January 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

Conseil International des
Machines à Combustion

CONSEIL INTERNATIONAL
DES MACHINES A COMBUSTION

INTERNATIONAL COUNCIL
ON COMBUSTION ENGINES

CIMAC was founded in Paris in 1951 where the first Congress took place. Originally CIMAC was organized as an industry event to discuss new ideas and developments within the engine and components industry together with institutes and universities.

It is supported by engine manufacturers, engine users, technical universitites, research institutes, component suppliers, fuel and lubricating oil suppliers and several other interested parties.

The National Member Associations (NMAs), National Member Groups (NMGs) and Corporate Members (CMs) as well as previous CIMAC Recommendations are listed at the end of this publication.

This document has been elaborated by the CIMAC Working Group 'Exhaust Emissions Control ' in January 2012.

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FOREWORD

Reports published by the Intergovernmental Panel on Climate Change (IPCC) have summarized the CO_2 being the most important greenhouse gas and therefore this component has been most in focus so far with regard to reduction efforts.

In addition to CO_2, aerosols are also affecting the climate. Unlike CO_2 and other warming gases, aerosols (e.g. sulphates) tend to cool the climate by reflecting light back to space before reaching the surface of earth. Black carbon (BC), however, absorbs light effectively, thus having an opposite and warming contribution.

The heating power absorbed by black carbon particles in the atmosphere reduces the radiation that reaches the earth surface. Depending on the underlying surface, e.g. snow, ice or sand and black carbon deposits, the net heating power for the surface is defined.

Discussions have started up among regulators, including International Maritime Organization (IMO), about the need and potential for restricting black carbon emissions as a measure for abating global warming. At IMO the Arctic region is especially in focus as black carbon deposits on ice and snow are expected to cause accelerated ice/snow melting (decreased albedo effect).

In order to facilitate the discussion, this CIMAC document was developed by the CIMAC Working Group 5 “Exhaust Emissions Control” for providing background information on black carbon emissions from large marine and stationary diesel engines. Definition, measurement methods, typical emission factors and proposed and potential abatement technologies are covered and discussed.

CIMAC Working Group 5 wants to thank especially Dr. Jyrki Ristimäki / Wärtsilä for his contribution to the development of this document.

Table of Contents

1. Definition of black carbon

The **term "black carbon (BC)"** does not have a distinct definition and is often considered as a synonym for soot. Black carbon is used when optical properties such as light adsorption of atmospheric aerosols is discussed. The term "soot" is commonly used for black, mostly solid carbonaceous material originating from combustion sources. However, soot can contain organic carbon (OC) and minerals (ash) in addition to elemental carbon (EC).

Measurement of light adsorption of smoke particles is not straight forward as several parameters are affecting the measurement result[i,ii] (light wavelength, etc). Additionally, black carbon refers mainly to pure carbon but some of the organic carbon can adsorb light.These light adsorbing organic components are usually called "brown carbon". The **term "Light-absorbing carbon (LAC)"** has been used in literature[iii] to cover all light adsorbing carbonaceous components contributing to global warming. Due to the small differences in the definitions, the term "black carbon" is often used instead of light absorbing carbon.

The Intergovernmental Panel on Climate Change (IPCC) sometimes uses the term "absorbing aerosols" and recognizes these particles as one of the important warming Short Lived Climate Forces (SLCF)[iv] . However, the IPCC often uses the term "black carbon" as a general term for these components.

2. Measurement methods

As discussed above black carbon is determined by its light absorbing capability resulting in black colour. As the definition is based on light absorption, black carbon should be measured by optical means. Optical measurements based on **filter darkening** or **photoacoustic methods** can be utilized. Several different types of filter darkening based techniques exist. Some rely on reflectance, some on transmittance and some measure both. The filter darkening method is widely used today by the engine industry (Bosch/ Filter Smoke Number (FSN) value) and is standardized in ISO 10054 and in ISO 8178, Part 3. Photoacoustic methods measure the sound, light adsorbing particles make when they are heated by laser light. Typically different measurement techniques give different results[v].

It should be noted, though, that the light absorption capability of carbon particles also depends on possible condensed compounds on the particle[vi] and the light wavelength used for the measurement[vii]. An example of mass adsorption dependence on wavelength is shown in Figure 1 (fixed particle size) – in practice this means that we get different result depending on the light wavelength used by the instrument. Additionally, coating of the particle alters the wavelength dependency.

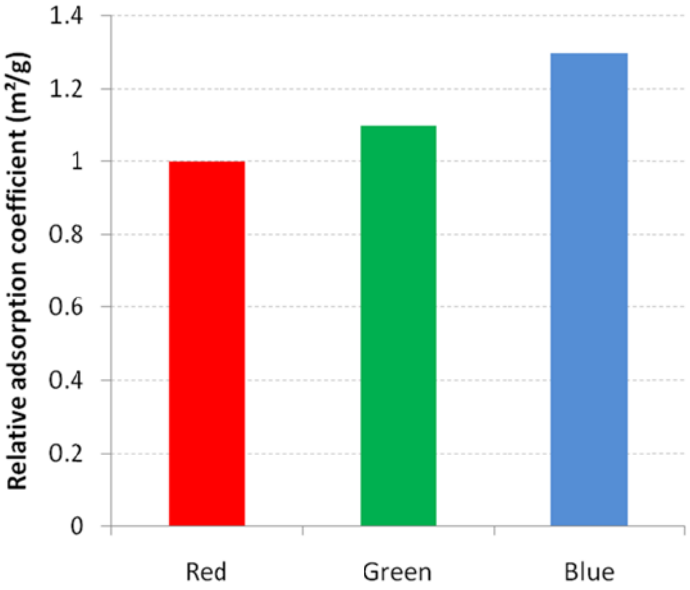


Figure 1 Example of relative mass adsorption coefficient for different wavelengths of visible light. At fixed particle size. ~30% differences can originate from the different wavelength used in measurement. Calculated according to Andreae and Gelencsér[iii]

As many of the instruments perform measurement close to ambient temperatures, the high temperature exhaust gas has to be cooled down before it is introduced to the instrument. The details of the cooling process affect the amount and type of condensed material on the black carbon particles and therefore also the measurement result.

