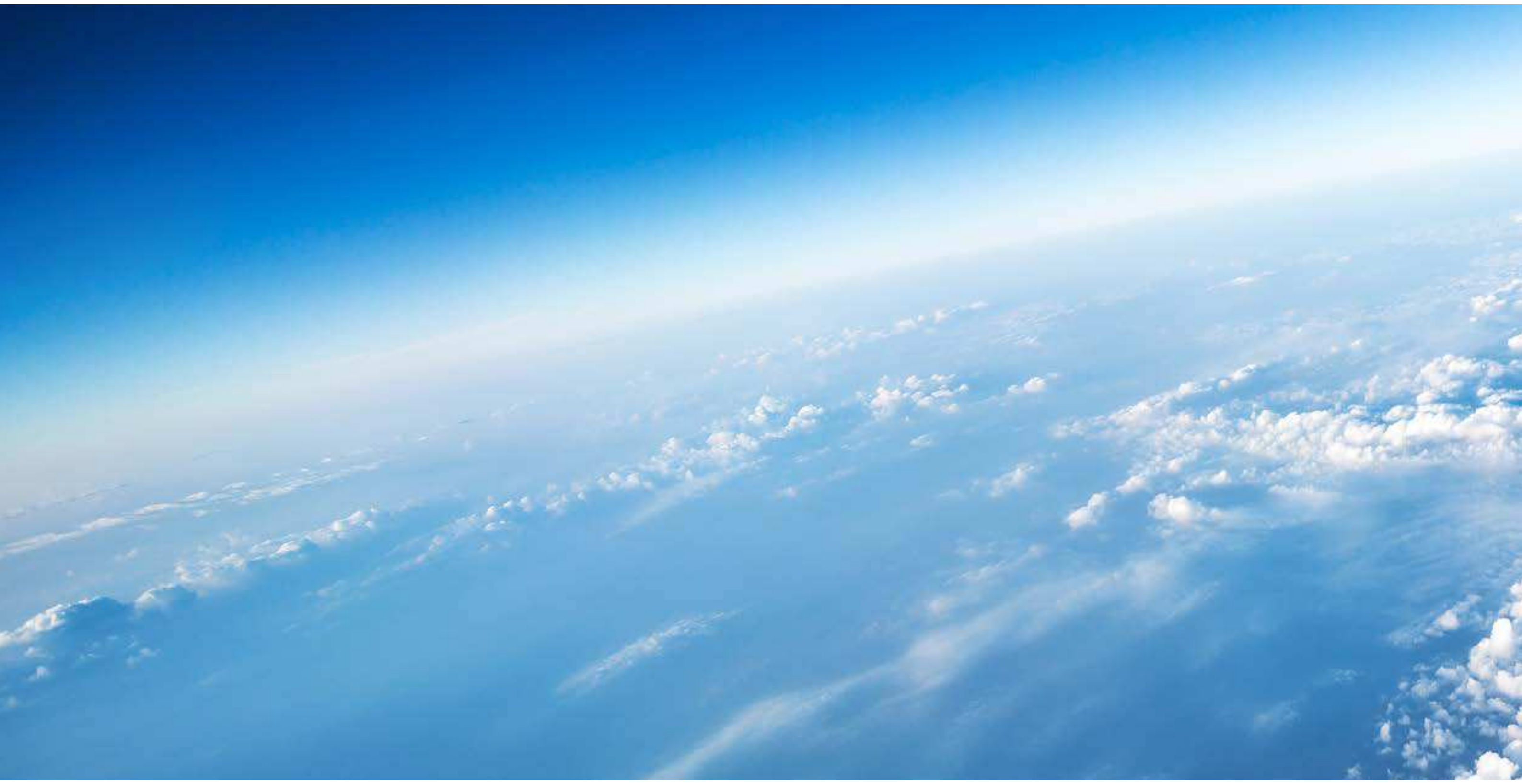
MARITIME

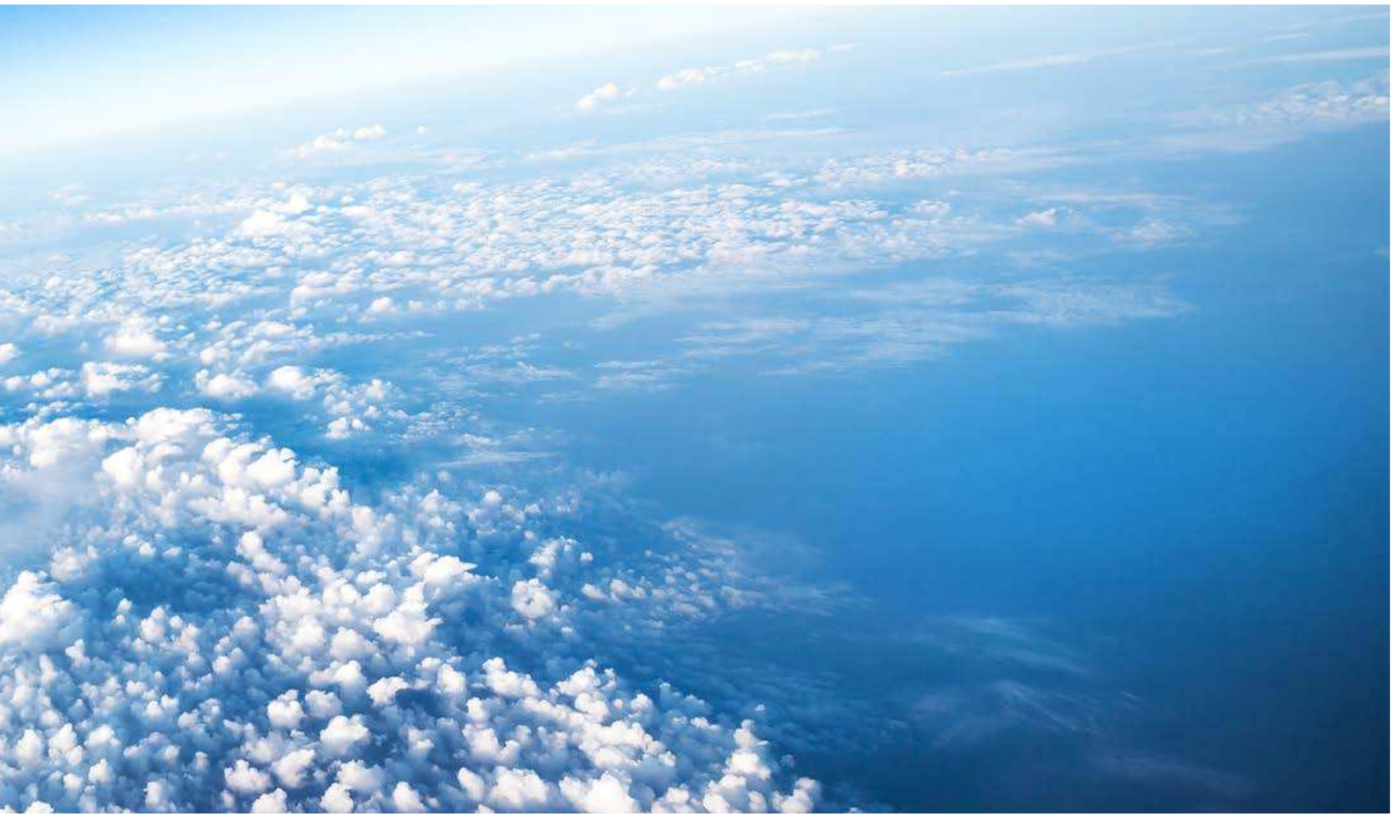
PARTICULATE MATTER AND BLACK CARBON

The global impact and what this means for shipping

SAFER, SMARTER, GREENER



CONTENTS



ABSTRACT

Recent studies on the effects of particulate matter (PM) and international initiatives to reduce emissions to air have prompted a growing interest in particulate emissions and the role they play in accelerating climate change. Recent studies looking at PM's effects on human health and how the shipping industry may be contributing to PM emissions have lead international organisations to question the suitability of the current legal framework on ship emissions.

