VTT Technical Research Centre of Finland

Control measures of black carbon emissions from marine diesel engines - focus on results obtained using measurement methods selected by the IMO

Aakko-Saksa, Päivi

Published: 13/12/2018

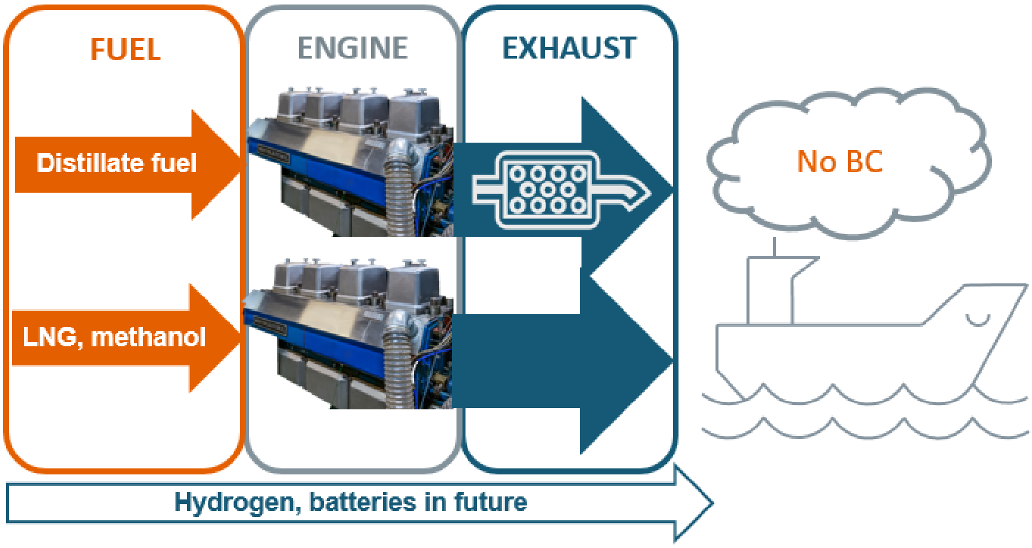
Document Version
Publisher's final version

Please cite the original version:
Aakko-Saksa, P. (2018). *Control measures of black carbon emissions from marine diesel engines - focus on results obtained using measurement methods selected by the IMO*. VTT Technical Research Centre of Finland. VTT Research Report, No. VTT-R-06900-18

VTT
http://www.vtt.fi
P.O. box 1000FI-02044 VTT
Finland

RESEARCH REPORT

VTT-R-06900-18



Control measures of black carbon emissions from marine diesel engines - focus on results obtained using the measurement methods selected by the IMO

Authors: Päivi Aakko-Saksa

Confidentiality: Public

Report's title

Control measures of black carbon emissions from marine diesel engines - focus on results obtained using measurement methods selected by the IMO

Customer, contact person, address Finnish Transport Safety Agency (Trafi) Jorma Kämäräinen, Chief Adviser P.O. Box 320, 00101 Helsinki	**Order reference** Dnro TRAFI/104791/02.03.01/2018
Project name Mustan hiilen tehtävät 2018 / Trafi	**Project number/Short name** BC_2018_Trafi
Author(s) Päivi Aakko-Saksa	**Pages** 60/60
Keywords black carbon, marine, engine, control measures	**Report identification code** VTT-R-06900-18

Summary

Black Carbon emissions (BC) increase global warming, particularly in the Arctic region through deposition on ice and snow. Additionally, BC emissions adversely affect air quality and human health. The International Maritime Organization (IMO) is evaluating the needs for control of BC emissions from marine diesel engines. A number of researchers and experts worldwide contributed to the voluntary BC measurement programmes, and in the discussions of the results in the five BC Workshops organized by the ICCT (International Council of Clean Transport). This report evaluates control measures of BC emissions from marine diesel engines based on the results obtained using the measurement methods selected by the IMO.

LNG as a fuel for ships would lead to almost BC-free operations, and methanol is also a clean-combusted fuel. Very efficient BC removal could be obtained with particulate filters combined with clean marine distillate fuels, although their durability and long-term performance are yet to be proven. Oxygen-containing biofuels reduce BC emissions even without a particulate filter. When produced from renewable sources, methane, methanol and diesel-type fuels (combined with particulate filter) would cut both BC and GHG emissions. Hydrogen/fuel cells and batteries would enable BC-free shipping, however, these are not mature technologies for large ships today. Renewal or retrofitting the mechanical injection systems of old engines with modern fuel injection systems would reduce the BC emissions, as well as tuning engines to low BC emissions (combined with NO_x reduction technologies). Modern engines would also enable the use of slow steaming without increased BC emissions from old engines. SO_x scrubbers, diesel oxidation catalysts and EGR seemed ineffective in reducing the BC emissions, however, some integrated or tailored solutions are available.

In summary, BC reduction technologies are available for marine diesel engines, although they are not without challenges.

Confidentiality	Public

Espoo, 13.12.2018

Written by	**Reviewed by**	**Accepted by**
Päivi Aakko-Saksa Principal Scientist	Kati Lehtoranta Senior Research Scientist	Jukka Lehtomäki Research team leader

VTT's contact address

PL 1000, FI-02044 VTT

Distribution (customer and VTT)

Customer and public server at VTT

Preface

Black carbon (BC) emissions increase global warming, particularly in the Arctic region through deposition on ice and snow. Additionally, BC emissions adversely affect air quality and human health. The International Maritime Organization (IMO) is evaluating the need for control of BC emissions from marine diesel engines. The IMO recognized the need for BC measurement studies to gain experience with the application of the definition and measurement methods, and invited interested Member Governments and international organizations to initiate, on a voluntary basis, BC measurement studies to collect data. Additionally, the ICCT (International Council of Clean Transport) organized five BC Workshops to present and discuss the BC measurement results obtained, and to increase understanding of the special features related to BC emissions from marine diesel engines using marine fuels, and related interactions with the measurement principles and BC control possibilities. A number of researchers and experts worldwide contributed to the voluntary measurement programmes on BC emissions from marine diesel engines, and discussions at the ICCT BC Workshops. Some of the key experts in this work are:

- Finland: Päivi Aakko-Saksa, Timo Murtonen, Hannu Vesala, Kati Lehtoranta, (Technical Research Centre of Finland Ltd. VTT), Hilkka Timonen, Kimmo Teinilä, Jukka-Pekka Jalkanen (Finnish Meteorological Institute FMI) Niina Kuittinen, Panu Karjalainen, Topi Rönkkö (Tampere University of Technology, TUT), Heikki Korpi (Wärtsilä), Jorma Kämäräinen, Anita Mäkinen (Trafi)
- USA: Kent Johnson, Wayne Miller, University of California, Riverside (UCR)
- Canada: Stephanie Gagne, National Research Council Canada
- Japan: Chiori Takahashi, National Maritime Research Institute (NMRI)
- EUROMOT: Peter Lauer, MAN
- ICCT: Bryan Comer

In Finland, research projects that contributed the most to the BC emissions results evaluated here were the SEA-EFFECTS BC project (Financial support from Tekes 40356/14, Trafi 172834/2016, and from several industrial partners) and the EnviSuM project (INTERREG, Trafi 58942/2017). This report was an assignment by Trafi (104791/2018). The results from the Finnish research programmes on BC have contributed to the IMO documents PPR 4/9/2, PPR 4/9/3, PPR 4/INF.7 and PPR 5/7/2.

This report evaluates control measures of BC emissions from marine diesel engines based on the published results obtained using the IMO selected methods. Co-operation between research institutes, organizations and companies is gratefully acknowledged. Without contributions in measurements, publications, reasoning and discussions it would not have been possible to accomplish the data generation and analysis that led to this report. In continuation, collaboration is sought for scientific articles. The outcome of this work was presented at the ICCT 5th BC Workshop in San Francisco.

Espoo 13.12.2018

Authors

Contents

Abbreviations

BC	Black carbon
BrC	Brown carbon
BTL	Biomass-to-liquids
CO	Carbon monoxide
CO_2	Carbon dioxide
CR	Common-rail
DF	Dual-fuel
DL	Detection limit
DMA	Marine distillate class according to ISO 8217
DME	Dimethyl ether
DOC	Diesel oxidation catalyst
EC	Elemental carbon
ECA	Emission Control Area
EGR	Exhaust gas recirculation
EsFF	Electrostatic fibrous filter
ESP	Electrostatic precipitator
FA	Vegetable oils and fats
FAME	Fatty acid methyl esters
FC	Fuel consumption
FSN	Filter smoke number
GHG	Greenhouse gases
GTL	Gas-to-liquids
HC	Hydrocarbons
HFO	Heavy fuel oil
HSD	High-speed diesel
HVO	Hydrotreated vegetable oils
ICCT	International Council of Clean Transport
IFO	Intermediate fuel oil
IMO	The International Maritime Organization
LFO	Light fuel oil
LII	Laser-induced incandescence
LNG	Liquefied natural gas
MAAP	Multi Angle Absorption Photometer
MAC	Mass absorption cross section
MCR	Maximum continuous rated power output
MDO	Marine diesel oil
MGO	Marine gas oil
MEPC	The Marine Environment Protection Committee
MSD	Medium-speed diesel
Mt	Megatonne
NO_x	Nitrogen oxides
OC	Organic carbon
PAH	Polyaromatic hydrocarbons
PAS	Photoacoustic Spectroscopy
PN	Particle number emission
PM	Particulate matter emission
PPR	IMO Sub-Committee on pollution prevention and response

RME	Rapeseed methyl ester
SCR	Selective catalytic reduction
SO_x	Sulphur oxides
SPN	Solid Particle Number
SSD	Slow-speed diesel
TC	Turbocharge
WiFE	Water-in-fuel emulsions
WES	Wet Electrostatic Scrubber
XTL	Feedstocks to liquids

1. Introduction

1.1 Black carbon

Black carbon increases global warming and its impact is particularly high in the Arctic region through deposition on ice and snow. This is an important aspect, as commercial shipping in the Arctic is expected to rise. The ship BC emissions are estimated to be responsible for 5% to 8% (100-year timescale) and 16% to 23% (20-year timescale) of the CO_2-equivalent climate warming impact from shipping in 2015. The contribution of marine diesel engines to the global BC budget is around 2%, although it is higher in the Arctic. (Comer *et al.*, 2017a). Balkanski et al. (Balkanski *et al.*, 2010) indicated that BC residence time in the atmosphere is around 7.3 days, and thus the ship plumes influence global warming and air quality at a distance from the source. BC emissions also adversely affects air quality and human health, particularly as the ship BC emissions mainly take place close to densely populated areas within 400 km of coastlines (Eyring *et al.*, 2010).

Particulate matter in marine diesel engine exhaust gas consists typically of BC, brown carbon (BrC), organic carbon (OC), inorganic ions (sulphates, nitrates), metals (e.g. Va, Ni, Fe, Ca, Na) and particle bound water. Scattering and absorption characteristics of these species are different and interfere with each other. Particles containing BC, BrC and/or metals typically have a dark colour and they absorb light, thus warming the climate. Instead, particles containing mostly organic carbon and/or inorganic ions are typically colourless or light in colour and, since they scatter solar radiation, they are considered to cool the climate. Some organic compounds are coloured, e.g. long-chain, polymeric, (poly)aromatic and refractory pyrolysed organic compounds absorb solar radiation and cause the material to appear brown (or yellow) and thus are called brown carbon. (IPCC 2013 ((Stocker *et al.*, 2013) and references in (Timonen *et al.*, 2017; Aakko-Saksa *et al.*, 2018)).

BC and BrC emissions form in the combustion of carbonaceous matter, while absorbing mineral dust is not commonly present in aerosols from combustion processes (Andreae and Gelencser, 2006). BC contains more than 80% of carbon in double bonded forms. Primary BC particles, 10–90 nm spherules, cluster together immediately after formation in a flame to form aggregates (Wentzel et al., 2003). Bond et al. (2013) defines BC as follows:

- BC strongly absorbs visible light with a mass absorption cross section (MAC) of at least 5 $m^2 g^{-1}$ at a wavelength of 550 nm
- BC is refractory with a vaporization near 4000K
- BC is insoluble in water, in organic solvents and in other components of atmospheric aerosol
- BC is an aggregate of small carbon spherules.

The electromagnetic spectrum with magnification of the visible wavelengths is shown in Fig. 1. Fresh BC absorbs light (solar radiation) at all visible wavelengths, also in the mid-visible and long wavelengths (550-950nm) where the contribution of other absorbing species is low. However, the strength of light absorption depends on composition, shape and particle sizes of BC, as well as on the mixing (Bond *et al.*, 2013; Yliskylä-Peuralahti *et al.*, 2016).

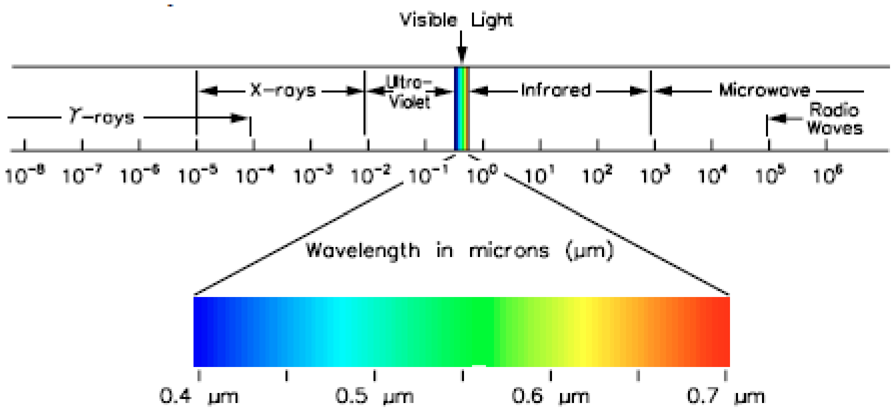


Figure 1. The electromagnetic spectrum, showing magnification of colours of the visible wavelengths between 400nm and 700nm (Malm, 1999)*.*

The distinction between BC and BrC is not straightforward (Fig. 2), as their absorption properties may be overlapping. Generally BrC absorbs light at shorter wavelengths than BC, and so do the small aerosol particles. (Yang et al. 2009, Andreae and Gelencser 2006). Absorption of BrC is strongest in UV wavelengths (300nm) and steeply decreases into visible wavelengths. The light absorption of BC is less dependent on wavelength than that of organic compounds, BrC and dust. (Lim et al. 2014, Collaud Coen et al. 2010, Yang et al. 2009).

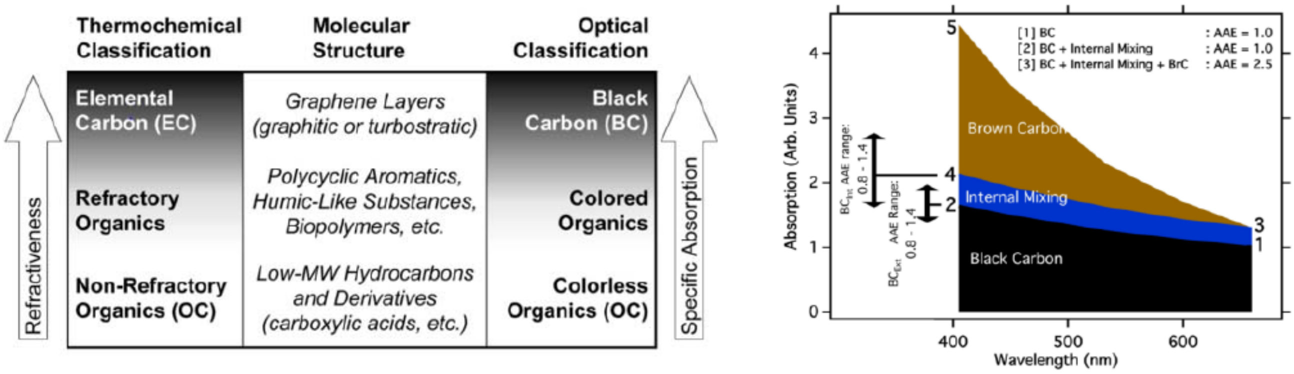


Figure 2. a) Classification and molecular structure of carbonaceous aerosol components (Pöschl, 2003) b) Absorption of Brown carbon as a function of wavelength (Lack and Langridge, 2013).

1.2 The IMO work on black carbon emissions

Ships are significant emitters, and thus their emission regulations are tightening. Shipping is facing decarbonizing targets, and emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x) are already limited in the specific Emission Control Areas (ECA), and for cruises within European ports. A global limit for fuel sulphur content of 0.50% m/m will apply in 2020 or an exhaust gas aftertreatment system for SO_x emissions is to be used. Particulate matter (PM) emission is limited in inland waterways, and a particle number emission limit is coming into force in 2020. These limits may expand to ocean-going ships, and new limits for BC and methane emissions are anticipated. None of the existing emission regulations directly reduce the BC emissions.

The International Maritime Organisation (IMO) is evaluating the need for regional and global control of BC emissions from marine diesel engines. The Marine Environment Protection Committee (MEPC) of the IMO started discussion on BC emissions in 2010 (MEPC 62). The

IMO accepted a definition for BC emissions according to Bond et al. (Bond *et al.*, 2013) in 2015 (MEPC 68). In 2017, the IMO selected three potential principles for the BC measurements. Now discussion has moved to the possible strategies for BC mitigation.

In atmospheric research, BC concentrations are determined using instruments designed for low ambient BC concentrations.[1] These instruments have a limited measurement range and very high dilution ratios, obtained with complex dilution systems, are needed to reliably measure high BC concentrations, for example, from current diesel engines or in malfunctions of the clean engine technologies. Complex dilution systems increase the uncertainty of the results. To note, elemental carbon (EC) measured based on the thermal-optical analysis principle is common in the atmospheric research, although its definition is not commensurate with the definition of BC. Both “BC” and “EC” are “proxies” as relevant calibration methods are not available.

Three potential principles for BC emission measurements selected by the IMO are filter smoke number (FSN), photoacoustic spectroscopy (PAS) and laser induced incandescence (LII). Instruments using the FSN principle are specifically developed for diesel engine exhaust gas measurements, and thus they overcome some challenges that are experienced with instruments designed for ambient air measurements. Using the FSN principle, exhaust gas dilution is not needed and raw exhaust gas can be used for measurements even at high BC concentrations. FSN is based on light absorption by monitoring the change in optical reflectance of visible light (peak from 550nm to 570nm) from a loaded filter relative to a clean filter. Conversion of FSN to the BC concentration is according to the equation provided by the manufacturer or correlations available in ISO 8178-1 (2006, eq. A. 16). FSN is a standardized method conforming to ISO 10054. Some instruments using the PAS and LII principles are also designed for measuring exhaust gas from internal combustion engines, however, dilution may be needed at high BC concentrations.

1.2.1 Goal

This work aims to provide a view on the effectiveness and status of different control technologies to reduce BC emissions from Slow-speed diesel (SSD) and Medium-speed diesel (MSD) marine diesel engines. Evaluation is based on the results of the experimental work on the BC emissions from marine diesel engines using the IMO selected measuring principles (FSN, PAS, LII). Especially important are the voluntary BC projects invited by the IMO and discussed at the ICCT BC Workshops. Results using BC measurement methods other than those selected by the IMO are discussed as supporting data. BC control technologies are evaluated in the following categories: engine technologies, fuels, exhaust gas treatment systems and other measures. A special chapter evaluates the effect of slow steaming on the BC emissions from old and modern engines, which is a preliminary attempt to understand the impact of slow steaming on the BC emissions from different marine engine technologies. Results obtained here are compared with the results of an update to the investigation of appropriate control measures (abatement technologies) to reduce BC emissions from international shipping (PPR 5/INF.7, (Lack, 2017)). Since the preparation of PPR 5/INF.7, new BC emission results are available from measurement campaigns.

---

[1] Instruments designed for atmospheric research are e.g. Multi Angle Absorption Photometer (MAAP) and Aethalometers measuring absorption, which is converted to BC mass by using the MAC value. In MAAP, BC concentrations are measured at 670nm and for conversion a MAC value of 6.6 $m^2\ g^{-1}$ is used (Petzold and Schönlinner, 2004), while in Aethalometers, a wavelength of 880nm and a MAC value of 7.77 $m^2\ g^{-1}$ are used (Drinovec *et al.*, 2015). Organic compounds and a water vapour coating on BC may enhance absorption causing a lensing effect inducing overestimated BC results (Yang *et al.*, 2009; Collaud Coen *et al.*, 2010; Lim *et al.*, 2014).

2. Methods of evaluation

2.1 Criteria

We used the following primary criteria in selecting the measurement campaigns for evaluation:

- BC measurement results obtained by using FSN, PAS and LII measurement principles selected by the IMO.
- Fuel comparisons (residual, distillate, oils and fats) conducted using different fuels in the same marine diesel engine, in the same measurement campaign using the same engine load and measurement protocol. Otherwise high differences in emissions from individual diesel engines could mask differences between fuels.
- Exhaust gas treatment systems studied by the BC measurements before and after the treatment system. Otherwise high differences in emissions from individual ships could mask influences of exhaust gas treatment systems.
- Different parameters compared based on the BC measurements at the same engine loads during one measurement campaign.
- Evaluation is focused on SSD and MSD marine diesel engines that are used in larger ships. HSD engines are discussed only briefly in relation to engine technologies.
- The results obtained with single-cylinder laboratory engines, engines below 1 MW and modified engines were excluded from evaluation, as these are not necessarily representative of commercial diesel engines.

One of the challenges with evaluations of the BC emissions from LNG and methanol fuelled engines lies in the different engine technologies. In this report, the BC emission data obtained is only from gas dual-fuel engines, while BC emissions results for other engine technologies using LNG as a fuel are not available.

Results that don't meet the criteria, for example, results obtained using other BC measuring principles than those selected by the IMO, are discussed as supporting information where appropriate. However, these results are marked as "other methods" in Figures of this report.

2.2 Minimum detection limit

The BC measurements, according to the IMO selected principles, can be measured using different instruments. Examples of these instruments and their detection limits are as follows:

- FSN: In the campaigns evaluated, FSN measurements were most commonly conducted using the AVL 415 SE instrument. The detection limit of this instrument is 0.020 mg/m^3 (FSN 0.002) and range is up to 32 g/m^3. Resolution of this instrument is FSN 0.001. A detection limit of 0.020 mg/m^3 represents a concentration of approximately 0.54 mg/kg fuel. An update of the AVL instrument is under development with a detection limit of 0.002 mg/m^3.
- PAS: AVL MSS has a detection limit of 0.001 mg/m^3, which represents a BC concentration of approximately 0.027 mg/kg fuel. The range of this instrument is up to 50 mg/m^3. Internal dilution system of instrument can be used.
- LII: Artium LII-300 has a detection limit of 0.001 mg/m^3 and a range up to 20 g/m^3.

The highest detection limit of the instruments mentioned is for the AVL 415 SE instrument, namely FSN 0.002. This is only a fraction of the visibility limit of appr. FSN 0.2.

2.3 The BC units

The BC results are evaluated in a unit of “BC g per kg fuel”. When the results were not given in this unit in the referenced sources, the following parameters were used for conversion of original units to “BC g per kg fuel”: fuel consumption 0.2 kg/kWh and exhaust gas flow of 7.4 kg/kWh. FSN was converted to the BC (mg/m^3) according to formula 1 when needed. Concentrations were converted to standard conditions of 273.15 K and 100 kPa (mass per Sm^3).

$$BC(mg/m^3)=5.32*FSN*EXP(FSN*0.3062)/0.405 \qquad (1)$$

2.4 Uncertainty

The uncertainty of measurements deserves consideration when the effects of control measures of BC emissions from marine diesel engines are evaluated. For comparisons of the BC emissions between different technologies, *repeatability* is an important factor, however, the following sources of uncertainties also need consideration:

(1) *Detection limits* of the BC emissions measurement instruments. Numerical comparisons of emissions are valid above the detection limit of instruments, for example, above BC of 0.54 mg/kg fuel when using AVL 415 SE instrument.

(2) *Stability of an engine*. Differences in the BC emissions compared should be higher than the variation in the BC output from the engine. As an example, repeatability of the BC measurements from an old marine diesel engine was <16 mg/kg fuel (0.5 mg/Sm^3, 0.003 g/kWh) at BC level >32 mg/kg fuel (>1 mg/m^3) (Aakko-Saksa et al. 2016).

