EXHAUST EMISSIONS FROM SHIP ENGINES - SIGNIFICANCE, REGULATIONS, CONTROL TECHNOLOGIES

Laurie Goldsworthy*

1 Overview

Shipping is the most fuel efficient means of moving freight, carrying more than 70% of the global freight task. Around 70% of ship emissions occur within 400km of land.[1] The impact of ship engine exhaust emissions on terrestrial air quality is under focus. Terrestrial air emission controls are outpacing controls on ship emissions. Ships generally use low quality fuel to reduce costs. This low quality fuel tends to have a high sulphur content. Emissions of oxides of sulphur (SOx) from shipping represent about 60% of global transport SOx emissions. Emissions of oxides of nitrogen (NOx) from shipping represent about 15% of global anthropogenic NOx emissions and around 40% of global NOx emissions from transport of freight. Shipping represents around 15% of global freight transport CO_2 emissions (2 to 3% of total global CO_2 emissions).[2]

Engine exhaust emissions can be divided into two broad categories – those which directly affect air quality and those which directly affect global warming.

2 Air Quality Emissions

2.1 Formation

In diesel engines, fuel is injected at high pressures into air which has been compressed by the moving pistons. This compression raises the temperature of the air sufficiently to cause the fuel to ignite. Combustion proceeds around the periphery of the fuel spray at temperatures around 2000°C.

Oxides of nitrogen are formed during the combustion process due to combination of nitrogen and oxygen from the air at these high temperatures. The diesel combustion process inherently produces relatively high levels of NOx, and the fuel properties only have a minor influence on the amount produced.

Oxides of sulphur form during the combustion process, by combination of the sulphur in the fuel with oxygen. The prime constituent of SOx is SO_2. The amount of SOx formed in an engine depends primarily on the concentration of sulphur in the fuel. SOx emissions from ship engines are relatively high because they burn high sulphur content fuels.

Particulate matter (PM) emissions are primarily formed by two separate mechanisms:

- Nuclei mode particles consist mainly of condensed hydrocarbons and sulphates. The gaseous precursors condense as temperature decreases in the exhaust system and after mixing with cold air in the atmosphere. The sulphates arise from combination of SOx and water in the exhaust.

- Accumulation mode particulates are formed during combustion by agglomeration of primary carbonaceous particles (99% C by mass) and other solid materials. The majority of the accumulation mode particulates form in the core of the burning fuel spray. They are known as 'black carbon' or 'soot'. Further, gases and condensed hydrocarbon vapours are absorbed into the surface of the particles. The formation of accumulation mode soot is inherent in the diesel combustion process and is only partially dependent on fuel quality.

The condensed hydrocarbons in the nuclei mode particles and on the surface of the accumulation mode particles contain toxic and carcinogenic hydrocarbons. The high sulphur content of marine fuels leads to relatively high levels of sulphate particulates.

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* Australian Maritime College, University of Tasmania.

[1] Jana Moldanováa et al, 'Characterisation of Particulate Matter and Gaseous Emissions from a Large Ship Diesel Engine' (2009) 43 *Atmospheric Environment*, 2632.

[2] S.B. Dalsøren et al, 'Update on Emissions and Environmental Impacts from the International Fleet of Ships. The Contribution from Major Ship Types and Ports' (2009) 9 *Atmospheric Chemistry and Physics* 2171; James J. Corbett et al 'Mortality from Ship Emissions: A Global Assessment' (2007) 41(24) *Environmental Science and Technology* 8512; Øyvind Buhaug et al, *Second IMO GHG Study 2009* International Maritime Organization (IMO) London UK April 2009; V Eyring et al, 'Emissions from International Shipping: 1. The Last 50 years' (2005) *Journal of Geophysical Research* 110.

Volatile organic compounds (VOCs) consist of unburnt or partially burnt hydrocarbons remaining from the combustion process, emitted as gases in the exhaust. They are also emitted directly from cargo such as oil and petroleum products by evaporation.

2.2 Impacts

Emissions from shipping are in part transported over land where they add to the pollutant load.

NOx emissions contribute to the formation of photochemical smog. Photochemical smog leads to elevated levels of ozone and production of hazardous organic compounds. Ozone is hazardous to human health and is also a greenhouse gas when in the lower atmosphere.

In sufficient concentrations SO_2 can adversely affect lung function.

As well as affecting air quality, SOx and NOx emissions contribute to acid rain.