Black carbon (BC) is one of the main points of discussion in this debate. BC is a light-absorbing component of particulate matter and is said to have a detrimental effect on climate forcing. The overall impact of shipping on PM / BC is presumably limited, but it may have a significant impact on a regional level, as ships may operate close to arctic areas and the number of these operations is expected to increase in the future.

The effects of PM on human health are not related to black carbon alone; they are dependent on the size distribution (ultrafine fraction of PM emissions) as well as the chemical composition of particles. Health implications have already been recognized and addressed in regulations for land-based (transport) sectors. However, they are still being discussed for the shipping industry.

This study provides further background on particulate matter and black carbon, their effects on the environment and human health as well as the current status of shipping's contribution to the overall anthropogenic impact. The paper also discusses potential ways to measure PM and BC, their origin and possible abatement technologies / strategies.

PARTICULATE MATTER (PM) AND BLACK CARBON (BC)

Particulate matter (PM) and black carbon (BC), a fraction of PM, have received increasing public attention, as they affect human health and the climate. Another reason for this is that ships' emissions take place in close vicinity to shore[1]. Plumes are often visible to the public in harbour areas and therefore receive more and more press coverage.

Various views exist about the magnitude of these emissions from shipping. There seems to be a lack of knowledge about the contribution that shipping makes to the overall anthropogenic black carbon emissions. The magnitude may suffer under the estimates of the effect of PM and BC emissions from shipping to which BC emission factors are applied and whether they represent an appropriate figure of the various ships' operational behaviour.

For other sectors, particularly the automotive industry, strict regulations on particulate matter emissions have been implemented in recent years. For shipping, it seems, not least in the eyes of the public, that there is a lack of regulations; politicians and environmental non-governmental organizations are therefore calling for action on this topic.

As an independent technical organization, DNV GL sees the need to look more closely at this issue.

This paper provides an introduction to the subject of PM and BC. It addresses basic topics such as the formation mechanism within the diesel process, the effects on health and climate, general measurement principles and the differences in measurement technologies for PM and BC. It also provides information about current (as relevant in other sectors) or potential abatement technologies. Overall, the paper underlines the challenges related to this topic.

We have also assessed shipping's contribution[2] to PM and BC emissions globally, despite the large uncertainties in the available data. There seems to be a need to gather more reliable information for the international research community.

Finally, this paper also offers some information about particulate matter regulations in other sectors and the current PM regulation in shipping.

What are particulate matter and black carbon?
Particulate matter (PM) is solid particles and liquid droplets suspended in air. PM varies in both size and composition. PM is divided into three different size categories – PM_{10}, $PM_{2.5}$ and $PM_{0.1}$ – which are distinguished based on the aerodynamic diameter. The corresponding diameters are given in the table below:

Particle	Short form	Diameter[3]
Coarse particles	PM_{10}	< 10 µm
Fine particles	$PM_{2.5}$	< 2.5 µm
Ultrafine particles	$PM_{0.1}$ or UFP	< 0.1 µm

The main source of anthropogenic particulate matter (PM) is the combustion of various sources of hydrocarbons, including coal, all fuels and biomass. These combustion processes take place in households, industry, in agriculture, road transport, on ships and

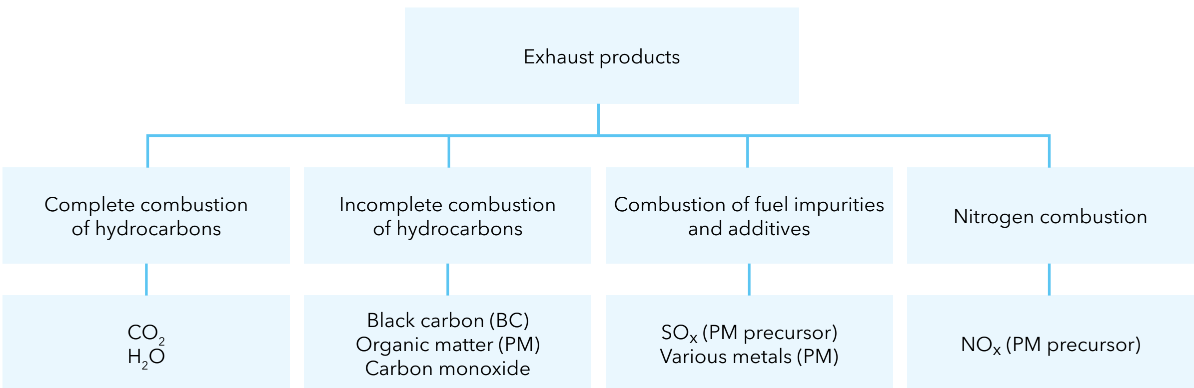


Figure 1: Exhaust gas products

[1] Ship traffic with respect to distance from shore, according to the Second IMO GHG Study: 1. within 200 nautical miles from shore: 70%; 2. within 50 nautical miles from shore: 44%; and 3. within 25 nautical miles from shore: 36%.

[2] Based on analysis of the literature at this stage

[3] The utterly accurate scientific expression would be: 50% cut-off diameter (see VDI 2066 Blatt 10 for the exact definition)