(3) *Instrument, dilution system and exhaust gas transfer* (e.g. in heated lines). For standardized methods, such as FSN, repeatability and reproducibility of the measurement method are known. Even then, exhaust gas composition may disturb BC determination and cause bias in the results. For instruments that need dilution, high uncertainty is related to this function.

In this evaluation, the BC emission level is inspected against points (1) and (2) when significance of the BC results is discussed. Uncertainties related to instruments, dilution etc. (point (3)) are included in the reporting of each research campaign.

3. Measurement campaigns

Measurement campaigns meeting the criteria defined in Chapter 2.1 are presented in Table 1.

Table 1. Measurement campaigns meeting the criteria defined for the evaluation of the BC measurement results in this report.

Id, engine	**Fuel**	**Exhaust gas treatment system**	**Reference**
UCR T1: small engine	DMA, RMB, RMG	No	Johnson 2016
UCR T2: on-board, modern ship	DMA	No	Johnson 2016
UCR T3: on-board, container ship, SSD 16.6 MW & 2xMSDs	HFO	Hybrid scrubber (Alfa Laval PureSOx)	Johnson 2016
UCR T3_ref: older studies a) 6.3 MW b) 74.6 MW c) 68.5 MW)	a) HFO-LS, MGO, b,c) HFO, MGO	No	Johnson 2016
EUROMOT: diesel and gas engines	One fuel per engine	No	Note: HSD engines in Annex 31, 32, 33, 34, 35 [a]
FI-1: Testbed, MSD 1.6MW	HFO, HFO 0.5%S, MDO, Bio30	No	Sea-Effects BC WP1, Aakko-Saksa 2016, PPR4/9/2, PPR4/9/3, PPR4/INF.7
FI-2: On board, modern cruise ship, MSD 9.6 MW	HFO 0.65%S	SCR+hybrid scrubber	Sea-Effects BC WP2, Timonen 2017, PPR/5/7/2
FI-3: On board, modern cruise ship, MSD 14.4 MW	HFO 0.65%S, MGO	Hybrid scrubber	Same as above
FI-4: On board, RoPax, MSD 4 x Wartsila 9L46D 10.4 MW	HFO 1.9%S, MGO	DOC+ open loop scrubber (ECO-DeSOx)	EnviSuM, Teinilä et al. 2018 PPR/5/7/2
The IMO selected BC methods were used also by, e.g. Lauer (2017, 2012), Buffaloe (2014, plume study), Ristimäki (2010), Sarvi (2009) and Stojcevski 2016.			

[a] MSD engine speeds are approximately from 300 rpm to 1000 rpm. Six EUROMOT engines in the middle category are HSD engines based on the engine speeds used in testing: *Annex 30*: 1151 rpm at 100% load and 1046 rpm at 75% load; *Annex 31*: Actual engine speed 1325 rpm, *Annex 32*: 1197-1899 rpm; *Annex 33*: 1900 rpm; *Annex 34*: >2000 rpm; Annex 35: >2000 rpm.

4. Engine technologies

4.1 Highlights

- Engine size and speed:
    - HSD engines emit higher BC emissions (0.1- 0.5 g/kg fuel) than SSD and MSD engines.
- Injection system has an impact on BC emissions:
    - Engines with mechanical fuel injection emit high BC emissions at low loads (e.g. up to 0.5 g/kg fuel).
    - Engines with modern injections systems (particularly common-rail) have low BC emissions regardless of engine load. Thus retrofitting old engines with modern injection systems would reduce BC emissions.
- Remarks:
    - **Engine tuning can reduce BC emissions** at the cost of increased NO_x that can be cut using SCR or EGR. CO_2 emissions and fuel consumption are also reduced by engine tuning.
    - Slide valves could reduce BC emissions from 2-stroke engines, while they are not applicable to 4-stroke engines. Needle sac volume is already reduced for 4-stroke engines.

4.2 General

Diesel engines are currently the almost solely used marine engine (CIMAC, 2012). Modern diesel and gas engines are very efficient, for example, specific fuel oil consumption is 170.6 g/kWh for 4-stroke engine Wärtsilä 31 (W31 brochure) and 159-170 g/kWh for 2-stroke engine MAN 5-9S50ME-B7/8 (MAN brochure). These are substantially lower specific fuel consumptions than 210 g/kWh in the 1970s (Di Natale and Carotenuto, 2015), and also engine emissions today are a fraction of those in the past. Therefore, further potential for emission reductions by using engine internal measures may be limited for new engine designs. Instead, retrofitting old engines with modern fuel injection systems, or engine tuning may offer a pathway to lower emissions.

4.3 Engine types and fuel injection

For the analysed data, BC emissions were higher for high-speed (HSD) engines than for MSD and SSD engines (Fig. 3). Engine stroke itself did not affect the BC emissions: BC emissions for 4-stroke MSD engines and 2-stroke SSD engines were in the same order of magnitude. Comer et al. (Comer *et al.*, 2017a) observed higher BC emissions for 4-stroke than for 2-stroke engines. However, this might be due to some high-emitting HSD engines in the group of 4-stroke engines.

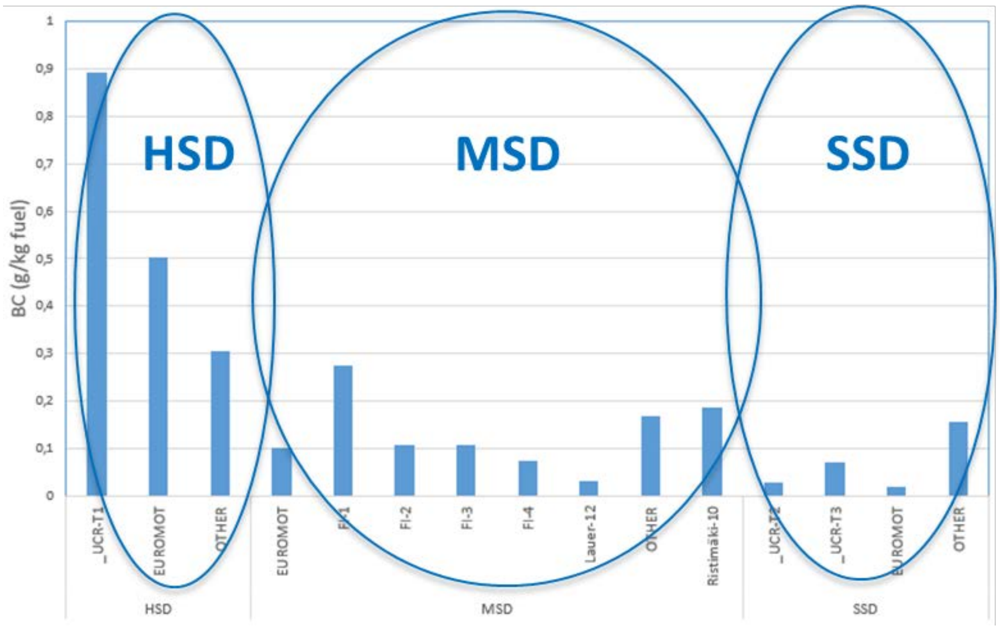


Figure 3. The BC emissions from HSD, MSD and SSD engines. Average of BC measured at different engine loads.

The BC emissions from engines in different engine power classes (engine sizes) are shown in Fig. 4. Some engines showed higher BC emissions than others. Smaller engines with a mechanical injection system had high BC emissions. Engines above 4 MW equipped with modern injection systems had, in most cases, BC emissions well below 0.1 g/kg fuel. The largest engines seemed to result in the lowest BC emission level. Johnson et al. (Johnson *et al.*, 2016) also observed increasing BC emissions with decreasing engine power.

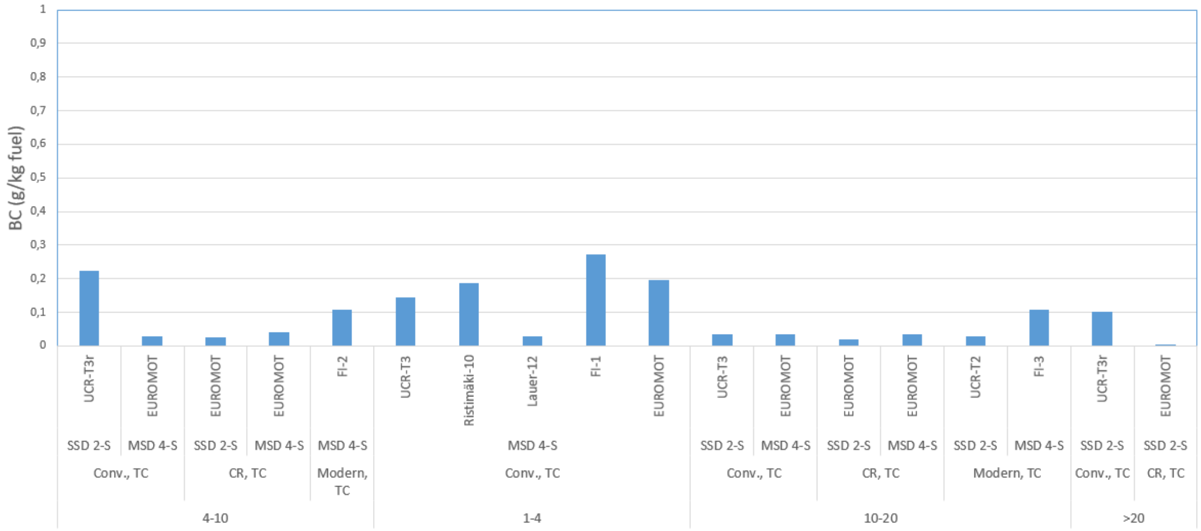


Figure 4. The BC emissions from MSD and SSD engines in different engine size classes.

In Fig. 5, engines equipped with common-rail and other modern fuel injection systems are shown in parallel to those equipped with conventional mechanical fuel injection systems. Engines with modern fuel injection systems had a lower BC emission level when compared to the engines equipped with mechanical fuel injection systems. Modern fuel injection systems and optimized injectors reduced the BC emissions, especially at low engine loads. With some limitations, the fuel injection systems in “old type” existing engines can be retrofitted for higher fuel injection pressures (e.g. common-rail).

The fuel injection valves can be designed to prevent fuel from evaporating into the combustion chamber and to avoid a resulting increase in BC emissions. Slide valves can be used in 2-stroke engines to reduce BC emissions, while needle sac volume reduction is feasible for 4-stroke engines. Slide valves can be retrofitted in some old large 2-stroke engines, however, in 4-stroke engines the sac volume has already been reduced without substantial further BC reduction potential. (CIMAC, 2012).

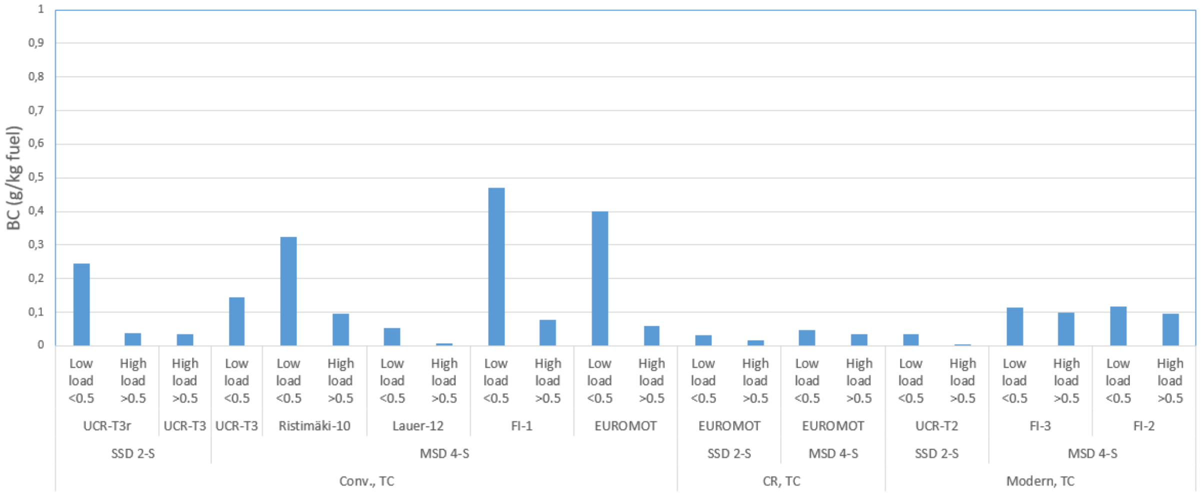


Figure 5. BC emissions from, conventional, common-rail (CR) and other modern injection systems equipped MSD and SSD engines.

Studies using other measurement methods than those selected by the IMO showed similar trends as observed here for the BC emissions from different engine types. For engines above 4 MW, high BC emissions were observed for three engines measured in two plume studies using “other methods”, e.g. BC emissions from 0.3 to 0.75 g/kg fuel at low engine loads for 7.2 MW engine. For two engines in the “other methods” class, the BC emission level was similar to our observations for modern engines (below 0.1 g/kg fuel). The plume results may indicate “real-world” BC emissions using low engine speeds close to the coastline.

4.4 Load-dependence of BC emissions

In the previous Chapter, in most cases, higher BC emissions were observed at low engine loads for old engines equipped with mechanical fuel injection systems, while engines equipped with modern fuel injection systems were relatively insensitive towards engine loads measured. Marine diesel engines are typically optimized for high engine loads, and thus elevated BC emissions may be observed at low engine loads if engine is equipped mechanical fuel injection system. This phenomenon is shown more clearly in Fig. 6, where load-dependence is evident for engines equipped with mechanical fuel injections system, while in Fig. 7 modern engines emit low BC emissions regardless of the engine load. There seems to be no substantial differences between SSD 2-stroke engines and MSD 4-stroke engines in this respect based on limited data. Once again, very high BC emissions are observed for HSD engines in Fig. 8, even 3.5 g/kg fuel, while BC emissions are typically below 0.1 g/kg fuel for modern SSD and MSD engines.

Load-dependence of the BC emissions has also been observed by Johnson et al. (Johnson *et al.*, 2016) and in the plume studies by Lack et al. (Lack *et al.*, 2011). EC emissions of 0.09 g/kg fuel were observed from the main engine of an ocean going PanaMax class container ship at

27-70% engine loads, (on-board), but almost double at 8% engine load by Agrawal et al. (Agrawal et al. 2008). Low engine loads are relevant when travelling, for example, close to port, in the Arctic routes, or when using slow steaming.

In a study by Anderson et al. (2015), the particle emissions increased by one order of magnitude when reducing engine load from 35% to idle. The reason for this was estimated to be due to the effect of the low combustion temperature leading to the heavy molecular weight organics deriving from the unburnt fuel and oil. Particle number emissions for distillate fuels (MDO, MK1 and MK3) were substantially lower than those obtained using an IFO fuel.

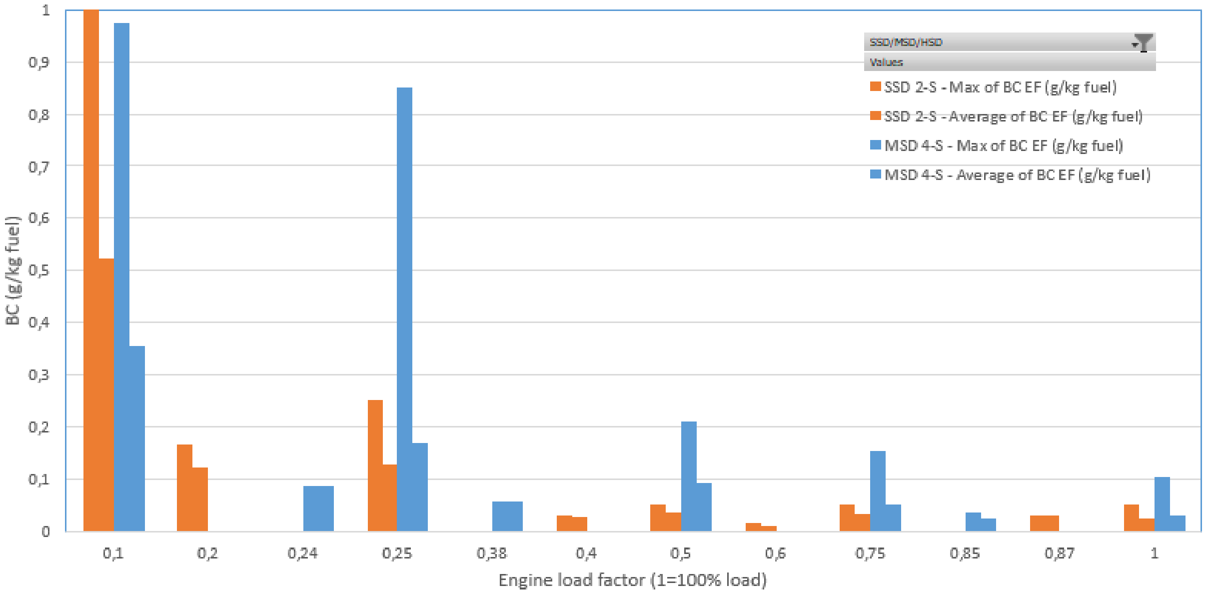


Figure 6. Average and maximum BC emissions measured from SSD and MSD engines equipped with conventional injection systems at different engine loads.

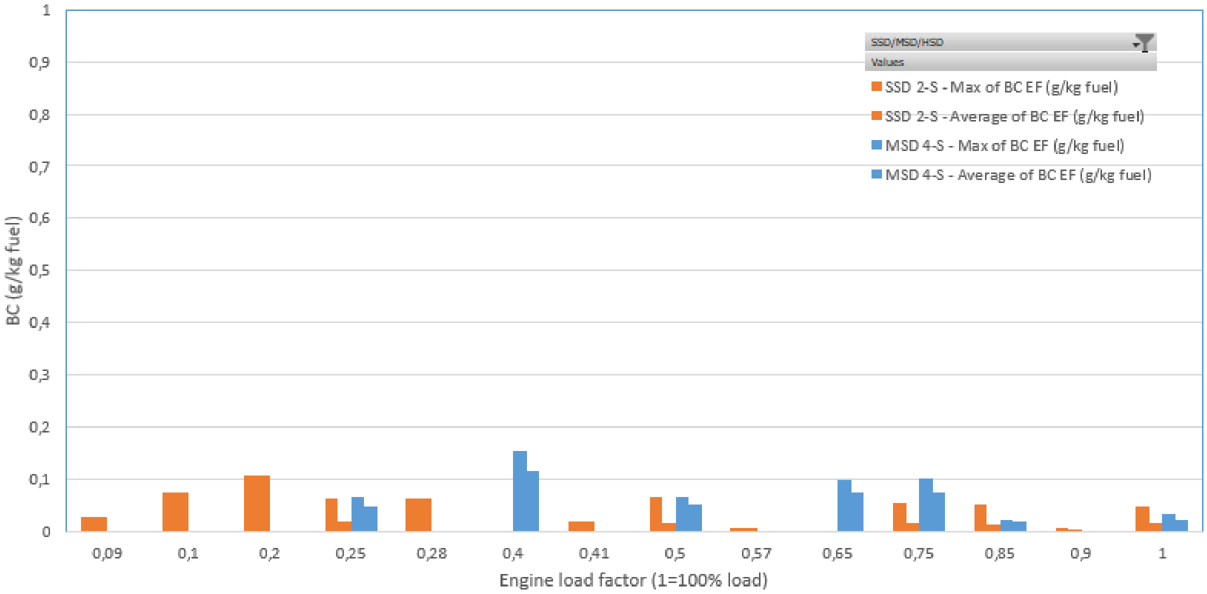


Figure 7. Average and maximum BC emissions measured from SSD and MSD engines equipped with modern injection systems at different engine loads.

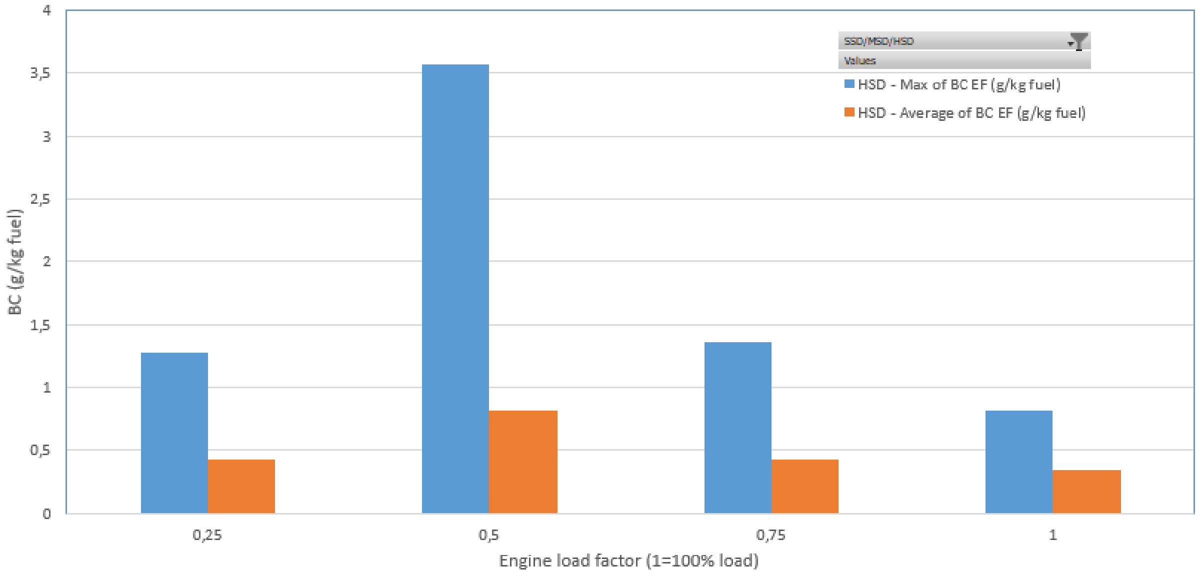


Figure 8. Average and maximum BC emissions measured from HSD engines equipped with conventional and modern injection systems at different engine loads (note scale).

4.5 Engine tuning to low BC emissions

Low PM tuning through in-cylinder technology combined with NO_x reduction technology can potentially reduce BC emissions. Additionally, CO_2 emissions and fuel consumption decrease. Without NO_x reduction technology, simultaneous NO_x and PM control is difficult, e.g. retarded injection timing reduces NO_x, but increases PM. (Ref. Dieselnet, accessed 8/2018, www.dieselnet.com/tech, MARPOL Annex VI).

Fig. 9 shows the NOx-PM trade-off principle based on the evolution of emission technology in heavy-duty diesel engines in the 1990s (Needham 1991). Both NO_x and PM reduce when moving from conventional diesel technologies to advanced diesel engine technologies, such as turbocharge (TC) and electronic engine control. PM can also be reduced by engine tuning and adopting a NO_x reduction technology, such as Selective Catalytic Reduction (SCR) or Exhaust gas recirculation (EGR). On-road engine manufacturers have achieved tight PM limits through in-cylinder technology alone, or in combination with NO_x reducing technologies (Dieselnet, accessed 8/2018, www.dieselnet.com/tech). Particularly in the US, engines have been calibrated to high-NO_x and low-PM operation, when CO_2 also reduces, and elevated NO_x is reduced by SCR or EGR. Despite low PM emissions, the particle number emissions may remain substantial. In Europe, the solid particle number (SPN) is limited for vehicles, and thus very efficient wall-through diesel particulate filters are needed.

For engine tuning to low PM/BC emissions, the NO_x reduction technologies are required to avoid elevated emissions. SCR technology is compatible even with high-sulphur marine fuels as monolithic fixed beds have square holes large enough to avoid clogging and poisoning. (CIMAC, 2012; Di Natale and Carotenuto, 2015; Timonen *et al.*, 2017; Teinilä *et al.*, 2018). Another technology to reduce NO_x is EGR, which reduces NO_x by mixing a part of the exhaust gas into the intake combustion air. Lower oxygen and higher water and CO_2 concentration in the intake air results in suppressed combustion temperatures and reduced NO_x formation. EGR tends to increase BC emission (CIMAC, 2012).

For marine diesel engines, the potential of engine tuning to reduce BC emissions is not proven, and the basics shown here are based on studies conducted with high-speed diesel engines. The respective information for MSD and SSD engines would be desirable. Additionally, NO_x/PM trade-off is not necessarily uniform with the NO_x/BC emission trade-off. Currently, NO_x

limits are higher for SSD than for MSD engines, and thus an engine tuning strategy might have more potential for MSD than for SSD engines.