Particulate matter from engine exhausts, especially the finer particles, can lodge in the lungs and move into the bloodstream, leading to cardiovascular and pulmonary disease. Corbett et al[3] estimated accelerated mortality from ship emissions. Their results indicated that particulate emissions from ships are responsible for approximately 60,000 cardiopulmonary and lung cancer deaths annually, mostly near coastlines in Europe, East Asia and South Asia. Their estimations are illustrated in Figure 1.

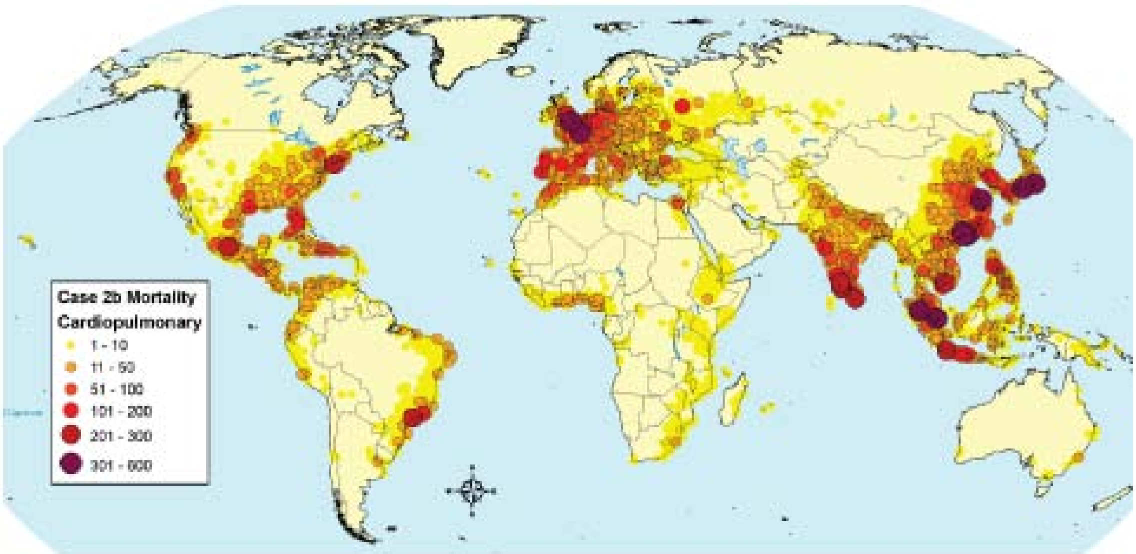

Figure 1 Estimated cardiopulmonary mortality attributable to ship particulate emissions, from Corbett et al.[4] Case 2b world fleet including auxiliary engines, all PM constituents (hydrocarbons, sulphates, black carbon).

SOx and NOx are partially regulated by IMO Marpol Annex VI, described in section 3.1, while particulate matter and VOCs are not regulated.

2.3 Technology for Reducing NOx Emissions

- Engine Tuning: New engines meet the IMO Tier 2 NOx limits, possibly with a small fuel consumption increase (up to 3%). This is achieved by combustion process optimization, including increased fuel injection pressure and delayed injection timing, increased compression ratio, reduced initial air temperature and optimised injection patterns. The use of electronically controlled high pressure fuel injection facilitates combustion optimisation, especially at low loads.

[3] James J. Corbett et al, above n 2.
[4] Ibid.

- The use of fuel water emulsions or direct water injection can result in 20% to 50% reduction. Addition of water to the combustion zone reduces peak combustion temperature and thus reduces NOx formation, as it is highly temperature dependent.

- Air humidification is an alternative way of introducing water, by mixing it with the air used for combustion. It can achieve up to 70% NOx reduction in 4 stroke engines.

- Exhaust Gas Recirculation (EGR) uses cooled exhaust gas mixed with the air used for combustion to reduce peak combustion temperatures. It can achieve up to 70% NOx reduction with a small fuel consumption penalty of around 2%.

- Selective Catalytic Reduction (SCR) can achieve up to 95% reduction. Urea is added to the exhaust stream and the mixture passed over a catalyst. The installation and maintenance costs are substantial, but the NOx reductions are high and the use of SCR allows the engine to be tuned for minimum fuel consumption. A number of SCR systems are in operation on ships.

- Reduced fuel sulphur will make SCR and EGR easier.

- Liquefied Natural Gas (LNG) can achieve very low NOx emissions without aftertreatment.

2.4 Technology for Reducing SOx Emissions

2.4.1 Scrubbers

Exhaust gas scrubbers can remove the majority of SOx emissions from the exhaust stream, as well as a significant proportion of the particulate matter. Various systems developed for marine use, use sea water, fresh water or chemicals to wash out or neutralise the SOx. There may be issues surrounding discharge of the waste water.