Conclusion: To make measurement results comparable, sampling parameters have to be strictly defined and the instruments identical.

An alternative to optical measurement of black carbon (BC) is measurement of **thermally stable carbon**. In thermal determination, the carbon may be divided into volatile and thermally stable, non-volatile carbon. Volatile carbon consists of hydrocarbons (referred also as **organic carbon; OC**) and stable carbon (referred as **elemental carbon; EC**).

Although there is correlation between thermally stable carbon and BC in some cases, universal correlation cannot be found. Note that elemental carbon (EC) can be considered as “black” but all black/light adsorbing carbon is not elemental carbon. In cases where the ratio of organic carbon to elemental carbon is high, pyrolysis of organic carbon to elemental carbon may bias the result significantly when using the thermal method.

A comparison between thermal and optical methods is presented in Figure 2.

A summary of the optical and thermal measurement methods is presented in Table 1.

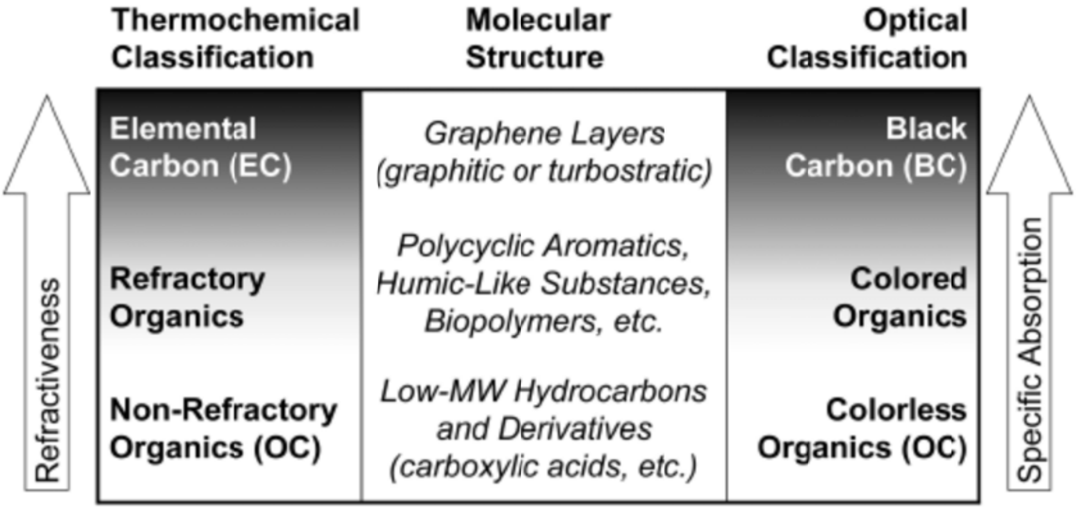


Figure 2 Example of classification of different carbon compounds with thermal and optical methods. Transformation from refractory organics to coloured organics is not straight forward.[viii]

Table 1 Examples of measurement instruments:

Instrument	**Method**	**Pros**	**Cons**
-	**Optical**	Directly related to light adsorption	Result depends on light wavelength and sampling parameters
Aethalometers (Including filter smoke meters)	Filter based light attenuation. (Measures filter paper blackening caused by a sample gas drawn through the filter) Measures light absorption changes in reflection / transmittance.	Relatively simple – several brands available. Easy, “robust” instruments available Wide use & knowledge. Low detection limit. The filter smoke measurement method is standardized in ISO 10054 and ISO 8178, Part 3.	Light wavelength used by the instrument and other compounds like water may affect the results. Multiple light scattering from deposited particles affect the measurement result – non-linear behaviour.
Photoacoustic methods	Sample gas is fired with intense laser light. Light absorptive particles that are hit by the laser, heat up rapidly and make noise. This noise is detected and concentration evaluated.	Measures directly from ambient particles – Measures absorption directly.	Typically one wavelength operation only. -> Does not give complete information of light absorption over different wavelengths. Requires dilution prior to measurement from diesel engines – high maintenance requirements. No standardized method.

Opacity meters	Light attenuation. Measures extinction of light in the direction of the light.	Easy, “robust” instruments available Standardized: E.g. ISO11614	Some light attenuation may be a result of redirection (scattering) instead of absorption. The scattered light is not distinguished from total extinction. =>These instruments do not measure absorption.
	Thermal (combustion)	Information of organic compounds can be obtained simultaneously – several different protocols exist.	No direct link to optical properties except in some very well defined cases – optical correction need be used to correct for pyrolysis in some cases. Laboratory equipment – not for field use
Several laboratory thermal oven systems exists	Particulate sample is heated in an oven. In first phase heating is performed in zero - oxygen (inert) atmosphere to evaporate organic compounds. In second phase, oxygen is introduced and elemental carbon is combusted to carbon dioxide (CO_2) that can be measured with a CO2 gas analyzer.	Several standardized methods exists. e.g. VDI 2465	No direct connection to black carbon and global warming. Optical correction need be used to correct for Black carbon in some cases

2.1 Recommended measurement method

Major criteria for selection of recommended measurement method:

- Proposed measurement method should be optical, as this is most relevant for the global warming aspect.

- Proposed measurement method should mirror the light absorption of Black Carbon deposits, e.g. opacity meters can be misleading.

- Measurement method should be standardized and have relatively robust instruments available for continuous use.

- Based on the criteria above CIMAC WG 5 recommends filter smoke meters
(ISO 10054:1998) to be used for measuring black carbon emissions.

2.2 Calculation of black carbon emissions from the FSN value

Following calculation can be used for obtaining emission factors for soot /black carbon from combustion engines.

Filter Smoke Number (FSN) is obtained from measurement device. Equation A.16 in ISO 8178-1 (2006) is used to derive the value for soot/black carbon concentration in exhaust gas.