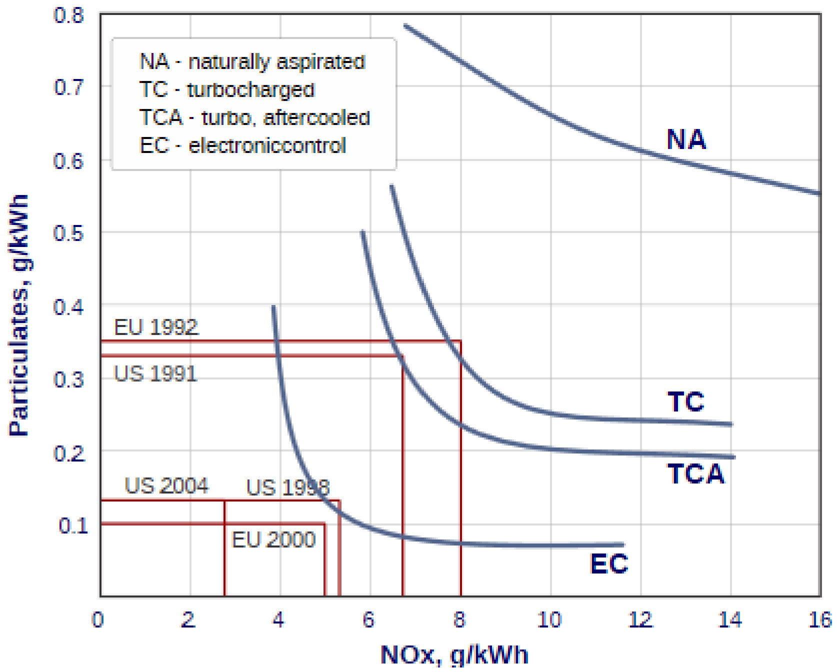


Figure 9. NO_x-PM trade-off for heavy-duty diesel engines. The thick blue lines represent emission levels that can be achieved by different engine technologies. The thin red lines reflect selected emission standards for heavy-duty diesel truck engines. (Needham 1991).

5. Fuels

5.1 Highlights

- Marine fuels in use today are mainly residual or distillate liquid fuels. All fossil fuels can be replaced by their chemically similar renewable counterparts.

- Observations regarding BC emissions for liquid fuels:
  - BC emissions were generally the highest for residual fuels. With an old engine, particularly high BC emissions were observed for low-sulphur residual fuel at low engine load.
  - Distillate fuels reduced BC emissions in most cases when compared to residual fuels.
  - Oxygen-containing biofuels substantially reduced the BC emissions when compared to residual or distillate fuels.
  - Methanol as the main fuel in a DF engine reduced BC emissions by 55-75% depending on pilot injection when compared with distillate as the main fuel in a DF engine.

- LNG in a DF engine resulted in extremely low BC emissions in all engine size classes.

5.2 Marine fuels and their renewable counterparts

Marine fuels used today are mainly residual or distillate liquid fuels. ISO 8217 specifies properties of, for example, the following marine fuel classes:

- Residual fuels (e.g. RMA, RMB) are classified by their viscosities (e.g., 10, 30, 80, 180, 380, 700).

- DMA (called also marine gas oil, MGO) is a general marine distillate that must be free from traces of residual fuel. DMA is primarily used in Category 1 marine engines (< 5 litres per cylinder).

- DMB (called also marine diesel oil, MDO) may have traces of residual fuel. DMB is typically used for Category 2 (5-30 litres per cylinder) and Category 3 (≥ 30 litres per cylinder) engines.

Special marine fuels, called “hybrid fuels”, may have low sulphur content, e.g. below 0.10% (m/m), even if other fuel properties resembled those of the residual fuels (Wright, 2016).

Generally, residual fuels represent the worst quality of marine fuels. They may contain substantial amounts of harmful substances, such as heavy metals and asphaltenes. Marine distillate fuels are cleaner than residual fuels, but still worse than road diesel. Some examples of fuel properties are presented in Table 2.

Table 2. Selected properties of one residual and two distillate marine fuels and road diesel.

	RMG 380 ISO 8217:2010	DMA (MGO) ISO 8217:2010	DMB (MDO) ISO 8217:2010	Road diesel *
Kinematic viscosity, mm²/cm	max. 380 (50 °C)	2-6 (40 °C)	2-11 (40 °C)	2-4
Cetane index, min		40	35	46
Sulphur, max., %(m/m)	statutory	1.5	2.0	0.001
Acid number, max., mg KOH/g	2.5	0.5	0.5	0.08**
Total sediment by hot filtration, %(m/m)		-	0.1	0.05
Carbon residue, max., %(m/m)	18	0.3	0.3	0.3
Pour point summer, max, °C	30	0	6	
Ash, max., %(m/m)	(0.15)	0.01	0.01	0.01

*) EN 590:2013/2017, ASTM D 975 **) WWFC Category 4

Renewable fuels are either bio-based or synthesized from renewable hydrogen and circular carbon dioxide. All fossil fuels can be replaced by their renewable counterparts, which are chemically similar but produced from bio- or renewable sources. Liquid hydrocarbon alternatives (distillates, road diesel, GTL, HVO, BTL, XTL) as well as oxygen-containing vegetable oils and fats are compatible with current marine diesel engines and infrastructure. Despite different production pathways, GTL, HVO, BTL and XTL are chemically relatively similar consisting of paraffins (alkanes), and thus have a higher hydrogen to carbon ratio than conventional marine fuels. These paraffinic fuels are of better quality than the road diesel fuel (http://www.iea-amf.org/content/fuel_information/paraffins).

Gaseous LNG (fossil methane), as well as renewable methane, requires special engines and infrastructure that is being built in many regions. Liquid methanol requires relatively small changes in engines and infrastructure. Marine diesel engines for dimethyl ether (DME), ammonia and hydrogen are not mature or commercial, although they are demonstrated. Table 3 illustrates the status of alternative fuels in view of their maturity for use in marine engines.

Table 3. Basic classification of alternative fuels for shipping.

Fuel	Fossil form	Bio or renewable counterpart	State	Commercial marine engines	Infrastructure
Liquid hydrocarbons	Residual Distillates GTL	HVO, BTL, XTL	Liquid	Yes	Yes
Vegetable oils, animal fats	No	Oils and fats	Liquid	Yes	Yes
Methanol	Fossil methanol	Renewable methanol	Liquid	Yes	Yes
Methane	LNG	LBG, SNG	Gas	Yes (newbuilds)	Emerging
Dimethyl ether (DME)	Fossil DME	Renewable DME	Gas	No (demos)	Very limited
Ammonia	Fossil ammonia	Renewable ammonia	Gas	No (demos)	Very limited
Hydrogen	Fossil hydrogen	Renewable hydrogen	Gas	No (demos)	Very limited

GTL = Gas-to-liquid; for example methane liquefaction using the Fischer–Tropsch process

5.3 Liquid fuels

5.3.1 Marine distillates versus residual fuels

Marine distillate fuels have different fuel properties than residual fuels, and switching these fuels is not always straightforward. When proper engine and emission performance is desired, marine diesel engines designed for residual fuel use may need adjustments for distillate fuel use, or even retrofitting (e.g. injectors). This applies particularly to old engines, whereas modest (or no) additional engine optimization is needed for modern marine diesel engines when changing from residual to distillate fuels.

Concerning the capability of distillate fuels to reduce BC emissions compared with residual fuels, CIMAC (CIMAC, 2012) found very little evidence to support this claim, while they found reports stating that BC emissions remained unchanged by switching from high to low sulphur fuels, and even some evidence of increased BC emission with in-use large diesel engines. A review by Lack and Corbett (Lack and Corbett, 2012) claimed that moving from residual to distillate fuels would reduce BC emissions by an average of 30% and potentially up to 80%, and 33% in an update by Lack (Lack, 2017).

In our evaluation, only a few studies tested different liquid fuels in the same engine. For example, the EUROMOT data did not contain any fuel comparisons using different fuels in the same engines. The results of the measurement campaigns meeting the criteria for fuel comparisons are shown in Fig. 10. Engine sizes in these studies vary from 1.64 MW to 14.4 MW. In most cases, distillate fuels reduced BC emission when compared to residual fuels indicating the BC reduction potential from negligible to over 50%, on average 26%. However, BC emissions also increased in a couple of cases when moving to distillate fuels from residual fuels.

For an old engine, high BC emission was observed when using low-sulphur residual fuel at low engine load. This is an alarming signal, as such fuels may be increasingly present when the global 0.5% fuel sulphur limit is in force in 2020. The engine in question was equipped with a mechanical injection system, and possibly this led to high BC emission at low loads when using low-sulphur residual fuel. New engines equipped with modern injection systems could be less sensitive to fuel changes. Also one HSD engine (not shown in Fig. 10), showed reduced BC emission when switching from a HFO (3.4% S) to MGO (0.02% S), but to a lesser extent than when switching from a LS HFO fuel to a LS MGO fuel[2] (Johnson *et al.*, 2016).

---

[2] High-speed 2-stroke Detroit Diesel Model 6-71N engine (naturally aspirated, in-line 6 cyl. 7 litres per cylinder, 2300 rpm, 187 kW, 2-stroke: BC reduced when switching from a HFO (3.4% S) to MGO (0.02% S), but to lesser extent for a LS HFO fuel and a LS MGO fuel. (DMA/RMA12/RMG380 at 27% load: 0.12/0.25/0.1 g/kg fuel; at 70% load 0.97/2.35/1.1 g/kg fuel). (Johnson *et al.*, 2016).

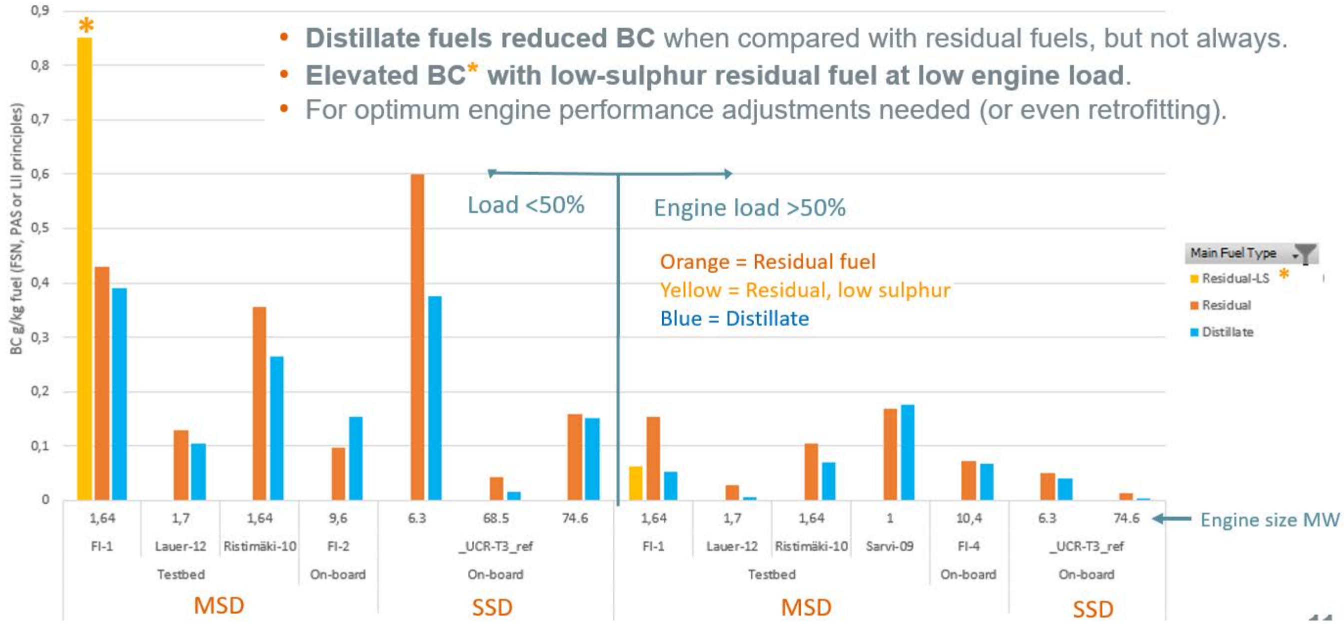


Figure 10. The BC emission measurement results for residual and distillate marine fuels from studies based on FSN, PAS or LII measurements of BC emissions.

From studies using methods other than FSN, PAS or LII for the BC measurements (Fig. 11), only in two projects were different fuels studied in one engine. In these cases, BC emissions increased when switching from residual to distillate fuel. Data for the 6 MW engine is from a study reported by Moldanova et al. (Moldanová *et al.*, 2013). The 1.64 MW engine is the same as the 1.64 MW engine in Fig. 10.

Replacing residual fuels with distillates reduces the sulphate portion of PM, while the rest of PM is not necessarily changed. However, when there are substantial differences in fuel viscosities, concentrations of heavy constituents (e.g. aromatics) and metals, changes in combustion and related PM characteristics[3] are quite expected, although probably more pronounced in old than in new engines.

---

[3] In some cases particle numbers have been higher for MGO than for IFO (refs in (Di Natale and Carotenuto, 2015). Anderson et al. (2015) reported that when using an IFO fuel blend (0.12%S) in comparison with MDO in Volvo Penta D3-110 engine, no or only small differences appeared in particle numbers, but differences were seen in particle diameters larger than 50 nm.

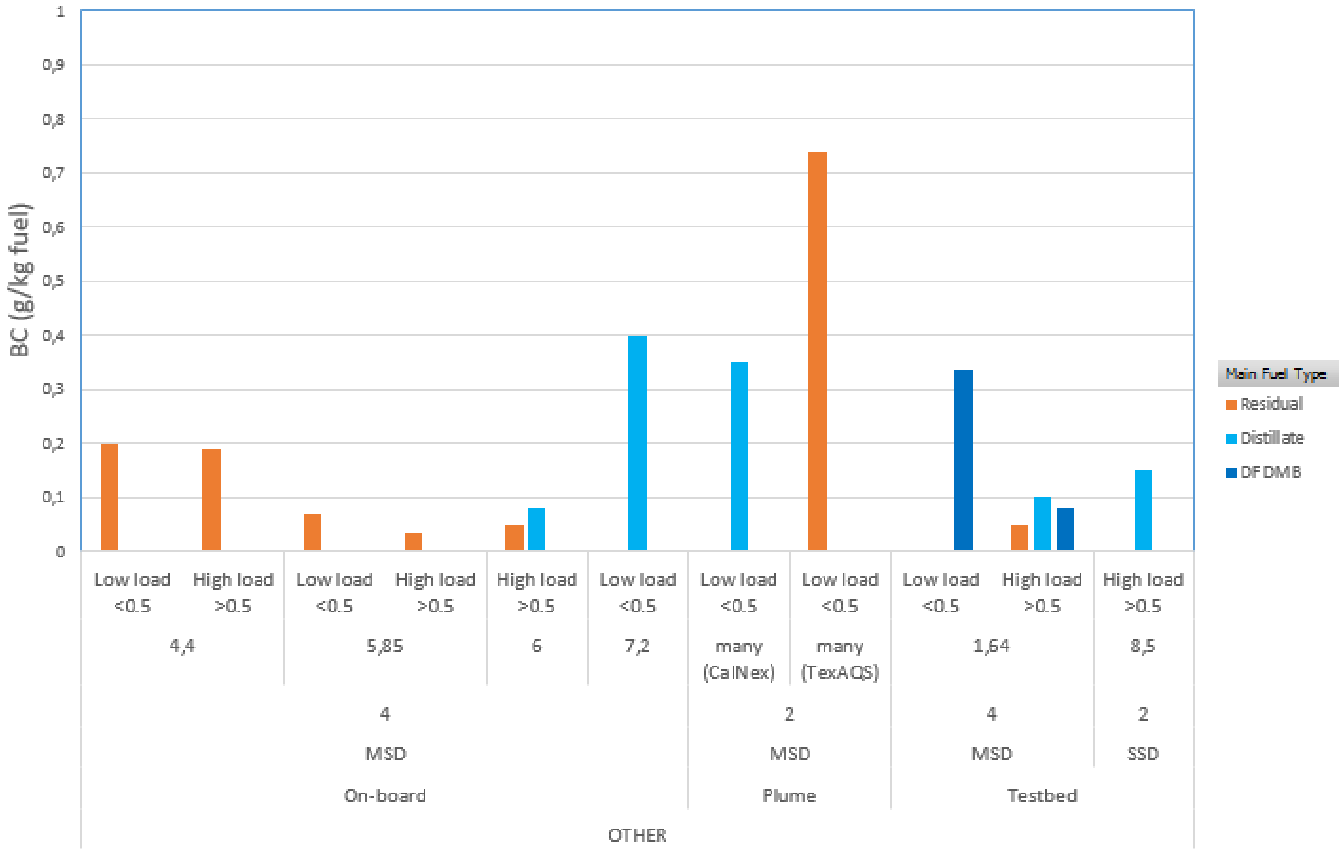


Figure 11. The BC emission measurement results from studies based on "other methods". Exceptionally also plume measurement results are shown here.

5.3.2 Renewable paraffinic fuels (GTL, HVO, BTL, XTL)

Concerning synthetic, bio and renewable liquid hydrocarbons (GTL, HVO, BTL, XTL) resembling diesel oil used in road vehicles, their effect on the BC emissions from marine diesel engines presumably resemble the effects observed for fossil marine distillates. However, these bio/synthetic fuels have a higher hydrogen to carbon ratio and are thus of better quality than even the cleanest road diesel fuel. Despite different production pathways, all of these fuels (GTL, HVO, BTL, XTL) are chemically relatively similar, consisting of paraffins (alkanes).

A number of studies on paraffinic fuels have been conducted on heavy-duty applications, and lower soot emission has been found for paraffinic fuels (e.g. HVO, GTL, BTL) than for conventional aromatic diesel fuel. Low soot emission for paraffinic fuels may originate from their high hydrogen to carbon ratio, although these fuels do not contain oxygen.

Only two emission studies were found on paraffinic fuels on marine diesel engines. Verbeek (Verbeek, 2014) reported a study of two inland ships comparing paraffinic fuel (GTL) with diesel (EN590). PM reduction from 16 to 60% and smoke reduction of 32% was observed. Betha (Betha *et al.*, 2017) reported a plume study on a HSD engine showing increased BC emissions with paraffinic HVO compared to ultra low sulphur diesel. However, plume measurements are not deemed to be appropriate for comparing two hydrocarbon liquid fuels. Furthermore, in this study engine load was not measured, and slight changes in weather conditions may have affected the results. Ushakov et al. (2013a) reported an increased number of exhaust particles for GTL compared with MGO, while soot emissions were not reported.

As a summary, paraffinic fuels indicate reduced BC emission, however, the number of studies using marine diesel engines is not sufficient for conclusions.

5.3.3 Vegetable oils, animal fats

For high-speed diesel engines, oils and fats are transesterified with methanol to improve their fuel properties. In this case, the product is a fatty acid methyl ester (FAME) commonly called biodiesel. For marine diesel engines, oils and fats are typically de-gummed and de-acidified, but not transesterified, and thus their properties are much worse than those of biodiesel.

Studies on biofuels in MSD and SSD marine diesel engines are sparse. The results of two studies meeting the defined criteria for fuel comparisons are shown in Fig. 12. In both cases, unesterified, oxygen-containing biofuels substantially reduced the BC emissions when compared to residual or distillate fuels. The marine diesel engines tested were relatively small MSD engines.

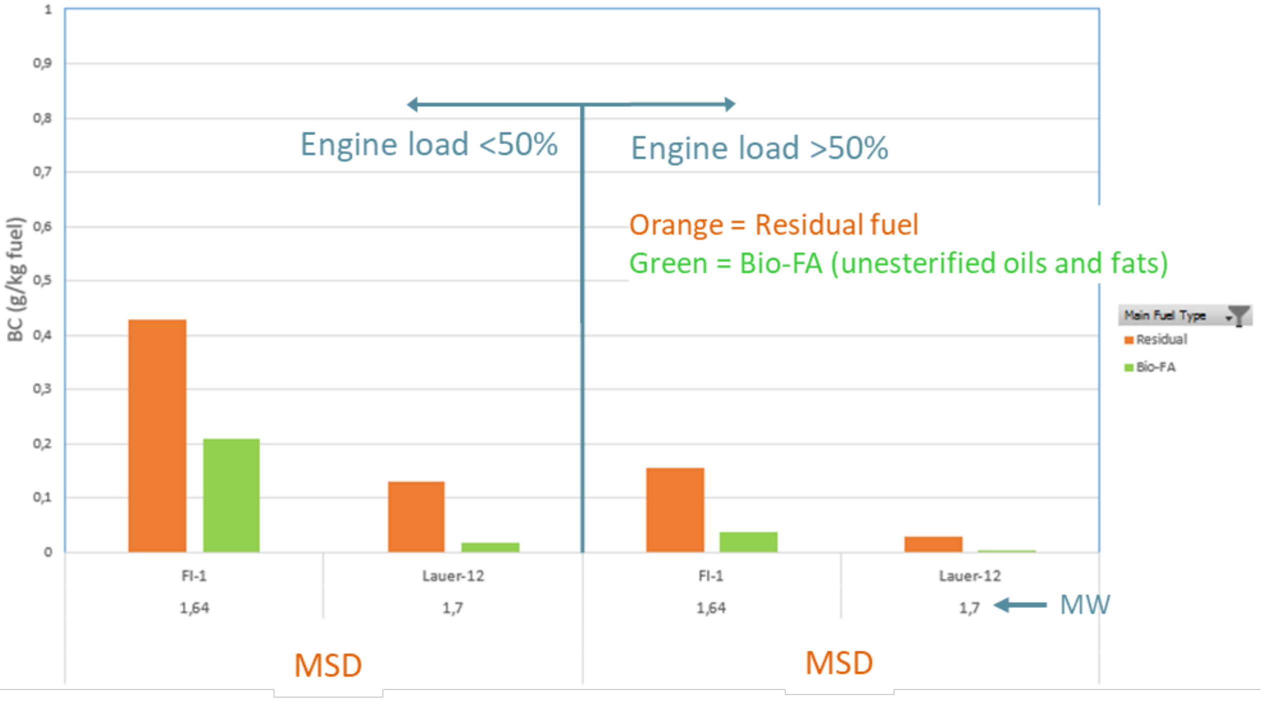


Figure 12. The BC emission measurement results for oils and fats in marine diesel engines in comparison with residual fuel. Studies based on FSN, PAS or LII measurements of BC emissions.

As concerns FAME type biodiesel, its effects on emissions from road and non-road applications are well-known. Use of biodiesel generally reduces PM and soot emissions, while NO_x emissions tend to increase (http://www.iea-amf.org/content/fuel_information/fatty_acid_esters). FAME type biodiesel has been studied in marine diesel engines by, for example, Jayaram et al. (2011 in (Di Natale and Carotenuto, 2015). Biodiesel (ULSF, soybean blends B20, B50) reduced PM and EC emissions in a marine diesel engine at 75% load (reduction of 20-42%). Biodiesel reduced particles sizes, while particle numbers elevated.

Petzold et al. (2011 in (Di Natale and Carotenuto, 2015), studied soybean, sunflower, palm oil and animal fat in a 400 kW single cylinder engine in comparison with MGO (< 0.1% S) and IFO (2.17% S). EC emission was up to 30% lower for palm oil and animal fat, but higher for soybean and sunflower oils. Biofuels showed higher PM emissions than marine fuel. The benefit of using biofuels was seen as low ash and sulphate emissions. The number of particles when using biofuels was similar to IFO, but the number of non-volatile particles was reduced by about 50%.

5.3.4 Methanol

Marine diesel engines for methanol use are commercially based on the methanol DF concept, and methanol is also used as marine fuel (http://marinemethanol.com/). Diesel engines can be retrofitted for methanol use.

Emission results from the use of methanol in marine diesel engines are sparse, particularly concerning BC emissions. Theoretically, the oxygen containing methanol molecule containing only one carbon atom is clean-combusting. Stojcevski (Stojcevski 2016) reported reduced BC emissions when using methanol instead of distillate as a main fuel in a DF engine. BC emissions were reduced by 55-75% depending on the pilot fuel injection when compared with distillate fuel. When diesel fuel is the main fuel in a DF engine, BC emissions are similar to diesel engines. For ships using methanol as fuel, results of on board BC emission measurements from marine diesel engines are not available.

