potential contribution to global warming it is necessary with knowledge on what particles to remove. Until now mass has been the only metric to regulate particulate emissions and there are currently concerns regarding the use of mass as the only metric for particle regulation. Removing particles contributing with high particulate mass might not reduce the health effect if the harmful particles have virtually no mass. These considerations are important to contemplate before deciding on how to reduce the effect of particle emissions on health and global warming.

Currently sulfur is a major contributor to PM emissions due to the high mass contribution when measuring with the ISO 8178 method. Reducing the amount of sulfur in the fuel will dramatically reduce the PM mass emissions from shipping. Whether it will reduce the health effect and climate effect of shipping is more uncertain. Reduced PM mass emission due to reduced sulfur content in fuel is found to both decrease and increase emissions of different types of particles that are believed to have negative effect on health. What the resulting effect will be is difficult to establish with the current level of knowledge. The effect on climate when reducing sulfur seems to be mostly negative since the black carbon lifetime increases due to longer life time in the atmosphere.

The effect on PM emissions is not only affected by the sulfur content of the fuel, but also highly affected by the fuel quality resulting from the fuel sulfur reduction. To predict the future PM emissions from ships more knowledge on the future fuels are needed.

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