THE CONTROL OF SHIPPING EMISSIONS
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1 INTRODUCTION

Over recent decades there has been a significant reduction in emissions from land based sources of air pollution. Increasingly stringent legislation at the European Union (EU) level has resulted in large reductions in emissions of sulphur oxides (SO\textsubscript{x}), nitrogen oxides (NO\textsubscript{x}) and particulate matter (PM) from stationary sources and road traffic. There has been, however, little control of these emissions from shipping until relatively recently, and even then has only been partially effective for sulphur dioxide (SO\textsubscript{2}). The impacts on NO\textsubscript{x} emissions have been modest. According to the European Environment Agency (EEA, 2013) emissions of NO\textsubscript{x} from international shipping in European waters are projected to increase and could be equal to land-based sources by 2020.

More than 90\% of global trade is carried by sea (IMO, 2012). Most international freight is transported on extremely large ships carrying bulk dry cargo, containers, fuel or chemicals. Furthermore, in the last decade the number of very large cruise ships, with associated high emissions, has increased markedly in coastal areas near tourist sites in Europe. These ships sail closer to towns and cities than cargo ships and therefore risk exposing the public to poor air quality.

A typical Aframax\textsuperscript{1} tanker may consume 18,000 t yr\textsuperscript{-1} of fuel of which approximately 85\% is consumed by the main engine. The remainder is equally split between the auxiliary engines and auxiliary boiler (Armstrong, 2013).

Marine diesel engines can be separated into three categories based on their rotational speed, as slow (<400 rpm), medium (400 -1000 rpm) and high (>1000 rpm) speed. Slow-speed engines are predominantly large two-stroke engines, whereas high- and medium-speed engines are typically four-stroke engines.

1.1 Shipping emissions

Marine diesel engines emit SO\textsubscript{x}, NO\textsubscript{x}, PM and CO\textsubscript{2} (carbon dioxide) as well as a range of volatile organic and other compounds. SO\textsubscript{2} emissions, and to a lesser extent PM, are dependent on the sulphur (S) content of the fuel. The major abatement method for these two pollutants has been limiting the S content of the fuel. The control of NO\textsubscript{x} emissions, and further control of PM, is more difficult as it requires changes in the design of the engine and/or the treatment of the engine’s exhaust gas. Measures to reduce these emissions can increase fuel consumption and the associated CO\textsubscript{2} emissions.

Globally shipping represents approximately 15\% and 13\% of NO\textsubscript{x} and SO\textsubscript{x} from anthropogenic sources respectively (IMO, 2015a).

EEA (2013) has estimated that emissions of NO\textsubscript{x} from international shipping within the EU-27\textsuperscript{2} waters may be equal to those from land based sources by 2020; while land-based SO\textsubscript{2}

\textsuperscript{1} Aframax is a medium-sized crude tanker. The tanker derives its name from AFRA which stands for Average Freight Rate Assessment.

\textsuperscript{2} EU-27 includes 27 European Union countries.
emissions will probably continue to exceed emissions from international shipping until 2030. Emissions of PM from both land- and sea-based sources are expected to decrease by more than 40 % between 2000 and 2030.

Most ship emissions within European waters occur close to the coast (Viana et al., 2014). These emissions contribute to high nitrogen dioxide (NO₂), sulphur dioxide (SO₂) and PM concentrations in coastal areas and, particularly, around ports with heavy marine traffic (Eyring et al., 2010). In addition, gaseous precursors of ozone (O₃) and PM emitted from ships may be transported in the atmosphere over several hundreds of kilometres, and contribute to air quality problems further inland, even though they are emitted at sea.

Global sea trade and the associated emissions are forecast to increase in the future. According to the IMO (2015a) shipping emitted about 3% of the global CO₂ emissions over the period 2007-2012. This is more than from aviation (Cullinane & Cullinane, 2013). The IMO (2015a) have predicted that fuel use and greenhouse gas (GHG) emissions could increase in the future despite significant regulatory and market-driven improvements in efficiency. Depending on future economic conditions and energy demand their business as usual scenarios predicted 50–250 % increase in emissions in 2050.

Most other emissions are also predicted to increase (IMO, 2015a). Methane emissions are projected to increase rapidly, albeit from a very low base, as the share of liquefied natural gas (LNG) used in shipping increases. Emissions of NOx are predicted to increase at a lower rate than CO₂ emissions as a result of engines with lower emissions entering the fleet. Emissions of PM show an absolute decrease until 2020, and SOx continue to decline through to 2050, mainly because of international limits in the S content of fuels.

Over the last decade there have been significant improvements in engine efficiency. Improved hull design and the use of ships with larger cargo carrying capacities have also led to an increase in fuel efficiency and a reduction in CO₂ emissions. According to the IMO (2012) a modern container ship uses only a quarter of the energy per cargo unit than a container ship did in the 1970s, although the former is likely to be significantly smaller with less carrying capacity. A modern large crude oil tanker is able to transport the same amount of cargo twice the distance compared with 20 years ago using the same amount of energy.

Within the EU shipping is responsible for the movement of over one third of goods transported (EU, 2014). Emissions from international shipping within European waters has been estimated to be responsible for approximately 14 million years of life lost (YOLL) due to exposure to PM<sub>2.5</sub> exposure and for 700 premature deaths due to exposure to O₃. It is also responsible for exceedances of acid and eutrophication critical loads over approximately 17,000 km<sup>2</sup> and 30,000 km<sup>2</sup> of natural habitats respectively. These adverse impacts are predicted to continue in the absence of any strengthening of international legislation, and may increase in the future (Campling et al., 2013).

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<sup>2</sup> EU-27 refers to the 27 European Union (EU) member states at the beginning of 2013; there are currently 28 members as Croatia join the EU in July 2013.
1.2 Scope of report

There are a wide range of measures available to reduce these impacts. Many are beginning to be used but widespread adoption is required to make a significant difference, which in turn is likely to require further regulation. The aim of this report is to provide some insight into these abatement measures. Brief descriptions of marine fuels and international emissions regulations are provided.

In 2013 the EEA published a comprehensive report on ship emissions and their impacts (EEA, 2013). This report does not aim to reproduce that work or that of Viana et al. (2014), which supports the EEA literature review. Instead it provides a brief summary firstly of the impacts of ship emissions on air quality, describes the limited evidence of the impacts of existing regulations on air quality and then reviews emission abatement strategies.

The discussion on abatement techniques covers technical measures for reducing emissions, operational changes to shipping and market-based measures. Much of the literature is on fuel efficiency and the reduction of CO$_2$ emissions and although these measures are important as SOx, NOx and PM emissions will also be reduced if less fuel is consumed; the main focus of this report is on specific measures that reduce these key air pollutants. It includes a discussion of fuel economy benefits of alternative fuels and operational changes, where evidence of the SOx, NOx and PM benefits are missing.

Major ports often have high volumes of heavy duty vehicles using their facilities and total emissions from these vehicles can be higher than from the ships themselves (Kuwayama et al., 2013). This report does not discuss these emissions as they are already controlled by European legislation.

2 MARINE FUELS

In the 1960s motor ships overtook steam ships in terms of both the number of vessels and their gross tonnage (GT), and by the start of the 21st century, motor ships accounted for 98 % of the world fleet (Vermeire, 2007). Today 95 % of the world shipping fleet use diesel engines.

A range of terms are used to describe marine fuels. For international shipping it is known as bunker oil or bunker fuel. It is essentially a type of diesel.

There are two basic types of marine fuel – distillate and residual. Distillate fuel is composed of the crude oil fractions that are separated by distillation in a refinery. Heavy fuel oil (HFO), also known as marine fuel oil (MFO) is pure or nearly pure residual oil. It has been described as a cross between a solid and a liquid, and is a very low quality fuel (Cullinane & Bergqvist, 2014). The highest quality marine fuel is marine gasoil (MGO) which is made from distillate only. Marine diesel oil (MDO) is a blend of MGO and HFO. This is also known as intermediate fuel oil (IFO).

The EEA (2013) has estimated that internationally, within the EU, 87 % of the marine fuel used in 2010 was HFO. In contrast, domestic shipping used approximately 60 % MDO or MGO and 31 % HFO.
Different fuels may be used near coastlines and inside harbours to comply with international or local regulations controlling, for example, the S content of marine fuel.

It is not anticipated that the current marine fuels will be replaced by other fuels in the foreseeable future other than in niche vessels (e.g. Eyring et al., 2005). There is some interest in the use of alternative fuels, particularly LNG as emissions of the key air pollutants are lower than from diesel engines, but the number in use is currently very small and is likely to remain so for the foreseeable future.

### 3 REGULATION OF SHIP EMISSIONS

#### 3.1 International Maritime Organization

International shipping is controlled by the voluntary agreement of United Nations member states, negotiated under the auspices of the International Maritime Organisation (IMO). The control of emissions is driven by the International Convention for the Prevention of Pollution from Ships (known as MARPOL) which came into force in 1983. Air emissions from ship engines, however, were first included in May 2005 when Annex VI of the convention entered into force. A revised Annex VI entered into force in July 2010. All EU countries with a coastline are signatories to the Annex, as well as several European countries outside the EU such as Norway and Russia.

