# Control measures of Black Carbon (BC) emissions from marine diesel engines

**Päivi Aakko-Saksa, VTT**
**ICCT's 5th BC Workshop**
**19-20 September 2018, San Francisco**

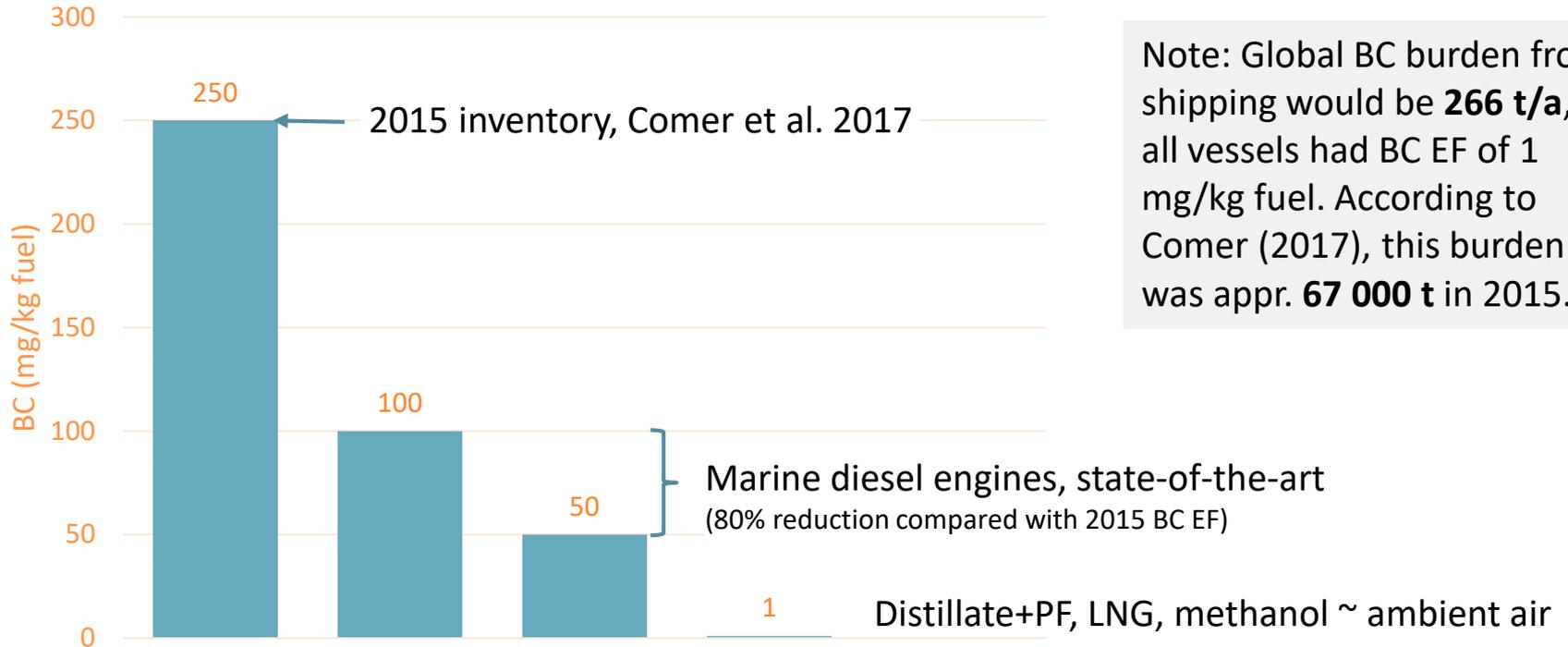*The Study was commissioned and financed by the Finnish Transport Safety Agency Trafi*

VTT

1

# Contents

VTT

# Objective

- Evaluation of the BC results obtained using methods  selected by IMO (FSN, PAS, LII)
- Fuel comparisons criteria: fuels studied in the same engine over one measurement campaign
- Scrubber comparison criteria: measurements before and after scrubber
- New data available after PPR 5/INF.7, for example, new scrubber studies

# BC emission factors (BC EF)



BC (mg/kg fuel)

250 — 2015 inventory, Comer et al. 2017

Marine diesel engines, state-of-the-art
(80% reduction compared with 2015 BC EF)

Distillate+PF, LNG, methanol ~ ambient air

Note: Global BC burden from shipping would be **266 t/a**, if all vessels had BC EF of 1 mg/kg fuel. According to Comer (2017), this burden was appr. **67 000 t** in 2015.
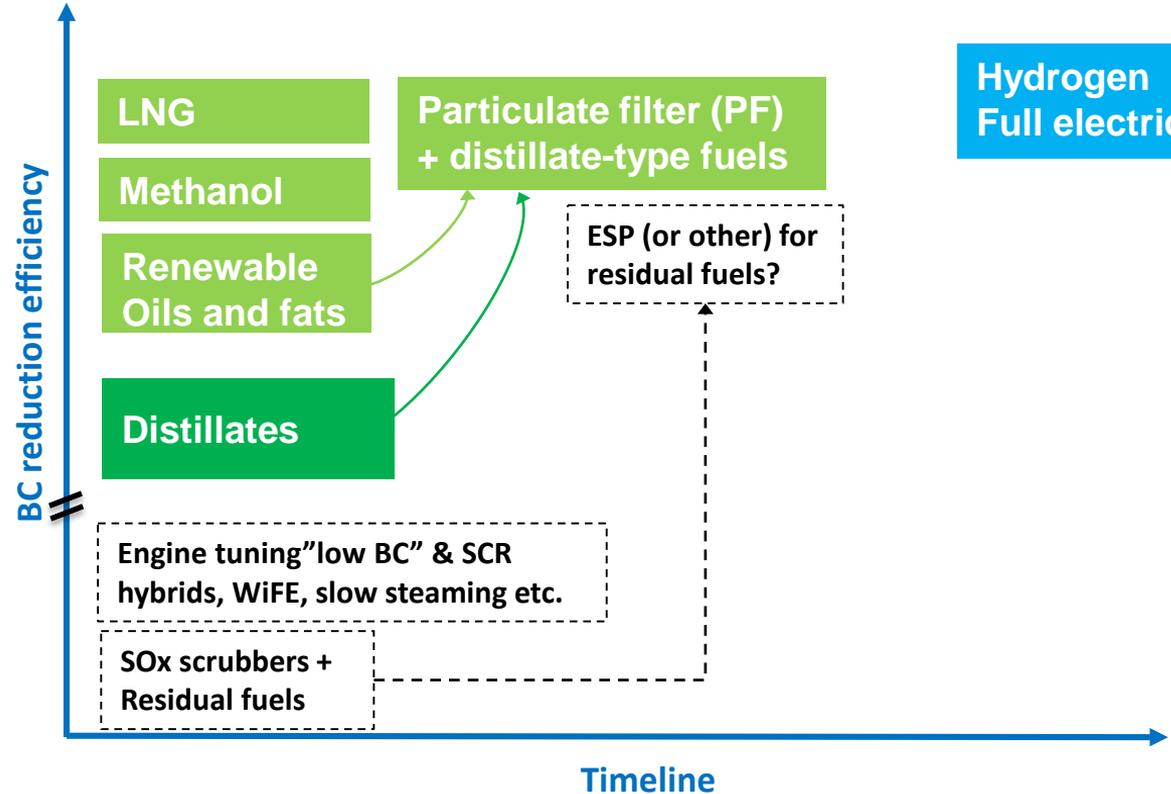
# BC control options for MSD and SSD