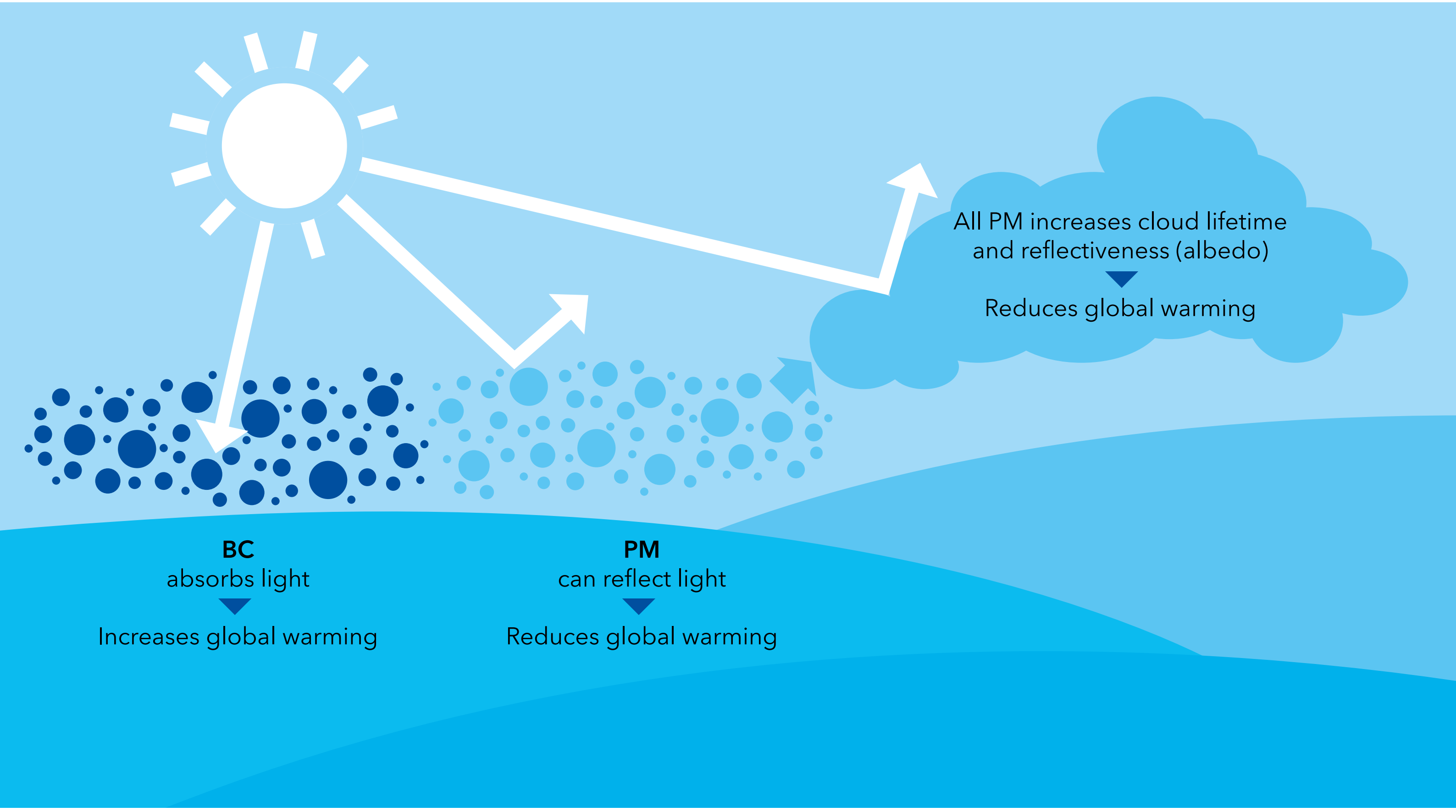


Figure 2: Illustration of the climate effect of PM

in various other types of transport, as well as wildfires. PM is composed of different chemicals. Black carbon (BC) is one of these fractions; organic matter (OM), various metals, nitrates and sulphates are the other main constituents.

Figure 1 shows the sources of different PM from fuel combustion. Some PM fractions, such as BC, OM and metals, are primary particles, which means that they are particles emanating from the combustion process and are present in the exhaust stream. Secondary particles, such as NO_x and SO_x, are gases when they are emitted, but after exiting the pipe, they turn into condensate and react to form various nitrate and sulphate particles (eg, ammonium nitrate and sulphuric acid).

The definition of black carbon was determined to be inconsistent in the scientific literature, as we found that various terms were used. Bond et al. /1/ suggested a commonly accepted definition in 2013. In addition to BC, elemental carbon, carbonaceous fraction and soot are terms being used. The International Maritime Organization (IMO) has applied the definition of Bond et al. /1/:

1. It strongly absorbs visible light with a mass absorption cross section of at least 5 m^2/g at a wave length of 550 nm.
2. It is refractory; that is, it retains its basic form at very high temperatures, with a vaporization temperature near 4000 K.
3. It is insoluble in water, in organic solvents including methanol and acetone, and in other components of atmospheric aerosol.
4. It exists as an aggregate of small carbon spherules.

The climate effects of PM

Particulate matter affects the climate in several ways. PM can lead to increased light absorption and light scattering as a direct climate effect. Black carbon is the major contributing fraction of PM that leads to increased global warming by absorbing light.

Another feature of PM is its potential for cloud formation and increased cloud lifetime (indirect climate effects). This feature of PM aerosols and their interactions with clouds reduce global warming, which means they have a cooling effect /2/.

Health effects of PM – size matters
The World Health Organization (WHO) has estimated that exposure to PM caused 3.7 million premature deaths worldwide in 2012. The reason for this is that both short- and long-term exposure to PM leads to an increased risk of developing chronic and acute cardiovascular and respiratory diseases, as well as lung cancer /3/.

Particulate matter affects health negatively, both as a result of the toxicological properties of the fractions of PM and the physical effects of particulates embedded in the lungs and other tissue/4/. PM_{10}, $PM_{2.5}$ and $PM_{0.1}$ all cause adverse health effects, but the smallest particles have the largest negative effect, since they can penetrate farther into the lungs and even pass directly into the bloodstream.

Some studies /5, 6, 7, 8/ indicate that black carbon has a greater deleterious effect on human health than other parts of PM. As this is a complex field of study, there are substantial uncertainties in the results and the available literature.

Emission vs. immissions
As a prerequisite, the discussion regarding air pollution requires a dedicated differentiation within the pollution process from any emission source (eg, stack) on the way reaching nature or living beings. It is therefore necessary to be able to differentiate between emissions and immissions.

Emissions are the form of the pollutant as it leaves the diesel engine or any stack in general. These "emissions" – when leaving the stack and entering the atmosphere – are subject to chemical and physical conversion processes. The pollutants are transported (wind) and, in the end, deposited somewhere (sedimentation, rain) within the atmosphere[4]. When pollutants enter systems affecting humans and the environment, they are called immissions. This definition is illustrated in Figure 3.

When talking about the impact of particulate matter from diesel exhaust, it is necessary to draw a clear distinction between emissions and immissions, as only the immissions are relevant for this aspect. When it comes to regulatory frameworks or reduction measures for any sector, emissions are the focus in nearly all cases.