Annex VI sets limits on ship emissions of SOx and NOx, and prohibits deliberate emissions of O₃ depleting substances. It also includes measures to control CO₂ emissions.

To reduce SOx emissions the S limit of marine fuels is currently set at 3.5 % (by mass) globally. This is to be reduced to 0.5 % in 2020 (or 2025 depending on the outcome of a review of fuel availability). Sulphur emission control areas (SECA) were established in the Baltic Sea in May 2007 and North Sea (which includes the English Channel) in November 2007. The maximum S content of fuels used in these areas was originally 1.5 %. This was reduced to 1.0 % in July 2010, and further reduced to 0.1 % from the beginning of 2015. The fitting of an exhaust gas cleaning system, or other technical method to limit SOx emissions to the same level as would occur with low S fuel is permitted.

NOx emissions from new and reconditioned marine engines with a power output over 130 kW are regulated as a function of engine speed. Ships built between 2000 and 2011 need to comply with the Tier 1 standards which range from 9.8-17.0 g kWh⁻¹. Ship engines built after 2011 need to comply with the Tier II standards (7.7-14.4 g kWh⁻¹). Ships operating within NOx emission control areas (NECAs) after 1 January 2016 need to meet Tier III standards (2.0-3.4 g kWh⁻¹). According to the IMO (2009) Tier 1 ship engines have 12–14 % lower NOx emissions per tonne of fuel combusted compared to pre-regulation (Tier 0) engines, while Tier 2 and Tier 3 are 25 % and 80 % respectively lower than Tier 1.

There are no NECAs in Europe. The only designated NECAs are along the west and east coasts of North America and near the coasts of Puerto Rico and the United States Virgin Islands.
Energy efficiency requirements were included in MARPOL Annex VI from July 2013. Performance-based energy efficiency requirements are set for certain new ships of 400 GT and above, which will be gradually tightened over time until 2025-2030 when there will be a 30% improvement over the average efficiency of ships built between 2000 and 2010. IMO has developed an energy efficiency design index (EEDI) which sets a minimum standard of energy efficiency for tankers, gas carriers, bulk carriers, general cargo ships, refrigerated cargo carriers and container ships. Further iteration of the EEDI is due from IMO for other types of ship.

The current energy efficiency regulations for new ships will incrementally increase between now and 2030, requiring 10%, 20% and 30% more efficient ships in 2015, 2025 and 2025 respectively. While for some ship types, such as container ships, this is achievable through the adoption of non-technical measures, a significant proportion of the tanker and bulk carrier fleets will require technology improvements.

All existing ships of 400 GT and above are also required to have a ship energy efficiency management plan (SEEMP).

3.2 European Union

In addition to the IMO requirements, the European Union has adopted several Directives limiting the S content of marine fuels. The basic legislation is Directive 1999/32/EC as amended by Directive 2005/33/EC, which designates the Baltic Sea and the North Sea as SECA s and limits the maximum S content of the fuels used by ships operating in these areas to those agreed by MARPOL. Directive 2012/33/EU implements MARPOL’s requirements for lower S content of marine fuels inside and outside of SECA s from 2015 and 2020 respectively.

Currently the maximum S content of marine fuels used in passenger ships in the EU, but outside the SECA s, is 1.5%; and that used by ships at berth in EU ports is 0.1%. In addition, the IMO global 0.5% S limit will be introduced in the EU in 2020 irrespective of any possible postponement.

Sulphur in marine fuels remains high compared to other transport modes. The maximum S content of fuels used in road and rail transport and non-road mobile machinery is 0.001%. For inland shipping (i.e. on navigable rivers, canals, sounds, lakes, inlets, etc.) from 2012 the S requirements have been the same as for road transport.

In April 2015 the EU adopted Regulation 2015/757 on the monitoring, reporting and verification of CO₂ emission from maritime transport as a first step towards the inclusion of maritime transport emissions in the EU’s GHG reduction commitment.

4 AIR QUALITY IMPACT OF SOₓ, NOₓ AND PM EMISSIONS FROM SHIPS

Emissions from shipping have a number of air quality impacts including contributing to poor local air quality, the formation of secondary pollutants which can influence air quality over a large area and S and nitrogen (N) deposition on sensitive ecosystems.
4.1 Emission Inventories

A number of inventories of shipping emissions from European waters have been prepared, however they cover different geographical areas, years, and estimation methodologies, and therefore the results are not directly comparable. According to the EEA (2013) CO₂ emission estimates vary by a factor of 3; NOx by a factor of 2 and SO₂ by a factor of 2.5.

National inventories are typically based on fuel statistics, including those submitted to the United Nations Economic Commission for Europe (UNECE) Convention on Long–range Transboundary Air Pollution (CLRTAP) and the United Nations Framework Convention on Climate Change (UNFCCC).

Under CLRTAP emissions from inland and domestic maritime shipping on international waters are included in the national inventory, but international maritime shipping is excluded. The fuels sold within each country for international shipping and the resulting emissions are reported as a memo item. One major shortcoming of this approach is that it is not known where the fuel is used. National emissions inventories reported to the UNFCCC follow a similar approach. It is recognised that using marine fuel statistics underestimates the real fuel use by shipping (e.g. Cullinane & Bergqvist, 2014). The EEA (2013) has suggested that a large fraction of shipping emissions are not accounted for in these ‘official’ inventories.

The EEA (2013) concluded that international shipping in European waters contributes 10-20 % of NOx emissions; 10-25 % of SO₂ emissions; and 15–25 % of primary PM₂.₅ emissions. NOx emissions in the EU-27 are expected to decrease by nearly 70 % between 2000 and 2030. Up to 2030, land based emissions are likely to continue to exceed the NOx emissions from international shipping in the seas surrounding Europe, but over a longer period international shipping emissions are likely to dominate (Campling et al., 2013). Conversely SO₂ and PM emissions are forecast to decline with the reduction in the permitted S content of marine fuels.

4.2 Air Quality

There have been few published studies on the contribution of shipping emissions to ambient air quality, and these mainly are modelling studies with a very small number based on measurements. The exceptions are studies looking at the impact of the reduction of S in marine fuels on ambient concentrations of SO₂ in Rotterdam and in the Mediterranean.

The Port of Rotterdam is Europe’s largest port (Port of Rotterdam, 2015). Average SO₂ concentrations measured close in Rotterdam were fairly constant between 2000 and 2006, but then decreased rapidly between 2007 and 2010, after the North Sea SECA was introduced in 2007. In 2010 concentrations were about 50 % below the 2000-2006 average (Velders et al., 2011, EEA, 2013).

Similar results have been found by Schembari et al. (2012) who analysed the impact of the introduction of S controls in selected Mediterranean harbours. SO₂ concentrations were measured on-board a cruise ship from August to October in both 2009 and 2010. The concentrations decreased significantly from 2009 to 2010 in three out of the four EU harbours with an average decrease in the daily mean concentrations of 66 %. This coincided with the introduction of the 0.1 % limit on fuels for ships at berth in EU ports. The decrease in SO₂ concentrations was, however, not statistically significant in the harbour of Barcelona because
of the large day-to-day variations. Measurements from monitoring stations in the harbour area as well as downwind of the harbour of Palma de Mallorca confirmed a decrease in the SO₂ concentrations from 2009 to 2010. No decrease was observed in the non-EU harbour of Tunis. Neither NOₓ nor black carbon (BC) concentrations showed significant changes in any of the harbours.

The North Sea, including the English Channel, is one of the busiest seas in the world, particularly in the southern section. Every day, 400 commercial vessels pass through the Strait of Dover, the busiest seaway in the world. In the UK an Air Quality Management Area (AQMA) for SO₂ was declared due to ship emissions, covering the East Docks in Dover. Data downloaded from Kent Air (2015) shows that the EU limit value for SO₂ has not been exceeded at the monitoring locations closest to the port. However, the UK 15-minute air quality objective (266 µg/m³ not to be exceeded more than 35 times per year) was exceeded in 2002, 2003 and 2006 at one or other of the monitoring sites. There has been no exceedence since the English Channel became a SECA in 2007, monitoring ceased in 2011 and in 2014 the AQMA was revoked (Dover District Council, 2014).

Viana et al. (2014) provides a summary of European source apportionment studies from coastal urban areas and concluded that the contribution of shipping emissions to annual mean concentrations are: PM_{10} 1–7 %; PM_{2.5} 1–14 %; and PM₁ at least 11 %, with higher percentages recorded in Mediterranean cities than in Atlantic coastal areas, although this could have been due to fewer northern Europe studies published. The above estimations referred mostly to primary PM emissions but no information was supplied on the contribution of secondary PM components such as nitrate and sulphate. Port activities also contribute PM emissions including the unloading and loading of tankers, cargo ships, and emissions of a large fleet of heavy duty vehicles associated with these operations. Shipping emissions of NOₓ are also thought to be responsible for 1- 5 % of the PM_{2.5} in North Sea countries. Although this appears to be small in terms of mass, the authors concluded that shipping may make a significant contribution to both particle number concentrations and toxicity. This is because primary particles emitted by ships are predominantly in the submicron size fraction and contains a number of metals found in marine fuels (mainly nickel, Ni and vanadium, V).