**LNG or methanol** (DF or Otto) are commercial technologies.

**Particulate filters (PF)** require **distillates/renewables** having low sulphur and ash contents.

**Hydrogen/full electric** offers zero BC emissions. Presently limited use/demonstrations.

**BC reduction potential uncertain** for "Low BC" tuning + SCR, hybrids (retrofit), WiFE, slow steaming.

**Minor/inconsistent** BC reduction using present $SO_x$ scrubbers (if not further developed).

**BC reduction efficiency**

LNG

Methanol

Renewable Oils and fats

Distillates

Particulate filter (PF) + distillate-type fuels

Hydrogen Full electric

ESP (or other) for residual fuels?

Engine tuning"low BC" & SCR hybrids, WiFE, slow steaming etc.

SOx scrubbers + Residual fuels

**Timeline**

VTT 2018

Dashed lines = BC reduction potential limited or not evidenced

5

# Marine fuels in the Arctic and globally

| Ship type (present) | Container ships, bulk carriers, oil tankers | Ferries, cruisers, RoRo, RoPax, passenger | Fishing vessels | |
|---|---|---|---|---|
| Engine type (present) | Mainly slow speed diesel (SSD), 2-stroke | Mainly medium speed diesel (MSD), 4-stroke | Mainly high-speed diesel (HSD) | Total |
| Marine fuel in the Arctic (geogr.) | Residual 1.63 mt<br>Distillate 0.08 mt | Residual 0.63 mt<br>Distillate 0.63 mt | Mainly distillates 2.4 mt | 5.4 mt (Winther 2017) |
| Marine fuel in the Arctic (Polar code) | 0.202 mt | 0.045 mt | 0.114 mt (other 0.075 mt) | 0.44 mt (Comer 2017) |
| Marine fuel globally | Residual 181 mt<br>Distillate 12 mt<br>LNG 0.03 mt | Residual 26 mt<br>Distillate 21 mt<br>LNG 2.3 mt | Residual 0.5 mt<br>Distillate 14 mt<br>LNG 0 mt | 266.3 mt ~10% of transport fuels (Comer 2017) |
| Comment on BC control using present fuels | Mainly residual fuels today → Challenging to reduce BC without fuel switch. | Appr. 50% of fuels distillates → PF option relevant. Also fuel switching needed. | Mostly distillates used → PF feasible. Also other options available. | |

VTT

# BC detection limit (DL) and significant BC differences

## Detection limits (DL)

- AVL 415 SE DL 20 µg/m$^3$ = appr. 0.00054 g/kg fuel (FSN 0.002, resolution 0.001). Anticipated update from AVL DL 2 µg/m$^3$.

- PAS and LII: DL 1 µg/m$^3$.

- DLs are below visibility limit and ambient PM (e.g. 20 µg/m$^3$ ~ 1/10 of the visibility)

→ **These DLs are appropriate**

## Signifigant BC differences?

BC repeatability **<0.016 g/kg fuel** (0.5 mg/Sm$^3$, 0.003 g/kWh) **at BC level >0.032 g/kg fuel** (>1 mg/m$^3$) found by Aakko-Saksa et al. (2016)

| | FSN | g/kWh | BC g/kg fuel | mg/Sm$^3$ |
|---|---|---|---|---|
| **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 (dieselnet)** | | | 0,0124 | |

Uncertainty of the BC measurements
a) instrumental uncertainty
b) engine exhaust stability.

| Id, engine | Fuel | Exhaust aftertreatment | Reference |
|---|---|---|---|
| UCR T1: small engine | DMA, RMB, RMG | No | Johnson 2016 |
| UCR T2: on-board, modern vessel | DMA | No | Johnson 2016 |
| UCR T3: on-board, container vessel, 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 | | 31, 32, 33, 34, 35 = HSD |
| FI-1: Testbed, MSD 1.6MW | HFO, HFO 0.5%S, MDO, Bio30 | | WP1, Aakko-Saksa 2016, PPR4/9/2, PPR4/9/3, PPR4/INF.7 |
| FI-2: On-board, modern cruise vessel, 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 vessel, 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 |

Other studies than those using FSN, PAS and LII principles evaluated as supporting data

IMO selected BC methods also in Lauer 2017, 2012, Buffaloe 2014 (plume study), Ristimäki 2010, Sarvi 2009, Stojcevski 2016.

# Fuel technologies

- General
- Renewable fuels
- Liquid hydrocarbons
- Vegetable oils and animal fats
- LNG
- Methanol
- Future options
- Fuel additives: WiFE, metals (colloidal catalysts)

# Marine fuels

## Marine fuels in ISO 8217

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

- **Distillate DMA** (called marine gas oil, MGO) free from residual fuel. Category 1 (< 5 L/cylinder) engines.

- **Distillate DMB** (marine diesel oil, MDO), traces of residual fuel. Category 2 (5-30 L/cyl) and 3 (≥ 30 L/cyl) engines.

- **Hybrid fuels** (<0.10%S) may have some fuel properties resembling residual fuels (Wright 2016).