Assumptions:

- Filter Smoke Number (ISO 10054:1998 defined) is similar to Bosch value
- Equation A.16 in ISO 8178-1 (2006) refers to soot. We consider here “soot” to be equal to “black carbon”

Black carbon concentration can be converted to specific emission (g black carbon)/ kg fuel used) by applying following equation:

$$EF_{BC} = \frac{BC_{conc}}{1.29 \, {}^{kg}\!/_{m^3}} \cdot \frac{Q_{exh}}{BSFC}$$

Where:

EF_{BC} = Fuel specific black carbon emission in g/kg fuel used

BC_{conc}= Black carbon concentration in g/m³ derived from e.g ISO 8178-1(2006)
equation A.16

Q_{exh} = Specific exhaust gas mass flow in kg/kWh on wet basis

BSFC = Brake specific fuel consumption in kg/kWh

Assuming a typical BSFC of 200 g/kWh and a specific exhaust gas mass flow of 7 kg/kWh a correlation between Filter Smoke Number (FSN) and black carbon emissions can be derived – see Figure 3.

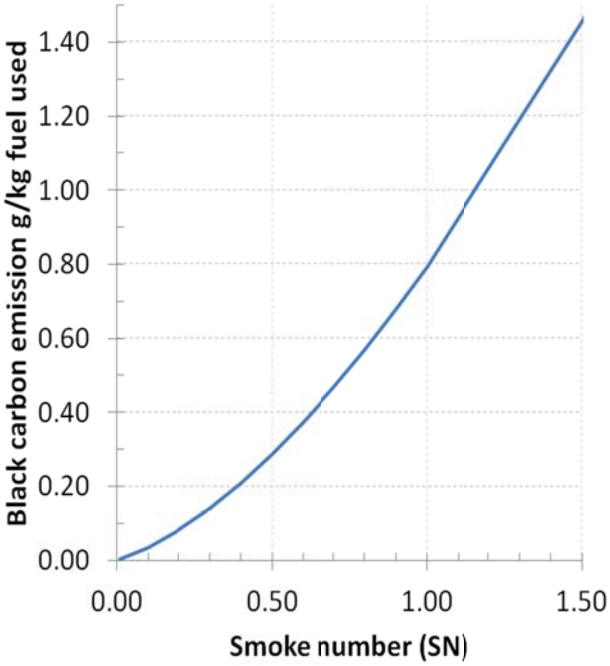


Figure 3. Estimation of black carbon emissions based on Filter Smoke Number measurement.

2.3 Restrictions on applicability of FSN measurement for transient conditions

To determine a measurable FSN it is necessary that a minimum amount of deposit is collected on the filter and several repeated samples are usually taken to obtain an average result. Consequently the time for collection may be in the magnitude of minutes, particularly for modern diesel engines with low emission values. Therefore, FSN determination for transient engine operation is not possible.

3. Large diesel engine exhaust particulate composition

Examples of measurements of the composition of exhaust particulate of a 4-stroke medium speed diesel engine operating on distillate/light fuel oil (LFO) and high sulphur heavy fuel oil (HFO) can be found in figures 4 and 5 respectively. They are presented with different fuel qualities as particulate emissions are highly fuel quality dependent. Data about fuel composition can be found in Table 2.

Similar results can be found also in other references[ix].

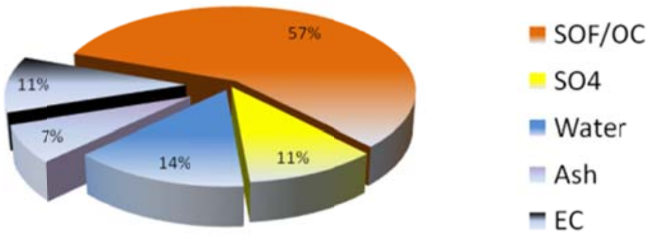


Figure 4. Particulate emission composition of a large 4-stroke medium speed diesel engine running on LFO at steady state high load. Sampling according to ISO 8178. Total particulate emission level in this case is 144 mg/kWh(shaft). Elemental carbon emission is about 15 mg/kWh(shaft). Thermal carbon determination with optical correction for pyrolysis of organic carbon (OC) to elemental carbon (EC). Adapted from Ristimäki et al.[xxvi]

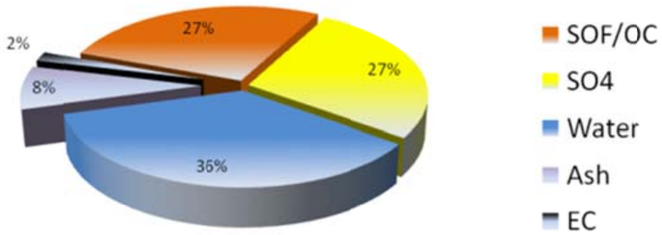


Figure 5. Particulate emission composition of a large 4-stroke medium speed diesel engine running on HFO quality 2 at steady state high load. Sampling according to ISO 8178. Total particulate emission level in this case is 505 mg/kWh(shaft). Elemental carbon emission is about 10 mg/kWh(shaft). Thermal carbon determination with optical correction for pyrolysis of OC to EC. Adapted from Ristimäki et al[xxvi].

Table 2. Test fuel specification:

	Unit	LFO	HFO quality 1	HFO quality 2
Viscosity @ 50°C	mm²/s	@40°C 3.4	167.2	498.0
Viscosity @ 80°C	mm²/s	1.699	39.5	87.49
Sulphur	% m/m	<0.05	0.89	2.42
Ash	% m/m	<0.01	0.02	0.07
Vanadium	mg/kg	<1	39	299
Sodium	mg/kg	<1	16	28
Aluminium	mg/kg	<1	3	14
Iron	mg/kg	<1	20	6
Nickel	mg/kg	<1	20	48
Calcium	mg/kg	3	28	13

NOTE: In this typical case above (large 4-stroke medium speed diesel engine) the measured elemental carbon (~ black carbon) emission is ~50% higher with distillate fuel (LFO) compared to heavy fuel oil (HFO).