Shipping can be responsible for up to 90 % of NOₓ concentrations in pristine areas (EEA, 2013), although the impact on European coastal areas is much smaller. Hammingh et al. (2012) have forecast that the shipping contribution to ambient NO₂ concentrations in the North Sea countries may be in the range 7-24 % in 2030, with the highest percentages occurring close to the busy shipping lanes in the Netherlands and Denmark. The shipping contribution to N deposition was forecast to be in the range 2-5 %.

Modelling undertaken for the EEA (2013) using the CHIMERE model with a 50 km resolution, shows that ship emissions are, on average, responsible for about 10 % of public exposure to particulate sulphate (SO₄^{2-}) and approximately 4-5 % of peak concentrations of PM_{2.5} and O₃. Western France, southern England, the Netherlands and northern Denmark are especially vulnerable to shipping contributions to ambient NO₂, SO₂, SO₄^{2-} and PM_{2.5}. For O₃ the highest contribution is found in the Mediterranean area and less in other coastal areas. The EEA (2013) has shown that there are hotspots in Europe where the contribution of shipping can be large, up to 80 % for NOₓ and SO₂, up to 25 % for PM_{2.5}, and up to 40 % for secondary PM. The largest influence of shipping on O₃ concentrations is in the Mediterranean area where it can contribute up to 15 % of average summer daily maximum concentrations.
These figures are likely to be underestimated as they do not account for emissions from domestic ships.

The contribution of international shipping to surface annual mean NO$_2$ and PM$_{2.5}$ concentrations in coastal areas is illustrated in Figure 1.

Figure 1: Modelled relative contribution of international shipping emissions (%) on annual mean surface NO$_2$ and PM$_{2.5}$ concentrations in 2005 using the Chimere model (EEA, 2013)

5 IMPACT OF CURRENT EMISSION REGULATIONS

5.1 Sulphur Oxides (SOx)

The limits on S in marine fuels introduced up to 2011 have been estimated to reduce the contribution of international shipping emissions to annual mean SO$_2$ concentrations from 44 to 27% over the sea and from 16 to 7% in coastal areas (EEA, 2013).

The introduction of the SECA in the North Sea and Baltic Sea in 2007 has been estimated to have reduced SOx emissions in these areas by more than half, with significant reductions in PM$_{2.5}$ emissions. The further reductions in the S content of fuels in SECA and EU ports between 2009 and 2011 resulted in SOx emissions from IMO-registered marine traffic reducing by nearly 30% and PM$_{2.5}$ emission by 15% (Johansson et al., 2013). In 2015, when the maximum S level in the SECA is reduced to 0.1%, SOx and PM$_{2.5}$ emissions will be reduced by 92% and 64% respectively compared to 2009 (Kalli et al., 2013).

It has been predicted that current legislation will reduce SOx emissions over the Mediterranean Sea from 764 kt in 2005 to 167 kt in 2020, but then emissions will begin to grow in the absence of further control. The introduction of a SECA extending 12 nautical miles (nm) from the coast would reduce emissions to 152 kt in 2020 and 180 kt in 2030; while extending the SECA for 200 nm would reduce emissions to 95 kt in 2020 and 113 kt in 2030 (Campling et al., 2013).
Contini et al. (2015) investigated the impact of the reduction of S in marine fuels used in tourist vessels over the period 2007 to 2012 on ambient PM$_{2.5}$ concentrations in Venice. In addition to the IMO requirements, a voluntary Venice Blue Flag scheme was introduced in 2007 which limited the S in fuel used by large cruise ships to 2.5 %. In 2008 this was reduced to 2 %. A decrease in the shipping contribution to measured PM$_{2.5}$ concentrations was observed from 7 % (±1 %) in 2007 to 5 % (±1 %) in 2009 and then to 3.5 % (±1 %) in 2012. The meteorological conditions during the measurement campaigns were similar, but the number of tourist ships increased, in terms of gross tonnage. The results of this study show that voluntary agreements can be effective in reducing the impact of shipping on local air quality in coastal areas.

5.2 Nitrogen Oxides (NOx)

According to the EEA (2013) the current controls on NOx emissions are not anticipated to lead to any reduction in international shipping contribution to annual mean NO$_2$ concentrations over the sea or coastal areas by 2020. This is due to the anticipated growth in marine traffic and the modest impact of the MARPOL Tier I and Tier II requirements.

According to Kalli et al. (2013) if the Baltic Sea and North Sea were both designated as NECAs, NOx emissions would decrease by 11 % in 2020 and 79 % in 2040 from the 2009 level. Most of the emissions are due to containerships, tankers, ro-ro$^3$ and general cargo ships.

Hammingh et al. (2012) investigated the potential benefit of introducing NECAs in the North Sea and Baltic Sea, using the EMEP model. NOx emissions from North Sea shipping are estimated to be 472 and 446 kt in 2009 and 2030 respectively. The 6 % reduction is due to the combination of the assumed efficiency improvements, the Tier II NOx emission standards and the increased assumed use of LNG as a clean fuel. Approximately one third of the emissions were estimated to be released within 12 nm of the shore; 89 % within 50 nm; and 97 % within 100 nm. Almost 10 % of the NOx emissions take place in ports.

The authors predicted that without the NECAs NOx emissions will be responsible for 7-24 % of North Sea coastal countries’ average NO$_2$ concentrations in 2030. The contribution to N deposition was estimated to be 2-5 % and NOx emissions were estimated to contribute 1-5 % of PM$_{2.5}$ concentrations in the North Sea countries.

The introduction of a NECA in the North Sea (including the English Channel) would reduce the shipping contribution to NOx emissions by approximately one third, and improve the air quality in the surrounding countries. It was estimated that the health benefits in 2030 would exceed the costs to international shipping by a factor of two (Hammingh et al., 2012).

Johansson et al. (2013) estimated that NOx emissions would to be slightly greater in 2011 than in 2009, as the impact of Tier II NOx emissions, introduced from 2011 only affects a small number of vessels, and more ship movements were predicted. The authors also estimated that the introduction of a NECA in the North and Baltic Seas would reduce NOx emissions by approximately 30 % between 2009 and 2030. The shipping contribution in

$^3$ Ro-ro = roll on-roll off
2030, averaged by country, to the deposition of oxidised N could reduce from 10-35 % to 7-28 % (Jonson et al, 2015).

Campling et al. (2013) predicted that NOx emissions from international shipping in EU waters would reduce by 47 % in 2030 and 66 % in 2050 from 2005 levels. A NECA extending 200 nm of all EU countries would reduce the total NOx emissions from European seas by 1 % in 2020; 35 % in 2030 and 56 % in 2050. Higher future reductions are due to increasing share of new ships which meet Tier III standards. A large percent of European NOx emissions occur in the Mediterranean Sea (46 % in 2005) and therefore applying a NECA in this area would have a significant impact on the total EU emissions.

One of the shortcomings of most air quality modelling studies is that they use a large grid resolution, and therefore the local detail is lost. A few studies have looked at the impact of local ship emissions. For example, the manoeuvring of ships in harbours and the loading and unloading of tankers was found by Keuken et al. (2005; cited in EEA, 2013) to make a significant contribution to harbour emissions, and near the waterways of the Port of Rotterdam. It was estimated that shipping contributes 5–7 ppb to ambient NOx concentrations close to the waterways. In Gothenburg shipping contributions to ambient NO2 concentrations have been reported to be of similar magnitude as the background concentrations (Isakson et al., 2001), and in Denmark it has been estimated that ship emissions in the ports of Copenhagen and Elsinore may contribute to exceedence of the EU’s hourly limit value for NO2 in a small area near to the harbours (Saxe & Larsen, 2004).

5.3 Particulate Matter (PM)

The EU limit values for PM10 and PM2.5 are not currently exceeded as a result of shipping emissions but the WHO guidelines of 20 and 10 µg m3 respectively are exceeded along the coasts of the Baltic Sea and the North Sea, suggesting that shipping may be causing health effects in populated coastal areas (Jonson et al., 2015). The highest PM2.5 emissions in 2011 were estimated to occur close to the coast of the Netherlands, in the English Channel, near south-eastern England and along the busy shipping lanes in the Danish Straits and the Baltic Sea (Johansson et al., 2013). The years of life lost (YOLL) per person due to PM2.5 exposure close to the major shipping lanes has been estimated to be 0.1–0.2 years at current emission levels (Jonson et al., 2015).

There are no specific limits on the PM emissions from ship engines. The reduction in the S content of marine fuels has, however, resulted in significant reductions in primary PM emissions but also in the formation of secondary PM sulphate from the atmospheric oxidation of SO2. In 2009 shipping was responsible for about 10 % of the calculated years of life lost (YOLL) in small and medium sized countries bordering the North Sea, and less for countries bordering the Baltic Sea as emissions are lower. The introduction of the controls on S in fuel has been forecast to reduce YOLL by 16-32 % by 2030, mainly due to the control of SOx emissions from ships (Jonson et al., 2015).