  Note: <0.1%S residual fuel not "clean" (may contain ash, PAHs etc.)
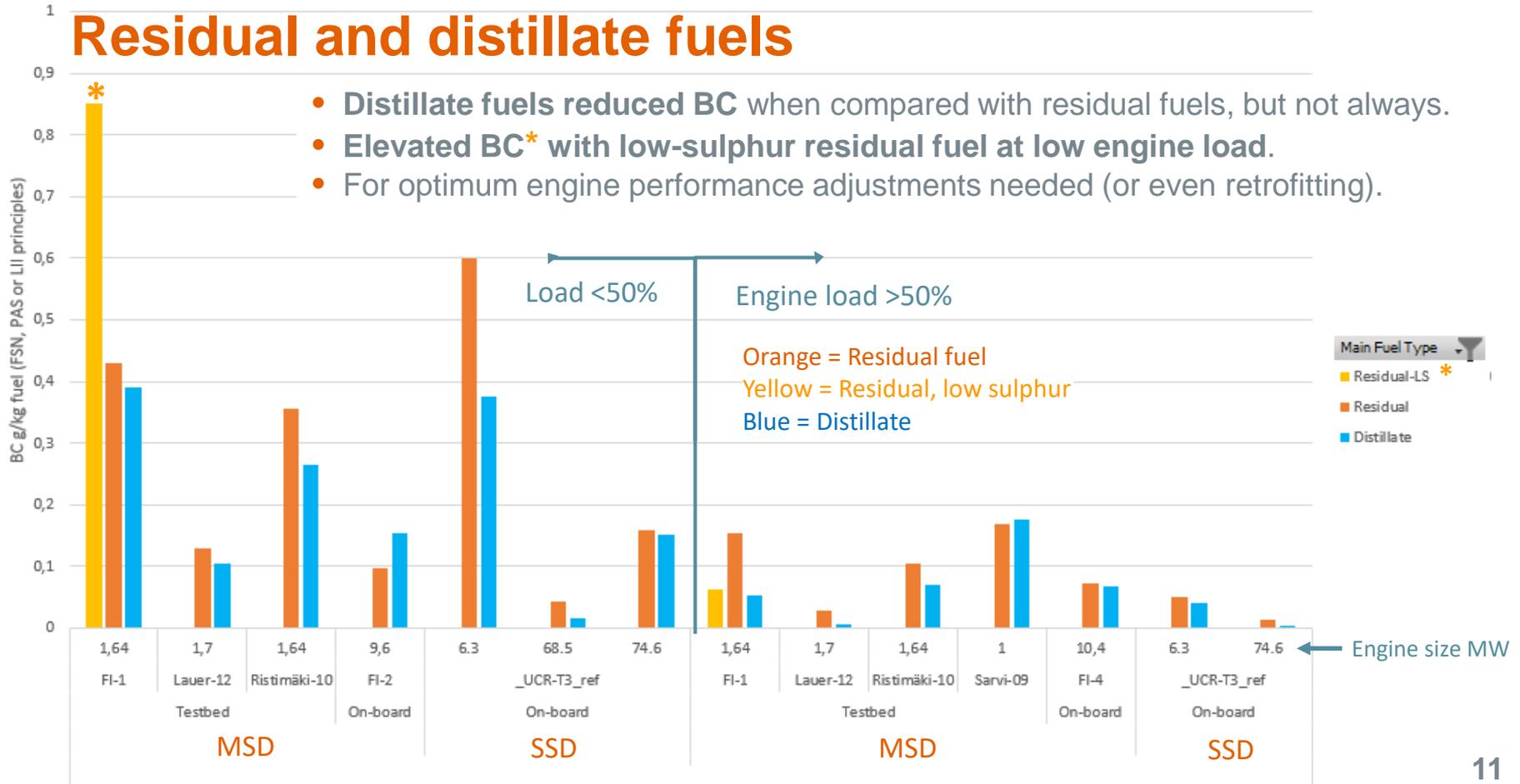
## Renewables can replace their fossil counterparts

- **Renewable liquid diesel-type fuels**
  - HVO, GTL, BTL, XTL
  - Vegetable oils and fats (FA) and their methyl esters (FAME)

- **Renewable methane**: similar to **LNG**.

- **Renewable methanol** e.g. retrofitting diesel engines.

- **Renewable hydrogen**.

  Note: renewable fuels are sulphur-free (possible impurities in unesterified FA)
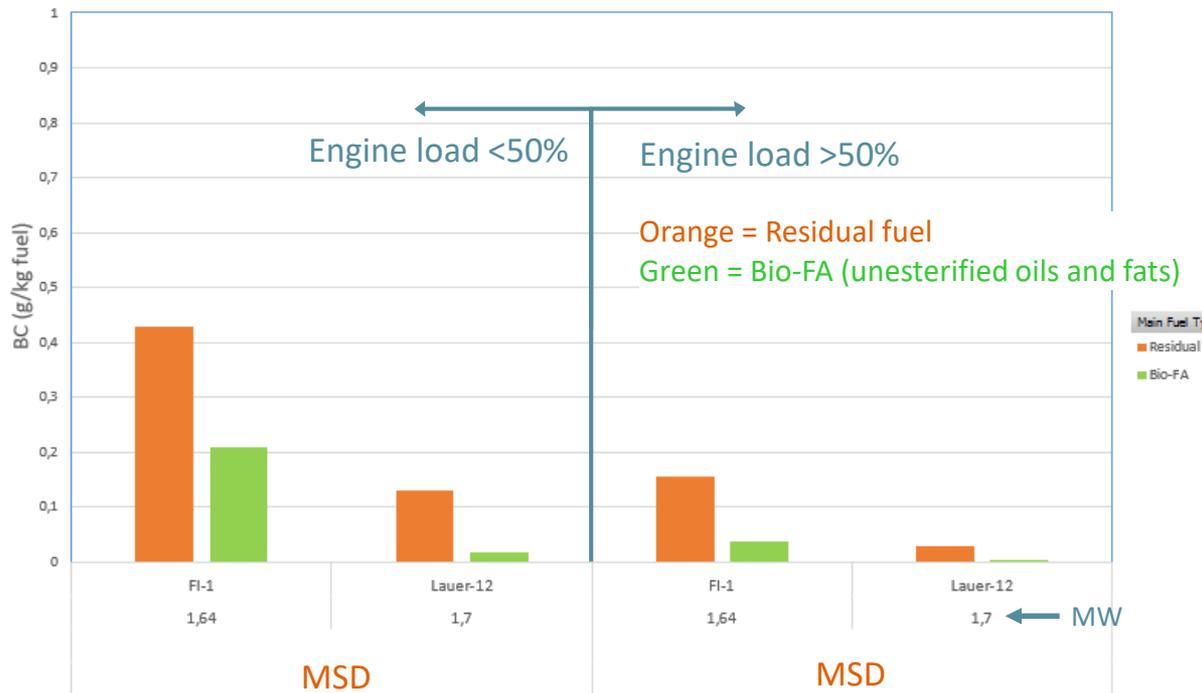
# Residual and distillate fuels

- **Distillate fuels reduced BC** when compared with residual fuels, but not always.
- **Elevated BC* with low-sulphur residual fuel at low engine load**.
- For optimum engine performance adjustments needed (or even retrofitting).

Load <50%   Engine load >50%

Orange = Residual fuel
Yellow = Residual, low sulphur
Blue = Distillate

Main Fuel Type
Residual-LS *
Residual
Distillate

Engine size MW

BC g/kg fuel (FSN, PAS or LII principles)

# Vegetable oils and animal fats

Unesterified oxygen-containing biofuels (fatty acids=FA) **reduced substantially BC** compared to residual fuels.