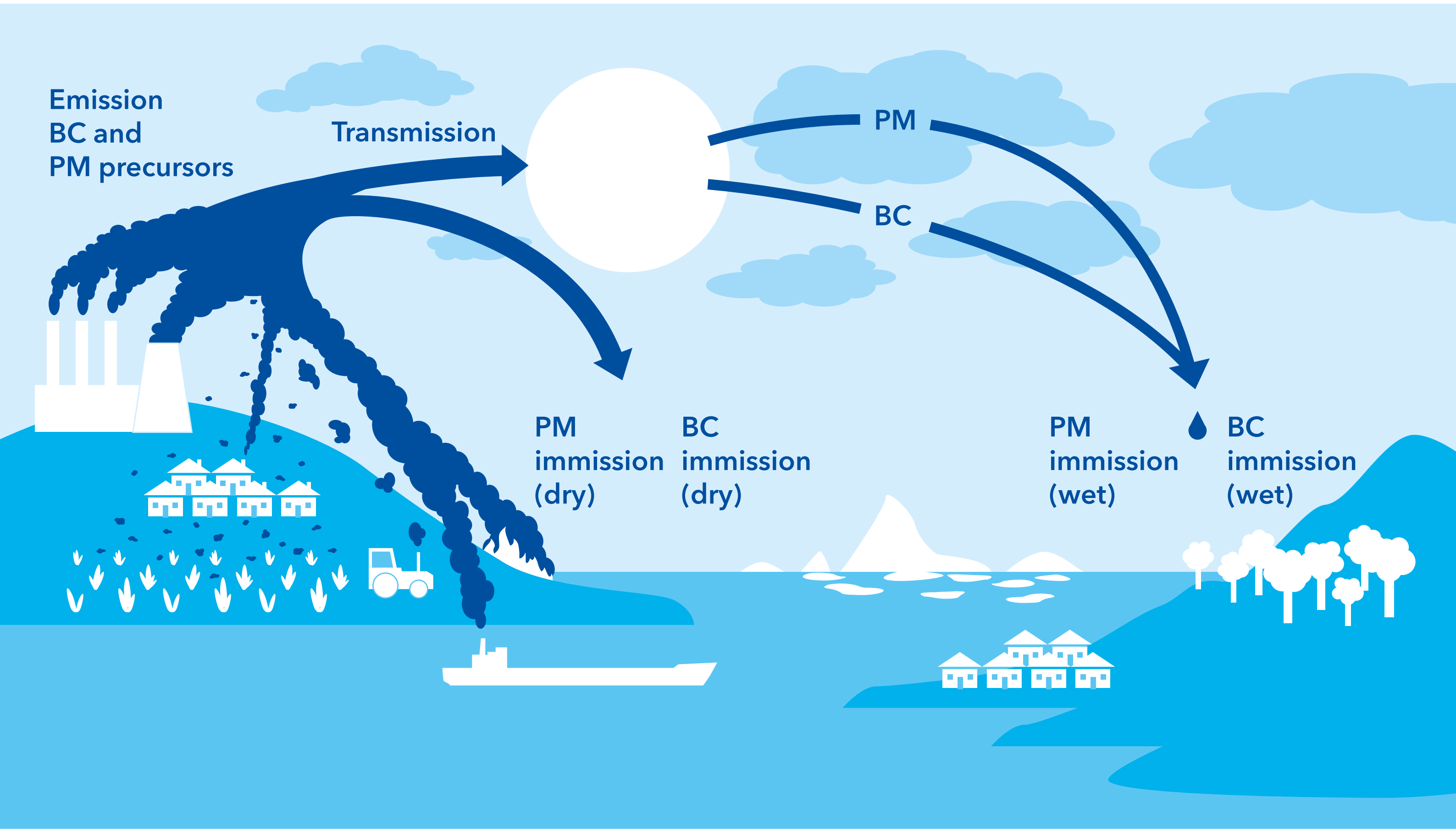


Figure 3: Illustration of emissions and immissions

[4]This is referred to as "transmission" in this context

PM and BC emission inventories

In general, emission inventories are performed by attributing an emission factor to the fuel consumption of a sector, though it could even be narrowed down to a single emission source. For example, shipping is estimated to burn approximately "x" tons of heavy fuel oil (HFO) in total per year and a PM emission factor of 6.2 kg/t HFO[5] is assigned. The result in relation to "x" tons of fuel is then obtained. The question now is how accurately an emission factor reflects the variety of ship operations and other influencing factors.

Several emission prediction models are available for fuel estimates and also for different (air) pollutants, so the problem is not finding results, but rather finding suitable, high-quality results. When comparing different models, large deviations occur for the following reasons:

- Difficulties in comparing local results with global results because **global models** do not need to be too precise at a local level. The model becomes too complex otherwise. More averaged factors are used to predict global climate effects.
- **Local models** take detailed local characteristics into account, such as waves, winds (environmental features such as shallow waters and tidal current) or different ship sizes, fuel use and operating conditions (emitter). It is difficult to scale up these results to a global model.
- Emission factors used for both PM and BC are often general and too simplistic.
  - Parameters affecting PM and BC emissions, such as engine load, engine type, injection systems, engine age and maintenance conditions, are rarely taken into account, if at all.
  - Fuel quality is considered only to a certain extent (HFO versus MGO).

Finding accurate and reliable data to determine emission factors is a challenge, especially for BC. Measurement techniques have not been commonly available for ship stack measurements. In addition, sample conditions and engine condition and parameters need to be representative and comparable. Also, more data from different types of vessels and their operations is needed to establish a more reliable base data set.

[5] This serves as an example. The figure stems from the "Entec Emissions Report 2010" (figure is for the year 2000)

Particulate matter, shipping inventories

A European Commission (EC) study /9/ states that the share of international shipping occurring in European waters is around 10% to 20% of global $PM_{2.5}$ emissions. In this study, several references derive a variety of PM-emission factors from 1.5 to 2.1 tons $PM_{2.5}$ per kiloton of CO_2. Global CO_2 emissions from international shipping accounted for 796 megatons in 2012 /10/, which accounted for 2.2% of global CO_2 emissions that year. This is distinct from "total shipping", which would also include national shipping. In this case, total shipping would account for 949 Mt of CO_2 (3.1% globally).

Black carbon inventory

Around 7,500 kilotons of annual BC emissions worldwide were calculated in the year 2,000, with a large uncertainty range from 2000 to 29,000 kilotons per year (Speciated Pollutant Emissions Wizard /SPEW/ /1/). Approximately 60% of the total BC emissions are attributed to energy-related sources, including the main anthropogenic sources, such as transport, industry and heating and power generation. The other 40% are attributed to open fires (wildfires), which can be anthropogenic in nature or not. Open fires are mainly located in tropical rainforests, whereas energy-related emissions are mainly located in the northern hemisphere. The distribution of energy-related BC sources (in total, around 4,500 Gg/yr) is shown in Figure 4 /1/.

The current PM and BC inventories have large uncertainties, and improved emission factors based on reliable data and a deeper understanding of BC and PM formation are needed.

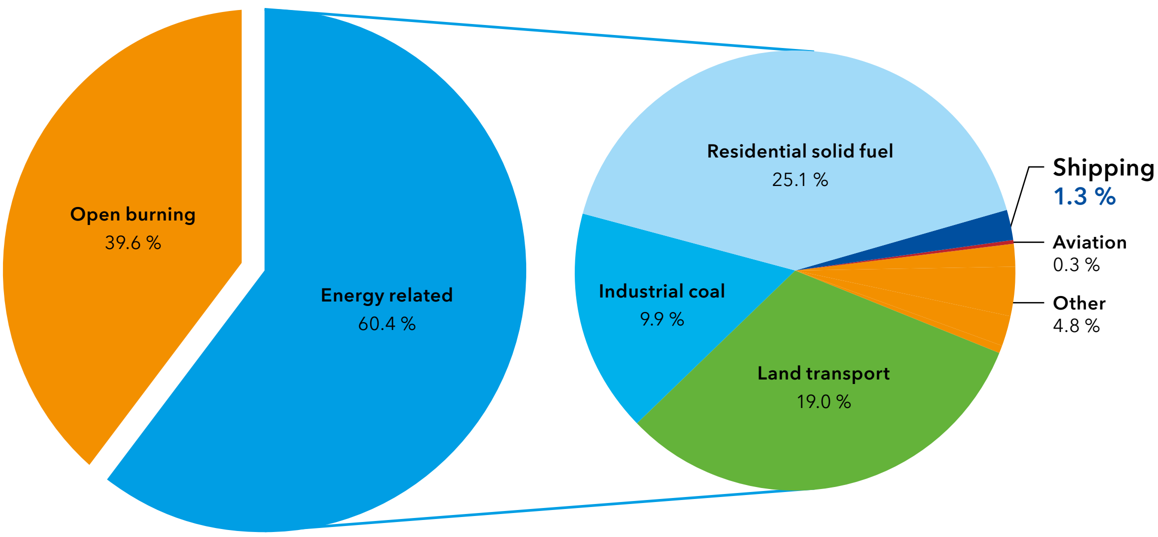


Figure 4: Total global energy-related BC emissions according to the SPEW model (2000) /1/

Particulate matter measurement
Particulate matter is well regulated on the emissions and the immissions side for many industries and applications. Different measurement protocols and techniques therefore exist, which are adapted to the specific environment and purpose. For example, the emission measurement for power plants is conducted at 160°C to evaporate water vapour and volatile organic compounds (VOC). The "dust" value obtained is then considered in relation to the emitted dry exhaust volume flow /11, 12/. The measurement protocol for non-road engines (ISO 8178:2006 /13/) requires a temperature between 42°C and 52°C and the particulate value obtained is considered in relation to the engine power [g/kW] provided during the test. This protocol applies to inland waterway vessels, too. For seagoing ships, this protocol might also be used, although there is no legal requirement for doing so. Nevertheless, DNV GL has extensive experience in measuring PM emissions according to ISO 8178:2006 (protocol on seagoing ships).