Emissions of BC from ships are a potential concern as these may have a greater impact on human health than total PM mass. The health effects from both short- and long-term studies are much higher for BC compared to PM10 and PM2.5 when the concentrations are expressed in µg m3 (WHO, 2012).
Lack & Corbett (2012) reviewed BC emissions from ship engines and concluded that emission per kg of fuel burnt increase 3-6 times at very low engine loads (less than 25 %) and that emission per nm can increase by 100 % depending on the engine load. Engines that are frequently operated at low loads because, for example they have adopted a slow steaming strategy to conserve fuel, can be re-calibrated to reduce BC emissions. The authors suggest that the fuel S regulations have reduced BC emissions by an average of 30 % and potentially much more. This is similar to the removal rate of SOx scrubbers. However the authors note that there is a need for more information on the impact of fuel composition (not just S content) on BC emissions and the efficacy of scrubbers for the removal of PM by size and composition.

Elemental carbon (EC; equivalent to BC, when both are expressed in mass/air volume) emissions were estimated by Jonson et al. (2015) to increase between 2009 and 2011 in the North Sea area by about 10 %, but then are forecast to reduce by over 30 % by 2030 due to the impact of the SECA.

Inland shipping in the Netherlands has been shown to increase annual mean ambient EC concentrations close to waterways by up to 0.5 μg m⁻³ (Keuken et al., 2014). This study also found that approximately 30 % of ships emit over 80% of the emissions, probably due to the engine type and poor maintenance. The authors suggest that targeting these ‘gross’ polluters may be the most effective approach to controlling emissions.

6 EMISSION ABATEMENT TECHNIQUES

6.1 Introduction

There are a number of strategies to reduce NOx, SOx and PM emissions from ships. They can broadly be divided into fuel quality improvements, alternative fuels, engine improvements, after-treatment, operational changes and market incentives. The adoption of many of these techniques is likely to be driven by the need to reduce fuel consumption; if significantly less fuel is used there will be co-benefits for both air quality and climate.

Technological measures to improve fuel economy introduced in recent years include improvements to on-board machinery, modified hulls to reduce vessel resistance, micro-bubble drag reduction⁴, improvements to the propeller and rudder, optimised engine rating, and the use of exhaust gas waste heat to generate electricity (Cullinane & Cullinane, 2013). However, according to Knott & Buckingham (2011) the greatest scope for fuel saving is through improvements to the power and propulsion system, at least for tankers.

There are also non-technical measures that can reduce fuel consumption such as taking account of the weather when routing, minimising the amount of time in port, and better planning of ship deployment across a fleet (Cullinane & Cullinane, 2013).

⁴ The injection of a layer of small air bubbles into the boundary layer of a ship. This is particularly effective when the hull has a polymer coating.
Over the last decade there have been significant improvements in engine efficiency. Improved hull design and the use of ships with larger cargo carrying capacities have also led to an increase in fuel efficiency and a reduction in emissions. According to the IMO (2012) a modern large crude oil tanker is able to transport the same amount of cargo twice the distance compared with 20 years ago using the same amount of energy.

However, according to an ICCT (2013) study there is a huge variation in energy consumption between ships. The best ships are about twice as efficient as the worst across major ship types, due to new ships’ technical improvements, operational speed practices, and ship size differences. For example, the top 5% of containerships have a CO₂ emission intensity (i.e. emission rate per unit of cargo carried) that is 38% lower than the industry average whereas the bottom 5% has 48% higher emissions. Even wider variation is seen in the other major ship types (e.g. tankers, general cargo, bulk carriers). Part of this variation is due to the rate that new more efficient technology is entering the fleet. Newer ships tend to have more sophisticated engine controls that allow them to more fully and more frequently benefit from speed reduction so that their operational in-use efficiency more closely matches the design efficiency.

If the best available technical and in-use practices were used across the international shipping industry, CO₂ emissions could reduce by approximately 50% by 2040 or more than 300 Mt even if freight transport doubled (ICCT, 2013; Wang & Lutsey, 2014). Other emissions would also reduce if significantly less fuel was consumed.

The international shipping industry is highly competitive and very cost driven. The optimal solution for pollution abatement will ultimately be determined by the capital and operational costs of the various options, which in turn are likely to be driven by fuel prices. For example, during periods of low fuel prices, switching to higher quality fuels to reduce S emission is likely to be the preferred option but when fuel prices are high after-treatment may become the preferred option. The current IMO regulations essentially allow ship owners to choose the best option, which is a function of engine size, annual fuel consumption in SECAs and likely future fuel prices (Lindstad et al., 2015).

### 6.2 Fuel Quality

Emission of SOx from ships is essentially proportional to the S content of the fuel and therefore the main method to reduce emissions is to remove the S. The same approach was used for road transport fuels. MARPOL does permit the use of after-treatment technologies to remove S from the fuel gases (described below) provided the emissions are no more than would occur with low S marine fuels, are approved by the relevant flag administration, and IMO is notified. However, as described below, sulphur in the fuel adversely affects the efficiency of NOx abatement on ships, and therefore is not the optimal environmental solution. The default means of SOx compliance with the MARPOL regulations is to use low S fuels.

It is thought unlikely that residual fuel oil meeting the 0.1% S content required from 2015 in SECAs will be widely available. It was anticipated that low S distillate products (MDO or MGO) will generally be used to comply. Existing ships have to be converted to use this fuel, and it typically costs about USD 300 per tonne more than 380 centistokes fuel oil (Lloyd’s
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Register Marine, 2015a). A number of marine fuel suppliers, however, have developed low S ‘hybrid’ fuels that combine the properties of distillate and residual marine fuels. These are heavy distillates that, like residual oils, require heating prior to combustion.

The 0.1 % S limit means that compliant fuel could easily be contaminated by higher S fuels used outside the SECAs. Strict segregation of fuels on board is required. Switching between fuels depending on whether the ship is in an SECA or not can cause engine problems due to the buildup of sludge. Distillate fuels clean the fuel system and tend to carry any sludge and sediments accumulated in the fuel tanks and pipelines, leading to higher levels of sludge deposition in the engine during the early stages of changeover (Lloyd’s Register Marine, 2015a). In addition, during fuel change-over the fuel system is subject to significant changes in temperature. This is because residual fuel oil needs to be heated but distillate does not. This temperature change can cause components to seize, increased wear and the loss of performance. Boiler and incinerator burners must also be able to use both fuels and the appropriate burner tips used. The low S ‘hybrid’ fuels are thought to minimise these problems.

Sulphur in the fuel can ‘poison’ the catalysts used in after-treatment devices to remove other air pollutants, such as those used in selective catalytic reduction (SCR) to reduce NOX emissions. For this reason it is generally preferable to reduce the S content of the fuel rather than to take the S out of the flue gases.

It has been estimated that for ships with a fuel consumption of more than 4000 t yr⁻¹ there would be an economic gain with the use of SO₂ scrubbers instead of 0.1 % S MGO, if the MGO is at least 50 % more expensive than HFO (Reynolds, 2011; cited in Johansson et al., 2013). Linsads et al. (2015) argues that there is no simple answer as to the best S abatement option, but a low oil price favours the options with the lowest capital expenditure (i.e. MGO or light fuel oil) while a high oil price makes SO₂ scrubbers more attractive.

It is thought, however, that a considerable proportion of the fleet, mainly older tonnage, will rely on distillate fuels for SECA compliance. It may not be the most cost-effective overall option, but it still remains the only technically viable option for some ships (Lloyd’s Register Marine & UCL Energy Institute, 2015). However this conclusion may have predated the commercialisation of the hybrid fuels, and it may be that these fuels are used for compliance instead of distillate fuels (Lloyd’s Register Marine, 2015b).

There is concern that the increased cost of shipping in the SECAs from 2015 may lead to a modal shift to land-based transport. Bergqvist et al. (2015), for example, has argued that increased costs, particularly if the North Sea also becomes a NECA, will result in the Swedish forestry industry transferring at least some of their cargo to land transport. Goods that previously were shipped from ports on the Swedish east coast would instead be shipped more frequently from ports on the west coast to reduce transport time within the SECA region.

Panagakos et al. (2014) also suggested that there may be a modal shift as a result of designating the Mediterranean a SECA. The authors found that the road-only route from

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5 0.1 % marine fuel was almost 70 % more expensive than 380 cst fuel oil on 16th June 2015 (http://www.bunkerworld.com/prices/)
Greece to Germany would be favoured for 5.2-17.1% of journeys, depending on the assumptions in the model. However, emissions are all lower on the road route. This is attributed to the longer distance of the combined transport option in comparison to the road-only one and the poor environmental performance of the Ro-Pax vessels.\(^6\)

### 6.3 Alternative Fuels

The main alternative fuels considered to be viable for some ship applications in the medium term are LNG\(^7\), and to a lesser extent electric-diesel hybrids and wind assisted propulsion. There are vessels using these fuels in operation today, albeit in very small numbers. Other alternative fuels, such as biofuels and methanol are unlikely to be used in significant quantities in the foreseeable future. Biofuels for maritime use will be in competition with road transport, and therefore are not considered to be real alternatives until advanced biofuels become available.