*Unesterified oils and fats can be used in the MSD and SSD marine engines. For use in HSD engines, FA needs transesterifation (fatty acid methyl esters = FAME, biodiesel).*



Engine load <50%

Engine load >50%

Orange = Residual fuel
Green = Bio-FA (unesterified oils and fats)

BC (g/kg fuel)

Main Fuel Type
Residual
Bio-FA

FI-1
1,64

Lauer-12
1,7

FI-1
1,64

Lauer-12
1,7 ← MW

MSD

MSD

# Paraffinic fuels (HVO, GTL, XTL)

- For 2 inland ships, tests comparing paraffinic fuel (GTL) with diesel (EN590) showed PM reduction from 16 to 60% and smoke reduction of 32% (Verbeek 2014).

- One plume study on HSD showed increased BC with paraffinic HVO (Betha 2018). We note that engine load seemed not comparable between fuels.

- A number of heavy-duty studies show lower soot for paraffinic fuels (e.g. HVO) than for conventional aromatic diesel explained by higher hydrogen/carbon ratio of paraffinic fuels.



*Burning of conventional diesel (left) and paraffinic diesel (right). Ref. ASFE*

# LNG DF

- **LNG DF: Extremely low BC emission in all engine sizes tested: 0.001-0.010 g/kg fuel**, except 0.083 g/kg fuel for one SSD engine (EUROMOT Annex 7).

- For LNG use, investments in ships and harbour infrastructure, as well as safety measures and space for tanks needed.

- *When distillate is main fuel in DF, BC emission is similar to diesel engines (Aurela et al. 2018).*
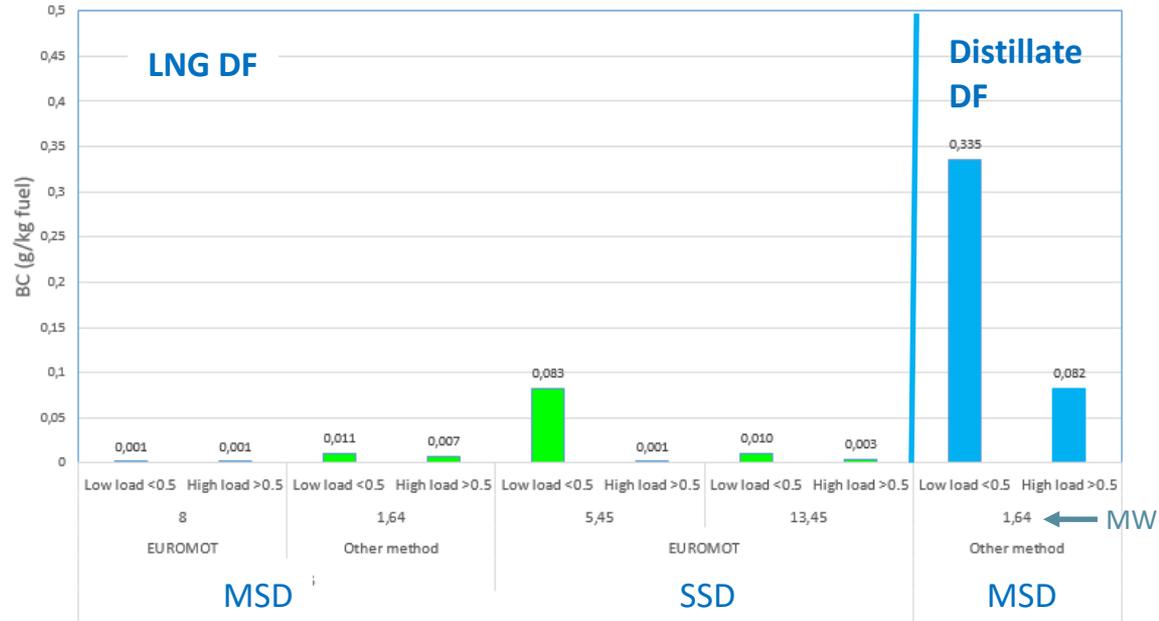
# Methanol

- Engines for methanol use are commercial and diesel engines can be retrofitted.

- When diesel fuel is a main fuel in the DF engine, BC emissions are similar to diesel engines.

- Methanol is liquid fuel produced from natural gas. Modified harbour infrastructure and safety measures are needed. Availability of methanol in short-term is a question.

- When methanol DF is compared with distillate fuel use in DF engine, BC reduction is 55-75% depending on pilot injection (Stojcevski 2016). Data on BC using methanol is scarse.
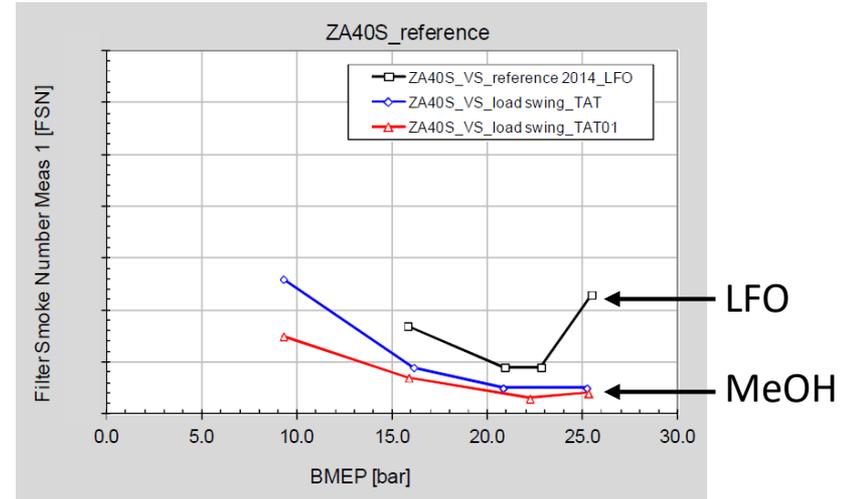


Figure from Stojcevski (2016).

Methanol DF results also in Haraldson (2015).

# Other fuel remarks

## Hydrogen Demonstrated in fuel cells.

## Dimethyl ether (DME)

**Gaseous fuel,** appropriate for diesel combustion. Manufactured from NG or methanol. Distribution infra and vehicles needed (demos in China and Japan).

## Ammonia

**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 e.g. in SCR. In principle, ammonia could be used in modified internal combustion engines or fuel cells.

## Nuclear Power No comments.

## Water-in-fuel emulsions (WiFE)

WiFE was developed for vehicles to reduce $NO_x$, e.g. PuriNOx, 20% water. **Water is not soluble in diesel fuel → emulsifier additive, or direct injection of water needed**. Wear of engine and stability of emulsion are of concern. Refs. CIMAC 2012; Noll 2002; US EPA 2002; Yoshimoto 2001.