2.4.1 Low Sulphur Fuels

The most straightforward method of reducing SOx emissions is to reduce fuel sulphur content. There is a limit to how low the sulphur content of heavy fuel oil can be reduced. Heavy fuel oil is largely composed of the thick residue from the crude oil refining process, to which lighter components have been added to bring it to a useable consistency. It is black in colour. The majority of shipping runs on heavy fuel oil. IMO Marpol Annex VI will allow global fuel sulphur content of 3.5% until 2020, a further decade from now. By comparison, the diesel fuel used for road transport (ULSD) contains only 0.0010% sulphur by mass. States requiring lower fuel sulphur can make their own rules or declare Emission Control Areas (ECAs) under IMO MARPOL Annex VI. Higher quality marine diesel fuels are available, but at a greater cost. These lighter fuels are known as Marine Diesel Oil (MDO) or Marine Gas Oil (MGO). ULSD, MGO and MDO are known generally as distillates. Some ships use MGO or MDO in their auxiliary engines for generating electricity. MDO and MGO are available at low sulphur content, down to around 0.1%. MDO and MGO are not generally available in Australia, and if ships were required to use fuel other than heavy fuel oil in or near port, they would either bring MDO or MGO with them or use Australian made ULSD, which has a very low sulphur content. Natural gas is another alternative fuel, but is not as easy to implement as low sulphur distillate.

3 Regulations and Incentives

3.1 IMO MARPOL Annex VI 2008

The International Maritime Organisation (IMO) enacted a revised Convention in 2008 for control of exhaust emissions from ships. The Convention is known as *MARPOL Annex VI*.[5] *MARPOL* is the *International Convention for Prevention of Pollution by Ships*. Annex VI deals with air pollution.

The previous Annex VI was enacted in 2005 and is sometimes known as *MARPOL Annex VI Tier1*. The current *Annex VI* puts a global cap on NOx emissions and sulphur content of fuels. Further, special ECAs can be enacted within which even stricter controls are required. The provisions of *MARPOL Annex VI* are:

[5] International Maritime Organization, *Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto (Revised MARPOL Annex VI)*, adopted 10 October 2008.

- 2005 Tier1 NOx for new engines post 2000
- 2010 ECA fuel sulphur 1% (currently 1.5%)
- 2011 global Tier 2 NOx for new engines (IMO Tier 1 less 15 to 20%) (engine tuning)
- 2012 global fuel sulphur 3.5% (currently 4.5%)
- 2015 ECA fuel sulphur 0.1%
- 2016 ECA Tier 3 NOx for new engines (IMO Tier 1 less 80%) (exhaust gas aftertreatment)
- 2020 global fuel sulphur 0.5% - if refineries can produce it, review in 2018
- Tier 1 NOx for engines greater than 5MW installed 1990 to 2000 (conversion kits)
- Under *Annex VI*, exhaust gas scrubbers can be used as an alternative to low sulphur fuel
- Reduced sulphur content will reduce fine particulate emissions significantly.

The USA and Canada have applied for designation of an IMO Emission Control Area (ECA) covering the Pacific coast, the Atlantic/Gulf coast and the eight main Hawaiian Islands, out to 200 nautical miles. The IMO has accepted the proposal. Regarding these new ship engine emission controls (IMO ECA plus HC and CO reductions), the US EPA has stated:

> By 2030, the coordinated strategy is expected to yield significant health and welfare benefits, annually preventing between 13,000 and 33,000 premature deaths, 1,500,000 work days lost, and 10,000,000 minor restricted activity days. The monetized health benefits are projected to range from $110 billion to $280 billion... These estimated benefits exceed the projected costs by a ratio of at least 30:1.[6]

3.2 Other Limits

Other emissions limits applied outside *MARPOL* include:

- 2010 fuel sulphur 0.1% at berth in European Union;
- 2009 distillate fuel, fuel sulphur 1.5%/0.5% depending on fuel aromaticity, in Californian waters;
- 2012 distillate fuel, fuel sulphur 0.1%, in Californian waters.

3.3 Emissions Taxes and Incentives

Taxes and incentives are in place to encourage reduced emissions. These include:

- Norwegian NOx tax on all industries including domestic shipping to meet Gothenburg Protocol obligations[7] - continuous measurement or calculation based on default indices
(tax in NOK = 15 x kg NOx emitted in Norwegian territory).
- Sweden differentiated harbour dues – NOx emissions, fuel sulphur content.
- Vancouver differentiated harbour dues – fuel sulphur content.
- Environmental Indices for NOx, SOx and CO_2 are being developed to allow selection of ships according to environmental performance.