The uptake of alternative fuels depends on the legislative and financial drivers. Increasingly stringent requirements to reduce CO\(_2\) emissions coupled with the cost of low S fuels are likely to increase the desirability of new technologies. A study undertaken by Lloyd’s Register Marine and UCL Energy Institute (2015) investigated the type of fuel that ship owners would select in 2030 for maximum profitability. The study considered oil tankers, chemical/products tankers, bulk carriers, general cargo ships and containerships. In all cases little uptake of methanol was forecast. It may be that the 2030 timeframe is too short or the drivers modelled were not strong enough.

In all cases there was forecast to be a reduction in the use of HFO, but it is likely to retain a substantial proportion of the marine fuel market. This is because HFO combined with SOx scrubbers is considered the most cost-effective option for the majority of the fleet and especially for tankers.

Further into the future, hydrogen (H\(_2\)) fuel cell powered ships may become viable, but this requires the H\(_2\) to be produced using renewable energy and a global H\(_2\) infrastructure to be established. The use of H\(_2\) as a marine fuel is not discussed further in this report.

### 6.4 Liquefied Natural Gas (LNG)

The first LNG-fuelled ships were LNG carriers, which have been in operation since 1964. Gas evaporated from these vessels’ cargo tanks was utilized as an additional propulsion fuel instead of releasing the gas to the atmosphere or installing complex re-condensation plants (Æsøy, 2011).

A small number of ships currently use LNG, mainly in Norwegian and North American waters and the Baltic Sea for short-distance shipping and ferry operations. Its use requires technical

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\(^6\) Ro Pax = roll on/ roll off passenger ship

\(^7\) LNG tends to be favoured over compressed natural gas (CNG) due to weight, and cost but particularly safety factors. Pressurised gas tanks are a major safety concern, and only storage in safe zones above the main deck is normally approved.
modifications to the ship engines and the installation of special fuel tanks. The use of LNG does not result in significant SO₂ or PM emission. NOx emissions are approximately 10% of those from burning traditional fuels (Æsøy, 2011). According to Lloyd’s Register Marine & UCL Energy Institute (2015) a gas engine can achieve Tier III emissions levels, however a dual fuelled engine cannot despite having lower NOx emissions than conventional engines.

Natural gas produces more energy per unit of carbon released than traditional fuels. However, emissions of methane (CH₄, a potent GHG) increase, particularly when operating outside the optimised load range. Overall the reduction in CO₂ equivalent emissions is under 20% (IMO, 2009).

Dedicated LNG engines are lean-burn spark injection engines. Dual-fuel engines are more complex and require an injection of diesel fuel for ignition and operate slightly differently depending on the fuel. High-pressure gas injection engines also require diesel for ignition. Diesel engines can be converted to run on LNG (Æsøy, 2015).

The current price for LNG in Europe and the USA suggests that LNG could be delivered for shipping at a price comparable to HFO and be commercially attractive compared to low S MGO (Germanischer Lloyd 2013). The attractiveness of LNG as a ship fuel compared to scrubber systems is determined by the share of operation inside an SECA, the price difference between LNG and HFO, and the investment costs for the LNG tank system. With 65% SECA exposure it has been estimated that the LNG system payback could be less than two years for smaller vessels. For a 2,500 TEU8 vessel LNG is attractive when the LNG delivered to the ship is the same price or cheaper than HFO based on energy content. The use of a waste heat recovery system further reduces the payback time (Germanischer Lloyd 2013).

LNG is forecast to be adopted gradually over the next 15 years. It is predicted that by 2030 30% of the fuel used for chemical/products tankers will be LNG (Lloyd’s Register Marine & UCL Energy Institute, 2015). There is likely to be a higher uptake of LNG for smaller ships because of the way installed power influences capital cost and DWT9 impacts the size of the LNG tank. Smaller ships have higher energy consumption per tonne moved than larger ships. Container ships are forecast to have the lowest penetration of LNG because the existing fleet is relatively new and the tonnage renewal tends to result in fewer but larger ships.

Ships with a LNG engine can cost as much as 20-25% more than ships with conventional engines, as least in the short term until there are standardised designs for LNG ships (Cullinane and Cullinane, 2013), although it depends of the type of ship. One of the main cost drivers is the need for pressurised or insulated storage tanks. The additional cost of the fuel system may equal to or more than the additional cost of the engine (Æsøy, 2015). In addition, the standard LNG storage tanks occupy approximately twice the space of traditional fuel tanks and there are a number of additional safety constraints.

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8 TEU = Twenty foot equivalent unit - a common unit used to define cargo capacity of container ships and container terminals

9 DWT - Deadweight tonnage - a measure of how much weight a ship is carrying or can safely carry
For LNG to be widely used a re-fuelling infrastructure will need to be established. That is developing, for example the Port of Singapore is investigating the development of a LNG bunkering facility. In Norway 23 coastal traffic vessels operate on LNG supplied by a distribution system that also supplies city bus fleets (Æsøy et al., 2015).

Campling et al. (2013) have estimated that if 10% of vessels are LNG fuelled in 2030 the emission reductions relative to 2005 would be approximately 2% for NOx and PM$_{2.5}$, and 1.5% for SO$_2$. If there was 50% LNG uptake in 2030 the reductions would be approximately 11% for NOx and PM$_{2.5}$, and 7% for SO$_2$.

### 6.5 Diesel-Electric Hybrids

Marine engines operate in constantly changing conditions due to the waves and wind, and therefore the main propulsion engines often do not operate at their optimum load for fuel consumption. To overcome this electric propulsion systems have been developed that enable the main engines to generate electricity at their optimum load and for electricity to be used either directly to turn the propeller or to be stored in batteries for later use. Power for propulsion may be provided by the diesel engine, the electric motor or both together, depending on the installation setup.

Marine fuel, or in some cases gas, is used to generate electricity on-board the ship. The system may have multiple generators and multiple motors, which are used to turn the propellers. In ships where the load on the propulsion system changes frequently, the savings provided by diesel-electric hybrids more than compensate for the loss in efficiency due to converting the mechanical energy produced by the diesel engine into electrical energy.

Queen Mary 2 was the first passenger ship to have an integrated electric propulsion system which comprises four marine diesel engines (each with 16.8 MW output) and two gas turbines (each with 25 MW output) giving a total of 117.2 MW. The engines and turbines generate electricity to power electric motors which drive the propellers. It enables economical cruising at low speed using the diesel engines but has the ability to sustain much higher speeds using the gas turbines when required. This system is more commonly used in naval vessels.

Having all of the engines produce electricity reduces the number of engines needed compared to the more traditional arrangement with one pool of engines providing electricity and another providing propulsion. This reduces the overall engine weight and space requirements as well as capital costs and maintenance costs. It also gives much better control of the propellers, which can result in fuel savings.

This approach has not yet been applied to large merchant ships. Dedes et al. (2014) suggest that installing hybrid power technology on-board dry bulk ships could reduce fuel consumption by 2-10%. This value depends on the ship’s dimensions, the electricity storage medium, and the demand for energy as well as whether the vessel is laden or not.

Diesel-electric hybrid ships currently in operation include CalMac’s hybrid ferries in Scotland, KOTUG’s hybrid tugs in The Netherlands, and Scandlines’ hybrid ferries which operate between Denmark and Germany.

All-electric drive systems are also a possibility but due to the energy requirements this approach is only suited for short trips with long port calls to allow batteries to be fully
recharged in between uses. The first entirely electric car ferry in the world, the Ampere, entered into service in Norway in 2015 (Siemens, 2015). The ferry travels across Sognefjord 34 times per day, with each trip taking approximately 20 minutes to make the 6 km crossing. The ferry, which is 80 m long, is driven by two electric motors, each with an output of 450 kW. Both are powered by lithium-ion batteries. The batteries have a combined capacity of 1,000 kWh. They are also recharged from a lithium-ion battery at each pier while the ferry waits. After the ferry has left the dock the battery slowly recharges from the grid until the ship comes back again to drop off passengers and recharge. The charging stations are housed in a small building about the size of a newsstand. The ship’s batteries are recharged directly from the grid at night after the ferry stops operating.

### 6.6 Wind Assisted Propulsion

The use of wind assisted propulsion\(^\text{10}\) has been promoted by some commentators to reduce fuel consumption and emissions. According to Lloyd’s Register Marine (2015c) viable technologies include rigid\(^\text{11}\) or square rig (DynaRig) sails, kites\(^\text{12}\), and Flettner rotors\(^\text{13}\). Ships using these technologies (or have been until very recently) include DynaRig sails on the 88m super yacht Maltese Falcon, the Flettner rotor installation on E-Ship 1 (an 11,000 DWT ro-ro cargo vessel used to transport wind turbines) and the towing kite on the 474 TEU BBC SkySails.

Rigid sails are flexible aerofoils, used either singly or with several foils attached to a single base. Multiple sets of foils may be deployed. When moved through the air they produce an aerodynamic force which can move the ship. According to Lloyd’s Register Marine (2015c) fuel savings of 10-40% have be quoted. There are a large number of concepts commercially available but no full scale installation is currently operational.

Square rig sails are freestanding canvas sails on rotating spars similar to those used on the old square riggers (clipper ships). Today, however, they can be fully automated and there is no rigging on the deck or mast. This technology may reduce fuel consumption by up to 50% but currently is only operational on the Maltese Falcon (Lloyd’s Register Marine, 2015b).