**WiFE for marine engines:** 45-50% BC reductions (ICCT 2017) or 50-90% (PPR 5/INF. 7). In engines equipped with conventional fuel injection, BC may reduce at low load. At high loads this can be offset (CIMAC 2012).

## Fuel-borne metals, "colloidal catalysts"

Vanadium in HFO may catalyze BC combustion (IMO 2015). In automotive sector, this kind of metals are called "fuel-borne catalysts". **Heavy metals are negative features in fuels** as many of them are toxic and cause harmful health and environmental effects.

# Exhaust gas aftertreatment

- $SO_x$ scrubbers
- Particulate filters
- ESP, bag filters
- Diesel oxidation catalysts

# Particulate filters (PF): challenges

▪ **Automotive DPFs not suitable when using marine fuels**. High sulphur and metal contents of fuels clogg filter pores. Fuel sulphur should be <0.05%; attempts to tolerate <0.2% sulphur content.

• **Filter size and back-pressure are of concern**. Tolerable pressure drop max. 30–50 mbar to protect turbocharger (100 mbar on-road).

• **Regeneration is challenging.** Passive regeneration with oxidation catalyst is difficult due to low exhaust temperature and $SO_2$ poisoning effect. Also $SO_3$ prohibit $NO_2$ formation. Active regeneration with burners require large and complex installations.

• **Removal of ash accumulated in PF is challenging.**

• **Reliability and durability are challenging**.

Refs. Johansen, K. (2015), Køcks, M. et al. (2017), CIMAC (2012), Corbett et al. (2010), Mayer et al. (2011)

# Particulate filters (PF): demonstrations

- Mitsui O.S.K. PF on ferry, 9 MW, IFO. **PM removal 80%,** 500 h. Regeneration not indicated. 2012.

- ECO-Jet. Sulphur-resistant $Pd/V_2O_5$ filter catalyst combusts soot, CO, and HC, PAHs. Catalyst-assisted passive soot regeneration, reverse pulse flow ash removal. Validation on cruise ship Queen Victoria, HFO (1%S), SCR and open flow scrubber. **PM filtration 80–92%.** Continuation not announced.

- Dinex F-SCR: integrated particle filter and SCR. A Danish inland ferry, marine diesel 0.1%S. **PN reduced >90%.** Efficiency drop during the day, better regeneration needed.

*Reliable, durable and proven PF system is not commercially available for marine engines using marine grade fuels. Such systems are demonstrated using clean distillate fuels. Backpressure and regeneration are challenging. Sulphur limit of 0.5% for marine fuels in 2020 will probably not provide sufficient fuel quality for filter technology.*

Refs. Johansen, K. (2015). Køcks, M. 2017 ETH.

# Electrostatic precipitators (ESP) and bag filters (BF)

**ESPs and BF from land-based industries not directly applicable for ships.** Large and rather expensive. Removal of <0.1μm particles challenging; as well as gas humidity and sticky oil droplets. Electrostatic fibrous filter (EsFF) mainly for indoor air.

**Wet Electrostatic Scrubbers (WES),** the Heterogeneous Condensation Scrubber (HCS) and the Bubble Towers (BT): WESP is ESP with wet walls, from which particles collected. Simple, low pressure drop, removal of soluble gases. Pilot (FP7 DEECON) **PM removal of 70-95%** at 0.01–0.5μm and $SO_2$ >56%, 200 kW engine, fuel 2%S. In HCS, particles enclosed in water droplets led to scrubber and bubble towers (high pressure drop).

*ESPs and bag filters are not commercially available for marine solutions.*

*Refs. Di Natale and Carotenuto 2015.*

# Particles are difficult to remove using scrubbers from diesel engine exhaust

$SO_x$ scrubbers are not designed for PM removal. Scrubbers could reduce large particles by sufficient inertia and small particles by Brownian diffusion and phoretic effects.

**Mass of diesel particles is mainly in size class (0.05-0.2 µm) that is difficult to remove by scrubbing (Greenfield gap).**

Refs. Mussatti 2002, Carotenuto et al., 2010b, Gregory, 2012 in Di Natale and Carotenuto 2015, Cherrier et al. 2017, Hesketh 1996.

**PM removal efficiency improves by**
- Increasing liquid-to-gas mass ratios.
- Using venturi (already used).
- Sticky and/or hygroscopic particles easier than dry particles.
- Reducing or growing size of soot particles
- Improving PM capture increases pressure drop.

Table in Mussatti (2002). Cut diameter = the collection efficiency of 50% with the scrubber.

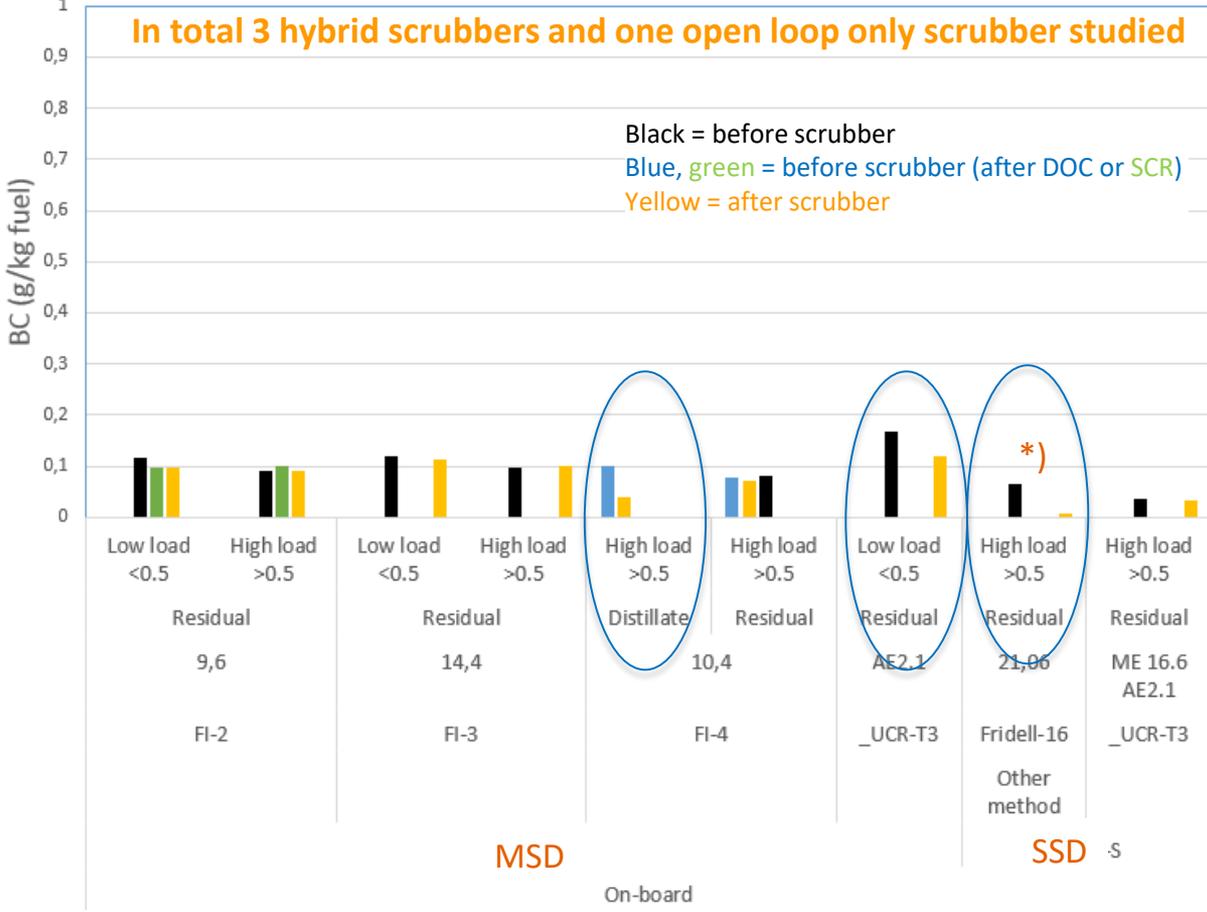| Scrubber Type | Pressure Drop (in. $H_2O$) | L/G Ratio (gal/1000 acf) | Liquid Pressure (psig) | Gas Velocities (ft/sec) | Cut Diameter (µm) |
|---|---|---|---|---|---|
| Spray Tower | 0.5-3 | 0.5-20 | 10-400 | 10 | 2-8 |
| Cyclonic | 2-10 | 2-10 | 10-400 | 105-140b | 2-3 |
| Venturi | 10-150 | 2-20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