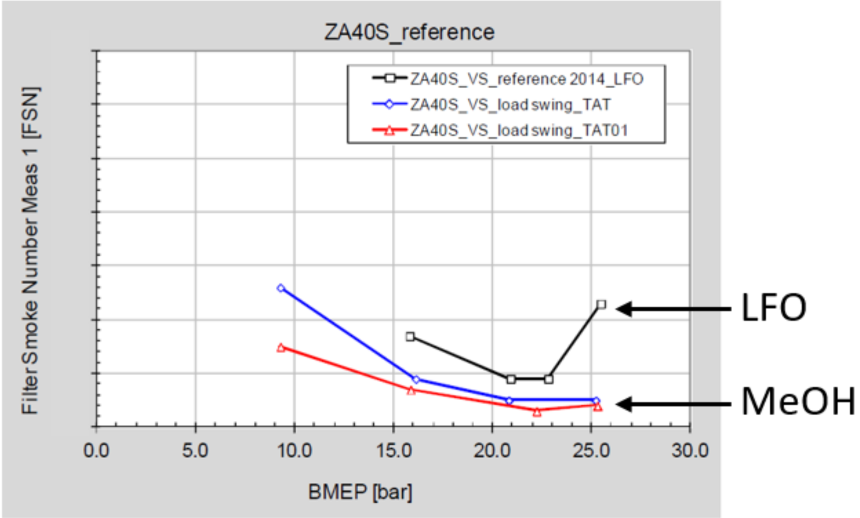


Figure 13. Filter smoke number when using light fuel oil (LFO) and methanol as fuels in the DF engine (Stojcevski 2016).

Methanol is liquid fuel produced from natural gas, and the production of methanol will likely be limited in the near future. Modified harbour infrastructure and safety measures are needed for using marine methanol.

5.4 LNG (methane)

Methane as a motor fuel can generally provide low SO_x, NO_x and PM emissions, while methane and carbon monoxide emissions may be elevated (Website http://www.iea-amf.org/content/fuel_information/methane). PM emissions measured from heavy-duty engines using LNG have been close to zero. Emission measurements from LNG fuelled marine diesel engines are sparse, especially concerning BC emissions. Furthermore, the currently available measurement results are from the gas DF engines, although other engine technologies are also available for methane use. PM emissions for LNG fueled engines are extremely low, only around 0.02 g/kWh, for example, in studies reported by Lehtoranta (Lehtoranta *et al.*, 2018) and Verbeek et al. (Verbeek, Bolech and den Uil, 2011).

The BC emission measurement results for LNG DF engines using the methods selected by the IMO are available from EUROMOT, and BC, PM and particle number results using the “other methods” in Lehtoranta et al. (Lehtoranta *et al.*, 2018) and Aurela et al. (Aurela *et al.*, 2018) (Fig. 14). In the EUROMOT data, natural gas used as a main fuel in the DF engines resulted in low BC emissions in all engine size categories tested, except for one SSD engine

(0.083 g/kg fuel, EUROMOT Annex 7). In all other measurements, the BC emission level was always extremely low when using LNG fuel, namely from 0.001 to 0.011 g/kg fuel and always below 0.007 g/kg fuel at high engine loads regardless of engine size. As a reference, the BC emissions from a diesel engine using distillate fuel as a main fuel is shown, however, high BC emissions observed at low engine load was presumably related to the laboratory engine measured (Aurela *et al.*, 2018).

Bio- or renewable methane could be used instead of fossil LNG as a main fuel or as a pilot fuel (in the engine starting phase) in LNG DF engines (refs. in (Di Natale and Carotenuto, 2015)). This would enable simultaneous reduction of GHG and BC emissions.

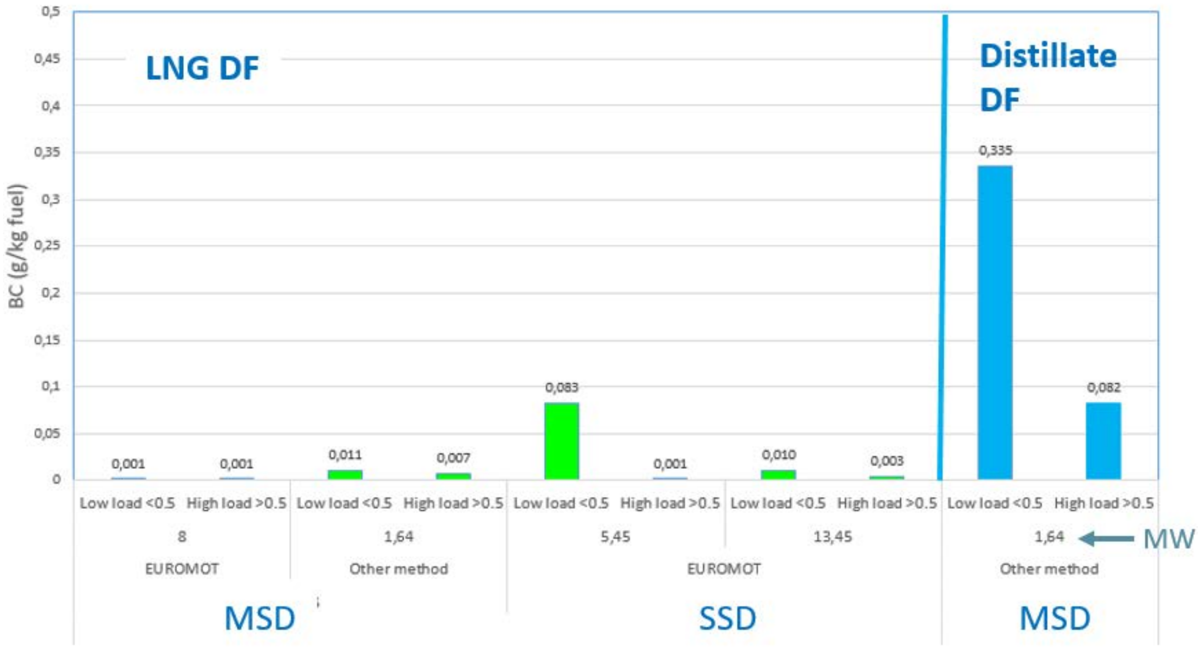


Figure 14. BC emission measurement results for DF engines using LNG as a main fuel. As a reference, BC emissions from a diesel engine using distillate fuel is also shown.

For LNG use, investments in ships and harbour infrastructure are emerging. Additionally, safety measures and space are needed for tanks on board ships. Economic aspects related to the price differential between LNG and conventional maritime fuels remains to be seen, as well as the growth of the LNG supply chain (Acciaro 2014 in (Di Natale and Carotenuto, 2015).

5.5 WiFE, metals and future fuel options

The WiFE, metals and future fuel options were not evaluated in detail in this study, because these were not included in the BC measurement programmes. However, concise comments on these technologies are given here.

Water-in-fuel emulsions (WiFE)

Water in fuel emulsions were developed to reduce NO_x emissions from heavy-duty on-road and off-road diesel engines, for example Lubrizol's PuriNOx contains approximately 20% water (Yoshimoto and Tamaki, 2001; Noll *et al.*, 2002; US EPA, 2002; CIMAC, 2012). Water is not soluble in diesel fuel, thus emulsifier additives are necessary to keep emulsion homogenous or direct injection of water can be used. Concerns over the use of WiFE include increased wear of the engine (contact with water) and the stability of diesel-water-additive emulsions (US EPA, 2002).

Comer et al. (Comer *et al.*, 2017a) reported 45-50% BC reductions from marine diesel engines when using WiFE, and Lack (Lack, 2017) of 50-90% reductions. WIFE tests in a ferry ship engine indicated a reduction of PM emissions of 42%, while energy loss was from 8% to 12% (refs in (Di Natale and Carotenuto, 2015)). WiFE generally increases the CO and HC emissions. Some studies combined WiFE with EGR, oxidation catalysts, and particulate traps. For combined WiFE and EGR, the increased smoke induced by EGR was suppressed with WiFE. Reductions in PM are claimed to be 2-3 times higher than the amount of water added. WiFE reduces engine power, which may bias the PM results. (Di Natale and Carotenuto, 2015). According to (CIMAC, 2012) WiFE improved BC emissions in some in-use engines equipped with conventional fuel injection systems on low load operation.

CIMAC (CIMAC, 2012) explained that the role of water in reduction of the BC emissions is based on improved fuel droplet dispersion and mixing in the combustion chamber (water in the fuel turns to steam), although at high loads this effect can be offset by the increase in injection duration (lower energy content - delay in end of combustion - increased BC emission). Modern fuel injection systems provide good fuel/air mixing over a very wide power range. Di Natale and Carotenuto (Di Natale and Carotenuto, 2015) explained that water reduces NO_x and PM emissions by lowering the combustion temperature, delaying injection, altering the fuel/air ratio (pre-mix period), bringing oxygen, and by the competitive partial oxidation and gasification reactions reducing the pyrolysis.

In conclusion, WiFE may reduce BC emissions in engines equipped with conventional fuel injection at low engine loads, while the benefit may be modest in modern engines. Using emulsifier additives or a separate injection system for water addition would increase costs.

Metals in fuel (“Colloidal Catalysts”)

Metals can act as catalysing agents, and in the automotive sector, metals in fuel additives are called “fuel-borne catalysts”. Fuel-borne metals are sometimes called also ”colloidal catalysts”. Residual marine fuels often contain metals, e.g. V, Ni, Fe and Na. Particularly, vanadium in may catalyse BC combustion (IMO 2015). Heavy metals are negative features in fuels as many of them are toxic and cause harmful health and environmental effects.

Future options: Hydrogen, DME, ammonia and other power sources

Hydrogen has been demonstrated in fuel cells for ships. Hydrogen is a gaseous fuel and its liquefaction is expensive. Today, hydrogen is manufactured from natural gas or methanol also it is increasingly produced by using renewable electricity. Distribution infrastructure is needed if hydrogen is to be used in shipping. Hydrogen is used most efficiently in fuel cells. However, when hydrogen is converted to e.g. methane and diesel-type synthetic fuels, these can be used in internal combustion engines.

Dimethyl ether (DME) can be manufactured from methanol. DME is a gaseous fuel and it requires special engines and fuel infrastructure. DME is compatible with the diesel cycle.

Ammonia is an invisible, toxic gas (NIOSH limit 25–30ppm long-term exposure, 300ppm immediately dangerous, 5000ppm fatal within minutes). Due to safety concerns, ammonia is converted to urea for use as a reducing agent in the exhaust gas treatment system (SCR). If safety issues are passed, ammonia could be used in fuel cells or modified internal combustion engines.

Nuclear power is being considered for ships, however, it is out of scope in this report.

6. Exhaust gas treatment systems

6.1 Highlights

- Particulate filters reduce BC emissions efficiently. Pre-commercial particulate filter systems are demonstrated for marine diesel engines, however, reliable and durable systems are not yet proven. Questions remain on the required fuel quality and feasibility of regeneration technology.
- ESPs and bag filters are large. There are some ESP-based developments for marine diesel engines, but success of this development is to be seen.
- SO_x scrubbers are mature technologies for ships today, but they did not significantly reduce BC emissions in most studies.
- Diesel oxidation catalysts (DOC) are designed for removal of exhaust organic species and SCR for exhaust NO_x emissions. Neither of these alone reduces BC emissions (could be integrated with other technologies).

6.2 Particulate Filters

Diesel Particulate Filters (DPFs) for automotive diesel engines have been used for decades. Efficient DPFs reduce more than 90% of emitted particles, provided that the fuel oil is sulphur-free diesel (below 0.001% sulphur content), meeting the most stringent on-road diesel fuel requirements. Even then, filter clogging may be an issue. DPFs have small channels (micrometre range) where solid PM is collected and periodically removed (regenerated) (Di Natale and Carotenuto, 2015). In Europe, the solid particle number limits for diesel vehicles are met only with the most efficient closed, wall-flow DPFs. Less efficient “open type filters” do not remove particles sufficiently to meet, e.g. the Euro 5/6 particle number limits. (Dieselnet https://www.dieselnet.com).

Automotive DPFs are not technically applicable when using marine fuels containing sulphur, ash and other impurities. Automotive PM consists almost entirely of BC, which is combustible in passive soot regeneration of a filter (NO_2 assisted), or active regeneration (oxygen at approximately 600 °C). Marine PM contains, e.g. metal oxides and sulphates, which are not combustible and prevent the use of regeneration strategies from automotive applications. Additionally, exhaust gas temperature (e.g. 330 °C) from marine diesel engines is too low for combustion of soot, and higher temperatures are not tolerated in the presence of ash-containing constituents to avoid exhaust valve damages and turbocharger turbine fouling. Platinum based catalysts are used in on-road applications for NO_2 generation, however, when using marine fuels SO_3 formation overrides NO_2 formation. Without periodic regeneration, the filter pores clog causing increased exhaust back-pressure until the engine operation stalls. In marine diesel engines, a maximum pressure drop of 30–50 mbar over filter is tolerated to protect the turbocharger, while in automotive applications a pressure drop can be up to 100 mbar. Development of suitable filter and regeneration technology for use in marine diesel engines is challenging, as well as the challenge of achieving reliability and durability for the filter system; vibrations caused by pressure pulses in the exhaust gas are notable. Filter size is also of concern on board a ship. (CIMAC, 2012; Di Natale and Carotenuto, 2015; Johansen, 2015).

Some DPF designs for marine diesel engines have been demonstrated. The results obtained with a ceramic filter manufactured by NGK, called CERALEC system, have been reported by (Nonokawa, Katsuki and Noshiro, 2016; Takahashi and Masuda, 2018). CERALEC is installed in auxiliary engines on 10 Pure Car Carriers using MDO (and HFO) fuels to prevent new cars from fouling due to acid particulates during loading and unloading of cars at ports. PM was removed from approximately 0.87 g/kg fuel to 0.03 g/kg fuel (30 mg/Nm^3 to 1 mg/Nm^3), while BC emission removal efficiency was not reported. Laboratory work with a 257 kW engine operating with HFO at 25% load showed BC emission reduction of 99% (before filter 80-90 mg/m^3 and after $\simeq$0.5mg/m^3, measured by MSS). Takahashi and Masuda (Takahashi and Masuda, 2018) reported on the DPF system design for the main engine of a cape size bulk carrier with a 17.78 MW main engine (filter element 150x150x500 mm, pore 5 µm, number of elements 480). Target exhaust gas temperature is 230 °C, PM input 80 mg/Nm^3 and output <20mg/Nm^3 with a reduction of >75%. Takahashi and Masuda (Takahashi and Masuda, 2018) concluded that a high efficiency of BC reduction (99%) is possible with a particulate filter for marine diesel engines, although concerns remain about engine exhaust back-pressure, negative effect on engine performance, space needed, blowers, regeneration of filters, additional energy consumption, and storage and disposal of the collected particulates.

Park (Park, 2018) reported on the DPF development for sub 1MW size marine diesel engines. Tests conducted with a 400 kW engine showed PM/BC emission reduction of 96%, while fuel consumption increased by 0.9%. Back-pressure was 57 mbar.

An early demonstration of DPF was conducted on a ferry (9 MW engine, IFO fuel) by Mitsui O.S.K. (2012). PM removal efficiency was 80% during an operation time of 500 h, but filter regeneration practices were not indicated (ref in (Di Natale and Carotenuto, 2015). Køcks et al. (Køcks *et al.*, 2017) reported on a demonstration with an integrated particle filter and SCR system (Dinex F-SCR) on an inland ferry using marine diesel with sulphur content below 0.1%. BC emissions were not measured, but the PN concentration was reduced by more than 90% by the filter. The efficiency of the filter dropped significantly during the day, which indicates the need for more frequent regeneration. Another demonstrated technology is the ECO-Jet system developed by Haldor Topsoe A/S, a multi-catalytic soot filtration for marine applications (Johansen, 2015). This system includes a catalyst-assisted passive soot regeneration (>350 °C) and "in situ" ash removal (reverse pulse flow). ECO-Jet uses a sulphur-resistant Pd/V_2O_5 filter catalyst that combusts soot, CO, and HC (including polyaromatic hydrocarbons (PAHs)). ECO-Jet was on full-scale validation on the cruise ship Queen Victoria using HFO at 1% sulphur content. The ship was also equipped with SCR and an open loop scrubber. PM filtration efficiency was 80–92% depending on engine load. As PM emissions were below 1 mg/m^3 in exhaust gas, BC emissions were presumably very low. ECO-Jet removed PAHs, metals, soot and ash from exhaust gas, which helps in meeting the IMO limits for PAH and turbidity in the discharge water of scrubbers.

BC emission reduction was high for particulate filters as reported by Takahashi and Masuda (Takahashi and Masuda, 2018) and Park (Park, 2018) and evidently also in tests reported by Johansen (Johansen, 2015) and Køcks et al. (2017) as PM emissions were almost negligible after particulate filters. However, the long-term feasibility or durability of particulate filter technologies is not yet proven for marine diesel engines using marine fuels, although pre-commercial concepts are available. One of the key questions is how clean fuel is needed for particulate filters, how regeneration performs and what is the BC emission reduction efficiency in the long-term? The sulphur limit of 0.5% for marine fuels in 2020 may improve the quality of some residual fuels, however, not necessarily sufficiently for use in particle filters as these fuels may still contain residual components, ash and other impurities. In some sources, the maximum sulphur content tolerated by filters to avoid filter clogging is thought to be 500 ppm (J. Corbett, Winebrake, and Green, 2010) or 2000 ppm (Mayer et al., 2011). However, particulate filters for marine engines may require even cleaner distillate fuels with below 0.1% sulphur content, such as DMA/MGO, having also low ash content.

6.3 Electrostatic Precipitators (ESP) and bag filters

Electrostatic precipitators (ESP) and bag filters are used in some large land-based industrial plants, however, they cannot be applied directly to marine diesel engines. When compared to wet scrubbers, ESPs and bag filters are larger and more expensive, although waste gas flow rates and temperatures are lower and they do not form sludge that requires treatment.

ESPs are based on corona effects to charge the particles and collect them on plates. The system is effective for particles with low inertia, but the main factors are particle conductivity and cohesiveness. Diesel particles are challenging due to their small particle size (<0.2 µm), gas humidity and sticky oil droplets. Removal of diesel particles can be improved by using lower electrical drift velocity and distance of collector plates and/or higher residence times. There are many ESP technologies, such as particle agglomerators, multi-stage ESPs and electro-cyclones. An electrostatic fibrous filter (EsFF) made of textiles that enclose charging wires is mainly feasible for indoor air quality control (refs in (Di Natale and Carotenuto, 2015)).

New ESP developments include Wet Electrostatic Scrubbers (WES), the Heterogeneous Condensation Scrubber (HCS) and the Bubble Towers (BT), however, these need a washwater treatment unit. The WES consists of an ESP whose collecting walls are wet by a film of liquid that collects the particles once they impact on its surface for gas streams up to 180,000 m^3/h. WES increases particle charging by using sprayed droplets as diffused particles collectors, in place of the ESP plates. Di Natale and Carotenuto (Di Natale and Carotenuto, 2015) note that WES has advantages of simplicity, low pressure drop and an ability to remove soluble gases. A WES pilot for diesel particles in FP7 DEECON project showed removal of 70% to 95% of particle numbers in the range of 10–500 nm, and SO_2 by 56% or more (200 kW diesel engine, 2% sulphur content of fuel). In another process, HCS, ultrafine particles are enclosed in water droplets and led to a conventional scrubber and bubble towers. However, the system may present high pressure drops due to the high water holdup (up to 1 m). (Di Natale and Carotenuto, 2015)

Takahashi and Masuda (Takahashi and Masuda, 2018) and Umezawa et al. (Umezawa *et al.*, 2017) presented new design of ESP system developed by Usui Co. for a marine diesel engine. For a new “ESP+C” system, exhaust gas flow rate design is 10–15 m/s, while it is traditionally low (around 1 m/s) compared to flow rate of the marine diesel engine exhaust gas (approximately 30 m/s). A high voltage power supply unit consumes electricity equivalent to 0.2% engine output. ESP-C system design for a 21.6 MW, 2-stroke main engine consists of two ESP units (each 2×2×3m). Back-pressure induced by this system is low. The main concerns are additional energy consumption and storage and disposal of the collected particulates. Also Park (Park, 2018) reported on ESP development for engines greater than 1 MW in size. PM/BC emission reduction was 91% and SO_x reduction 97%. Back-pressure was only 31 mbar.

ESP-based systems may achieve high particulate reduction at low pressure drop, and are suitable for present exhaust gas temperatures, however, they are large in size and there are electrical risks in installations (high voltage). Furthermore, storage and disposal of removed particulate matter is needed (also maybe “Protection reagent” CaO etc. is needed) and energy consumption increases. Material limitations may lead to the need for flue gas cooling (to 190 °C)(CIMAC, 2012; Takahashi and Masuda, 2018).

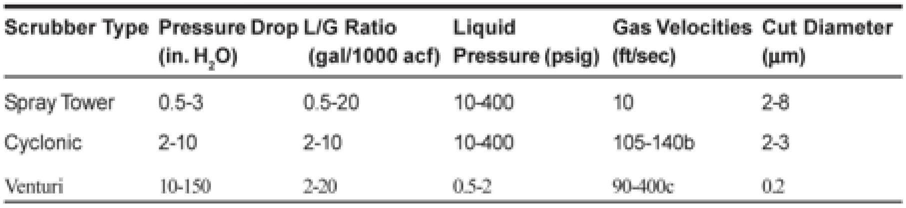
6.4 SO_x Scrubbers

6.4.1 General

Currently, SO_x scrubbers are installed on board ships. In principle, scrubbers could be designed for reducing PM as in stationary point sources. However, efficient removal of both SOx and BC emissions simultaneously is difficult (Miller, 2018).

PM removal in scrubbers is based on the impaction, diffusion, interception and/or absorption onto liquid droplets. There are numerous types of wet scrubbers that have different PM collection efficiencies (Table 4). Venturi scrubbers are more effective than simple spray towers, however, the PM reduction efficiency of all these scrubbers is low for particles below 0.2 µm (Mussatti, 2002), which is the typical size class of particles from marine diesel engines.

Table 4. Operating parameters for particulate wet scrubbers. Cut diameter is the diameter at which the collection efficiency of the scrubber is 50%. (Mussatti, 2002).



Scrubber Type	Pressure Drop (in. H_2O)	L/G Ratio (gal/1000 acf)	Liquid Pressure (psig)	Gas Velocities (ft/sec)	Cut Diameter (µm)
Spray Tower	0.5-3	0.5-20	10-400	10	2-8
Cyclonic	2-10	2-10	10-400	105-140b	2-3
Venturi	10-150	2-20	0.5-2	90-400c	0.2

Large particles (approximately >2 µm) have sufficient inertia to be collected by wet or dry scrubbers or cyclones, and even with the SCR (Di Natale and Carotenuto, 2015). Inertial effects are useless for smaller particles, however, very small particles can be captured based on Brownian diffusion phenomena or phoretic effects or by applying electromagnetic forces. Particles in the Greenfield gap (0.05-2µm) are particularly difficult to remove since inertial properties and diffusional behaviour are insufficient for hydrodynamic interactions(Di Natale and Carotenuto, 2015; Cherrier *et al.*, 2017). Particles from marine diesel engines fall in the Greenfield gap. According to Di Natale and Carotenuto (Di Natale and Carotenuto, 2015), wet scrubbers are particularly useful in the removal of PM that is sticky and/or hygroscopic, PM emissions in the presence of soluble gases and with high moisture content are difficult to remove, as well as dry PM emissions.

The majority of marine scrubbers include a Venturi unit prior to a SO_2 absorption tower, which favours interactions among particles and sprayed droplets removing particles >1µm (Hesketh, 1996). Special cyclonic scrubber designs (Cleanmarine) reduce the particles down to a size of 0.5 µm. Scrubbers (wet and dry) may reduce the number of nanoparticles as a consequence of their Brownian diffusivity (Carotenuto et al., 2010b in (Di Natale and Carotenuto, 2015)), however, nanoparticles do not contribute substantially to the BC mass. When the PM collection efficiency of scrubbers increases, related challenges also increase, such as back-pressure, lower gas flow rates and temperatures (Di Natale and Carotenuto, 2015).