Towing kites are deployed at high altitude when the vessel is at sea, and are recovered near to port to enable passage under bridges or through other navigational constraints. The system comprises a towing kite fabricated from high-strength textile, a towing rope, a launch and recovery system, and a control system for automated operations. One or more towing kites may be used. By flying at high altitude they can take advantage of the higher wind speeds.

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\(^{10}\) Also known as ‘motorsailing’.

\(^{11}\) Also known as ‘wingsails’

\(^{12}\) Also known as ‘skysails’

\(^{13}\) Flettner rotors use the Magnus effect (the perpendicular force that is exerted on a spinning body moving through a fluid stream) for propulsion. Large vertical cylindrical ‘rotorsails’, powered by a motor, are used to power a ship. The German wind-turbine manufacturer Enercon uses a new rotor-ship named E-Ship 1 to transport its products.
There are currently two operational installations, one prototype and several more commissioned. Fuel savings may be in the range 10-35% (Lloyd’s Register Marine, 2015c).

Flettner rotors are available commercially, but have only been installed on one ship recently (the E-ship 1 in 2010). Since December 2014 a trial has been underway on a 9,700 DWT ro-ro ship by Norsepower Ltd.

Some forms of wind assisted propulsion can be installed on standard ship designs and this might lower the threshold for wider use of wind assisted propulsion. One of the barriers to adoption is that these systems are relatively complicated to operate and adjust as wind conditions change. Its efficiency is often dependent on the crew’s expertise. Other concerns include the impact on cargo capacity and accessibility to ports due to the height of Flettner rotors and masts.

As maximum permitted S levels decline, fuel prices for low S maritime fuels are likely to increase. An analysis undertaken by Lloyd’s Register (2015c) suggests that technologies that result in fuel savings of 10% would be financially unattractive even at high fuel prices, but technologies that reduce fuel consumption by 30% on ships that consume more than 30 t d\(^{-1}\) would have a payback period of less than 5 years if fuel prices per tonne were USD 600 per tonne or more (the typical price in August 2014 before prices began to fall). However current fuel prices are around 350 USD (Bunkerworld, 2015).

6.7 Engine improvements

6.7.1 Sulphur Oxides (SOx)

There are no engine improvements that will reduce SOx emissions, other than those that improve fuel consumption.

6.7.2 Nitrogen Oxides (NOx)

NOx emissions are mainly produced at high engine temperatures generated when engines operate under load. To reduce NOx the combustion temperature needs to be reduced or the exhaust gas treated to remove the NOx. There are several methods to reduce the combustion temperature but these tend to increase fuel consumption. The main option for meeting the Tier III limits is exhaust gas recirculation (EGR).

EGR has been widely used in automotive applications and is a mature technology. It returns a proportion of the exhaust gas to the combustion chamber, reducing the amount of oxygen available during combustion. This reduces the combustion temperature and less NOx is produced. In some EGR systems the exhaust gas is cooled to further reduce emissions. For high- and low-speed marine diesel engines EGR can reduce NOx concentrations sufficiently to comply with the IMO Tier III requirements, however for medium speed marine engines the NOx reduction is not sufficient (Blatcher & Eames, 2013).

Sulphur in the exhaust gas can lead to a risk of corrosion, and therefore EGR is best used with low S fuels (<0.2%) (Lövblad & Fridell, 2006) or with a SOx scrubber (see next section). MAN’s second generation ERG system, for example, integrates the engine, scrubber, cooler and other components into a single unit. Fitted to a two stroke low-speed marine engine this
can achieve Tier III NOx levels. However, the use of ERG can increase VOC, PM and CO emissions due to the reduced engine efficiency (Lloyd’s Register, 2015a).

Historically the most widely used technique to reduce NOx emissions has been the use of slide valves in the engine. These have been used as standard on most new slow-speed 2-stroke engines since 2000 but are not sufficient to meet Tier III standards.

In the future advanced fuel injection for more precise control of the combustion process, which is commonly used in automotive applications, may offer an alternative technique to meet the Tier III standards.

### 6.8 After-treatment Technologies

#### 6.8.1 Introduction

The fitting of after-treatment technologies to ship engines requires both statutory certification (issued by or on behalf of a flag administrator) to show that the equipment meets the required performance criteria and classification society approval (class approval) to show that the equipment does not present an unacceptable risk to the ship and the essential equipment required for the ship’s operation.

The use of after-treatment devices reduces the exhaust gas temperature. To ensure that the exhaust gas clears the ship the exhaust gas duct outlet may have to be redesigned to increase the velocity of the exhaust as it exits the funnel. This is particularly important for passenger ships (Lloyd’s Register Marine, 2015a).

#### 6.8.2 Sulphur Scrubbers

An alternative method to reducing the S in fuel is to use exhaust gas treatment to remove the SOx. SOx scrubbers can achieve emission reduction of over 99%, the equivalent of using 0.1% S fuel, and manufacturers typically claim between 70-90 % PM removal (Lloyd’s Register, 2015a).

Sulphur scrubbers use open (seawater) or closed (freshwater) systems to react SO2 with an alkali to form sulphate (SO₄²⁻) ions. In an open system the carbonates, bicarbonates, and other anions naturally found in seawater is used to remove the SO₂. The reaction of SO₂ with calcium carbonate (CaCO₃), for example, rapidly forms CO₂ and calcium sulphate (CaSO₄). In some seas, such as the Baltic Sea, there is limited alkalinity and an alkali may need to be added.

Due to the already high SO₄²⁻ concentrations in seawater the discharged water from open systems is through to have a negligible effect on concentrations in the open sea.

Freshwater scrubbers typically use a 50 % sodium hydroxide (NaOH) solution, which needs to be stored on-board at temperatures between 20-50°C. Alternative alkalis can be used such as magnesium oxide (MgO) and sodium bicarbonate (NaHCO₃), which are less hazardous than NaOH.

In areas where there is sensitively to the discharge of the water from an open system, the installation of washwater tanks on-board enables closed loop systems to operate with no discharge for a period of time, depending on the size of the tank. Hybrid scrubbers are
available which can operate in either in open or closed loop mode. This provides flexibility where the seawater alkalinity is too low or where there is regulation of washwater discharge, particularly close to shore and in inland waters. There are also hybrid systems that can operate in open and closed mode simultaneously.

IMO guidelines required acidity, turbidity and polycyclic aromatic hydrocarbon (PAH) concentrations to be continuously monitored in washwater discharged to sea and to meet defined limits. The wastewater can be treated on-board to meet these limits. There are concerns about contaminants which are not monitored such as metals and the potential to accumulate in sediment on the bed of closed docks and other areas with limited water exchange (Lloyd’s Register, 2015a).

Dry scrubbers which use dry calcium hydroxide (Ca(OH)$_2$) as the reactant to remove SOX from the exhaust gas have been used commercially on ships. This technique is widely used in industry on land, however the only marine supplier has gone out of business.

Wet scrubbers significantly cool the exhaust gas and therefore are not suitable for installation before a waste heat recovery unit or a NOx reducing catalyst unless a heater is installed to raise the exhaust gas temperature. Dry SOX scrubbers do not cool the exhaust gas so are suitable for use with SCR.

An analysis undertaken by Lloyd’s Register and UCL Energy Institute (2015) suggests that scrubbers are the most cost-effective option for the majority of the fleet and especially for tankers. However, the fall in marine fuel prices since the study was undertaken has reduced the demand for scrubbers (Platts McGraw Hill Financial, 2015), and it may be that most ships will use low S fuel until prices rise significantly.

**6.8.3 Selective Catalytic Reduction (SCR) for NOx Abatement**

Selective catalytic reduction (SCR) is a proven technology used for many years to reduce NOx emissions from stationary sources, and increasingly from road vehicles. It can reduce NOx emissions from ship engines by 80-90% (Lloyd’s Register, 2015a). However, the Tier III NOx standards are modest compared to the Euro VI heavy duty vehicle emission limits (ICCT, 2014).

According to the ICCT (2014) MAN B&;W successfully tested the first SCR system on a vessel in the San Francisco Bay area over 25 years ago. The next trial was by Wärtsilä which equipped three two-stroke ro-ro vessels with SCR. These ships had an average NOx emission of 2 g kWh$^{-1}$ over 10 years of continuous operation. Since then more than 3,000 vessels have been fitted with SCR. Today SCR is installed on the main and auxiliary engines and boilers.

SCR continuously removes NOx by creating a rich microclimate where NOx is converted to nitrogen (N$_2$ and H$_2$O) by reaction with ammonia (NH$_3$), while the overall exhaust remains lean. NH$_3$ is produced from an aqueous solution of urea stored in a tank on-board the vessel. The urea solution is injected into the exhaust stream upstream of the SCR where it forms gaseous NH$_3$ which is stored on the catalyst. The NOx from the engine reacts with the stored NH$_3$ to produce N$_2$ and water.