1

# BC before/after scrubber

**BC reduction clear in 2 cases of 8 (or 3 cases of 9):** FI-4 distillate & UCR-T3 MSD at low load (& Fridell-16*).

Alfa Laval PureSOx different results in two studies → **scrubber type not determining**

BC reduction for a MSD, but not for three other MSDs. Slight BC reduction for SSD+MSD, but high for one SSD*) → **engine type (SSD, MSD) not determining**

VTT 2018



In total 3 hybrid scrubbers and one open loop only scrubber studied

Black = before scrubber
Blue, green = before scrubber (after DOC or SCR)
Yellow = after scrubber

*) A study by Fridell and Salo (2014) is shown although they did not use the IMO selected methods: BC reduction of 89% over scrubber. RoRo, SSD 21.06 MW, **Alfa Laval PureSOx** scrubber. BC measured by a soot scan transmissometer.

# Diesel Oxidation Catalysts (DOCs)

- DOCs are common in automotive diesel engines. DOC removes organic species in exhaust, also those associated with PM, but not BC, by default.
- Also in study "FI-4", **DOC did not reduce BC from marine engine exhaust**.
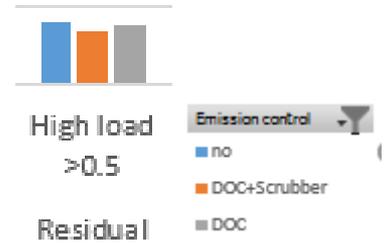


# Selective Catalytic Reduction (SCR)

- SCR is designed for NOx reduction, not for PM reduction.
- Very large particles would be captured by SCR, but they are typically not present in diesel exhaust.
- In study "FI-2", **no significant change in the BC emission was observed over SCR** (Fig. on the right side).

# Engine technology

- Size
- Speed
- Load
- Injection
- Low BC tuning & SCR
- EGR
- Hybrids/alternative powertrains

Low engine loads e.g. in coast/ports and in the Arctic routes.

VTT

# Engine technology

## SMALL ENGINES EMIT HIGHER BC
- For <4MW, BC high at low loads: 0.1-0.5 g/kg fuel. BC for >4 MW in most cases <0.1 g/kg fuel.

## HSD EMIT HIGH BC
- HSD engines emit higher BC (0.1- 0.5 g/kg fuel) than SSD and MSD engines in most cases.

## INJECTION SYSTEM AFFECT LOAD-DEPENDENCE OF BC
- Engines having mechanical fuel injection emith high BC at low loads (e.g. up to 0.5 g/kg fuel).
- Low BC with modern injections systems regardless of engine load, e.g. common rail (CR).

## INJECTION slide valves for 2-stroke engines
- Slide valves can be retrofitted in some old 2-stroke engines.
- Needle sac volume already reduced for 4-stroke engines, further potential hardly left (CIMAC 2012).

*Note: Exceptionally high BC in some studies (3 engines and 2 plume studies, BC 0.3-0.75 g/kg fuel).*

## The BC emissions from different engine types

# Low BC tuning & SCR

**Low PM tuning through in-cylinder technology combined with SCR → Low PM/BC & NO$_x$.** Also $CO_2$ and fuel consumption reduces.

Without SCR, 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 NOx limits are higher for SSD than for MSD engines. Thus SSD engines can already be tuned towards lower PM than MSD.*
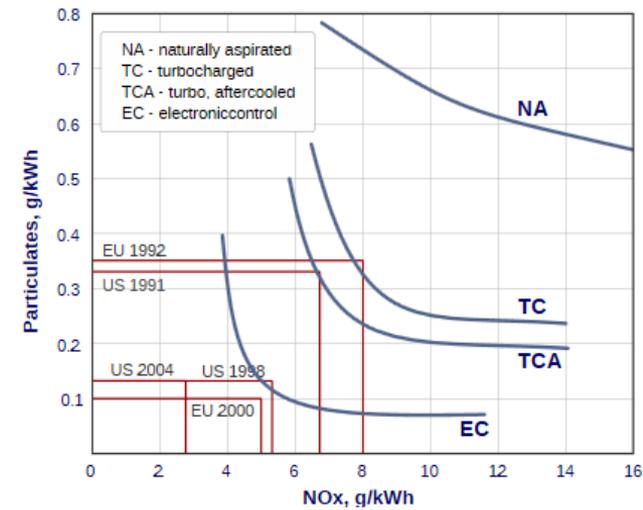


NOx/PM trade-off: evolution of emission technology in heavy-duty diesel engines in the 1990s. (Needham 1991).