4. Literature data review

4.1 Emission factors

Literature data for black/elemental carbon emissions of ship engines vary with a factor of about 10 (from 0.1 up to 1 g/kg fuel burned[x,xii] ; Table 3). Some of the variation can be explained by differences in the measurement methods.

Table 3. Examples of black carbon emission factors reported in literature.

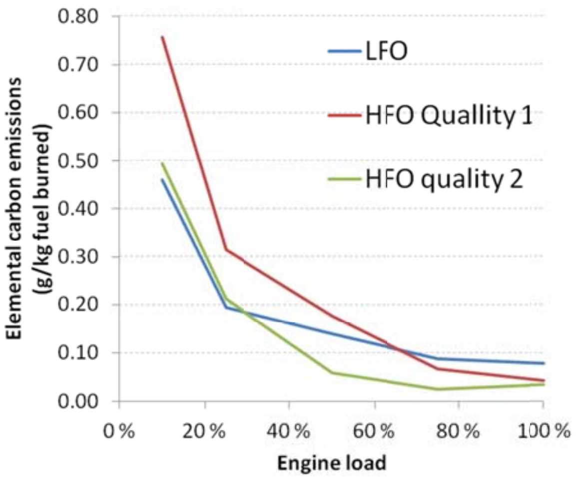
BC emission fuel burned	g/kg	Method of determination
Lack et al [xi]	0.36-1	Optical /photoacoustic
Agraval et al [x]	0.1	Thermal
Corbett et al [xii]	0.37	-
Petzold et al [xiii]	0.06 (85% load) - 0.36 (10% load)	Optical
Petzold et al [xiv]	0.179±0.018	Optical

Figure 6 shows examples of measurement results from a large 4-stroke medium speed engine. We notice that:

- The overall BC emission level is below 0.2 g/kg fuel burned at high load
- FSN values for large diesel engines operating on high load are typically in the range of 0.1 – 0.35, indicating a typical black carbon emission level of 0.05 – 0.20 g/kg fuel used (calculated from Figure 3)
- Switching from residual fuel operation to light fuel operation does not necessarily decrease black carbon emission.

This agrees well with the results of Agrawal et al.[x] and is only ~1/5th of the high estimate values presented by Lack et al[xi]

The conclusion for shipping is that the emissions of black carbon seem to be highly overestimated in many investigations. Lack et al[xi], estimate the contribution of shipping to the global LAC emissions to be ~1.7%. This value is obviously overestimated because they start from an emission factor that is up to 5 times higher than indicated in this report. <u>The probable contribution of shipping seems to be well below 1%. This is further supported by the other references[xv].</u>



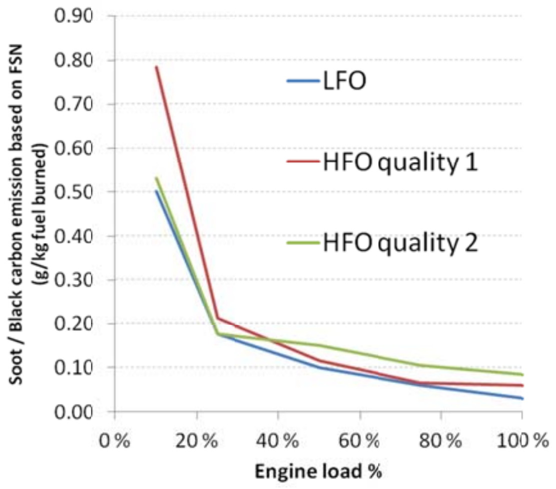


Figure 6. Examples of the measured steady state black carbon emissions from a medium speed 4-stroke large diesel engine. Two alternative measurement methods: Thermal measurement of element carbon (EC) on the left and soot/black carbon emission based on filter smoke number (FSN) on right. Thermal carbon determination with optical correction for pyrolysis of OC to EC.Data about the fuel qualities can be found in Table 2. Source: Wärtsilä

4.2 Comparison with vehicle emissions

We concluded above in section 4.1 that a typical black carbon emission factor for large HFO burning marine engines at steady state high load (typical engine load range) is in the range of 0.05 - 0.20 g/kg fuel used.

Assuming a typical brake specific fuel consumption (BSFC) of 200 g/kWh we calculate a typical high load steady state specific black carbon emission in the range of 10 – 40 mg/kWh which is well below EURO III (limit: 100 mg/kWh) and well in line with EURO IV (limit: 25 mg/kWh) and EURO V (limit: 20 mg/kWh).

NOTE: This is not a fully appropriate comparison i.e. high load result vs. test cycle result and marine fuel quality vs. automotive fuel quality. However, it gives an indication of the high combustion efficiency of large diesel engines resulting in relatively low soot/black carbon formation even when burning a low grade quality fuel.

4.3 Black carbon emission sources

Black carbon originates from incomplete combustion. These sources include both natural and anthropogenic sources. It is estimated that ~40% of BC emissions originate from open biomass burning[xvi]. A similar proportion is estimated for fossil fuel burning and the remaining 20% is from biofuels. The contribution of shipping to global black carbon emissions is most probably well below 1%[xi].

Although there has been an increase in the global BC emission over the 20th century[xvii], the deposition over the Greenland ice seems to be decreasing since 1910[xviii,xix] and also in latest years[xx]. Decrease in Greenland BC deposition is explained by changes in global BC emission pattern. While US and Europe dominated the global BC emission in the beginning of 1900, Asian countries are the current major emitters of BC.

Evaluation of Arctic BC sources suggests “a large amount of Arctic pollutants, especially black carbon, travels to the arctic at high altitudes”[xxi]. Koch and Hansen[xxi] estimated that 37% of arctic BC comes from biomass burning, 21% from South Asia, 18% from Europe, 14% from Russia, 9% from North America and 7% from aircraft (see appendix for Figure 10). Shipping was not included in the estimation but Figure 3 in Appendix (from an article by Lack et al[xi]) would suggest that the contribution of shipping is less than 1%.

5. Radiative forcing

Radiative forcing for various compounds is illustrated in Figure 7.