NOx reduction typically requires the exhaust temperature to be in the range 300-500°C, below this the NOx removal is not efficient and above this there may be thermal damage to the catalyst. At lower temperatures S forms deposits of ammonium sulphate ((NH$_4$)$_2$SO$_4$) and
bisulphate (NH$_4$HSO$_4$) which buildup on the surface of the catalyst, adversely affecting its performance and lifespan. As the catalyst performance declines unreacted NH$_3$ will slip past the catalyst. An oxidation catalyst may be fitted after the SCR to oxidise CO, unburnt hydrocarbons (HCs) and any NH$_3$ that has passed the reducing catalyst. An oxidation catalyst may also be fitted upstream of the SCR to oxidise NO to NO$_2$. This increases the rate of NOx reduction and allows the size of the system to be reduced. However oxidation catalysts are very sensitive to the S content of the fuel.

There is a trade-off between NOx emissions from an engine and fuel consumption. Using SCR enables the engine to be calibrated for higher engine-out NOx emissions and better fuel economy. In NECAs the engine can be tuned to meet Tier III emission limits, but outside the NECA the settings can be changed to meet Tier II with improved fuel efficiency.

Typically it takes 30-90 minutes for a ship engine to warm up to enable the SCR to operate efficiently, unless pre-warming is fitted. Extended periods operated a low loads will result in longer start-up times and may result in the SCR not reaching its operating temperature. It is not yet clear how authorities will view ships that are non-compliance during the warming period (Lloyd’s Register Marine, 2015a).

Most SCR systems have been fitted to four-stroke medium speed engines, although they can be fitted to two-stroke low-speed engines. The temperature of the exhaust from four stroke engines is sufficiently hot for the SCR system to be placed after the turbocharger. If NOx control is not required, e.g. outside a NECA, the urea injection can be turned off and the exhaust gas can continue to flow through the SCR.

Techniques to reduce the operating temperature of SCR or increasing the exhaust temperature as it enters the SCR are being developed. These include reducing the amount of air in the combustion chamber and preheating the exhaust upstream of the catalyst; adjusting injection timing, bypassing part of the exhaust through a heated hydrolysis catalyst which allows the urea to be injected at exhaust temperatures as low as 150°C, heating the urea dosing system prior to injection to maximise efficiency and for ships with multiple engines to shut down one or more engines and running fewer at higher power (ICCT, 2014).

Manufacturers of marine SCR systems do not recommend that they are used with fuel containing more than 1% S (Lloyd’s Register, 2015a).

An analysis of NOx and NH$_3$ emissions from main and auxiliary engines fitted with SCR shows that the majority were below the Tier III limit and had low NH$_3$ emissions. However, no clear correlation between the S in the fuel and the NOx reduction was found (Brynolf et al., 2014).

6.8.4 Integrating SOx and NOx Abatement

Whilst in theory on-board SOx and NOx abatement can work together there may be significant issues. SCR is poisoned by high concentrations of S in the exhaust gas, and therefore should to be placed after the SOx scrubber. On the other hand the exhaust gas temperature is too low after the SOx scrubber for the SCR to work. This can be overcome by preheating the exhaust gas between the SOx scrubber and the SCR, but this requires significant amounts of energy increasing fuel consumption and CO$_2$ emissions. This is not an issue with dry scrubbers (Lloyd’s Register Marine, 2015a).
6.8.5 Particulate Matter (PM) Abatement

Diesel particle filters (DPFs) have been widely used to control PM emissions from road vehicles, and emissions can be reduced by over 95%. Marine DPF technology is, however, not fully developed (Kubush, 2014). The lack of development is likely to be due to the absence of emission limits for ships, and the fact that S control reduces PM emissions, albeit not as efficiently as a DPF fitted to a road vehicle.

A small number of large yachts have used DPFs to control emissions mainly from auxiliary engines. This technology has also been used for some harbour craft (e.g. tugs) and inland vessels. In Switzerland, since 2007, DPFs have been required to be fitted to new and replacement (where this is technically and financially feasible) engines on passenger and cargo ships (Swiss Federal Office for the Environment, 2012). Similar legislation

They are not, however, generally used on ocean going vessels, where they have to withstand the effects of salty water. The DPFs need to have stainless steel housings, exclude water intrusion, be insulated and easily maintained. There have been some trials with DPF on a few ocean going vessels, however little information on their efficacy is publicly available. According to Kubush (2014) a trial of a DPF fitted to a medium speed auxiliary engine on an ocean going vessel had relatively poor performance due to the high S content of the fuel (0.07 %) and high ash lubricant. Mitsui O.S.K. Lines (MOL) (MOL, 2015) announced a demonstration test of a DPF on an ocean-going vessel in 2012. This DPF system was also installed on an auxiliary engine. The PM collection efficiency was reported to be 80%, which is relatively low compared to automotive DPFs. The filter also “significantly reduced black smoke emissions”. The DPF system regenerates one unit at a time, with the exhaust gas flow to the regenerating unit bypassed and the three remaining units filtering the exhaust gas. The filter is regenerated using an internal heating system.

In early 2015 the German research ship “Heincke” was refitted with new engines, each equipped with a diesel particulate filter (DPF) and SCR catalyst. This is thought to be the first seagoing ship worldwide which used a combined system of DPFs and SCRs and runs completely on Marine Diesel Oil (MDO) (Naturschutzbund Deutschland, 2015).

One of the challenges in developing DPF systems for use with residual fuels is very high content of ash that cannot be oxidized during regeneration and accumulates in the filter.

As noted above the use of low S fuel reduces the PM emissions. There is some evidence, albeit limited, that the use of these fuels can also reduce BC emissions, although it is not clear whether it is due to these fuels being distillate or due to the S content. A 30% reduction in BC at 100% engine load has been observed with low S fuel (Lack & Corbett, 2012). SOx scrubbers have also been shown to be effective at reducing PM emissions, with efficiencies quoted of 90% or more (Cullinane & Cullinane, 2013). Lack & Corbett (2012) concluded that this technology can remove 40-70% of the BC. Although more research is needed to characterise the BC control over varying loads, it appears that scrubbers provide similar BC reduction as switching from high S residual to low S distillate fuels.

6.9 Ship operating procedures

Fuel costs can be 30-60% of a ship’s operating costs and therefore there is significant economic pressure to reduce consumption, particularly when marine fuels are expensive.
There are a large number of operational measures to improve fuel consumption, and reduce costs, include increasing back haul loads, using hub-and-spoke distribution, maximising the size of ships, improving logistic systems, reducing the time spent in port and loading cargo to optimise trim and draft (Cullinane & Cullinane, 2013). This section discusses the two main operating methods used for reducing emissions of the air quality pollutants: slow steaming and shore-based power.

### 6.9.1 Slow Steaming

One of the main methods utilised since the global recession in the late 2000s to save fuel has been to reduce cruising speeds. This is known as ‘slow steaming’ and is defined as operating a vessel at below 60 % of maximum engine load (Cullinane & Cullinane, 2013). This strategy is not appropriate for all shipping sectors, for example passenger ferries, which operate to a timetable.

As a rule of thumb, engine power output is a third power function of speed. Hence, when a ship reduces its speed by 10 %, its engine power is reduced by 27 %. Because the voyage takes longer, the total energy required is reduced by 19 % (Faber et al., 2012). There is a diminishing return in practice as the ship’s engine, propeller and hull are taken further away from their design conditions.

Slow steaming also reduces SOx, PM and NOx emissions from ships. Campling et al. (2013) have estimated that mandating slow steaming within 200 nm of the EU coastline would reduce NOx emissions by 22 % and SO₂ and PM emissions by approximately 18 %.

During the period 2007–2012 the average reduction in at-sea speed, relative to design speed, was 12 % and the average reduction in daily fuel consumption was 27 % (IMO, 2015a). Reduction in daily fuel consumption in some oil tankers was approximately 50 %, and some containerships reduced energy use by more than 70 %. According to Germanischer Lloyd (2013) all major international container lines have implemented slow steaming and some have cut average speeds from approximately 24 knots to 18 knots or even down to 14 knots.

Ships with several engines are able to shut down one or more engines when reducing their speed, but for ships with one main engine, it means lowering of the engine load. This can lead to an increase in PM emissions and higher specific fuel consumption because the engine is not running at its optimal engine load (Kalli et al. 2013).

A MAN PrimeServ survey (2012), suggests that most ship operators operate slow steaming some of the time, but few do so all the time; the prime reason being to reduce fuel costs. Since the survey the cost of marine fuels has fallen, and it is not known whether this has influenced the frequency of slow steaming.

Global demand for shipping is increasing and it is uncertain as to whether the use of slow steaming will continue. When there is spare shipping capacity, slow steaming is one way of making use of the over-supply of ships, but when there is an under supply it makes economic sense to reduce journey times.

The Danish shipping company Maersk believes that slow steaming will continue to be important in the future as it has ordered 20 18,000 TEU ships fitted with engines specifically designed to be operated at lower speeds. These ships are the world’s largest container ships. The company claims the combined benefits of economies of scale and lower speed will reduce
CO₂ emissions by 50 % per container moved on Asia-Europe voyages compared to the industry average. The ships also recover waste heat to provide extra propulsion. Without this, the ships’ fuel consumption and CO₂ emissions would be approximately 9 % higher (Maersk, 2015).