Marpol Annex VI NOx limits
(https://www.dieselnet.com/standards/inter/imo.php)

7
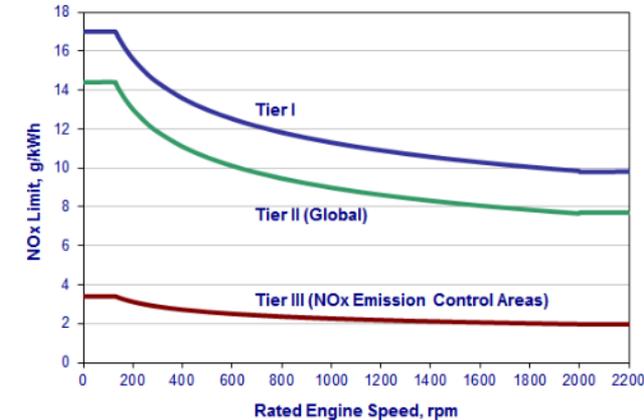
# BC emission control measures
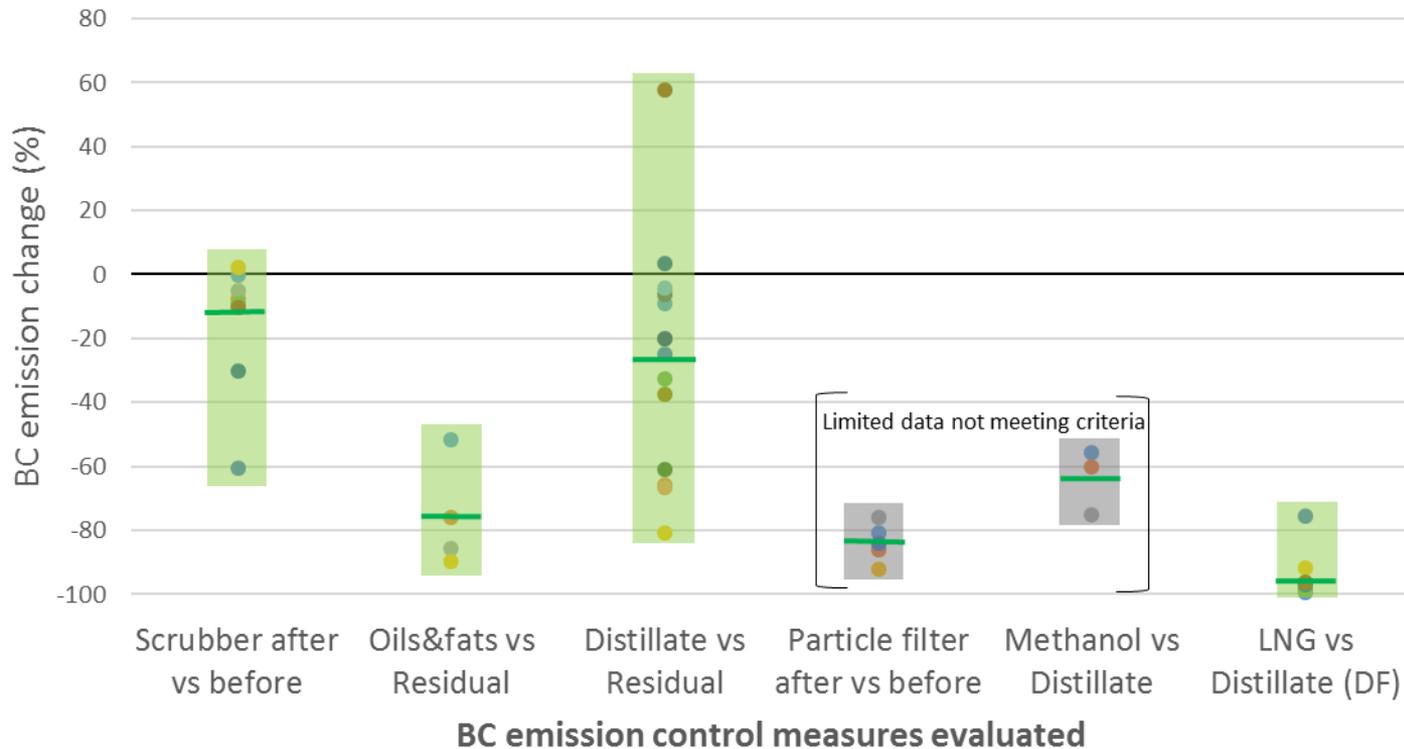


One marker illustrates a data point of comparison. Green line is an average of data points.

28

# Comparison with PPR 5/INF. 7

## Alternative fuels and fuel switching

- **LNG:** BC red. **94%** vs **>85%** PPR 5/INF. 7.
- **Methanol:** BC red. **55-75%** vs **>97%** PPR 5/INF. 7
- **Biofuel (oils and fats):** BC red. **76%** vs **50-75%** PPR 5/INF. 7
- **Distillates:** BC red. **26%** vs **33%** PPR 5/INF.7.

## Exhaust treatment

- **Particulate filters:** short demos, no BC data, soot red. in Johansen (2015) **76-92%**. vs **85% or >99%** in PPR 5/INF.7.
- **SOx scrubbers:** BC red. in 2 of 8 cases, average **15%** vs **38% or 45%** in PPR 5/INF.7

## Engine and propulsion system

- "Low BC" tuning + SCR; Hybrids (retrofit) for old engines; Slow steaming. BC reduction potential?



IMO INTERNATIONAL MARITIME ORGANIZATION

E

SUB-COMMITTEE ON POLLUTION PREVENTION AND RESPONSE
5th session
Agenda item 7

PPR 5/INF.7
29 November 2017
ENGLISH ONLY

CONSIDERATION OF THE IMPACT ON THE ARCTIC OF EMISSIONS OF BLACK CARBON FROM INTERNATIONAL SHIPPING

An update to the investigation of appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping

Submitted by Canada

Table 2  Summary of BC abatement technologies from this update

| BC Reduction Strategies | BC Reduction | Drawbacks |
|---|---|---|
| LNG | 93.5% | New engine investment |
| DPF - Low Sulphur Fuel | ≥99% | Economic Incentives |
| DPF - High Sulphur Fuel | 85% | Technology maturity |
| WiFE | 70% | Technology maturity |
| Scrubbers - High Sulphur Fuel | 45% | Retrofit + capital and maintenance costs |
| Scrubbers - Low Sulphur Fuel | 37.5% | Retrofit + capital and maintenance costs |
| HFO – Distillate | 33% | Increased fuel costs |
| Slow Steaming – De-Rating | 15% | Complex fleet dynamics |
| **Alternative Fuel Strategies** | | |
| Biodiesel – 100% | 50-75% | |
| Biodiesel Blend – 20% | 10-30% | |
| Methanol – DME | 97% | |
| Nuclear | 95% | |
| **Engine Options** | | |
| Slide Valves | 10 – 50% | |
| **Exhaust Treatment** | | |
| Electrostatic Precipitators | 10 – 90% | |
| Selective Catalytic Reduction | 0 – 30% | |

# Conclusions

- **LNG DF** showed extremely low BC emissions. **Methanol DF** also had low BC emissions.