Black carbon measurement
BC has not been regulated for any industry or emission source yet. As a result, no standard method for measuring BC in stacks/exhaust pipes has been developed yet. There are many measurement techniques in use and commercially available, exclusively for research purposes, which take one of the different properties of BC as a basis for measurement. Some measurement systems can measure (semi-) continuously, while others need a sample from a filter /14/.

The measurement methods presented and discussed recently at IMO include:

- **Photo-acoustic method:**
  Particles are heated for a split second by a laser beam and cool down again immediately. The alternate heating and cooling leads to thermal expansion and contraction, resulting in pressure waves, which are detected as sound. The method uses the light absorption property. BC absorbs considerably more light than other particles, and the sound that is detected is assigned as the measurement of the light absorbed /14, 15/.

- **Laser-induced incandescence (LII):**
  Particles are heated by a laser beam up to 4,000 K. At this temperature, BC starts glowing, vaporizes and emits blackbody radiation. The blackbody radiation is used to identify and determine mass. A second effect, namely the scattering of the laser beam, can be used to determine the BC particle size /14, 16/.

- **Filter-transmission techniques:**
  A sample of exhaust gas flows through a filter, and the particles are gathered on the filter. The light transmission and attenuation of the filter is measured continuously. The BC mass is calculated with empirical mass attenuation coefficients, which are subject to ongoing discussions /17, 18, 19/. For a well-known source, such as an engine, it should be possible to find a commonly accepted coefficient /20/. As stated above, the measurement principle entails a great deal of potential bias, but many commercially available systems manage to reduce it significantly /14, 21, 16/.

- **Filter smoke number (FSN):**
  The particles are collected in a filter, and the backscattering is measured continuously. The FSN is standardized in ISO 10054:1998. Many atmospheric scientists criticize the FSN because it ignores most of the biases of measurements based on the light-absorbing property /14/. Parts of the industry support the FSN strongly due to the existing data, low expense for the device and its widespread prevalence in the internal combustion engines industry.

The different principles yield very different results which cannot be converted for comparison with each other without difficulties and potential biases /14, 22, 23, 17, 24/. When comparing black carbon data, it is vital to ensure that the same measurement principle has been used. Every measurement technique has its distinct bias, advantages and disadvantages. For example, many techniques based on the light absorption effect can be influenced by coatings, other light-absorbing and scattering particles or even gases, depending on the wavelength used for the measurement /18, 21/. If a filter-based method is used, the filter will absorb and scatter the light, too, and some technologies correct for these biases. Other techniques rely on the thermal stability of BC, but they are sensitive to the charring of other particles. Some refined methods have also been established to reduce these effects /24, 25/.

Regulatory frameworks in other transport sectors
Particulate matter emissions in the transport sector are regulated with varying degrees of stringency. The most stringent regulations are applied in road transport because this sector has the highest fuel consumption rates compared to other sectors, and with the additional reasoning that the emissions occur in close proximity to residential areas. Actually, road transport is the only sector where PM emissions are regulated by particle mass and particle number (EURO6).

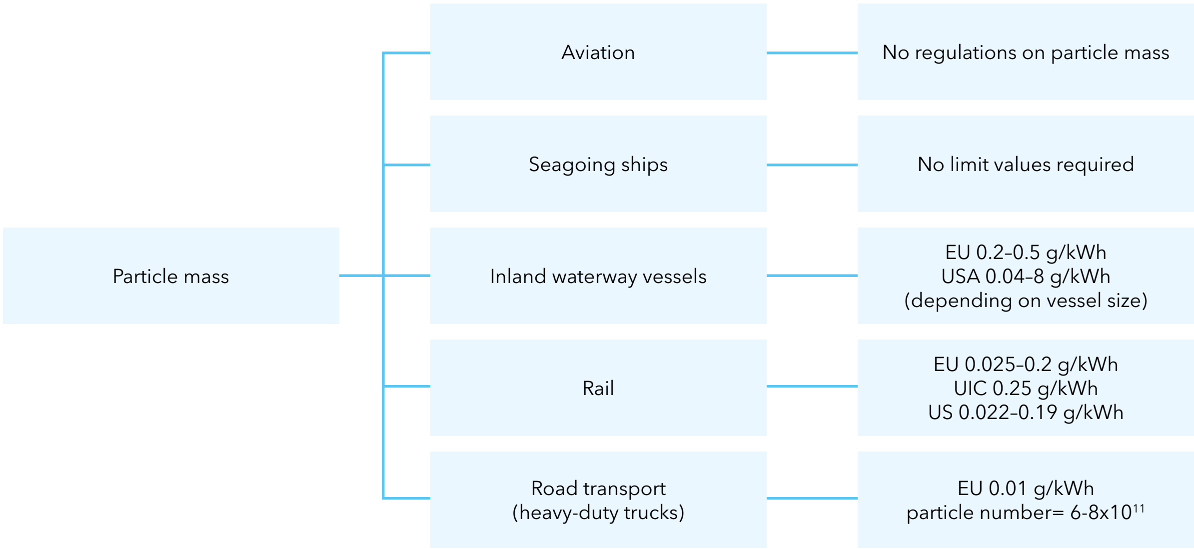


Figure 5: PM emission regulations, extracted by VDMA source /26/

The particle number takes into account the impact of ultrafine particles, which comprise a major portion of the particle number, but only a minor part of the particle mass /25/.

Other sectors, such as inland waterway vessels and locomotives, which limit PM mass, have – compared to the EURO 6 level – less stringent maximum values. But it is important to recognize that different testing cycles make a direct comparison between the automotive sector [g/km] and industry [g/kWh] nearly impossible. In another sector, aviation, no regulation on particulate matter is in place. The IMO has indirect regulations by limiting the maximum sulphur content in fuel oils of ships. It is a well-known fact that the particulate matter emissions decrease with declining sulphur content in fuel.

Black carbon is nowhere directly addressed in any regulation of the transport sector.

Background for discussion at the IMO

The IMO and its Maritime Environmental Protection Committee (MEPC) have been actively drawing attention to the particulate matter emissions of ships since the mid-1990s. In the protocol MP/CONF. 3/34 of 1997 (MARPOL Annex VI), the sulphur content of fuels is limited for international trade and for environmental protection areas in particular. Without addressing PM emissions directly, the IMO deliberately takes measures to reduce the particulate matter emissions of ships in terms of mass. Since the by-products of the chemical reaction - sulphur and water - are one of the core contributors to PM mass, by implementing a sulphur cap, the PM mass emissions are reduced simultaneously. In this regard, IMO has continuously taken measures to reduce PM mass emissions of the shipping industry by further reducing the international and local sulphur limits. This reduction scheme, however, mainly addresses another impact of this PM fraction: acid rain and the acidification of sensitive waters.