- We can conclude:Contribution from aerosols in general is negative (causing cooling) – sulphate, organic carbon mineral dust (except for black carbon)
- Contribution from black carbon is positive (causing warming)
- Particulates generated when operating engines on heavy fuel (HFO) contain ash components (i.e. ~minerals) and sulphates. Consequently, “HFO-particulates” tend to have less radiative force than those generated during operation on distillate fuel (LFO) and the overall contribution of shipping to global warming will change from cooling to warming due to reduction in fuel sulphur content[xxii,xxiii]

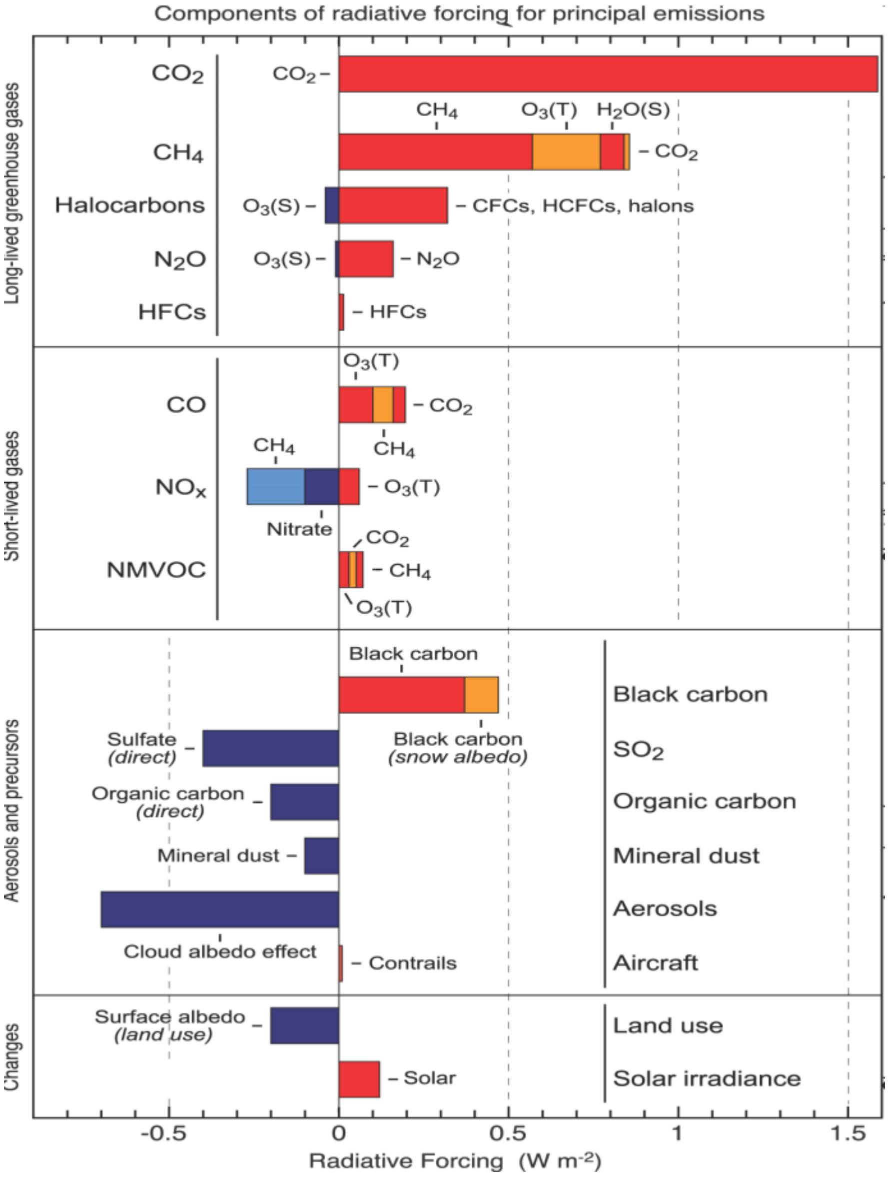


Figure 7. Radiative forcing for various compounds[iv].

From Figure 7 can be seen that organic carbon (OC) cools the climate. Following conclusion has been made by Bond et al (2011)[xxiv]: “the lowest organic matter to black carbon mass ratio required to produce a neutral effect on top-of-atmosphere direct forcing is 15:1 for any region.” It is notable from Figure 4 and Figure 5 that the OC/BC ratio for LFO is lower than with the HFO. Additionally, with HFO, the OC/EC ratio is typically higher than 15.

6. Proposed and potential black carbon abatement measures

Various black carbon abatement measures are proposed in various documents to be applied on large diesel engines. However, proposed measures are seldom viable or feasible from technical or economical point of view.

In the following the viability and feasibility of some proposed and potential abatement measures are briefly discussed.

6.1 Improvement of the combustion process

Diesel engines are known for high thermal efficiency i.e. low specific fuel consumption and as a consequence low specific CO_2 emission. In this respect the diesel process is best in the class compared to other prime movers. The high thermal efficiency is achieved by means of an efficient combustion process also resulting in relative low black carbon emissions (see section 4.2).

For engine manufacturers the improvement of thermal efficiency has been one of the most important sales arguments for decades. Consequently, focus has been for long on improving the combustion process and reducing unburned compounds i.e. reducing smoke/soot/black carbon formation - there is no large leap to be expected from further improvements.

Conclusion: potential for further black carbon reduction by engine internal measures is only marginal on new engine designs.

6.2 Switch to distillate fuel (LFO)

Switching to low sulphur fuel and distillate fuel (LFO) has sometimes been proposed as a means for reducing black carbon emissions.

However, very little evidence is provided to support this claim, especially with in-use engines. On the contrary, recent reports state that “BC emission factors are statistically unchanged by low sulphur fuels”[xxv]

There is some evidence (Figure 6 and also in literature) that switch to LFO with current in-use large diesel engines, may even result in increase of the black carbon emissions[xxvi].

Conclusion: Switching to distillate fuel (LFO) will typically not result in reduced black carbon emissions from large engines.