6.4.2 SO_x scrubbers

SO_x scrubbers are installed on board several thousands ships, however, only in a few studies have BC emissions been measured before and after scrubbers. In the studies listed below, three hybrid type scrubbers had open and closed loop properties, and one scrubber had only the open loop property. An Alfa Laval PureSOx scrubber was used in two studies.

- FI-2: modern cruise ship, 4-stroke engine ~10 MW, SCR and a **hybrid SOx scrubber**. Residual fuel with 0.65% sulphur content. (Timonen *et al.*, 2017).
- FI-3: modern cruise ship, 4-stroke engine ~14 MW, a **hybrid SOx scrubber**. Residual fuel with 0.65% sulphur content. (Timonen *et al.*, 2017)
- FI-4: RoRo passenger (RoPax) ship equipped, four engines (Wartsila 9L46D, 514 rpm, 10.4 MW) equipped with an **open loop SOx scrubber** (ECO-DeSOx, Ecospray Technologies), and a diesel oxidation catalyst (DOC, Ecospray Technologies). Sulphur content of residual fuel was 1.9 wt%. (Teinilä *et al.*, 2018).
- UCR-T3: Container ship, 1987. Scrubber was connected to main engine (1987, Tier 0, Mitsui B&W 2-stroke, SSD 16.6 MW, 98.1 min^{-1}) and two auxiliary engines (Wartsila, 6R32D 2.1 MW, MSD, 4-stroke diesel engines). **Retrofit SOx scrubber (Alfa Laval**

PureSOx, MY2015) was used in the “open loop” mode at sea and “closed loop” mode in port (fresh water/sodium hydroxide (NaOH) solution). The results from the open and closed loop modes were not statistically different. (Johnson *et al.*, 2016).

- Fridell-14: the roll-on roll-off ship Ficaria Seaways, two-stroke 21.06 MW main engine, and a **SOx scrubber system (Alfa Laval PureSOx, see above)** having open and closed loop modes. Only the open (seawater) mode was used during the measurements. For analyses of BC concentrations, a soot scan transmissometer (Model OT21, Magee) was used, which is different from the methods selected by the IMO. (Fridell and Salo, 2014).

- Yang et al. (Yang et al. 2017) presented results of three ships, 1) Container ship with Mitsui Man B&W 16.6 MW engine and Alfa-Laval scrubber 2) Cruise ship with Wärtsilä 4 x 12.6 MW engines without scrubber and 3) Ro-Ro Hyundai Man B&W 15.6 MW engine with Wärtsilä scrubber. Using high-sulphur residual fuels, the major component in PM was sulphate. No reduction in PM with scrubber was observed, and potentially more sulphate was formed in scrubber. EC was analysed, but Yang et al. did not present the EC results.

In studies FI-2, FI-3 and FI-4 by (Timonen *et al.*, 2017) and (Teinilä *et al.*, 2018), the effect of SO_x scrubbers on the BC emissions was not significant: difference in the BC emissions over scrubber was below 10% (<10 mg/kg fuel) at the BC emission level of approximately 100 mg/kg fuel (Fig. 15). This applied when using residual fuels, while a decrease of BC emissions over scrubber was observed when using distillate fuel in a study by (Teinilä *et al.*, 2018). Although the combination of low-sulphur distillate fuel and scrubber is not practical, this result indicates that changing particle properties may affect the particle removal efficiency of scrubbers.

In the UCR-T3 study by (Johnson *et al.*, 2016), BC emission reductions of 12% and 17% (5 mg/kg fuel) over scrubber were observed for combined exhaust gas from SSD and MSD engines at 50% and 75% engine loads, however, no BC emission reduction was observed at 100% engine load. BC emission reductions between 1 and 5 mg/kg fuel at 50-100% engine loads are low, and probably not significant when measurement uncertainty is taken into account. Instead, at 25% engine load, when only the MSD engine was running, the BC emissions reduced significantly (30%, 51 mg/kg fuel).

The only study that observed high BC reduction over SO_x scrubber was published by Fridell and Salo (Fridell and Salo, 2014). At 75% engine load, BC reduced from 64 to 7 mg/kg fuel (89%) from the studied SSD engine. Also PM reduced by 75%. The number of solid particles was not much reduced by the SO_x scrubber, which is somewhat in contradiction to the observed BC emission reductions.

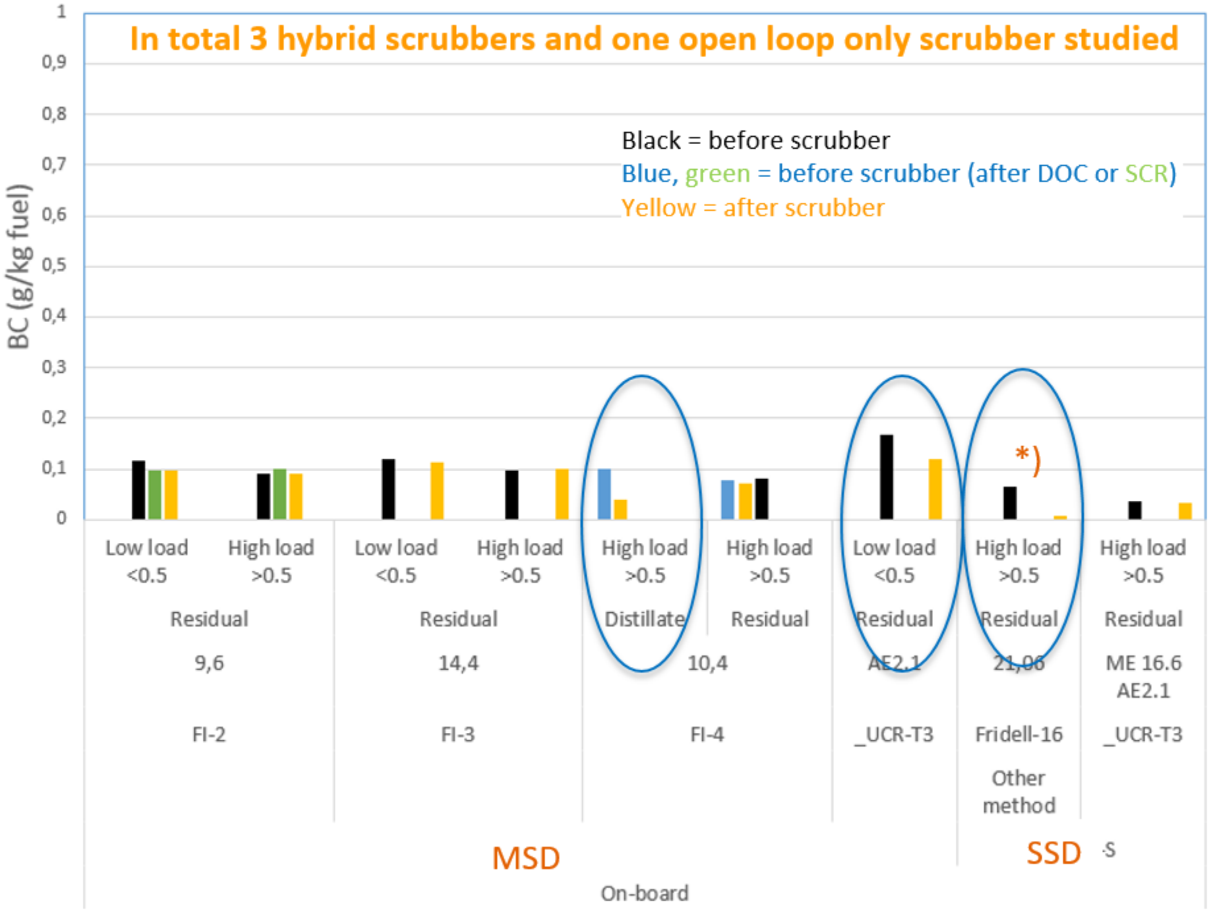


*Figure 15. The BC results for marine diesel engines using SO_x scrubbers. Circles indicate cases where BC removal was observed over SO_x scrubbers. One of these studies ("Fridell-14") was conducted using a soot scan transmissometer (marked with *) that is not included in the BC measurement methods selected by the IMO.*

Explanations for the differences in the observed effects of SO_x scrubbers on BC emissions may originate from differences between a) SO_x scrubbers b) engines c) exhaust gas properties d) measurement principles or e) fuel.

- *SO_x scrubbers:* Most of the SO_x scrubbers studied were hybrid types, while one of the scrubbers was open loop only. An Alfa Laval PureSOx scrubber was used in two studies of SSD engines: one study (Johnson *et al.*, 2016) observed no significant or only a modest reduction in BC emissions, while another study (Fridell and Salo, 2014) observed a very high reduction in BC emissions. Differences between seawater and chemical scrubbing were not observed, although in theory, particle removal efficiency could be higher for seawater scrubbing as efficiency improves with increasing liquid-to-gas mass ratio (more seawater is required than basic/alkaline compounds)(Gregory, 2012 and Carotenuto et al., 2010b in (Di Natale and Carotenuto, 2015). → *BC emission reduction in 2 cases of 8 (or 3 cases of 9 if Fridell-14 is accounted for); Scrubber type seemed not to be a determining factor for the BC emission measurement results amongst the scrubbers studied.*

- *Engines (SSD, MSD):* A 30% BC reduction was observed for one MSD engine at 25% load (UCR-T3), while significant BC reductions over scrubber were not observed for three MSD engines (FI-2, FI-3, FI-4). For SSD engines, one study (Fridell and Salo, 2014) of two observed reduction in BC emissions with contradiction to the results. → *BC emission* *reduction seemed not to be dependent on engine type (reduction for 1 of 3 MSDs, slight reduction for SSD+MSD, reduction for 1 of 2 SSDs).*

- *Exhaust gas properties:* Exhaust gas properties are largely dependent on fuel, engine and load. For example, at low engine loads organics may dominate over sulphates in PM; even when using high-sulphur fuels as lower combustion temperature does not support SO_3 formation. When using HFO as fuel, exhaust gas particles potentially contain asphaltenes, polyaromatic molecules and char (Mullins, 2010; Corbin *et al.*, 2018), meaning "wet" sticky organics associated with BC and sulphates. Distribution of chemical compounds in different particle size classes is not straight forward, for example, soot and metals can be present in many size classes. Lu et al. (Lu *et al.*, 2006) analysed ship plumes over the Vancouver area observing the main mode in the elemental and organic carbon at 70nm and the sulphate mode at 150nm. Data on the particle mass size distributions in relation to the compositions from marine diesel engines from recent measurement campaigns in Finland have been preliminarily analysed and discussed (Niina Kuittinen, Päivi Aakko-Saksa), but not published yet. The main findings are presented below.

    - *HFO as fuel*: *mass peak <0.1µm*: organic compounds dominate, but also BC, metals and some sulphates present; *mass peak 0.1-0.4µm*: sulphates dominate, heavy organics and metals present; *mass >0.4µm*: large liquid droplets and artefacts (from walls of exhaust duct, lube etc.)

    - *Lower-sulphur fuels:* peak moves to smaller size class (sulphate diminishes at 0.1-0.4µm); *monomodal distribution peak at <0.1µm*: BC associated with relatively light organics; *bi-modal distribution:* peak at <0.1µm dominated by BC associated with organics and metals; 0.1-0.3µm: BC, sulphates and organics.

  The studies evaluated here indicate that a SO_x scrubber might more efficiently remove small particles. However, this issue requires more research and analysis.

- *Measurement methods:* The measurements methods are sources of uncertainty, particularly when exhaust gas dilution is used. However, quality control is handled within each laboratory and campaign, and thus not discussed here.

Earlier studies on the SO_x scrubbers have not included measurement of the BC emissions, whereas PM has often been used as a proxy for BC. Lack et al (2009) assumed that the share of BC is 15% of PM, and an update presented in PPR 5/INF.7 by (Lack, 2017) is still mainly based on the PM emission measurement results. It is noticeable that the share of BC in PM varies depending on marine engine, fuel and exhaust treatment system.

Is PM reduced over scrubber? Aerosol species that are "permanent" in PM from marine diesel engines, viz. present in PM regardless of dilution or cooling, are BC, heavy organic compounds, metal oxides and metal sulphates. Instead, hydrated sulphuric acid and semivolatile organic compounds condense on particles from the gas phase during diluted sampling before scrubber, while they are not present in PM after scrubber due to transfer in the scrubber liquid. Thus, the PM reduction over scrubber observed reflects reduced hydrated sulphuric acid and semivolatile organic compounds. Using "hot sampling" before scrubber would reveal this phenomenon, as semivolatiles do not condense in the sampling at high temperatures. Thus PM emissions may reduce over scrubber, even if BC emissions remained.

6.4.3 Integrated scrubber and Exhaust Gas Recirculation (EGR)

MAN has announced development of EGR integrated with an SO_x scrubber for reduction of SO_x, NO_x and PM emissions (brochure). Achievements presented include reduced SO_x

scrubber size of approx. 30% and the simplified water treatment system. The system is feasible for using HFO with NO_x/SO_x compliance and the PM reduced with approx. 80% compared to HFO.

6.5 Diesel Oxidation Catalysts (DOCs) and Selective Catalytic Reduction (SCR)

Diesel oxidation catalysts are common in automotive diesel engines. They remove organic species in exhaust gases, also those associated with PM. However, oxidation catalysts do not significantly remove BC emissions by default. Also in the study reported by (Timonen *et al.*, 2017; Teinilä *et al.*, 2018), DOC did not reduce BC emissions from marine diesel engine exhaust gas (Fig. 16).

SCR is designed for NO_x reduction, not for PM reduction. Very large particles would be captured by SCR, however, sufficiently large particles are practically not present in diesel engine exhaust gas. SCR could also remove some organic species of PM. Not surprisingly, significant changes in the BC emissions were not observed over the SCR in the measurements (Fig. 16).

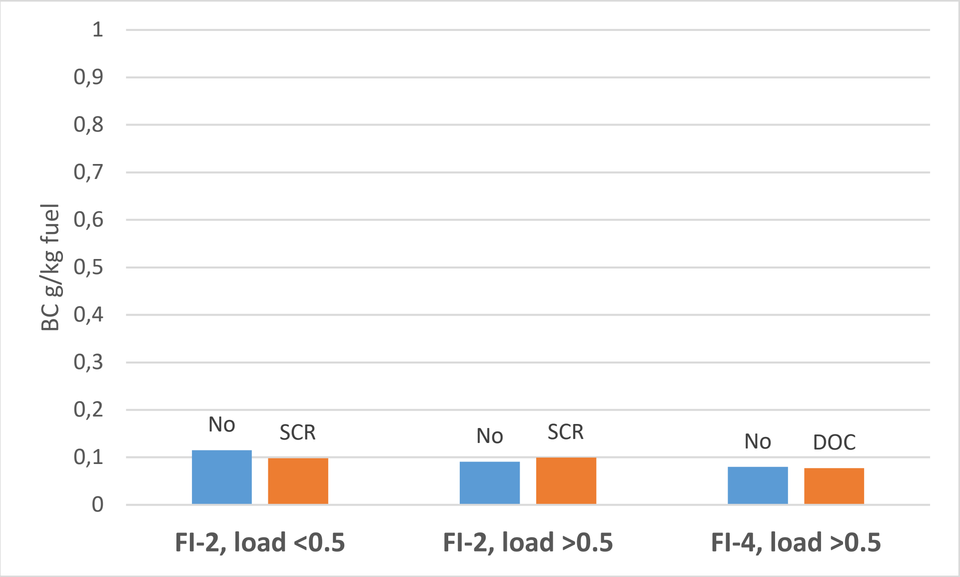


Figure 16. The effect of SCR and oxidation catalyst on the BC emissions.

7. Slow steaming

7.1 Highlights

- Slow steaming means reduced ship speed from the “normal” design value, e.g. about 25 knots for fast ship types (e.g. container ships). Reducing ship speed by 20% may enable fuel savings of about 40% and related CO_2 reductions. At high fuel prices or in the case of excess fleet, slow steaming is common. Slow steaming is discussed in relation to reducing GHG emissions of shipping.
- Published fuel consumption and emission measurements on slow steaming are sparse. Studies typically focus on container ships that also consume a lot of marine fuel oil.
- Engines are designed for running at 70-85% load, and technical concerns arise if lower loads are used. Thus de-rating and retrofitting may be needed.
- The effect of slow steaming on energy consumption of the whole transport system is a complicated issue requiring advanced modelling and optimization tools.
- **The effect of slow steaming on black carbon emissions:**
  - For modern common-rail marine diesel engines, BC emissions reduce along with reduced fuel consumption. However, the load range recommended by the engine manufacturer should be respected.
  - For old marine engines equipped with mechanical fuel injection system, BC emissions increase at lower than the optimum engine loads.

7.2 Slow steaming basics

Slow steaming means reduced speed of a ship. “Normal speed” is 20-25 knots (or higher), “slow steaming” 18-20 knots and “extra slow steaming” below 18 knots according to Rodrique (Rodrigue, 2017). Slow steaming reduces fuel consumption of ships, and thus it is commonly used when fuel prices are high or in excess of merchant fleet prices during financial recession (Sanguri, 2012). Over recent years the markets have favoured lower speeds for container ships, although, they still tend to operate at higher speeds than, e.g. oil tankers and bulkers (Sanguri, 2012). Design speeds for some ships have already decreased being, e.g. around 20 knots, and even lower speeds are used in practice. The slow steaming concept is discussed particularly in relation to container ships, which traditionally have tight time constraints and thus also high design speeds. Container ships are also globally among the largest maritime fuel consumers and CO_2 emitters. This role of container ships is anticipated to further grow with their larger sizes despite their low numbers (Corbett, Wang and Winebrake, 2009).

The energy needed for moving a ship depends on the resistance of air and water. At lower ship speeds resistance is lower than at higher ship speeds (Fig. 17). The relationship between ship speed and fuel consumption follows the so-called “cubic law”, in which fuel consumption (relative to engine power required) is multiplied by a factor of $(S_o/S_d)^3$, in which S_o is operational speed and S_d is design speed. Thus the saving in fuel consumption as a percentage is higher than the speed reduction in percentage. For example, an approximately 20% speed reduction enables an approximately 40% reduction in fuel consumption. The “cubic law” equation is used in the modelling of the effects of slow steaming on emissions, for example by Corbett et al. (Corbett, Wang and Winebrake, 2009). However, this equation is not universal as desired speed and ship architecture (propeller design; ship hydrodynamics and aerodynamics) interact with air and water resistance and the power required. The theoretical relationship between ship speed, fuel consumption and engine power is illustrated in Fig. 18.

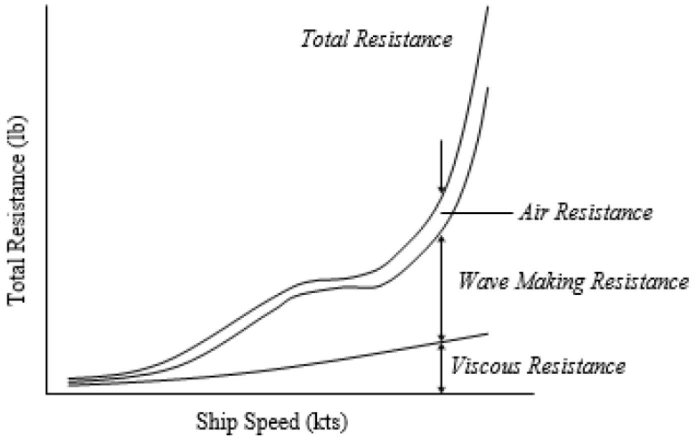


Figure 17. Increasing hull resistance requires more energy (ref. US Naval Academy https://www.usna.edu/NAOE/_files/documents/Courses/EN400/02.07%20Chapter%207.pdf)

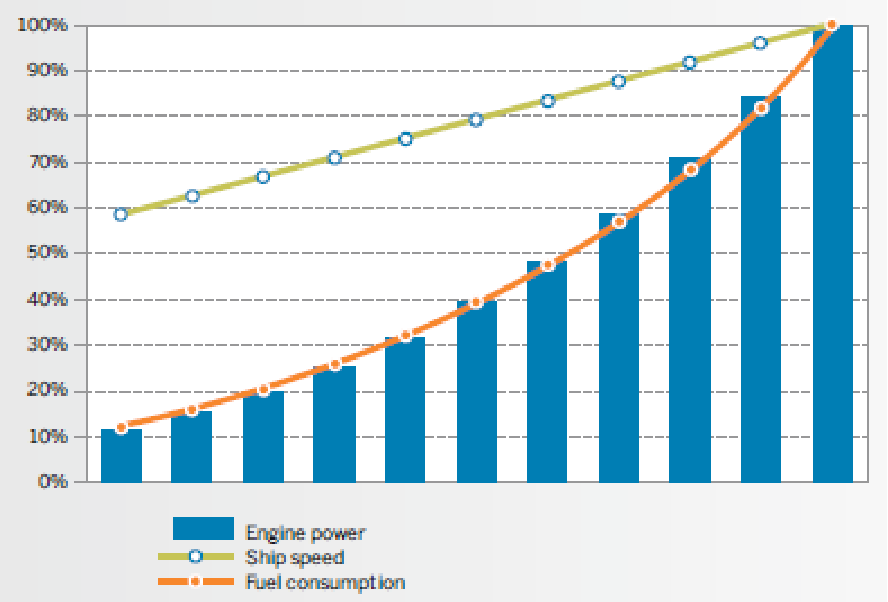


Figure 18. Correlation between ship speed, required engine power and fuel consumption (Wiesmann, 2010)*.*

As mentioned, the “cubic law” is often used in the evaluation of slow steaming effectiveness, while publications on the actual measured fuel consumptions at different ship speeds are sparse. Additionally, the results on the speed-dependence of fuel consumption are affected by weather conditions, the route selected, sea currents and water depth. However, some published data is available. Psaraftis et al. (Psaraftis, Kontovas and Kakalis, 2009) reported for a Panamax container ship and a RoPax ferry that fuel consumption reduced by 9-37% when ship speed reduced by 5-20% from an original 20-24 knots. Khan et al. (Khan, Agrawal, *et al.*, 2012) measured one Panamax and one post-Panamax class container ship when the ship speed was reduced from cruise speed (approximately 24 knots) to 15 knots or below. They observed, for example, a reduction of 43-56% in CO_2 emissions when the ship speed was reduced to 15 knots. The reduction in CO_2 emissions is proportional to the reduction in fuel consumption. Górski et al. (Górski, Abramowicz-Gerigk and Burciu, 2013) analysed data published by Germanischer Lloyd for a large container ship with a capacity of 13,000 TEU and main engine power of approximately 70 MW (Table 5). Reducing the speed by approximately 10% reduced fuel consumption by approximately 22% at the respective main engine load of approximately 75%.

Table 5. Relationship between engine load, ship speed, fuel consumption for 13,000 TEU container ship ((Górski, Abramowicz-Gerigk and Burciu, 2013) *on Germanischer Lloyd data).*

Main engine load	Main engine power	Ship speed	Voyage duration	Fuel cons.	Fuel cons. reduction	NOx emission		Increase/decrease of NOx emission	
%MCR	kW	kn	days	t/voyage	%	t/day	t/voyage	t/voyage	%
100%	70000	25.0	16.6	5030	–	20.8	345.8	–	–
75%	52500	22.7	18.3	3930	22%	20.8	380.5	34.6	10%
50%	35000	19.8	21.0	3030	40%	16.8	352.8	7.0	2%
25%	17500	15.7	26.5	1990	60%	9.1	240.4	–105.4	–31%

Fig. 19 shows examples of fuel consumption based on several sources (Bialystocki and Konovessis, 2016; Timonen *et al.*, 2017). According to Rodrigue ((Rodrigue, 2017) referring to Notteboom & Carriou 2009), fuel consumption per day for different container ship size classes reduces along with speed (Fig. 19a). Reaching a destination takes a longer time at lower ship speed and thus fuel consumption results from different studies were converted to fuel consumption per distance to give comparable values (Fig. 19b). Fuel consumption reduces substantially along with reducing speed, however, slope is smoother in Fig. 19b than in Fig. 19a. Reducing speed of container ships from 25 to 20 knots shows about a 40% reduction in fuel consumption per travelled distance, while about 50% per day in this example. Similar conversion of fuel consumption units from per day to per distance was carried out for a car and truck carrier reported by Bialystocki and Konovessis (Bialystocki and Konovessis, 2016). In this case, reducing ship speed by 25% (from 20 to 15 knots) led to fuel savings of 26%. For one cruise ship, results were obtained during a period where four engines of the ship were running in different combinations due to the needs of a research project, and not optimised for normal operations. However, it is noted that speed of cruising ship was slow already slow.