As outlined in chapter 3.1, the main impact of PM immissions is as follows:

- A direct negative affect on human health
- The darkening of icy areas due to reduced albedo effect, which increases melting

However, global warming cannot be attributed to the PM fraction consisting of sulphur. Essentially, the tremendous consequences of global warming – especially the melting of polar ice caps due to a reduced albedo effect – have guided the discussion at Pollution Prevention and Response (PPR, before BLG) and MEPC to the BC fraction for about six years. Taking into account the complexity of the chain from emissions source to immissions, the respective impact and other general circumstances, IMO found in a first step a compromise on the definition of the PM fraction to be subject to further consideration, namely of "Black Carbon" as described in the chapter above. At MEPC 68 in May 2015, the committee agreed on the definition being proposed during PPR 2 (January 2015) by Bond et al. /1/. This definition is now taken as the basis for the further course of action. More research and investigations are required on how to measure BC on ships, and the IMO has requested member states and organizations to implement voluntary measurement campaigns on black carbon. The findings from the campaigns then need to undergo close analysis and review. Only once they have been subject to intense scrutiny further steps can be envisaged.

Background on PM formation
An ideal combustion of hydrocarbons would lead to the production of only CO_2 and H_2O. This is practically unfeasible for two main reasons:

- The presence of a variety of components in the fuel and air
- Because of a non-uniform distribution of reactants in the combustion chamber, resulting in incomplete combustion

The formation of these pollutants may depend on many factors. They can be influenced by engine design/configuration, and many factors are of an operational nature, such as engine load, fuel quality, (ambient) temperature and pressure.

There are several gaps in the general knowledge about the chemistry and physics behind BC formation, especially related to the early stages of its formation. The importance of these studies is found not only in the possibility to reduce the impact of emissions, but also in improving the combustion process for better performance and efficiency. A general idea of the process from molecular structures, which leads to the formation of BC, is illustrated in Figure 6.

Experimental research on diesel engine BC formation has been performed mainly within the automotive industry and has identified the stages that involve BC formation:

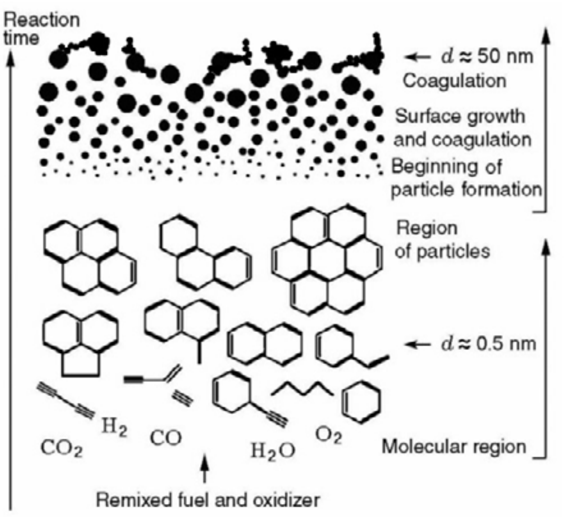


Figure 6: Growth of primary molecular structures to BC aggregation /28/

1. Formation of BC in fuel-rich zones of the inhomogeneous premixed combustion
2. Formation from fuel injected into flames
3. Formation from fuel injected into burned gases
4. Oxidation of BC, reducing the BC emissions

In principle, the automotive industry's experience can be used and applied to big bore engines (shipping), and by influencing the aforementioned parameters, the BC emissions from shipping can be reduced.

Abatement technologies
Particle emissions in general can be reduced by preventing them from being formed (internal engine processes, which relates to influencing the parameters, as mentioned in the section above) or by removing them from the exhaust gas (i.e., "after-treatment").

Internal measures (combustion improvement)
Particulate emissions arise during the combustion process of diesel engines. Low-oxygen areas in particular cause high particle emission rates. However, a major part of these particles will be oxidized during the progressive combustion process. Consequently, there are two different possibilities for reducing particulate emissions with internal engine processes:

- Avoid low-oxygen areas in the cylinder
- Strengthen the particle oxidation in the engine

The various internal abatement technologies are shown in Figure 7, covering the use of low-sulphur fuel, changing of combustion parameters and even the use of water emulsion. Most of the internal processes can be improved/ realized by applying a common rail system (CR) to the engine. Particulate emissions will decrease significantly with CR-supported injections. It should be noted that improved combustion (in this regard, combustion at higher temperatures) quite often has the effect of increasing NO_x emissions. This technical term is called the "PM/ NO_x trade-off".

Another way of reducing particulate emissions is to apply a "water-in-oil" emulsion, though only if traditional mechanical injection is used. In this case, sometimes a slight effect on increased fuel efficiency is detected, too. But with new common rail technology, no PM benefit can be demonstrated any longer; in contrast, very negative effects on the engine due to cavitation might occur. However, this technology is rarely used in diesel engines. Nevertheless, retrofit solutions for existing traditional pump/nozzle technology can be found, as there is a positive effect on visible smoke and a slight improvement of efficiency.

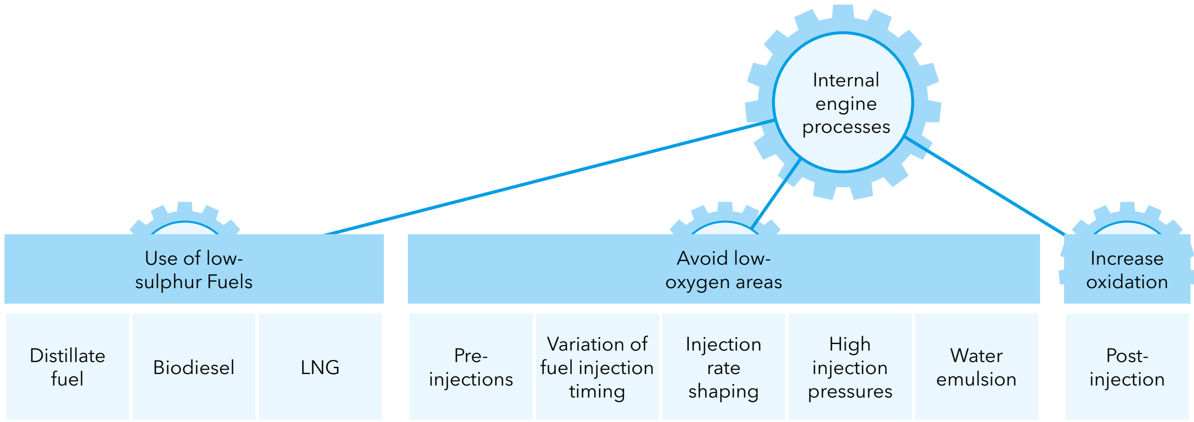


Figure 7: Overview of different internal processes for reducing particulate emissions

External measures (after-treatment)
Many different methods exist with the potential to reduce particulate emissions from exhaust gas. A number of them reduce PM as a kind of side effect, as their primary purpose is to reduce other pollutants. The main options are various filter methods, scrubbers, selective catalytic reduction (SCR) catalysts and cyclones (see Figure 8).

Various filters are used in land-based industries. In the automotive industry, closed particulate filters are used exclusively. Closed filters are, in general, not suitable for the use of residual fuels with high sulphur content /27/ due to the risk of clogging. Another technical consideration is that particulate traps commonly use a catalytic layer to enable a reduced "light-off" temperature, meaning that the oxidation of BC (self-regeneration effect) takes place at lower temperatures than the BC oxidation temperature actually is (about 550°C). The challenge for shipping is the use of HFO, containing heavy metals that damage the potential catalytic layer for self-regeneration effects.