6.3 Fuel injection valve design

One essential aspect of the fuel injection valve design is to prevent fuel oil from evaporating uncontrolled into the combustion chamber and subsequently “escaping” unburned to the exhaust resulting in hydrocarbon and black carbon emissions. The most common strategy is to reduce the exposed needle sac volume of the fuel injection valve.

In large 2-stroke engines old types of fuel valves are considered to be a significant contributor to emissions of engine related black carbon.

Conclusion: Replacing fuel injection valves in some large 2-stroke engines can result in substantial reduction of black carbon. However, in 4-stroke engines the sac volume has already been reduced so that the potential for further black carbon reduction by sac volume reduction is marginal or non-existing.

6.4 Water-in-fuel emulsions

Water in fuel emulsions were originally used for reducing NO_x emissions. In some in-use engines equipped with conventional fuel injection system having a low fuel injection pressure, improved black carbon emissions is often seen on low load operation due to improved fuel droplet dispersion and mixing in the combustion chamber as the water in the fuel turns to steam. However, at high loads this beneficial effect can be offset by the increase in injection duration caused by the lower energy content of the emulsion, the delay in end of combustion often causing an increase in BC emissions. Modern fuel injection systems provide good fuel/air mixing over a very wide power range.

Conclusion: On “old type” engines reduced black carbon emissions are often seen at engine low load – not at high load. Only minor (if any) improvement in modern engines with high injection pressures.

6.5 High fuel injection pressure with e.g. Common Rail fuel injection system

Modification of the fuel injection system in “old type” in-use engines for utilizing higher fuel injection pressure is a means to reduce black carbon emissions especially at engine low load e.g. conversion to a modern Common rail fuel injection system (other means are also under development).

Conclusion: Substantial reduced black carbon emission at low load.

6.6 Exhaust Gas Recirculation (EGR)

EGR is used to reduce NO_x emission by mixing a part of the exhaust gas into the intake combustion air. Lower oxygen and higher water and carbon dioxide concentration in the intake air result in suppressed combustion temperatures and reduced NO_x formation.

Lower combustion temperatures and reduced oxygen achieved with EGR tends to result in higher soot/black carbon formation. Additionally EGR tends to slightly increase specific fuel consumption.

Conclusion: EGR is a measure to reduce NO_x – not black carbon. On the contrary black carbon emissions tends to increase unless countermeasures are taken.

6.7 Diesel Particulate Filter (DPF)

In Diesel Particulate Filters the exhaust flow is forced though very small channels (µm range) where solid particulate matter is collected. This technology is used in some truck engines and rail engines using ultra low sulphur diesel fuel, but there is no demonstrated DPF technology available for large marine and stationary engines operating on typical "non-automotive" fuel quality.

A large pressure difference is needed for forcing the exhaust flow through the small channels i.e. the engine will experience a high backpressure. High backpressure will result in high thermal load of the engine. Large diesel engines have to be able to operate on typical marine and/or stationary diesel fuel qualities on the market containing ash compounds which put limitations on the exhaust temperatures – too high thermal load will result in unacceptable risks for exhaust valve damages and turbocharger turbine fouling.

Additional challenges:

- The DPF system would need to be very large.
- Mechanical strength due to vibrations caused by pressure pulses in the exhaust gas typical for this size of engine.
- The ash components of the particulates cannot be burnt away during the regeneration phase causing increasing backpressure and finally clogging of the filter.

Conclusion: Diesel Particulate Filter (DPF) is not a feasible solution for large diesel engines. There is no existing demonstration installation in this scale.

6.8 Bag Filters and Electrostatic Precipitators

Bag filters and electrostatic precipitators are used in some large land-based industrial sources, coal-fired power plants, etc. Below some typical pros (+) and cons (-) are given for Bag Filters and Electrostatic Precipitators.

Bag Filters:

+ Relatively good particulate reduction
- Large size

For 18 MW_{shaft} engine typically (can vary somewhat with suppliers):

- Height: 14 meters
- Width: 11 meters
- Length: 8 meters
- Weight: 60 tonnes

- "Protection reagent" (CaO, etc) required in order to protect the filter from clogging=> storage need
- Waste disposal (removed particulate/protection reagent) => storage need
- Flue gas fan is needed due to high pressure drop
- Maximum flue gas temperature limited typically to 190 degrC (material limitation)
  => flue gas has to be cooled. Typical diesel flue gas temperature is 250 – 400 degrC.

Electrostatic precipitators:

+ Relatively good particulate reduction
+ Low pressure drop
+ Withstand high exhaust gas temperature
- Large size

For 18 MW_{shaft} engine typically (can vary somewhat with suppliers):

- Height: 15-20 meters
- Width: 6 meters
- Length: 11 meters
- Weight: 80 tonnes

- Electrical risks in marine installations (due to high voltage, sea, etc)
- Removed ash (particulate) storage and disposal aspects

Conclusions: The systems are extremely bulky and there is limited experience of these systems applied to diesel engines. Bag filters and Electrostatic precipitators are not viable/feasible systems for large marine diesels.

6.9 Selective Catalytic Reduction (SCR)

SCR is a feasible system for reducing NO_x emissions – not black carbon. The impact on black carbon is negligible or zero. SCR is able to reduce the amount of unburned hydrocarbons, but not black carbon.

Conclusion: There is no indication that SCR would reduce black carbon.

6.10 DeSOx systems / Scrubbers

There are several types of DeSOx systems / scrubbers on the market for reducing SO_x from the exhaust gases.

These systems have also some ability to reduce particulate emissions. In practise the particulate reduction efficiency is highly affected by operational and measurement conditions i.e. the reported reduction levels are only indicative. Whether scrubbers reduce the black carbon part of the particulate to significant degree is unclear at present.

Conclusion: DeSOx systems and -scrubbers have a reducing effect on black carbon, but a consolidated view of the magnitude of the benefit has yet to be formed.