Some coastal areas have mandatory or voluntary ship speed reductions, mostly to reduce whale strikes, but also to improve air quality (Lack & Corbett, 2012). For example, there is a voluntary speed reduction (VSR) program at the Ports of Los Angeles and Long Beach. It is implemented within 20 and 40 nm from the ports respectively. Approximately 61 %, 56 % and 69 % reduction in CO₂, NOx and PM₂.₅ emissions respectively were observed by reducing vessel speeds from cruise speed to 12 knots or less in the VSR zone (Miller et al., 2012).

There is concern that if a ship reduces speed without any adjustment to the engine BC emissions will increase due to combustion inefficiency. Lack & Corbett (2012) reviewed the literature and concluded that absolute BC emissions (mass per distance travelled) can increase by an average of 30 % if the engine load is reduced to 40 %. Load reductions from 100 % to 20 % and 10 % can increase BC emissions by 60 % and 90 % respectively if the engine is not re-tuned for the lower load. Based on the review of available data, BC emissions appear to remain constant over the load range of 80 – 100 % and BC emissions are therefore likely to increase when an engine is operated at less than 80 % load.

Most ships are optimised for a certain speed, and steaming at lower speeds might also have unforeseen consequences for engine maintenance and fuel consumption. Future ships are likely to be designed for an optimal speed range, allowing for a wider variation in speed than today.

6.9.2 Shore-based power (cold ironing)

Most ships turn off their main engine (mainly used for propulsion) at berth and rely on their auxiliary engine for electricity generation. The main exception is oil tankers which use the main engine to load and unload cargo. They may also use boilers to generate steam. A few major ports provide shore side electrical power as an alternative to using the auxiliary engines. This is known as cold ironing or high voltage shore connection (HVSC) systems. An international standard was adopted in 2012, and a number of ports globally are considering adopting this method to reduce emissions (Theodoros, 2012). A low voltage international standard is currently being developed.

The use of shore based power has been implemented at all ports in Alaska and California, the Swedish ports of Gothenburg and Stockholm, and the Belgium port of Antwerp. European ports considering the implementation of cold ironing include Rotterdam, Bergen, Oslo, Helsinki and Rome (Theodoros, 2012). This measure improves local air quality. For example, a study of the Rotterdam-Dordrecht area where there are extensive port facilities concluded that the large-scale deployment of shore-based power could significantly reduce the remaining number of poor air quality hotspots. The major barriers are the high costs of insulation or retrofitting of power systems on ships and the expansion of electricity lines ashore (Hammingh et al., 2007).
6.10 Market-Based Measures

The technical and operational measures outlined above are not considered sufficient to reduce emissions from international shipping due to the projected growth in world trade (Cullianne & Cullinane, 2013). Therefore the IMO has considered the use of fiscal incentives to encourage industry to invest in more fuel efficient technology and to operate ships more efficiently. A number of proposals have been submitted but little progress appears to have been made in recent years (IMO, 2015b).

The Swedish Maritime Administration was the first to introduce low emission incentives. In 1996 environmentally differentiated fairway dues were introduced to provide an incentive to invest in low NOx technology. The scheme has been revised several times and today the reduction in fee starts at 6 g kWh\(^{-1}\) reaching a maximum reduction at 0.4 g kWh\(^{-1}\) (Brynolf et al., 2014). Ships certified to 0.4 g kWh\(^{-1}\) are exempt from the GT based fairway fees. This emission level is well below the IMO Tier III limit and the aim is to provide an economic incentive for ship owners to install NOx SCR on auxiliary engines.

A number of ports also provide fiscal incentives for low emission ships. The World Ports Climate Initiative (2015) has developed an Environmental Ship Index (ESI) to enable ports to provide a consistent approach to classifying vessels based on their SOx and NOx emissions. By June 2015, 27 ports, mainly in northern Europe but also in Asia, North America, and the Middle East, were participating in the scheme (IACCSEA, 2015).

The larger Swedish ports also differentiate their port dues on the basis of their own environmental criteria. In Gothenburg, for example, the port dues were increased if the S content of the fuel exceeded 0.2 % and for ships with NOx emissions below 12 g kWh\(^{-1}\) a discount was applied that increases progressively. With effect from 2015 the Environmental Ship Index (2015) and the Clean Shipping Index (2015) have been used to set port tariffs. There is an additional discount for LNG ships (Port of Gothenburg, 2015).

A number of ports in Belgium, Canada, Latvia, Lithuania, the Netherlands, Oman, New Zealand, Portugal and South Africa also reduce port dues for vessels with a Green Award certificate (Green Award, 2015). This is an independent certification scheme subject to annual verification and is valid for three years.

In 2007 Norway introduced a tax on NOx emissions from ship engines above 750 kW. The tax is applied to ships within Norwegian territorial waters, but for Norwegian registered vessels it is applied to emissions within 350 nm of the Norwegian coast. Voluntary agreements between the Norwegian Government and companies in the offshore sector exempt them from the tax for three years provided they make payments to a NOx fund (IACCSEA, 2015).

The Maritime and Port Authority of Singapore uses its own scheme to encourage Singapore-flagged ships to have low fuel consumption. Ships exceeding the requirements of the IMO’s EEDI are given a 50 % reduction of the initial registration fees and a 20 % rebate on annual tonnage tax.

A different type of market-based scheme to encourage low emission shipping is RECLAIM. This is a local cap-and-trade programme implemented in Los Angeles which allows ships to trade NOx and SOx emissions with installations from other industries located in the coastal area (Nikopoulou et al., 2013).
7 SUMMARY AND CONCLUSIONS

Ship emissions can make a significant contribution to poor air quality in populated coastal areas and to the formation of secondary pollutants such as ozone and sulphate aerosols further inland. These emissions are poorly controlled compared to land-based emissions due to the need for international agreement. Emissions from and-based combustion plant greater than 50MW have been controlled in the EU for almost 15 years, yet many ships have installed engines with a higher combined rating but uncontrolled emissions. Abatement measures exist and many have already been demonstrated and commercialised for use on ships.

SOx emissions have started to be controlled and there is some evidence that ambient concentrations of SO2 have reduced as a consequence in SECAs and EU ports. The S content of marine fuels will reduce globally to 0.5 % in 2020 (or 2025), however this is two orders of magnitude higher than that permitted for land-based transport. Low S fuels enable catalyst based abatement systems to work most effectively, however production of these fuels increase the energy use in the refinery. If IMO continues to allow wet scrubbers to be used as an alternative to reducing fuel S controlling NOx emissions is likely to be difficult and the fuel economy benefits of SCR will not occur.

The IMO Tier I and Tier II NOx limits will do little to reduce overall NOx emissions from ships in the short term as they only apply to new or reconditioned engines. Vessels meeting the more stringent Tier III limits are only mandated for the NECAs and there are currently no NECAs in Europe. As Tier III NOx emission control systems can be by-passed when outside a NECA NOx emissions may increase in Europe as shipping increases in the future. This will depend on how quickly fuel consumption for ships reduces and the uptake of alternative fuels, particularly LNG.

There are no international limits on PM emissions from ships, although measures to reduce SOx emissions also reduce PM emissions, including BC. No specific PM abatement technology is used on ocean going ships.

Fuel consumption from international shipping was controlled for the first time in 2013 but it applies only to certain large ships. The current measures are unlikely to be sufficient to control the growth in shipping emissions as global trade and the associated maritime traffic is forecast to increase significantly in the future. The EU has made some progress in agreeing a fuel efficiency monitoring programme; the first step towards including ship emissions in its GHG emission reduction target. Significant fuel savings will reduce the emissions of SOx, NOx and PM.

The European SECAs are in northern Europe. There is a case for designating the Mediterranean Sea a SECA, but it is likely to be politically difficult to get agreement among all the nations with a Mediterranean coastline for an SECA covering the whole sea. From 2020 the S limit in marine fuel will be 0.5 % throughout the EU and in EU ports it is already 0.1 %, and therefore a significant reduction in emissions, estimated by Campling et al. (2013) to be almost 80 % will occur anyway. However due to the anticipated increase in shipping, emissions will grow in the future in the absence of further control, and therefore a SEAC within the EU territorial waters may be the best pragmatic solution, i.e. possible to get agreement on within IMO.
The designation of the North Sea (including the English Channel), Baltic Sea and Mediterranean Sea as NECAs would reduce emissions significantly, although the benefits could take around 30 years to occur as the Tier III limits only apply to certain new ships. There would be similar problems however, to the designation of the Mediterranean Sea as a NECA as there would be for a SECA, and, at least initially, restricting it to EU territorial waters may ease the designation process.

There are a wide range of measures available to reduce SOx, NOx and PM emissions, but their adoption will only be driven by legislative or fiscal drivers. Due to the international nature of shipping regulations need to be agreed either within the EU or IMO and the adoption of regulations within these institutions is a long slow process. This includes the designation of SECAs and NECAs, which have to be agreed by IMO.

There are some local measures which can be introduced to reduce emissions. Ports can invest in shore based power to reduce SOx, NOx and PM emissions from berthed ships; emissions differentiated port duties and fairway dues can be used to encourage investment in emission abatement; and local restrictions can be introduced.
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