In other sectors, open filter systems, with lower potential for blockage, are an alternative method for reducing particulate emissions /27/, but the catalytic layer would also have difficulties to withstand HFO operation. In industrial plants, other filter types, such as fabric, catalytic (similar to a fabric filter, but other materials are used) and electric filters, are commonly applied in land-based coal-fired power plants. These filter systems have the potential to reduce particulate emissions from shipping, but they must be proven to work on board a ship.

The cyclone can remove particulates from the exhaust gas as well. It uses the centrifugal force in a conical chamber and can be only applied to deposit large particles /28/. A well-known method for reducing SO_x emissions in the shipping sector is a scrubber. Removing SO_x will also reduce particulate emissions as a side effect of the scrubber /27/. Another method that is generally used in the automotive sector to eliminate NO_x emissions would also reduce particle emissions, since nitrates (NO_x salts) are also a part of particulate emissions. SCR will reduce NO_x and thus reduce particulate emissions /29/.

Installation of abatement technologies on the operational environment ship
Some of the exhaust gas after-treatment methods outlined above are obviously difficult to install on board a ship, which is not only due to tremendous space requirements. The weight of the technologies must also be taken into account. Suitable abatement technologies should consider installation costs and, as residual fuel oil use is common practice for ship installations above 1 MW of power output per engine, they must be suitable for this operation. The most important aspect is to ensure the safe and reliable operation of the engine. A sufficiently long lifetime of the abatement technologies must therefore be ensured and, in case the abatement technology fails, it must not result in a shutdown of the engine. Main engine operability is of utmost importance to ship safety, as without propulsion, a ship is not safe, especially when it is close to shore.

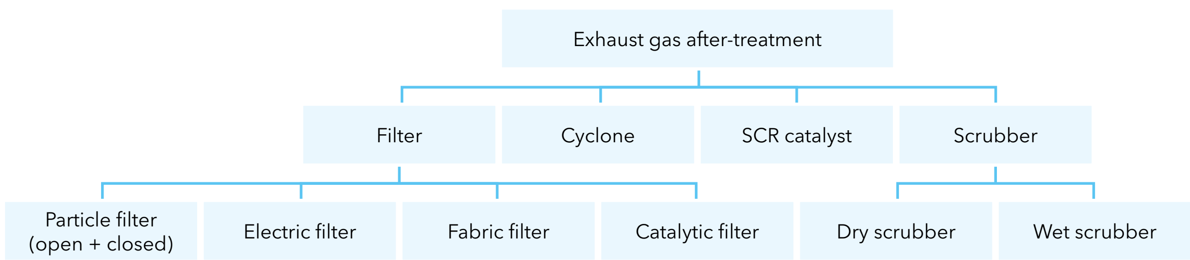


Figure 8: Overview of different exhaust gas after-treatment methods to reduce particle emissions

CONCLUSION

Particulate matter emissions from shipping have been on the regulatory agenda for decades. The term "PM" addresses the health and the climate effect at the same time. The IMO has already addressed the PM emissions indirectly via the reduction of the fuel sulphur content. The global fuel sulphur reduction scheme was adopted within the framework of MARPOL, in its revised version, in 2008. About five years ago, the IMO joined the global discussion on black carbon in order to address the detrimental "climate effect" it has in arctic areas, as existing climate models are experiencing difficulties in explaining the amount of ice melting. It seems that the reduced albedo effect has a greater impact than experts previously envisaged, and forecasting models require continuous input based on the latest research. More advanced BC emission factors are also needed in order to show which operational factors influence BC emissions. These could include engine load, fuel quality, maintenance condition, etc.

After defining what black carbon means for shipping at the IMO in 2015, this issue and its implications for possible regulations for the shipping industry need to be investigated from scratch. The scientifically correct definition of BC as such was an achievement, but it seems that it comes with a significant drawback. The commercially available measurement devices for BC were developed and used for measuring BC as "immissions". This means that they are effective in measuring BC in environments with high air dilution, such as the arctic. It is still unclear whether this technology would be adequate for measuring BC emissions in a tail pipe with much higher emission concentrations. Currently, there is no standard methodology for carrying out these measurements. Therefore, basic research tests (measurement campaigns) are necessary in order to gather more experience in this field, to test available equipment and to compare the results with those of established PM emission measurement technology.

Another challenge created by the definition of BC is that it is defined according to the following four properties: light absorption, refraction, insolubility in water and its existence as aggregated carbon spherules. Existing BC measurement devices are unable to measure black carbon by applying all four BC characteristics at the same time. Hence, additional work is necessary to test different devices which rely on different properties and check whether they show similar or (ideally) equal BC results.

Our review of the regulatory schemes in place in other transport sectors has revealed that BC emission legislation does not yet exist. Other transport sectors focus on regulating PM emissions, and the strictness of the emissions limits varies depending on a regulation's application (road, train, non-road mobile machinery, etc.), though we expect a general trend towards stricter PM limits. Taking into account the challenges we face in trying to measure BC emissions from shipping, it would be premature to make any predictions regarding potential regulatory frameworks which may govern BC emissions from shipping in the future.

The best abatement technologies can only be identified when it is clear what kind of technology will be available for measuring BC in shipping. For example, if regulations were to mainly address bigger particles, you would need different abatement technologies than if regulations were to target smaller BC particles.

Considering the fact that more research is necessary in regard to black carbon emissions from shipping, we would advise ship operators to run their vessels as efficiently as possible. Reductions in fuel consumption lower overall emissions, and optimized engine operation minimizes PM and BC emissions.

DNV GL will follow any further discussions on black carbon and particulate matter very closely and will be available to advise interested stakeholders.

BIBLIOGRAPHY

/1/ Bond TC et al.. Bounding the role of black carbon in the climate system: A scientific assessment. Journal of Geophysical Research Atmospheres.; 2013.

/2/ Intergovermental Panel on Climate Change (IPCC). The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate.; 2013.

/3/ World Health Organisation (WHO). Fact sheet No 313, Ambient (outdoor) air quality and health.; 2014.

/4/ World Health Organisation (WHO). Review of evidenceon health aspects of air pollution – REVIHAAP Project. Bonn.; 2013.

/5/ Cassee FR, Héroux M, Gerlofs-Nijland ME, Kelly FE. Particulate matter beyond mass: recent health evidence on the role of fractions, chemical constituents and sources of emission. Inhalation Toxicology.; 2013

/6/ Tuomisto JT et al.. Uncertainty in mortality response to airborne fine particulate matter: Combining European air pollution experts. Reliability Engineering and System Safety.; 2007

/7/ Grahame TJ. Public health and components of particulate matter: The changing assessment of black carbon. Journal of the Air & Waste Management Association.; 2014

/8/ Oeder S et al.. Particulate Matter from Both Heavy Fuel Oil and Diesel Fuel Shipping Emissions Show Strong Biological Effects on Human Lung Cells at Realistic and Comparable In Vitro Exposure Conditions. PLoS.; 2015.

/9/ European Environment Agency (EEA). The impact of international shipping on European air quality and climate forcing. Luxembourg.; 2013.

/10/ International Maritime Organisation (IMO). Third IMO Grennhouse Gas Study 2014.; 2014.

/11/ European Parliament and the Council of the European Union. Directive 2010/75 on industrial emissions (integrated pollution prevention and control). Official Journal of the European Union.; 2010.