7 Conclusions and recommendations

Definition of Black Carbon

- CIMAC WG 5 recommends the wide definition of black carbon covering all light adsorbing components.
- “Light absorbing carbonaceous compounds“ (LAC) would be a better term to be used instead of “black carbon” (BC).
- In practise black carbon can be regarded rather similar to “Soot”.
- Black carbon does not fully correlate with “Elemental carbon”, but both indicate rather similar particulate properties.

Measurement of Black Carbon

- CIMAC WG 5 recommends the Filter Smoke Meter (FSN) measurement method according to ISO 10054 to be used for measurement of black carbon.
- ISO 8178-1:2006 equation A.16 can be used to convert the Filter Smoke Number to soot/black carbon concentration in the exhaust gas.

Contribution of Large Diesel Engines to Global Black Carbon & Resulting Climate Change

- Large diesel engines emit black carbon and aerosols into the atmosphere. However, the relative contribution this makes to the change in global climate is less clear.
- Atmospheric black carbon and surface deposition is considered to contribute positively to global warming and to accelerated melting of ice and snow in the Arctic. However, aerosols like those emitted in the exhaust of large heavy fuel oil (HFO) burning engines tend to offset atmospheric heating effect to some degree.
- The specific black carbon emissions from large marine and stationary diesel engines operating on heavy fuel oil (HFO) at high load are no worse than that of current diesel road vehicles being only 0.05-0.20 g/kg fuel used which compares well with Euro IV & V levels.
- Various articles reviewed by CIMAC WG 5 (references) also suggest that shipping is a minor contributor to black carbon emissions. Some data suggests that the figure could be up to 1.7% whilst other data, including results from engine tests, suggests that the actual figure is much less, probably <1%.

- Large diesel engines operating on heavy fuel oil (HFO) tends to generate less or equal amount of black carbon compared to those operating on distillate fuel oil (LFO).

- Bond et al (2011)[xxiv] has concluded that the lowest organic matter to black carbon mass ratio required to produce a neutral effect on top-of-atmosphere direct forcing is 15:1 for any region. Higher ratio means cooling effect. Some literature data suggest that the organic matter to black carbon mass ratio with heavy fuel oil (HFO) fuels are higher than with LFO[xxvi,xxvii,xxviii].

- Switching to the use of low sulphur, lighter fuels instead of heavy fuel oil (HFO) in large engines is unlikely to reduce the climate warming effect of exhaust emissions from these engines; it could even have the opposite effect due to higher (often) specific black carbon emissions and the resulting reduction in exhaust sulphate aerosols content.

Potential Abatement Measures

- Improvement of the combustion process – only marginal potential.

- Switching to low sulphur and distillate fuel – will typically not result in reduced black carbon emissions.

- Fuel injection valve design – reduced sac volume.
- Substantial reduced black carbon can be seen in some “old type” 2-stroke engines.
- Only marginal reduction in 4-stroke engines.

- Water- in-fuel emulsions – in some “old type” engines a reduction of black carbon can be seen at low engine loads.

- High fuel injection pressure e.g. Common rail – substantial reduced black carbon emission at low load.

- Exhaust Gas Recirculation (EGR) – black carbon tends to increase unless countermeasures introduced – no reduction.

- Diesel Particulate Filter (DPF) – not a feasible solution for large diesel engines operating on non-automotive fuel qualities.

- Bag Filters and Electrostatic Precipitators – not viable systems for large marine diesels

- Selective Catalytic Reduction (SCR) – there is no indication that the black carbon part of the particulates would be reduced.

- DeSOx-systems and -scrubbers – Most probably they have a reducing effect on black carbon, but a consolidated view of the magnitude of the benefit has yet to be formed.

8 Appendix

Annual mean deposition fluxes of BC globally by Koch and Hansen (2005)[xxi]. Numbers in parentheses give the <u>average contribution to arctic BC deposition.</u>