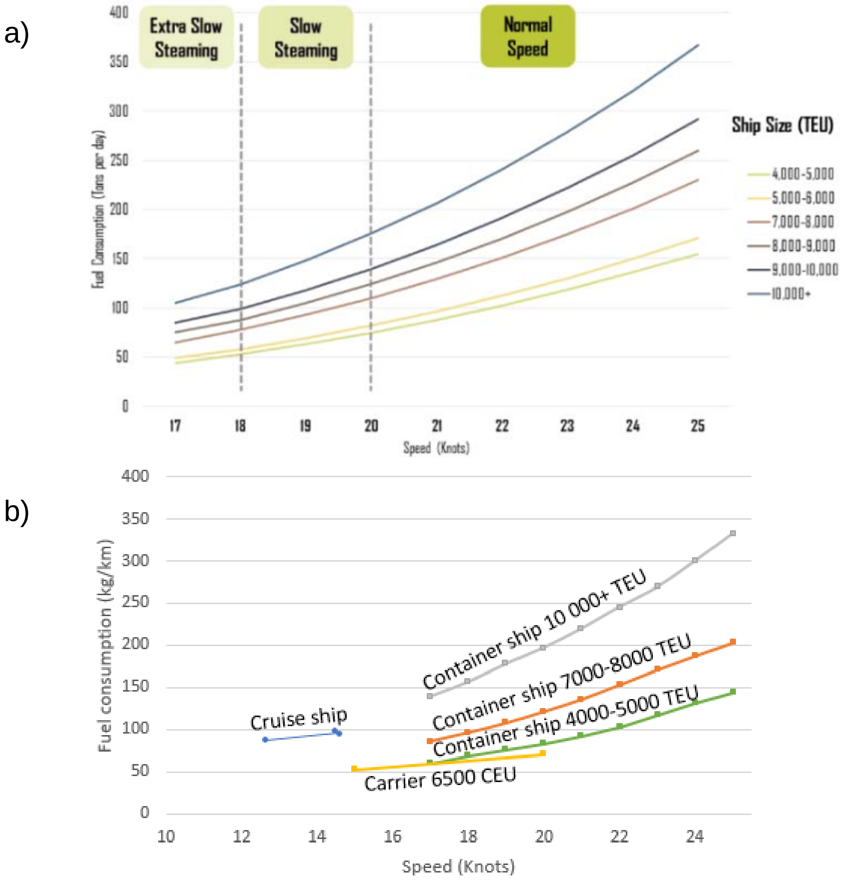


Figure 19. a) Fuel consumption (tons per day) of container ships according to Rodrigue (Rodrigue, 2017). *b) Fuel consumptions converted to distance basis (kg fuel per km travelled) for container ships, car and truck carrier and a cruising ship. Converted data (tons per day) is adapted from Rodrigue (2017), Bialystocki (2016) and Timonen et al. (2018).*

In summary, slow steaming is an efficient tool for reducing the fuel consumption of ships on the condition that technical concerns are solved and engine manufacturer's recommendations are followed. The benefit of slow steaming is at a maximum when speed is reduced, but the engine is still operated at the optimum load range where its efficiency is at the highest. For ships with only one engine, slow steaming typically means operating the engine at a lower load than designed. In this case one option is to reduce engine load by "de-rating" engine to perform optimally at low loads, however, then engine performance at high engine loads may suffer. In container ships, one large SSD 2-stroke engine is typically used. For ships with several engines, low ship speeds can be achieved by running some of the engines at the recommended load range, while other engines are not running.

Slow steaming may lead to fuel savings of 15% to 19% for a 10% speed reduction and 36–39% for 20% speed reduction. However, the fuel economy of the total system is dependent on a number of factors other than just fuel consumption of ships, for example ship size, route and weather planning, port time, and shifts in transport modes. Energy recovery units could be used and plant design has an important role (ballast water and trimming) as well as weight reduction (Górski, Abramowicz-Gerigk and Burciu, 2013). Slow steaming may lead to the need for more ships, delayed deliveries, increased freight rates and modal shifts to rail traffic. Low speeds are already used when travelling in regions with intense traffic, and during manoeuvring in harbour areas. (EPA, 2000; IMO 2009; Petzold et al., 2011). Due to complex interactions of total transport system, optimization and modelling with advanced programs is needed to maximize fuel savings (e.g. (Ilus, Heikkinen and Pyörre, 2012; Di Natale and Carotenuto, 2015; Kim *et al.*, 2016))

7.3 Black carbon and slow steaming

Reduced ship speed reduces fuel consumption. For modern marine diesel engines, black carbon emissions are proportional to fuel consumption over a wide engine operating range, e.g. 40-100% engine loads in the studies reported by Timonen et al. (Timonen *et al.*, 2017) and Teinilä et al. (Teinilä *et al.*, 2018). Thus, the lower fuel consumption achieved by slow steaming is presumably reflected as lower BC emissions for modern diesel engines.

The effect of slow steaming on the BC emissions are quite the opposite for old diesel engines equipped with mechanical fuel injection systems than for modern diesel engines, as increased BC emission at low loads have been observed, e.g. in Aakko-Saksa et al. (Aakko-Saksa, 2016) and Teinilä et al. (Teinilä *et al.*, 2018) and generally in studies shown in Chapter 4.4 for both MSD 4-S and SSD 2-S engines. Based on the BC emissions measured at 10%, 25%, 50%, 75% and 100% engine loads from old engines, the balance between reduced fuel consumption and increased BC emissions at low engine loads was estimated (Fig. 20). When using the average load-dependence presented in Chapter 4.4, BC emission is already much higher at 50% engine load than at the optimal engine operating range, even when the BC emission is compensated with the fuel savings. For some old engines, for example in campaign FI-1 using HFO fuel (Aakko-Saksa, 2016), compensated BC emission may remain at the same level as at optimal engine operating range down to for example 25% engine load.

The results indicate that slow steaming could decrease the BC emissions from ships with modern engines, whereas for older engines equipped with mechanical injection systems, the risk of increased BC emissions is high when operating outside of the optimal load range. Thus slow steaming does not seem a practical option for old marine diesel engines. However, more data on BC emissions from old engines equipped with mechanical injection systems is needed, and on a wider set of engines.

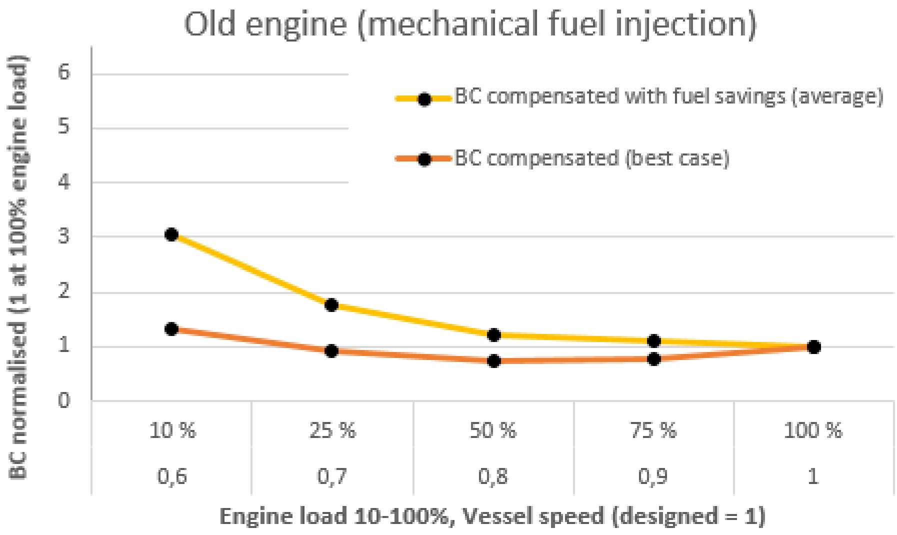
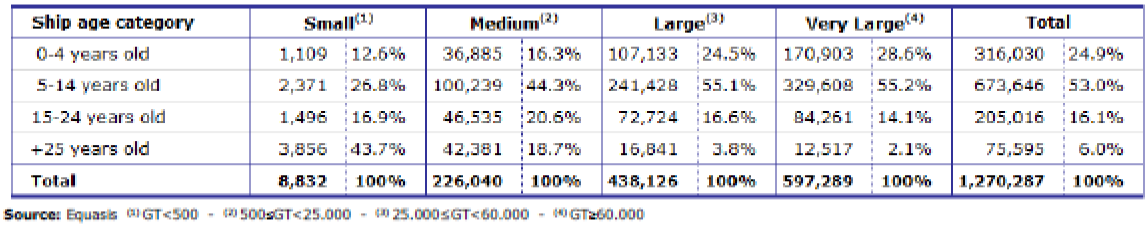


Figure 20. Estimated balance between reduced fuel consumption and increased BC emission at low engine loads for old engines equipped with a mechanical fuel injection system (based on BC emissions data in Chapter 4.4).

As BC emissions are different for old and new engines, the age of the ship is of interest. Statistics for the age of the world merchant fleet in 2016 are shown in Table 6. Categories included are general and special cargo ships, container ships, Ro-Ro cargo ships, bulk carriers, oil and chemical tankers, gas tankers, passenger ships, offshore ships, service vessels and tugs. Fishing vessels are not included in these statistics among some other vessel categories. From these categories, 24-28% of large and very large ships are recently built, within 0-4 years, while only 12-17% of medium and small ships are as new.

Modern fuel injection systems have been used for at least 10 years, and thus ships using engines younger than 14 years may have modern injection systems. Most small ships are older than 15 years (approximately 61%), while only 39% of medium-sized ships and 16-22% of large and very large ships are older than 15 years. The oldest ships of the merchant fleet are the likely to have high BC emissions at low engine loads.

Table 6. World mercantile fleet gross tonnage (1000 gt) by age and size (Equasis, 2016).



Ship age category	**Small(1)**		**Medium(2)**		**Large(3)**		**Very Large(4)**		**Total**	
0-4 years old	1,109	12.6%	36,885	16.3%	107,133	24.5%	170,903	28.6%	316,030	24.9%
5-14 years old	2,371	26.8%	100,239	44.3%	241,428	55.1%	329,608	55.2%	673,646	53.0%
15-24 years old	1,496	16.9%	46,535	20.6%	72,724	16.6%	84,261	14.1%	205,016	16.1%
+25 years old	3,856	43.7%	42,381	18.7%	16,841	3.8%	12,517	2.1%	75,595	6.0%
Total	**8,832**	**100%**	**226,040**	**100%**	**438,126**	**100%**	**597,289**	**100%**	**1,270,287**	**100%**

Source: Equasis (1) GT<500 - (2) 500≤GT<25.000 - (3) 25.000≤GT<60.000 - (4) GT≥60.000

8. Other measures

8.1 Engine maintenance

Engine maintenance is a significant factor affecting the exhaust gas emissions from engines. High soot emissions during engine failures could be avoided by proper and regular maintenance procedures. Well-maintained engines performing properly are also in the interest of shipping companies, as they consume less fuel and repairing damaged engines is expensive. In this report, the importance of engine maintenance for BC emissions from marine diesel engines is recognized. Engine maintenance is at least a method to avoid excess BC slip.

8.2 Hybrid/energy storage, full battery/FC electric

The use of alternative propulsion systems (wind, solar, hybrid) and waste heat recovery units can be effective means to reduce fuel consumption and the emissions of shipping. Hybrid technologies are already used in shipping, for example, batteries or fuel cells as auxiliary power sources in combination with internal combustion main engines. Hybrid technologies could enable the avoidance of high BC emissions at low engine loads from old marine diesel engines. However, hybrid systems are most feasible for new-builds, for which a strong load-dependence of BC emissions is not evidenced. The potential of hybrid/energy storage systems for BC avoidance from old ships depends on their retrofitting possibilities.

Dedes et al. (2012) in (Di Natale and Carotenuto, 2015) estimated that integrating hybrid batteries and a diesel–electric main propulsion system led to fuel savings of up to 19-28% for ships. In other studies in (Di Natale and Carotenuto, 2015), savings between 5% and 15% were achieved using the waste heat recovery fuel, and for low-speed two-stroke diesel engine, using turbochargers and an Organic Rankine Cycle enabled energy reductions of up to 9%. (Di Natale and Carotenuto, 2015). In cases where BC emissions follow fuel consumption, fuel savings also mean reduced BC emissions.

Full battery/fuel cell electric systems have zero BC emissions. These systems are used in some small vessels and ferries travelling short distances. However, their potential as the main power source for larger and ocean-going ships is limited at least in the short term.

8.3 Planning, policies and regulations

Measures to cut BC emissions from shipping, other than those directly related to the exhaust gas output from marine diesel engines, include, for example, planning and policies. However, these are not within the scope of this report.

In the discussion of slow steaming, planning was identified as one of the key factors as it relates to the environmental effects of shipping. Optimization of travelling strategies, the logistic chain and routing (also weather routing) can substantially reduce global travelling distances, fuel consumed and emissions generated. For example, “Ship Energy Efficient Management Plan, SEEMP” aims to reduce the environmental effects of shipping.

Policies are key to achieving BC reduction targets. These may include expanding or establishing BC emission control areas, prohibiting the use of residual fuel to enable particulate filter adaption, establish BC emission standards for ships, include BC emissions in climate strategies, promote ship retrofitting and exhaust gas treatment systems etc.

9. Discussion

9.1 Overview

Discussion of the BC control measures here reveals the development of the BC emission factors along with development of the engine technology, also in relation to the real-life considerations. The discussion then moves on to the efficiencies of individual BC control measures, and their potential in the near future. Finally, the feasibility of different BC control measures for different marine sectors is discussed. The data evaluated in this report originate from a number of measurement campaigns described in Chapter 3 and Appendix 1.

9.2 BC emission factors

There is high uncertainty associated with the BC emission factors due to the large variation of individual engines and measurement conditions. The BC emission factor of 0.35 g/kg fuel published by Corbett et al. (2010) has been used in many emission inventories, and many other BC emission factors have been reported, even higher than 0.35 g/kg fuel (D. A. Lack and Corbett 2012; Jana Moldanová et al. 2010; J. Moldanová et al. 2013; Andreas Petzold et al. 2011; Harshit Agrawal et al. 2008). A BC emission factor of 0.15 ± 0.17 g/kg fuel was reported for 139 vessels on the Elbe river in Germany (Diesch *et al.*, 2013). A recent BC emission inventory, reported by Comer (Comer 2017), used the BC emission factor of 0.25 g/kg fuel, and at the same time suggested that shifting from HFO to distillate fuels can reduce the BC emissions. Winther (2017) reviewed the BC emissions from marine diesel engines, and ended up in the following fuel-dependent BC emission factors: BC 0.155 g/kg fuel for HFO (2.5%S), BC 0.065 g/kg fuel for IFO (0.5%S), BC 0.056 g/kg fuel for MDO (0.1%S) and 0.00155 g/kg fuel for LNG.

According to data evaluated in this report, modern diesel engines show BC emission factors between 50 and 100 mg/kg fuel, which is substantially lower than the BC emission factors used in the inventories. The lowest BC emission level was observed for LNG DF marine engines, namely approximately 1 mg/kg. It is noticeable that using existing state-of-the-art marine diesel engine technology (best available technology) already leads to a substantial reduction in the BC emissions when compared to older engines (Fig. 21). This effect is emphasized at low engine loads.

Another aspect concerning seemingly low BC emissions from modern marine diesel engines is to recognize that there are not many further significant measurable BC reduction steps. For example, if the repeatability of engine output of the BC emission is approximately 0.016 g/kg, there are 12.5 BC reduction steps when moving from BC emission of 0.25 to 0.05 g/kg fuel, while there are only three steps for further reduction to zero the BC emissions. This emphasizes that using the best available engine technology already gives a substantial BC emission reduction, and that the BC mass reductions should be evaluated in parallel to percentage reductions of BC emissions.

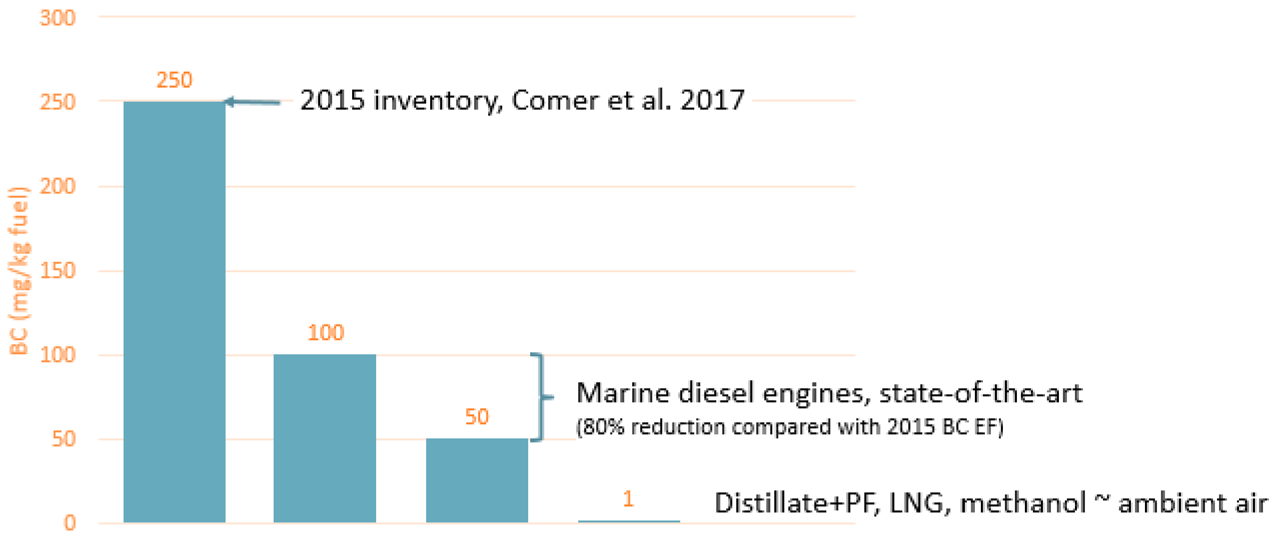


Figure 21. BC emission factors from marine diesel engines used in the 2015 inventory, and measured BC emissions from modern marine diesel engines, LNG DF engines and particulate filter equipped engines in this evaluation.

As mentioned, the BC emission level measured from LNG DF marine engines and some other close to zero BC technologies are approximately 1 mg/kg fuel, which is one fiftieth of that from the clean state-of-the-art diesel engine with BC emissions of 50 mg/kg fuel. Cleanliness of technologies with BC emissions of only 1 mg/kg fuel is understood when noting that this BC emissions is equivalent to approximately 37 µg/m^3, which is close to the ambient BC concentrations in some regions, and not far from the PM2.5 limit of 10 µg/m^3 defined by WHO for ambient air (Table 7).

Table 7. Examples BC emissions in different units and from different sources.

	FSN	BC g/kWh	BC g/kg fuel	BC mg/m^3
Inventory 2015	0.51	0.05	0.25	8.7
Marine diesel engine, present example	0.115	0.01	0.05	1.73
DF gas	0.002	0.00017	0.00084	0.026
Hydrogen, Full electric	0	0	0	0
Ambient air limit for PM2.5 (WHO)				0.010
PM CARB LEV III LD*			0.0124	

*The CARB LEV III standards include PM limits of 3 mg/mi from 2017 and 1 mg/mi from 2025 (CARB 2011, https://www.dieselnet.com/tech/measure_dpm.php) (PM of 1 mg/mi represents about 0.0124 g/kg fuel).

Real-life BC emissions from marine diesel engines

Emission measurements are typically carried out in a testbed (in an engine laboratory), on board a ship from exhaust ducts or from the ship plume. In the testbeds, engine sizes do not often reach those used in large ships. On board measurements are carried out in more realistic conditions than the testbed measurements, however, typically only steady-state engine loads are measured. Plume measurements are often conducted close to the coast or a port when transient and low engine loads are used. Thus plume measurements may reflect the worst-case or real-life BC emissions from ships. Plume measurements are not suitable for studying modest differences in BC emissions, e.g. between residual and distillate fuels, as variation of weather conditions may mask the parameters studied. However, plume studies increase understanding of the BC emissions during challenging ship operations, in a manner of understanding the other extreme. This is particularly important for the Arctic research, as ship speeds are low in the Arctic. Plume studies are needed to confirm low BC emissions from BC control technologies in challenging conditions.

9.3 Efficiency of BC emission control measures

BC emission levels from marine diesel engines can be improved by using clean fuels, by exhaust gas treatment systems or by engine and propulsion system design. The results of this evaluation are summarized in Fig. 22 and also in the timeline in Fig. 23.

The most effective BC emission control measures evaluated are LNG DF, methanol DF and particulate filters combined with marine distillates (or renewables) achieving as low as 1 mg/kg fuel BC emission level. These technologies are already commercial or pre-commercial, although their availability and costs may hinder their fast adoption on a large-scale. As concerns LNG or methanol DF engines, BC emissions are low only when using these fuels as main fuels; for particulate filters, their performance and durability still needs to be proven. ESP-type exhaust treatment systems are in the early phases of development, and their potential remains to be seen (thus marked with dashed line in Fig. 23).

Marine distillate fuels removed BC emissions to some extent and oxygenated biofuels (oils & fats) quite efficiently compared to using residual fuels in marine diesel engines. Clean distillate fuels are enabling technology for particulate filters, and they also could be applied to a large existing ship fleet.

Many engine related BC emission control measures are relevant for old engines, such as renewal or retrofitting modern engine injection systems or tuning engines to low BC emissions (combined with SCR/EGR to cut elevated NO_x emissions). However, the efficiency of these measures cannot be evaluated quantitatively in the same way as the BC emission reduction potential of the other BC emission control measures evaluated here. However, the BC reduction potential of engines equipped with modern injection systems is supported by their low BC emission levels (below 50 mg/kg fuel).

Avoidance of increased BC emissions at low engine loads from old engines is closely related to slow steaming considerations. Slow steaming may offer substantial BC emission reduction when using modern marine diesel engines, whereas for old engines equipped with mechanical injection systems, BC emissions may increase even when compensated for by reduced fuel consumption at reduced ship speeds.

Hydrogen and full electric solutions don’t emit BC or other emission species. However, they are not mature technologies today for the main engines of ocean-going ships, and it may take a while before they are. It is noticeable that synthetic fuels produced from renewable hydrogen and recycled CO_2, can resemble marine distillates, LNG and methanol.

SO_x scrubbers were not efficient in BC emission reduction based on the data evaluated, however, they could be combined with other technologies.

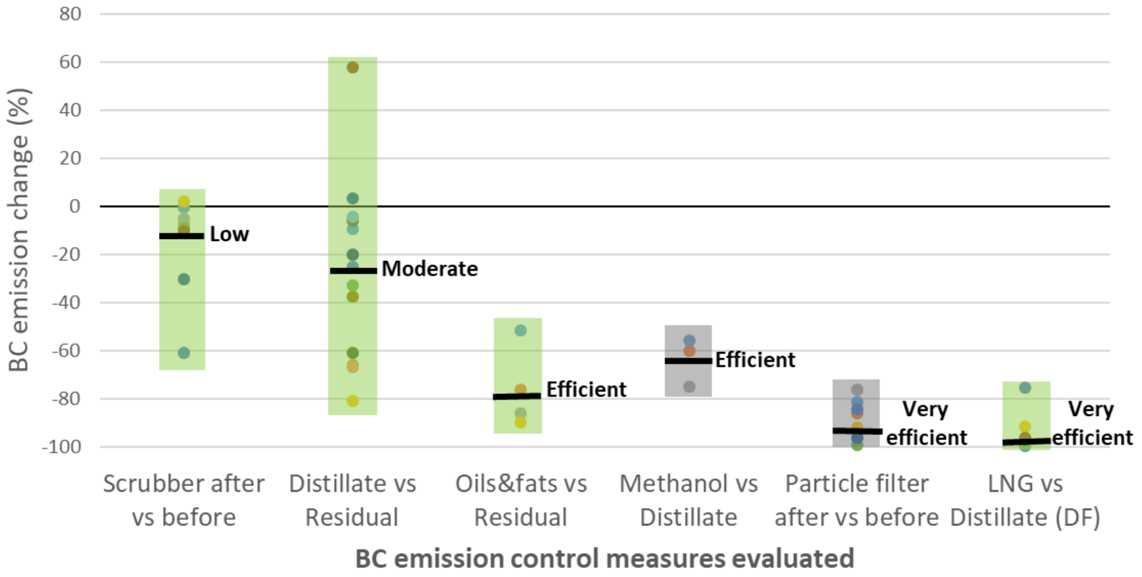


Figure 22. One marker illustrates a data point of comparison. Green line is an average of data points. Grey colour indicates limited data and measurements not meeting the criteria defined in Chapter 2.