- **Biofuels containing oxygen** reduced BC emissions compared with residual fuel.

- Very low BC emissions could be achieved using **particulate filters, however, only when combined with distillate-type fuels (or renewables).**

- **SO$_x$ scrubbers** did not reduce BC significantly in the most cases studied.

- Engine tuning (low BC&SCR) and e.g. retrofit solutions reduce BC, but quantification is difficult.

- Zero BC emissions for **full electric and hydrogen/fuel cell solutions**.

# References

Aakko-Saksa, P. et al., 2017. Black carbon emissions from a ship engine in laboratory (SEA-EFFCETS BC WP1),

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

ASFE, Paraffinic fuels for Europe, http://www.synthetic-fuels.eu

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, 51(2), pp.123–134. Available at: http://dx.doi.org/10.1080/02786826.2016.1238034.

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.

Cherrier, G. et al., 2017. Aerosol particles scavenging by a droplet: Microphysical modeling in the Greenfield gap. Atmospheric Environment, 166, pp.519–530.

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 combustion engines. Available at: http://www.cimac.com/cms/upload/workinggroups/WG5/black_carbon.pdf.

Bryan Comer et al, Heavy Fuel Oil Use in Arctic Shipping in 2015, ICCT, 1 (2016).

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

Corbett, JJ. Wt al. 2010. "An Assessment of Technologies for Reducing Regional Short-Lived Climate Forcers Emitted by Ships with Implications for Arctic Shipping." Carbon Management 1(2): 207–25.

Dieselnet, www.dieselnet.com.

EUROMOT data, IMO PPR 4/9

Haraldson, L., 2014. Methanol as a Marine Fuel - Engine manufacturers' perspective. In Methanol as a marine fuel Seminar, 8 May 2014. Gothenburg, p. 46.

IMO (2015) International Maritime Organization, Investigation of Appropriate Control Measures (Abatement Techonologies) to Reduce Black Carbon Emissions from International Shipping.

IMO Documents: PPR 4/9 (EUROMOT), PPR4/9/2, PPR4/9/3, PPR4/INF.7, PPR5/7/2, PPR5/INF.7

Johansen, K., 2015. Multi-catalytic soot filtration in automotive and marine applications. Catalysis Today, 258(x), pp.2–10. Available at: http://dx.doi.org/10.1016/j.cattod.2015.06.001.

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

Køcks, M. et al., 2017. Shipboard characterization of a combined particle filter and NO x -reducing technology: Influence on particle number concentration, particle size distribution and gas emissions.

Lauer, P., 2017. Black Carbon Emission of Marine Diesel Engines Black Carbon. In ICCT 4th BC Workshop, 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.

Mayer, A., Czerwinski, J., Bonsack, P., Karvonen, L. et al., "DPF Systems for High Sulfur Fuels," SAE Technical Paper 2011-01-0605, 2011.

Moldanova, J. et al., 2013. SI: Physical and chemical characterisation of PM emissions from two ships operating in European emission control areas. Atmospheric Measurement Techniques, 6(12), pp.3577–3596.

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. Available at: http://www.epa.gov/ttn/catc/dir1/cs6ch2.pdf.

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

Ntziachristos, L. et al., 2016. Particle emissions characterization from a medium-speed marine diesel engine with two fuels at different sampling conditions. Fuel, 186, pp.456–465. Available at: http://dx.doi.org/10.1016/j.fuel.2016.08.091.

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.

Ristimaki, J., Hellen, G. & 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.

Sarvi, A., Fogelholm, C.J. & 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.

Stojcevski, T., Jay, D. & Vicenzi, L., 2016. Methanol Engine in a Ferry Installation. 28th CIMAC World Congress, (Paper 099), p.13.

Teinilä, K. et al., 2018. Effect of aftertreatment on ship particulate and gaseous components at ship exhaust.

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

Verbeek, R., Downstream, S. & Nederland, C., 2014. Assessment of pollutant emissions with Shell GTL fuel as a drop in fuel for medium and heavy-duty vehicles , inland shipping and non- road machines.

Winther, M. et al., 2017. Emissions from shipping in the Arctic from 2012-2016 and emission projections for 2020, 2030 and 2050, Available at: http://dce2.au.dk/pub/SR252.pdf.

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

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.

**VTT**

# Thank you

*The Study was commissioned and financed by the Finnish Transport Safety Agency Trafi*

*paivi.aakko-saksa@vtt.fi*
*jorma.kamarainen@trafi.fi*
*anita.makinen@trafi.fi*

# Other remarks

- **Exhaust Gas Recirculation (EGR)** reduces $NO_x$ but at the same time EGR tends to increase soot/BC emission, if BC reduction technology is not combined.

- **Engine maintenance** affect the exhaust emissions, also BC. However, it is not actual BC control method, it is rather a method to avoid excess BC slip.

- **Hybrid/energy storage:** Hybrid technologies e.g. batteries or fuel cells (FC) combined with diesel engines could alleviate increased BC at low loads from old engines (however, most feasible for new-builds). Hybrids reduce BC also through increasing energy efficiency, as well as turbochargers (TC) and an Organic Rankine Cycle, wind propulsion and solar energy. (Di Natale and Carotenuto 2015)

- **Full battery/FC electric:** Full battery/fuel cell electric systems are used/demonstrated in some vessels travelling short distances. However, their potential as the main power source for ocean-going vessels remains to be seen.

# BC control options discussed

**1.   Fuel type (Alternative Fuels)**

Liquefied Natural Gas (LNG), Distillate Fuel, Biodiesel, Methanol, *Nuclear Power, Hydrogen, Ammonia,* Other Renewable Fuels

**2.   Fuel Treatment**

Water-in-fuel Emulsions (WiFE), *Colloidal Catalysts*

**3.   Exhaust Gas Treatment**

Diesel Particulate Filters (DPF), Exhaust Scrubber (Exhaust Gas Cleaning System EGCS), Exhaust Gas Recirculation (EGR), Electrostatic Precipitators (ESP), *Selective Catalytic Reduction (SCR), Diesel Oxidation Catalysts (DOCs), EGR with Scrubbers, SCR+DPF*

**4.   Engine and Propulsion System Design**

*Engine Stroke Type, Slide Valves, Engine rating,* Engine control technology, *Full battery electric, Hybrid/energy storage*

**5.   Ship Design** *Improving Energy Efficiency*

**6.   Operational Measures**

Slow Steaming, Engine Load, *Voyage optimization, Training, Trim optimization, Adaptive engine/condition based maintenance*

**7. Regulatory Measures**

*More ECAs, Residual Fuel ban, BC emission standard, Include BC in GHG strategies, 0.50% Global Fuel Sulphur Cap, Engine Tier*

**8.   Other Measures** *Scrappage & Shore Power*