/12/ European Committee for Standardization. EN 13284-1:2001 Stationary source emissions – determination of low range mass concentration of dust; 2002.

/13/ International Organization for Standardization. ISO 8178:2006 Reciprocating internal combustion engines – Exhaust emissions measurement.; 2006.

/14/ Lack DA et al.. Characterizing elemental, equivalent black, and refractory black carbon aerosol particles: A review of techniques, their limitations and uncertainties. Analytical and Bioanalytical Chemistry.; 2013

/15/ Arnott WP et al.. Photoacoustic spectrometer for measuring light absorption by aerosol: Instrument description. Atmospheric Environment.; 1999

/16/ Kondo Y et al.. Consistency and Traceability of Black Carbon Measurements Made by Laser-Induced Incandescence, Thermal-Optical Transmittance, and Filter-Based Photo-Absorption Techniques. Aerosol Science and Technology.; 2011

/17/ Slowik JG et al.. An Inter-Comparison of Instruments Measuring Black Carbon Content of Soot Particles. Aerosol Science and Technology.; 2007

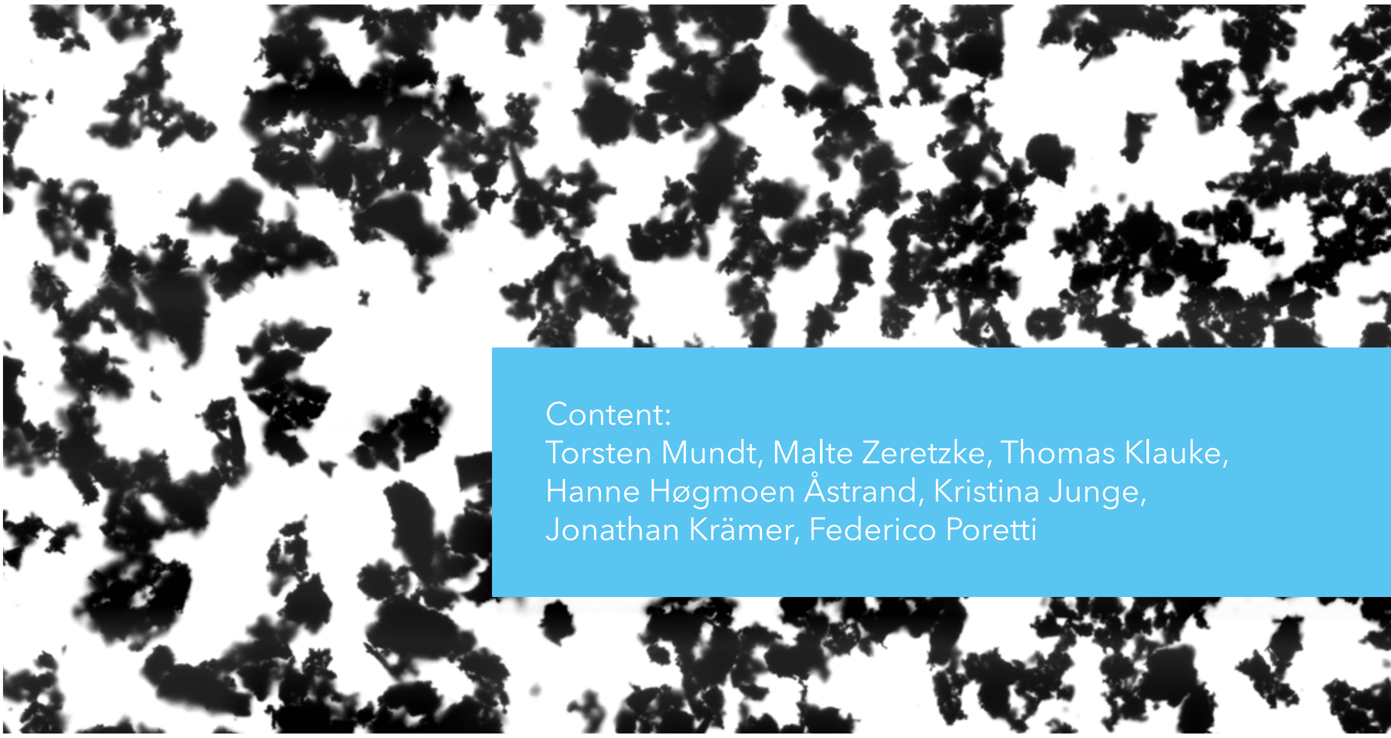
/18/ Andreae MO and Gelencsér A. Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols. Atmospheric Chemistry and Physics ; 2006

/19/ Zhi G et al.. Comparison of elemental and black carbon measurements during normal and heavy haze periods: implications for research. Environmental Monitoring and Assessment.; 2014

/20/ Sheridan PJ et al.. The Reno Aerosol Optics Study: An Evaluation of Aerosol Absorption Measurement Methods. Aerosol Science and Technology.; 2005

/21/ Snyder DC and Schauer JJ. An inter-comparison of two black carbon aerosol instruments and a semi-continuous elemental carbon instrument in the urban environment. Aerosol Science and Technology.; 2007

/22/ Hitzenberger R et al.. Intercomparison of thermal and optical measurement methods for elemental carbon and black carbon at an urban location. Environmental Science and Technology. ;2006
/23/ Watson JG, Chow JC, Chen LWA. Summary of methods and comparison studies for organic and elemental carbon: Implications for visibility and global warming. Regional and Global Perspectives on Haze. ; 2004
/24/ Birch ME and Cary RA. Elemental Carbon-Based Method for Monitoring Occupational Exposures to Particulate Diesel Exhaust. Aerosol Science and Technology.; 1996
/25/ Kelly FJ and Fussell JC.Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. Atmospheric Environment.; 2012.
/26/ Verband Deutscher Maschinen- und Anlagenbau (VDMA). Abgasgesetzgebung Diesel- und Gasmotoren Frankfurt am Main.; 2008.
/27/ Buchholz B. Vorlesung Schiffsdieselmotoren. At the University of Rostock, Lehrstuhl für Kolben- und Strömungsmaschinen.; 2015
/28/ Umweltbundesamt (German Federal Environmental Agency). BVT-Merkblatt zu Abwasser- und Abgasbehandlung/-management in der chemischen Industrie. Berlin.; 2003.
/29/ Sinzenich H, Wehler K, Müller R. Selektive katalytische Reduktion: Abgasnachbehandlung zur Verringerung von Stickoxidemissionen. MTU Friedrichshafen GmbH.; 2014.



Content:
Torsten Mundt, Malte Zeretzke, Thomas Klauke, Hanne Høgmoen Åstrand, Kristina Junge, Jonathan Krämer, Federico Poretti

SAFER, SMARTER, GREENER

DNV GL – Maritime
Brooktorkai 18
20457 Hamburg
Phone: +49 40 36149 0
www.dnvgl.com/maritime

About DNV GL

Driven by its purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. Operating in more than 100 countries, our 15,000 professionals are dedicated to helping our customers in the maritime, oil & gas, energy and other industries to make the world safer, smarter and greener.

DNV GL is the world's leading classification society and a recognized advisor for the maritime industry. We enhance safety, quality, energy efficiency and environmental performance of the global shipping industry – across all vessel types and offshore structures. We invest heavily in research and development to find solutions, together with the industry, that address strategic, operational or regulatory challenges.

Design: Maritime Communications **ID:** 957266