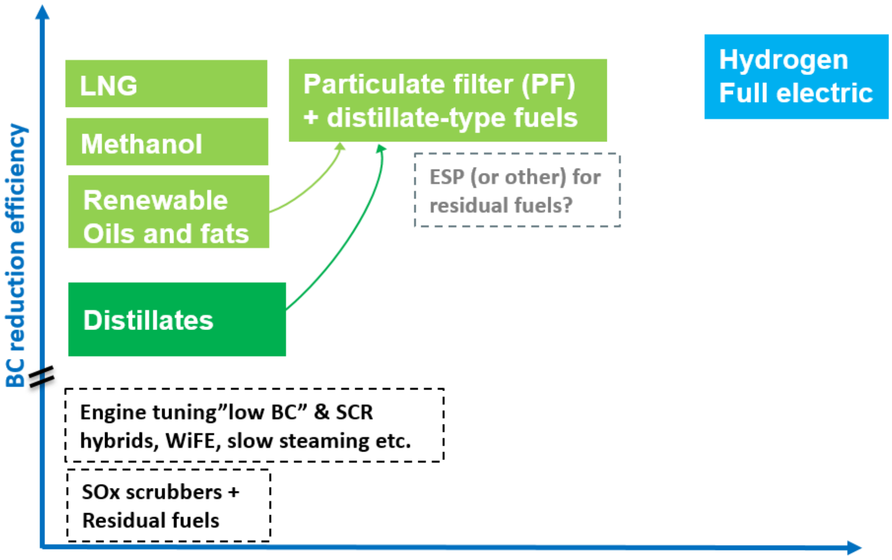


Figure 23. Green colour indicates efficient and at least pre-commercial solutions. Blue colour indicates efficient solutions, but not mature as main engines for large ships. Dashed-line means that solutions are not efficient or potential uncertain.

The results from this evaluation are compared with other evaluations in Tables 8 and 9. All studies found LNG, particulate filters and distillates as potential BC emission reduction technologies. In studies other than PPR 5/INF.7, methanol, biodiesel and many engine related technologies were found to be potential BC emission reduction technologies. Instead, PPR 5/INF.7 found scrubbers as potential BC emission reduction technology, which was not the case in the other evaluations. Here, conclusions on SO_x scrubbers were based on eight BC studies, while conclusions of PPR 5/INF.7 were based mainly on PM studies and on one BC study. PPR 5/INF.7 reported a high BC emission reduction efficiency for methanol, however, at least partly based on the results with gaseous DME fuel that is not used as marine fuel today.

Table 8. Summary of the efficiency of the BC emission reduction technologies evaluated in this report in comparison to findings presented in PPR 5/INF.7.

BC emission reduction technology	**BC emission reduction in this report (%)**	**BC emission reduction in PPR 5/INF.7 (%)**	**Conclusion**
LNG DF compared with distillate as main fuel.	94%.	>85%	**Very efficient**
Particulate filters (after vs before).	88%.	85% or >99%	**Very efficient** *Clean distillate fuel needed.*
Methanol DF compared with distillate as main fuel.	55-75%	>97% (actually refers to DME)	**Efficient**
Distillates compared with residual fuels.	26%	**33%**	**Moderate**
Oxygenated biofuels (oils and fats) compared with residual fuels.	76%	50-75%	**Efficient** *Stability and cleanliness problems*
SOx scrubbers BC removal only in 2 of 8 cases	15%	38% or 45% (refers to PM studies and one BC study)	**Not efficient**
DOC, SCR or EGR alone	0%		**Not efficient**
Modern (common-rail) injection technology, tuning for diesel engines etc.	Not quantified		
Note	Full batteries or hydrogen/fuel cells enable zero BC when feasible.		

Table 9. Short lists of potential BC emission reduction measures in this report, PPR 5/INF.7 and ICCT (Comer 2018).

	This report	**PPR 5/INF.7**	**ICCT 2018**
Fuel type	• LNG DF* • Distillate (enabling particulate filters) • Methanol DF • Oils and fats	• LNG • HFO to distillate fuel • *Water in fuel emulsion*	• LNG • Distillate • Biodiesel • Methanol
Exhaust treatment	• Particulate filters • ESP-type solutions	• Diesel Particulate Filters • *Scrubbers*	• DPF alone or DPF w/ SCR combined with clean distillates • ESP
Engine and Propulsion System Design	• Engine retrofit to common-rail • Engine tuning to low BC emission (NO_x cut with EGR/SCR) • Hybrids • Full batteries or hydrogen/fuel cells		• Engine tuning to low BC emission (NO_x cut with EGR/SCR) • Engine controls (common-rail) • Full BEV • Hybrid/power storage • Full BEV • Fuel cells (hydrogen, ammonia, etc.)
Other	Slow steaming only to engines with modern fuel injection system	Slow Steaming with de-rating	Shore power

*) BC results were available for Gas DF marine engines. Other types of marine engines for LNG use presumably lead to at least as low BC emission level as LNG DF.

9.4 Marine sectors / BC emission control

For the BC emission control measures, we identified important marine BC emitters that could achieve most BC emission reductions, and feasibility of BC emission control measures for each marine sector.

Ship emission inventories are based on fuel consumption data. In 2015, global marine fuel consumption was 266.3 Mt, which is approximately 10% of transport fuels consumed globally (Table 10). Container ships, bulk carriers and oil tankers (mainly SSD 2-stroke engines) consume over 70% of marine fuels, mainly residual fuel. 19% of marine fuels are distillates used mostly in MSD 4-stroke engines. Fishing vessels consume only approximately 2% of marine fuels. LNG represented only 2.4% of global marine fuels in 2015. (Comer *et al.*, 2017a).

In the geographic Arctic, 5.4 Mt of marine fuels are consumed annually, and about 42% of these are residual fuels (Winther *et al.*, 2017). It is notable that a high share of fuel is used in smaller vessels having HSD engines (e.g. fishing ships), namely 45% of total marine fuels consumed in the Arctic. In the Arctic, as defined by the Polar Code (excluding Scandinavia), marine fuel consumption is about 0.44 Mt annually. With a residence time of 7.3 days, BC emissions originating in Scandinavia potentially reach Arctic ice and snow.

Based on fuel consumption data, the most significant marine emitters of BC emissions seem to be

- Globally: container ships, oil tankers (SSD 2-stroke).
- In the Arctic: all shipping sectors are important.

Table 10. Fuel consumption by main engine type in 2015 (Comer *et al.*, 2017a).

	SSD, e.g. container ships, oil tankers (Mt)	**MSD, e.g. ferries, cruisers, RoRo, RoPax, passenger (Mt)**	**HSD, mainly small, e.g. fishing vessels (Mt)**	**Total (Mt)**
Global[a]	**Res. 180.5***, 2.3** Dist. 12.2*, 0.4** LNG 0.03	Res. 26.2**, 0.26* Dist. 20.7**, 0.5* LNG 2.3	Res. 0.5**, 0.01* Dist. 13.7**, 1* LNG 0	Res. 210.3 Dist. 49.5 LNG 6.5
	tot. 192.7*, 2.8**	tot. 48.9**, 0.7*	tot. 14.1**, 1*	tot. 266.3 [a]
The Arctic (geographically)[b]	Res. 1.63 Dist. 0.08	Res. 0.63 Dist. 0.63	Res. 0 Dist. 2.43	Res. 2.26 Dist. 3.14
	tot. 1.72	tot. 1.26	tot. 2.43	tot. 5.40
The Arctic (Polar code)[c]	0.202	0.045	0.114 (other 0.075)	0.44
Note	Mainly residual fuels and 2-stroke	Approx. 50% distillates, mainly 4-stroke	Mostly distillates and 4-stroke.	

SSD = Slow speed diesel MSD = Medium speed diesel HSD = High speed diesel *2-stroke **4-stroke
Res. = Residual fuels, Dist. = Distillate fuels

[a] Global fuel consumption in 2015 (Comer et al. 2017). Steam/gas turbine: residual fuel 0.21/0.6 Mt, distillates 0.2/0.75 Mt and LNG 4.1/0.02 Mt.

[b] Arctic fuel consumption by main engine type in 2016. Data generated from (Winther et al. 2017).

[c] (Comer *et al.*, 2017b)

Evaluation of the different BC emission reduction technologies for different marine sectors is presented in Table 11. For small vessels having mainly HSD engines (4-stroke) and using mainly distillate fuels, many BC control options are available. These vessels can use particulate filters, LNG, methanol, and even hydrogen and batteries are demonstrated. HSD diesel engines have high BC emissions compared to SSD and MSD engines when no BC emission control measures are applied.

For ferries etc. (mostly MSD 4-stroke), marine distillate fuels are already substantially used and thus particulate filters could be considered if proven feasible and durable. LNG DF and methanol DF are also feasible when distances between ports are appropriate.

Large ships, such as container ships, oil tankers and bulk carriers, which mostly have SSD 2-stroke diesel engines, use mainly residual fuels and they are the most demanding ship types for possible new BC emission reduction measures. However, many of these ships are relatively new, with state-of-the-art engines and thus BC emission levels are relatively low. For ocean-going ships travelling long distances liquid methanol might be an option, and also LNG depending on bunkering infrastructure. Potential of particulate filters or ESP-type solutions for the largest ships may be limited. Some tailored solutions, such as integrated scrubber/EGR systems, have been suggested.

For all types of old ships with engines with mechanical fuel injection systems, retrofitting of common-rail injection (or renewal of an engine) could be an option to reduce BC emissions. Engine tuning to lower BC emissions and cutting elevated NO_x by SCR or EGR is also an option to consider.

All in all, there are control measures for BC emissions from marine diesel engines that seem to have potential to reduce the global warming impact and adverse health and environmental effects of shipping. If all ships only emitted BC emissions of 1 mg/kg fuel, the mean annual global BC emission burden of shipping would be 266 t (assuming 266 Mt fuel used), which is 1/250 of that (67 000 t of BC emissions) reported in the 2015 inventory of Comer et al. (Comer *et al.*, 2017a) using the BC emission factor of 250 mg/kg fuel.

Table 11. BC emission control measures for different engine types. Combinations marked with green colour are considered as the most potential.

	SSD, e.g. container ships, oil tankers	**MSD, e.g. ferries, cruisers, RoRo, RoPax, passenger**	**HSD, mainly small, e.g. fishing vessels**
Starting BC emission level	*Moderate or low (new fleet)*	*Moderate (old fleet)*	*High*
LNG, methanol	**Feasible** Infrastructure barriers.	**Feasible** Infrastructure barriers.	**Feasible**
Particulate filters (PF) + <0.1%S clean distillates [b,c]	**Pre-commercial** Fuel and space barriers.	**Pre-commercial** Fuel and space barriers.	**Feasible**
Full hydrogen/FC, full electric	**Not mature** as main power.	**Not mature** as main power.	**Demonstrated**
Moderate BC reduction: *BC/NOx tuning&SCR *Retrofitting common-rail (or hybrids)	BC reduction potential unclear	BC reduction potential unclear	**Feasible**

SSD = Slow speed engine MSD = Medium speed engine HSD = High speed engine

[a] Renewable fuels could replace their fossil counterparts. For example renewable diesel, methane and methanol

[b] Includes particulate filters designed for marine fuels and their combinations with other technologies, such as SCR.

[c] ESP development in too early phase for conclusions.

10. Conclusions

Control measures of black carbon emissions from marine diesel engines vary in their efficiency, feasibility and maturity. Full battery or hydrogen/fuel cell ships are free from BC and other emissions, however, these are not mature technologies for larger ships today.

One of the most effective BC control measures is LNG, which showed almost negligible BC emissions when used as a main fuel in the DF engines. Growth of LNG as marine fuel is tied to the enlargement of the fuel infrastructure and distribution system. Methanol is also a clean-burning fuel, and is used today in a few ships. Dual-fuel engines for LNG or methanol are capable of using distillate fuels, which is not the case for mono-fuel engines for LNG or methanol. Using renewable methane or methanol enables the reduction of GHG emissions as well as negligible BC emissions. From the fuel technologies considered, biofuels containing oxygen reduce the BC emissions compared with residual fuel, while the respective results using advanced synthetic renewable fuels were limited.

Particulate filters combined with clean marine distillate fuels could offer an efficient BC removal technology, however, their performance and durability is not yet proven. Combined with renewable liquid fuels, this pathway could offer low GHG emissions alongside negligible BC emissions. ESP-type systems are in too early a development phase for conclusions. SO_x scrubbers suggested as BC emission control measures were not effective, although their integration potential is identified.

For old SSD and MSD engines, retrofitting of mechanical fuel injection systems with common-rail would reduce BC emission at low engine loads. This is an important aspect also for slow steaming, which could otherwise increase BC emissions from old diesel engines although it decreases BC emissions from modern diesel engines. Engine tuning to lower BC emissions and cutting increased NO_x emission by SCR or EGR is also one option to reduce BC emissions from marine diesel engines.

Many BC emission reduction technologies are easier to adapt to HSD engines than to SSD and MSD engines. HSD engines already use distillate fuel, have small engine sizes and high BC emissions. However, several BC emission control measures are also feasible for MSD and SSD engines, particularly for newbuilds. Some pathways towards zero BC emissions from marine diesel engines are schematically illustrated in Fig. 24.

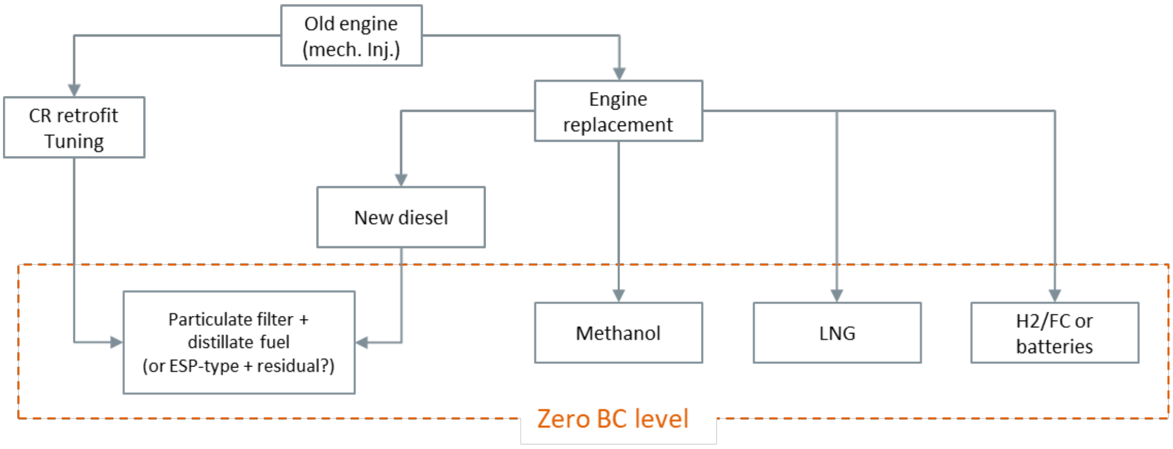


Figure 24. Schematic examples towards close to zero BC emissions from shipping.

References

Aakko-Saksa, P. *et al.* (2018) ‘Considerations in analysing elemental carbon from marine engine exhaust using residual, distillate and biofuels’, *Journal of Aerosol Science*, 126(September), pp. 191–204. doi: 10.1016/j.jaerosci.2018.09.005.

Aakko-Saksa, P. et al. (2016) ‘Black carbon measurements using different marine fuels, CIMAC Paper 068’, *28th CIMAC World Congress*.

Agrawal, H. *et al.* (2008) ‘Emission measurements from a crude oil tanker at sea.’, *Environmental Science & Technology*, 42(19), pp. 7098–103. doi: 10.1021/es703102y.

Agrawal, H. *et al.* (2008) ‘In-use gaseous and particulate matter emissions from a modern ocean going container vessel’, *Atmospheric Environment*, 42(21), pp. 5504–5510. doi: 10.1016/j.atmosenv.2008.02.053.

Agrawal, H. *et al.* (2010) ‘Emissions from main propulsion engine on container ship at sea’, *Journal of Geophysical Research Atmospheres*, 115(23), pp. 1–7. doi: 10.1029/2009JD013346.

Anderson, M. *et al.* (2015) ‘Characterization of particles from a marine engine operating at low loads’, *Atmospheric Environment*. Elsevier Ltd, 101, pp. 65–71. doi: 10.1016/j.atmosenv.2014.11.009.

Aurela, M. *et al.* (2018) ‘Primary and secondary particle emissions from dual-fuel marine engine’, in Clusius, P., Enroth, J., and Lauri, A. (eds) *Proceedings of the NOSA-FAAR Symposium 2018, Report series in aerosol science, N:o 208 (2018)*, p. 1 of 144.

Balkanski, Y. *et al.* (2010) ‘Direct radiative effect of aerosols emitted by transport: From road, shipping and aviation’, *Atmospheric Chemistry and Physics*, 10(10), pp. 4477–4489. doi: 10.5194/acp-10-4477-2010.

Betha, R. *et al.* (2017) ‘Lower NOxbut higher particle and black carbon emissions from renewable diesel compared to ultra low sulfur diesel in at-sea operations of a research vessel’, *Aerosol Science and Technology*. Taylor & Francis, 51(2), pp. 123–134. doi: 10.1080/02786826.2016.1238034.

Bialystocki, N. and Konovessis, D. (2016) ‘On the estimation of ship’s fuel consumption and speed curve: A statistical approach’, *Journal of Ocean Engineering and Science*. Elsevier B.V., 1(2), pp. 157–166. doi: 10.1016/j.joes.2016.02.001.

Bond, T. C. *et al.* (2013) ‘Bounding the role of black carbon in the climate system: A scientific assessment’, *Journal of Geophysical Research Atmospheres*, 118(11), pp. 5380–5552. doi: 10.1002/jgrd.50171.

Buffaloe, G. M. *et al.* (2014) ‘Black carbon emissions from in-use ships: A California regional assessment’, *Atmospheric Chemistry and Physics*, 14(4), pp. 1881–1896. doi: 10.5194/acp-14-1881-2014.

Celo, V., Dabek-Zlotorzynska, E. and McCurdy, M. (2015) ‘Chemical characterization of exhaust emissions from selected Canadian marine vessels: The case of trace metals and lanthanoids’, *Environmental Science and Technology*, 49(8), pp. 5220–5226. doi: 10.1021/acs.est.5b00127.

Cherrier, G. *et al.* (2017) ‘Aerosol particles scavenging by a droplet: Microphysical modeling in the Greenfield gap’, *Atmospheric Environment*, 166, pp. 519–530. doi: 10.1016/j.atmosenv.2017.07.052.

CIMAC (2012) 'Background information on black carbon emissions from large marine and stationary diesel engines - definition, measurement methods, emission factors and abatement technologies', *The international council on combusition engines*. doi: 10.1017/CBO9781107415324.004.

Collaud Coen, M. *et al.* (2010) 'Minimizing light absorption measurement artifacts of the Aethalometer: evaluation of five correction algorithms', *Atmospheric Measurement Techniques*, 3, pp. 457–474. doi: 10.5194/amt-3-457-2010.

Comer, B. *et al.* (2017a) 'Black Carbon Emissions and Fuel Use in Global Shipping, 2015', *ICCT, The International Council on Clean Transportation*.

Comer, B. *et al.* (2017b) 'Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025', *International Council on Clean Transportation (ICCT)*, (May), p. 68 pp. Available at: https://www.theicct.org/publications/prevalence-heavy-fuel-oil-and-black-carbon-arctic-shipping-2015-2025.

Corbett, J. J., Wang, H. and Winebrake, J. J. (2009) 'The effectiveness and costs of speed reductions on emissions from international shipping', *Transportation Research Part D: Transport and Environment*. Elsevier Ltd, 14(8), pp. 593–598. doi: 10.1016/j.trd.2009.08.005.

Corbett, J., Winebrake, J. and Green, E. (2010) 'An assessment of technologies for reducing regional short-lived climate forcers emitted by ships with implications for Arctic shipping', *Carbon Management*, 1(2), pp. 207–225. doi: 10.4155/cmt.10.27.

Corbin, J. C. *et al.* (2018) 'Brown and Black Carbon Emitted by a Marine Engine Operated on Heavy Fuel Oil and Distillate Fuels: Optical Properties, Size Distributions, and Emission Factors', *Journal of Geophysical Research: Atmospheres*, 123(11), pp. 6175–6195. doi: 10.1029/2017JD027818.

Diesch, J. M. *et al.* (2013) 'Investigation of gaseous and particulate emissions from various marine vessel types measured on the banks of the Elbe in Northern Germany', *Atmospheric Chemistry and Physics*, 13(7), pp. 3603–3618. doi: 10.5194/acp-13-3603-2013.

Drinovec, L. *et al.* (2015) 'The "dual-spot" Aethalometer: An improved measurement of aerosol black carbon with real-time loading compensation', *Atmospheric Measurement Techniques*, 8(5), pp. 1965–1979. doi: 10.5194/amt-8-1965-2015.

Equasis (2016) 'The world merchant fleet in 2016 - Statistics from Equasis'. doi: 10.1017/CBO9781107415324.004.

Eyring, V. *et al.* (2010) 'Transport impacts on atmosphere and climate: Metrics', *Atmospheric Environment*. Elsevier Ltd, 44(37), pp. 4735–4771. doi: doi:10.1016/j.atmosenv.2009.04.059.

Fridell, E. and Salo, K. (2014) 'Measurements of abatement of particles and exhaust gases in a marine gas scrubber', *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, 230(1), pp. 154–162. doi: 10.1177/1475090214543716.

Górski, W., Abramowicz-Gerigk, T. and Burciu, Z. (2013) 'The influence of ship operational parameters on fuel consumption', *Scientific Journals of the Maritime University of Szczecin*, 36(108), pp. 49–54. Available at: http://repository.am.szczecin.pl/handle/123456789/529.

Ilus, T., Heikkinen, A. and Pyörre, J. (2012) 'Challenges in vessel speed optimisation (Eniram report)'.

Jayaram, V. *et al.* (2011) 'Real-time gaseous, PM and ultrafine particle emissions from a modern marine engine operating on biodiesel', *Environmental Science and Technology*, 45(6), pp. 2286–2292. doi: 10.1021/es1026954.

Jiang, Y. *et al.* (2018) ‘Sources of variance in BC mass measurements from a small marine engine: Influence of the instruments, fuels and loads’, *Atmospheric Environment*, 182(February), pp. 128–137. doi: 10.1016/j.atmosenv.2018.03.008.

Johansen, K. (2015) ‘Multi-catalytic soot filtration in automotive and marine applications’, *Catalysis Today*. Elsevier B.V., 258(x), pp. 2–10. doi: 10.1016/j.cattod.2015.06.001.

Johnson, K. *et al.* (2016) ‘Black Carbon Measurement Methods and Emission Factors from Ships’.

Kasper, A. *et al.* (2007) ‘Particulate Emissions from a Low-Speed Marine Diesel Engine’, *Aerosol Science and Technology*, 41(1), pp. 24–32. doi: 10.1080/02786820601055392.

Khan, M. Y., Giordano, M., *et al.* (2012) ‘Benefits of two mitigation strategies for container vessels: Cleaner engines and cleaner fuels’, *Environmental Science and Technology*, 46(9), pp. 5049–5056. doi: 10.1021/es2043646.

Khan, M. Y., Agrawal, H., *et al.* (2012) ‘Greenhouse gas and criteria emission benefits through reduction of vessel speed at sea’, *Environmental Science and Technology*, 46(22), pp. 12600–12607. doi: 10.1021/es302371f.

Khan, M. Y. *et al.* (2013) ‘Measuring in-use ship emissions with international and U.S. federal methods’, *Journal of the Air and Waste Management Association*, 63(3), pp. 284–291. doi: 10.1080/10962247.2012.744370.