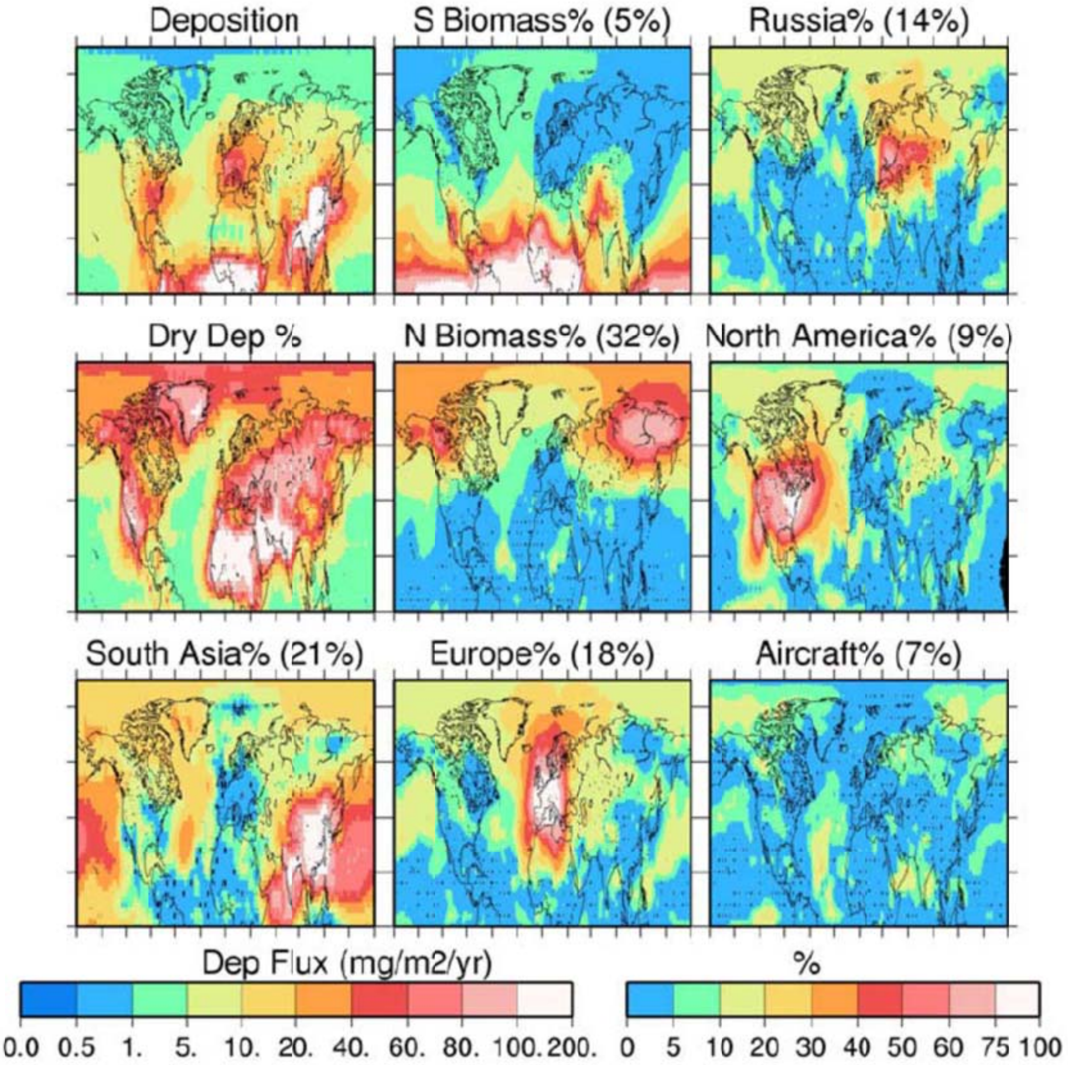


Figure 10. (top left) Annual mean deposition flux, (middle left) percent of total deposition from dry deposition, and percent contributions from regional experiments. Numbers in parentheses are average percent contribution to BC deposition flux in the Arctic.

Contribution of shipping to arctic LAC for January from Lack et al[xi].

L13815 LACK ET AL.: CARBON AEROSOL EMISSIONS FROM SHIPS L13815

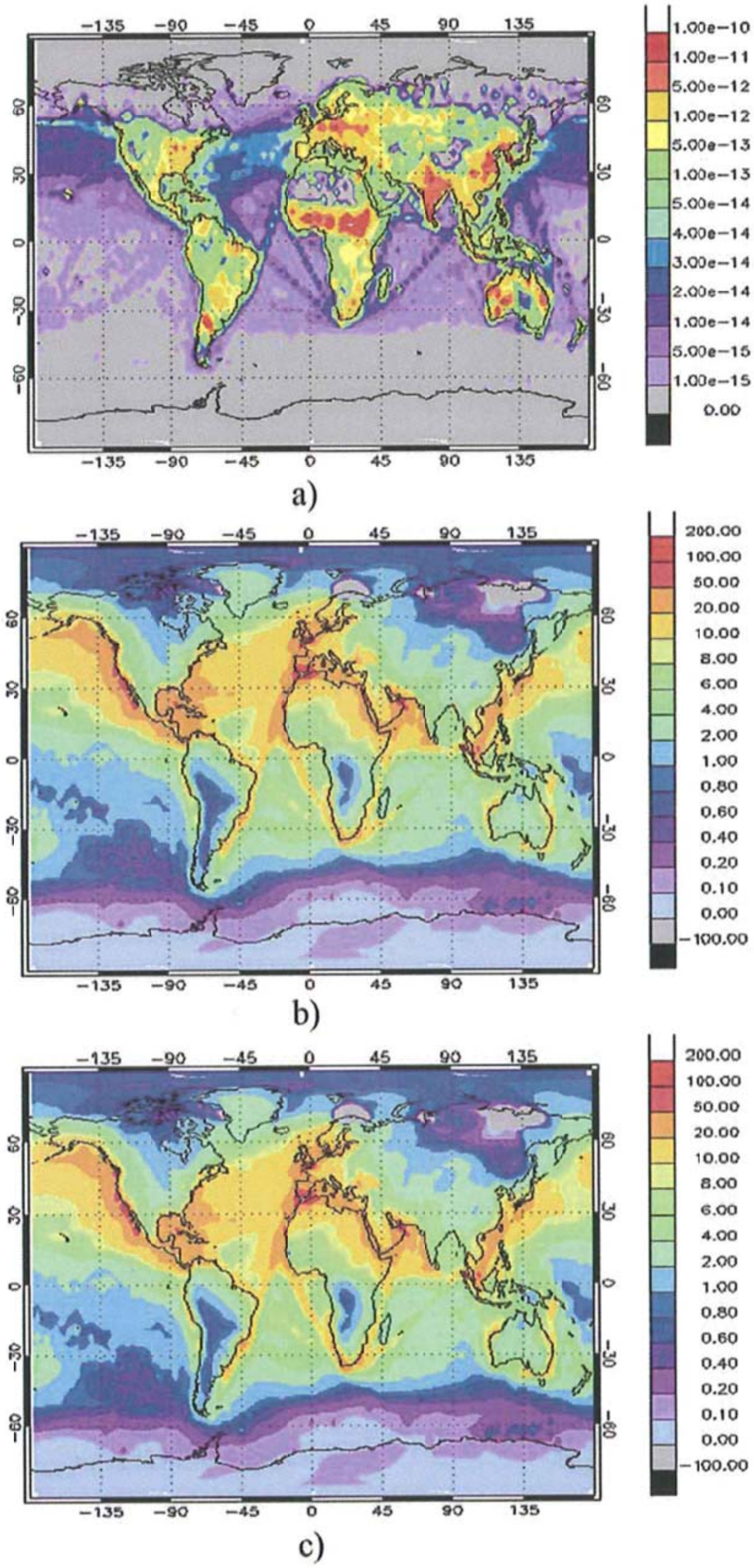


Figure 3. (a) Global surface emission of LAC (kgm^{-2} s^{-1}) with shipping emissions shown over ocean regions. (b) Absolute difference in LAC surface concentrations (ngm^{-3}) from shipping after transport. (c) Percentage difference in LAC surface concentrations from shipping after transport (for January).

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