Kim, J. G. *et al.* (2016) ‘Optimizing ship speed to minimize total fuel consumption with multiple time windows’, *Mathematical Problems in Engineering*, 2016. doi: 10.1155/2016/3130291.

Kindbom, K., Fridell, E., Skårman, T., Nielsen, O.-K., Saarinen, K., *et al.* (2015) ‘Improved emission inventories of SLCP: Background analysis’, *TemaNord*, (523), p. 180. Available at: https://books.google.ca/books?id=TCB9CAAAQBAJ%0Ahttp://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A807348&dswid=-1570.

Kindbom, K., Fridell, E., Skårman, T., Nielsen, O.-K., Winther, M., *et al.* (2015) ‘Improved emission inventories of SLCP: Background analysis’, p. 180.

Køcks, M. *et al.* (2017) ‘Shipboard characterization of a combined particle filter and NOx - reducing technology: Influence on particle number concentration , particle size distribution and gas emissions’, in *ETH*.

Lack, D. (2017) ‘An update to the investigation of appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping. PPR 5/INF.7’.

Lack, D. A. *et al.* (2011) ‘Impact of fuel quality regulation and speed reductions on shipping emissions: Implications for climate and air quality’, *Environmental Science and Technology*, 45(20), pp. 9052–9060. doi: 10.1021/es2013424.

Lack, D. A. *et al.* (2014) ‘Characterizing elemental, equivalent black, and refractory black carbon aerosol particles: A review of techniques, their limitations and uncertainties’, *Analytical and Bioanalytical Chemistry*, 406(1), pp. 99–122. doi: 10.1007/s00216-013-7402-3.

Lack, D. A. and Corbett, J. J. (2012) ‘Black carbon from ships: A review of the effects of ship speed, fuel quality and exhaust gas scrubbing’, *Atmospheric Chemistry and Physics*, 12(9), pp. 3985–4000. doi: 10.5194/acp-12-3985-2012.

Lauer, P. (2012) ‘On the correlation of black carbon , filter smoke number and PM related elemental carbon measured at large medium speed 4-stroke Diesel engines', in *ETH*, pp. 4–7.

Lauer, P. (2017) 'Black Carbon Emission of Marine Diesel Engines Black Carbon. In ICCT 4th BC Workshop, Washington.', pp. 4–5.

Lehtoranta, K. *et al.* (2018) 'Particle mass and number emissions from marine engines preparing for the upcoming sulphur cap limits', in *22nd ETH Conference, June 18th - 21st, 2018 at ETH Zurich, Switzerland*, pp. 1–2.

Lim, S. *et al.* (2014) 'Absorption and scattering properties of organic carbon versus sulfate dominant aerosols at Gosan climate observatory in Northeast Asia', *Atmospheric Chemistry and Physics*, 14(15), pp. 7781–7793. doi: 10.5194/acp-14-7781-2014.

Lu, G. *et al.* (2006) 'Identification and characterization of inland ship plumes over Vancouver, BC', *Atmospheric Environment*, 40(15), pp. 2767–2782. doi: 10.1016/j.atmosenv.2005.12.054.

Malm, W. C. (1999) 'Introduction to Visibility (Air Resources Division, National Park Service, Cooperative Institute for Research in the Atmosphere [CIRA], NPS Visibility Program)', *Colorado State University, Fort Collins*.

Miller, J. W. (2018) 'Brief on Understanding BC Removal by Wet Scrubbers. Fifth ICCT Workshop on Marine Black Carbon Emissions.'

Moldanová, J. *et al.* (2010) 'Characterisation of particulate matter and gaseous emissions from a large ship diesel engine', *DLR Deutsches Zentrum fur Luft- und Raumfahrt e.V. - Forschungsberichte*. Elsevier Ltd, 43(10), pp. 38–44. doi: 10.1016/j.atmosenv.2009.02.008.

Moldanová, J. *et al.* (2013) 'Physical and chemical characterisation of PM emissions from two ships operating in European emission control areas', *Atmospheric Measurement Techniques*, 6(12), pp. 3577–3596. doi: 10.5194/amt-6-3577-2013.

Mullins, O. C. (2010) 'The modified yen model', *Energy and Fuels*, 24(4), pp. 2179–2207. doi: 10.1021/ef900975e.

Murphy, S. *et al.* (2009) 'Comprehensive simultaneous shipboard and airborne characterization of exhaust from a modern container ship at sea', *Environmental Science and Technology*, 43(13), pp. 4626–4640. doi: 10.1021/es802413j.

Mussatti, D. (2002) 'Particulate Matter Controls - Wet Scrubbers for Particulate Matter (Chapter 6 EPA-452/B-02-001)', *United state Environmental Protection Agency*, p. 62.

Di Natale, F. and Carotenuto, C. (2015) 'Particulate matter in marine diesel engines exhausts: Emissions and control strategies', *Transportation Research Part D: Transport and Environment*. Elsevier Ltd, 40(600), pp. 166–191. doi: 10.1016/j.trd.2015.08.011.

Noll, J. D. *et al.* (2002) 'The effects of water emulsified fuel on diesel particulate matter concentrations in underground mines', (Howes 2000), pp. 159–164.

Nonokawa, M., Katsuki, T. and Noshiro, S. (2016) 'Ceramic Filter for Ship Diesel Engines — PM (black carbon) removal technology using the CERALLEC ® system', *NGK Insulators Paper*.

Ntziachristos, L. *et al.* (2016) 'Particle emissions characterization from a medium-speed marine diesel engine with two fuels at different sampling conditions', *Fuel*. Elsevier Ltd, 186, pp. 456–465. doi: 10.1016/j.fuel.2016.08.091.

Park, S. (2018) 'PM/BC Reduction by DPF and wet-ESP for marine ship engines: Recent R&D

in Korea. ICCT’s 5th Workshop on Marine Black Carbon Emissions.’

Petzold, A. *et al.* (2008) ‘Experimental studies on particle emissions from cruising ship, their characteristic properties, transformation and atmospheric lifetime in the marine boundary layer’, *Atmospheric Chemistry and Physics*, 8(9), pp. 2387–2403. doi: 10.5194/acp-8-2387-2008.

Petzold, A. *et al.* (2011) ‘Operation of marine diesel engines on biogenic fuels: Modification of emissions and resulting climate effects’, *Environmental Science and Technology*, 45(24), pp. 10394–10400. doi: 10.1021/es2021439.

Petzold, A. and Schönlinner, M. (2004) ‘Multi-angle absorption photometry - A new method for the measurement of aerosol light absorption and atmospheric black carbon’, *Journal of Aerosol Science*, 35(4), pp. 421–441. doi: 10.1016/j.jaerosci.2003.09.005.

Psaraftis, H. N., Kontovas, C. A. and Kakalis, N. M. P. (2009) ‘Speed reduction as an emissions reduction measure for fast ships’, in *10th International Conference on Fast Sea Transportation*, pp. 0–8.

Ristimaki, J., Hellen, G. and Lappi, M. (2010) ‘Chemical and physical characterization of exhaust particulate matter from a marine medium speed diesel engine’, *CIMAC Congress 2010*, Paper # 73, p. 11.

Rodrigue, J.-P. (2017) ‘The Geography of Transport Systems, Fourth Edition, Routledge.’, p. 440. doi: ISBN 978-1138669574.

Sanguri, M. (2012) ‘The Guide to Slow Steaming On Ships’, *Marine Insight*. Available at: http://www.marineinsight.com/wp-content/uploads/2013/01/The-guide-to-slow-steaming-on-ships.pdf.

Sarvi, A., Fogelholm, C. J. and Zevenhoven, R. (2008) ‘Emissions from large-scale medium-speed diesel engines: 2. Influence of fuel type and operating mode’, *Fuel Processing Technology*, 89(5), pp. 520–527. doi: 10.1016/j.fuproc.2007.10.005.

Sippula, O. *et al.* (2014a) ‘Particle emissions from a marine engine: Chemical composition and aromatic emission profiles under various operating conditions’, *Environmental Science and Technology*, 48(19), pp. 11721–11729. doi: 10.1021/es502484z.

Sippula, O. *et al.* (2014b) ‘Particle emissions from a marine engine: Chemical composition and aromatic emission profiles under various operating conditions’, *Environmental Science and Technology*, 48(19), pp. 11721–11729. doi: 10.1021/es502484z.

Stocker, T. *et al.* (2013) *Climate Change 2013: The Physical Science Baisis*.

Streibel, T. *et al.* (2017) ‘Aerosol emissions of a ship diesel engine operated with diesel fuel or heavy fuel oil’, *Environmental Science and Pollution Research*. Environmental Science and Pollution Research, 24(12), pp. 10976–10991. doi: 10.1007/s11356-016-6724-z.

Takahashi, C. and Masuda, A. (2018) ‘New research on Black Carbon control’.

Teinilä, K. *et al.* (2018) ‘Effect of aftertreatment on ship particulate and gaseous components at ship exhaust’, pp. 1–28.

Timonen, H. *et al.* (2017) ‘Black carbon measurement validation onboard (SEA- EFFECTS BC WP2). Report VTT-R-04493-17.’

Umezawa, K. *et al.* (2017) ‘Technology for reducing emissions from marine diesel engines — Reduction of black carbon emission and suppression of wastewater pollution from scrubber

—', pp. 1–14.

US EPA (2002) 'Impacts of Lubrizol's PuriNOx Water/Diesel Emulsion on Exhaust Emissions from Heavy-Duty Engines. Report EPA420-P-02-007.'

Verbeek, R., Bolech, M. and den Uil, H. (2011) 'Alternative fuels for sea shipping. TNO-060-DTM-2011-04219.', (January), p. 4. Available at: http://ec.europa.eu/transport/urban/vehicles/road/clean_transport_systems_en.htm.

Verbeek, R. P. (2014) 'Assessment of pollutant emissions with GTL as a drop in fuel for medium and heavy-duty vehicles, inland shipping and non-road machines-Final'.

Wiesmann, A. (2010) 'Slow steaming - a viable long-term option?', *In Detail - Wärtsilä Technical Journal*, pp. 49–55.

Winther, M. *et al.* (2017) *Emissions from shipping in the Arctic from 2012-2016 and emission projections for 2020, 2030 and 2050*. doi: Scientific Report from DCE – Danish Centre for Environment and Energy No. 252.

Wright, A. (2016) 'Marine Fuel Quality 2015 - An Objective Review Report (Loyd's Register Marine TID 8108)'.

Yang, M. *et al.* (2009) 'Attribution of aerosol light absorption to black carbon, brown carbon, and dust in China - Interpretations of atmospheric measurements during EAST-AIRE', *Atmospheric Chemistry and Physics*, 9(6), pp. 2035–2050. doi: 10.5194/acp-9-2035-2009.

Yliskylä-Peuralahti, J. *et al.* (2016) 'Polaarikoodin turvallisuus- ja ympäristö- vaatimusten yhteensovittaminen Suomessa, Valtioneuvoston selvitys- ja tutkimustoiminnan julkaisusarja 11/2016', pp. 1–82.

Yoshimoto, Y. and Tamaki, H. (2001) 'Reduction of NOx and Smoke Emissions in a Diesel Engine Fueled by Biodiesel Emulsion Combined with EGR', (724).

Zetterdahl, M. *et al.* (2016) 'Impact of the 0.1% fuel sulfur content limit in SECA on particle and gaseous emissions from marine vessels', *Atmospheric Environment*, 145, pp. 338–345. doi: 10.1016/j.atmosenv.2016.09.022.

Other data sources

EUROMOT data, PPR 4/9. Measurement data derived from the application of the draft Black Carbon Measurement Reporting Protocol – Summary. Submitted by the European Association of Internal Combustion Engine Manufacturers (EUROMOT).

PPR 4/9/2. Preliminary results from Black Carbon (BC) measurements, 11 November 2016. Submitted by Finland. Different BC emission measurement methods were compared. Similar results were obtained using FSN, PAS and MAAP despite the different measurement principles of the methodologies used. Additionally, for an old diesel engine in a laboratory, dependencies were found between BC emissions with regard to fuel used and engine loads, but reduced fuel sulphur content did not necessarily reduce BC emissions. EC analysis was found to be challenging; particularly for the samples from ships using residual marine fuels (see also (Aakko-Saksa *et al.*, 2018).

PPR 4/9/3. Experience with MAAP measurements, 11 November 2016. Submitted by Finland. The MAAP measurement method designed for ambient BC measurements requires high dilution ratios (DRs) to keep BC concentrations within the measurement range when diesel engine exhaust gas is measured. High DRs require special instrumentation and experienced personnel. Uncertainty due to the DR is directly reflected in the BC measurement results and the parameters of MAAP measurements need careful inspection for reliability of the results; MAAP was not considered to be practical for on board measurements. Pre-treatment may alleviate the bias between different BC measurement techniques, however, at the cost of complexity of the test set-up.

PPR 4/INF.7 is a summary of the CIMAC article (Aakko-Saksa et al. 2016) and includes the SEA-EFFECTS BC results obtained in laboratory.

PPR 5/7/2. Black Carbon emission measurement results for 4-stroke marine diesel engines, using various fuels, and with and without scrubber, 1 December 2017. Submitted by Finland. The BC emission measurement results from two on board ship measurement programmes, one from the SEA-EFFECTS BC project and one from the EnviSuM project. Altogether, the BC measurements covered four 4-stroke MSD marine diesel engines at various engine loads. The effect of fuel quality on BC emissions from ship diesel engines was demonstrated by using fuels with different sulphur contents ranging from below 0.1% to up to 2.5%. Furthermore, the effect of a scrubber on the BC emissions was presented, based on the on board measurements conducted on two ships. The BC emission measurement results are based on the FSN methodology.

PPR 5/INF.7. An update to the investigation of appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping, 29 November 2017. Submitted by Canada.

IEA-AMF Fuel Information system website www.iea-amf.org/content/fuel_information/, accessed in October 2018.

Needham 1991. Dieselnet. (https://dieselnet.com/), accessed in October 2018.

US Naval Academy https://www.usna.edu/NAOE/_files/documents/Courses/EN400/02.07%20Chapter%207.pdf

APPENDIX 1

FSN, PAS, LII measurement methods. 4-stroke MSD engines.

ID	Rated power MW	Engine year	No of engine loads	Emission control	Fuels	Method	Reference
FI-2 Onboard	~10	2016	2 (0.75, 0.4)	Scrubber	HFO, DMA	FSN, PAS	(Timonen *et al.*, 2017)
FI-3 Onboard	~14	2016	2 (0.75, 0.4)	Scrubber, SCR	HFO, DMA	FSN, PAS	(Timonen *et al.*, 2017)
FI-4 Onboard	~10	2007	many*	Scrubber, DOC	HFO, DMA	FSN, PAS	(Teinilä *et al.*, 2018)
FI-1 Testbed	1.6	<2000	2 (0.75, 0.25)	No	HFO, IFO, MDO, Bio30	FSN, PAS	(Aakko-Saksa et al. 2016, 2017)
E-16 Testbed	7.2	2016	5*	No	DMA	FSN	EUROMOT
E-17, E-18 Testbed	10.8	2015	5*	No	DMA	FSN	EUROMOT
E-19 Testbed	10.4	2014	5*	No	DMA	FSN	EUROMOT
E-20 Testbed	5	2013	4*	No	DMA	FSN	EUROMOT
E-21 Testbed	6	2014	5*	No	DMA	FSN	EUROMOT
E-22, E23 Testbed	3.5	2012	5*	No	HFO	FSN	EUROMOT
E-24, E-25 Testbed	4	2016	4*	No	DMA	FSN	EUROMOT
E-28, E-29 Testbed	3.5	2009	5*	No	RME	FSN	EUROMOT
E-27 DF Testbed	8	2016	4*	No	DMA	FSN	EUROMOT
E-26 DF Testbed	8	2016	4*	No	NG/DMA	FSN	EUROMOT
Testbed	1.7		4*	No	HFO, Biofuels	FSN	(Lauer, 2012)
Testbed	<2		2 (0.37, 0.60)	Scrubber, SCR	MDO, HFO	PAS, TOA, LII	(Lauer, 2017)
Testbed	1.64	<2000	4*	No	HFO, LFO	FSN	(Ristimaki, Hellen and Lappi, 2010)
1-cyl. Testbed	1		4*	No	HFO, LFO	FSN	(Sarvi, Fogelholm and Zevenhoven, 2008)

*Engine loads 10-100% of MCR

FSN, PAS, LII measurement methods. 2-stroke SSD engines.

ID	Power (MW)	Engine year	No of engine loads	Emission control	Fuels	Method	Reference
UCR-T2 Onboard	69.68	2011	4	No	DMA	FSN, LII, PAS	(Johnson *et al.*, 2016)
UCR-T3 Onboard	ME16.6 AE2.1	1987	3	scrubber (before/after)	HFO	FSN, PAS	(Johnson *et al.*, 2016)
E-10 Testbed	11.335	2015	5	No	DMB	FSN	EUROMOT
E-11 Testbed	28.31	2015	5	No	DMA	FSN	EUROMOT
E-13, E-14 Testbed	11.08	2014	5	No	DMB	FSN	EUROMOT
E-15 Testbed	10.201	2007	6	SCR	RMG	FSN	EUROMOT
E-01, E-04 Testbed	6.513	2007	5	SCR	DMA	FSN	EUROMOT
E-09 Testbed	6.509	2007	4	SCR	RMG	FSN	EUROMOT
E-12	6.1	2014	5	No	DMA	FSN	EUROMOT

Testbed							
E-3, E-6 Testbed	13.45	2016	4-5	No	DMX	FSN	EUROMOT
E-8 Testbed	5.45	2015	4	No	DMA	FSN	EUROMOT
E-2 DF, E-5 DF Testbed	13.45	2016	5	No	NG/DMX	FSN	EUROMOT
E-7 DF Testbed	5.45	2015	4	No	NG/DMA	FSN	EUROMOT
UCR-T1 Testbed	0.19	1980	2 (0.25;0.75)		DMA,RMB RMG	FSN, LII, PAS	(Johnson *et al.*, 2016)(Jiang *et al.*, 2018)
Testbed	7.08		2 (0.25, 0.75)	-	HFO, MDO	FSN, PAS, LII, TOA	(Lauer, 2017)

“Other” measurement methods. 4-stroke MSD engines.

	Rated power MW	**Engine year**	**No of engine loads**	**Emission control**	**Fuels**	**Method**	**Reference**
Onboard	5.85		3 (0.24-0.85)	SCR	HFO(0.5S) RMB(0.1S)	MAAP	(Zetterdahl *et al.*, 2016)
Onboard	7.2	1989	1 (0.27)	No	MDO	MAAP, TOA(EC)	(Kindbom, Fridell, Skårman, Nielsen, Saarinen, *et al.*, 2015)
Onboard	several	1977, 1980, 2010	1	No	IFO, MDO	TOA(EC)	(Celo, Dabek-Zlotorzynska and McCurdy, 2015)
Onboard	0.9 (aux)		many	-	MGO	TOA(EC)	(Agrawal et al. 2008)
Onboard	6		1 (0.57)	-	HFO, MGO	Reflectometer	(Moldanová *et al.*, 2013)
Onboard	4.4		2	-	HFO	Reflectometer	(Moldanová *et al.*, 2013)
Onboard	0.87		1 (0.47)	-	MGO	Reflectometer	(Moldanová *et al.*, 2013)
Testbed	8		many (0.85-1)	-	HFO	TOA(EC)	(Petzold 2008)
Testbed	1.64	<2000	1 (0.75)	No	HFO, LFO	TOA(EC)	(Ntziachristos *et al.*, 2016)
Testbed	0.08		1 (0.35)	-	HFO,MDO on-road		(Anderson *et al.*, 2015)
1-cyl.	small		many	-	HFO on-road	TOA(EC)	Sippula 2014(Sippula *et al.*, 2014a)
1-cyl	0.4		4 (0.1-1)	-	HFO,MGO, Biofuels	MAAP, TOA(EC)	(Petzold *et al.*, 2011)
Plume	many	many	many	-	HFO, LSF	PAS, SP-AMS	(Buffaloe *et al.*, 2014)

“Other” measurement methods. 2-stroke SSD engines.

	Rated power MW	**Engine year**	**No of engine loads**	**Emission control**	**Fuels**	**Method**	**Reference**
Onboard	74.6		4 (0.1-0.6)	No	HFO, MGO	PAS, TOA(EC)	(Johnson *et al.*, 2016)
Onboard	68.6		1 (0.25)		HFO, MGO	TOA(EC)	(Johnson et al., 2016
Onboard	21.06		1 (0.51)	Scrubber (before/after)	HFO	soot scan transmissiometer	(Fridell and Salo, 2014)
Onboard	54.84	1998	many (0.25-0.90)	No	HFO	TOA(EC)	(Agrawal *et al.*, 2010) (Murphy *et al.*, 2009)
Onboard	50.27	1995	5 (0.08-0.7)	-	HFO	TOA(EC)	(Harshit Agrawal *et al.*, 2008)(Kindbom, Fridell, Skårman, Nielsen, Winther, *et al.*, 2015)

Onboard	36.74	1997	4 (0.25-1)	-	HFO	TOA(EC)	(Khan *et al.*, 2013)
Onboard	68.53	2010	5 (0.1-1)	No	HFO, MGO	TOA(EC)	(Khan, Giordano, *et al.*, 2012)
Onboard	20.2	1985	1 (0.84)	No	HFO	TOA(EC)	(Moldanová *et al.*, 2010)
Onboard	15.75		many (0.13-0.85)	-	HFO	TOA(EC)	(H. Agrawal *et al.*, 2008)(Kindbom, Fridell, Skårman, Nielsen, Winther, *et al.*, 2015)
Onboard (UCR-T3r)	6.3	0	5	No	LS-HFO, MGO	PAS, TOA(EC)	(Johnson *et al.*, 2016)
Onboard		1986	1 (0.7)	No	IFO	TOA(EC)	(Celo, Dabek-Zlotorzynska and McCurdy, 2015)
Onboard		2008	1 (0.85)	No	IFO	TOA(EC)	(Celo, Dabek-Zlotorzynska and McCurdy, 2015)
Testbed	8.5	2007	1	No	MDO	TOA(EC)	Kasper 2007(Kasper *et al.*, 2007)
Testbed	7.08		1 (0.75)		HFO MGO	TOA(EC)	MAN report
Testbed	1.64 DF	<2000	2 (0.85, 0.4)	No	NG /road	Aethalometer	(Aurela 2018)
Plume	46.96		1 (0.85)	No	HFO-2.45S	PSAP	(Petzold *et al.*, 2008)
Plume	68.7+ Aux+boilers	2008	22 vs 12 knots	No	HFO DMA		(Lack *et al.*, 2011)
Plume	many	many	many	-	MDO	MAAP	(Diesch *et al.*, 2013)
Plume	8.2	1982			MGO	white light attenuation	Moldanova et al. 2009
Plume	many	many	many		HFO	PAS, SP-AMS	(Buffaloe *et al.*, 2014)

HDS engines

Testbed/on-board	**Stroke**	**Rated power (MW)**	**Engine year**	**No of engine loads**	**Emission contro**	**Fuels**	**Method**	**Ref**
E-30, E-31, E-32, E-33 Testbed	4	9.1; 7.4; 1; 1.5	2010; 2014; 2013	4	No	EN590	FSN	EUROMOT
E-34, E-35 Testbed	4	3.1; 1.4	2010; 2015	4	No	EN590	FSN	EUROMOT
UCR-T1 Testbed	2	0.19	1980	2	No	DMA, RMB, RMG	FSN, LII, PAS	(Johnson *et al.*, 2016) (Jiang *et al.*, 2018)
Testbed	4	0.08		1 (0.35)	No	HFO, MDO, road	visible light reflectom	(Anderson *et al.*, 2015)
Testbed	4	0.375		5 (0-0.95)	No	FAME, road	TOT(EC)	(Jayaram *et al.*, 2011)
1-cyl.	4	0.08		many	No	HFO, road	TOA(EC)	(Sippula *et al.*, 2014b)
1-cyl	4	0.08		1(0.5)	No	HFO, road	TOA(EC)	(Streibel *et al.*, 2017)
Plume	2		1981	many	No	HVO, road	SP2	(Betha *et al.*, 2017)
Plume	4	many	many	many	-	HFO, LSF	PAS, SP-AMS	(Buffaloe *et al.*, 2014)