[6] Environmental Protection Agency, *Regulatory Announcement: EPA Proposal for Control of Emissions from New Marine Compression-Ignition Engines at or above 30 Liters Per Cylinder* (2009) <http://www.epa.gov/nonroad/marine/ci/420f09029.htm>.

[7] *Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*, 1999, is a protocol to the *Convention on Long-range Transboundary Air Pollution 1979*. The Protocol agreed to the reduction of acidification, eutrophication and ground level ozone to agreed levels by 2010 – Sulphur, NOx, VOC, and Ammonia.

DNV Clean Design certification limits emissions of NOx, SOx and refrigerants.

4 Emissions at Berth (Hotelling)

Ports are frequently close to urban areas. Diesel generators on ships are used to make electricity for hotelling loads, cargo handling, and ballast pumping. Oil fired boilers are used to heat fuel or cargo, make steam for steam driven cargo pumps and to make hot water. Cruise ships have high hotelling loads providing air conditioning, lighting, refrigeration, cooking, etc. Two measures being implemented to reduce emissions at berth are:

- Fuel switching, currently involving use of low sulphur fuel while at berth, will reduce SOx and PM emissions. The future may also see ship generators designed to run on LNG at berth to further reduce SOx and PM emissions and also reduce NOx.

- Shore power (alternative maritime power, cold ironing). Ship electricity is supplied from the land grid. This shifts air quality emissions away from the port. The net gain depends on the shore power source. Diesel engines are generally more efficient than the existing large scale electricity generating facilities operating on coal or natural gas, so the use of shore power can result in a net increase in greenhouse gases. However, diesel engines produce more NOx and particulate matter. The use of shore power for ship electricity doesn't replace the on-board boilers so the SOx reduction from the use of shore power is not necessarily as big as for fuel switching. Some ports are implementing LNG powered auxiliary generators at the port to provide ship electricity.

5 Natural Gas

Natural gas is composed primarily of methane and contains virtually no sulphur. Engines running on natural gas produce less than 20% of the NOx and PM from diesel engines on liquid fuel. SOx emissions are negligible.

Dual fuel diesel engines use natural gas as the main fuel source with a small amount of diesel fuel injected to initiate the combustion. They can run with 80% to 99% of fuel energy from gas. They are particularly suitable for marine usage because they can revert to 100% liquid fuel operation immediately if the gas supply fails, providing a high degree of propulsion reliability for ship safety.

The engine technology is well developed and a range of duel fuel engines are available from the major engine manufacturers. Gas only engines are also available and will be used in multi-engine arrangements.

The use of natural gas can also result in 25% greenhouse gas reduction if the combustion system is well designed, so that there are no significant emissions of methane. The emissions from gas engines can meet the most stringent IMO NOx and SOx emissions limits (IMO Tier 3 in ECAs) without aftertreatment. Particulate emissions are very low compared with liquid fuelled diesel engines.

Australia's *MV Accolade* has been operating successfully out of Adelaide on compressed natural gas for about 20 years.

Liquefied Natural Gas (LNG) allows greater fuel quantities in a given space than compressed natural gas. The gas is stored as a very cold liquid in highly insulated tanks at moderate pressures. The technology for storage and safe handling is well developed.

Norway is establishing significant LNG infrastructure for domestic shipping. LNG is an attractive fuel for Australian domestic shipping. Australia has vast reserves of natural gas, while our oil is running out.

6 Greenhouse Gas Emissions

Shipping produces around 15% of global transport CO_2 emissions, while shipping performs around 70% of the global freight task. The mass of CO_2 emitted per tonne-km for shipping is around 30% of road transport, making shipping an attractive option for reducing greenhouse gas emissions. Ship CO_2 emissions are compared with rail, road transport (trucks) and aviation in Figure 2.

CO_2 is the main greenhouse gas emitted by ships. Methane (CH_4) and nitrous oxide (N_2O) emissions from ship engines have a minor global warming role compared with CO_2. Further, SOx, NOx, PM and VOC also have a minor role in global warming. Particulate matter arising from SOx emissions has a potential cooling effect and/or creates local climate disturbance (see section 6.1). The sulphur content of marine fuels will decrease due to IMO MARPOL Annex VI and other measures.

There are interaction between greenhouse gas mitigation measures and air quality mitigation measures. For instance, reducing NOx emissions can increase fuel consumption and thus increase CO_2 emissions.

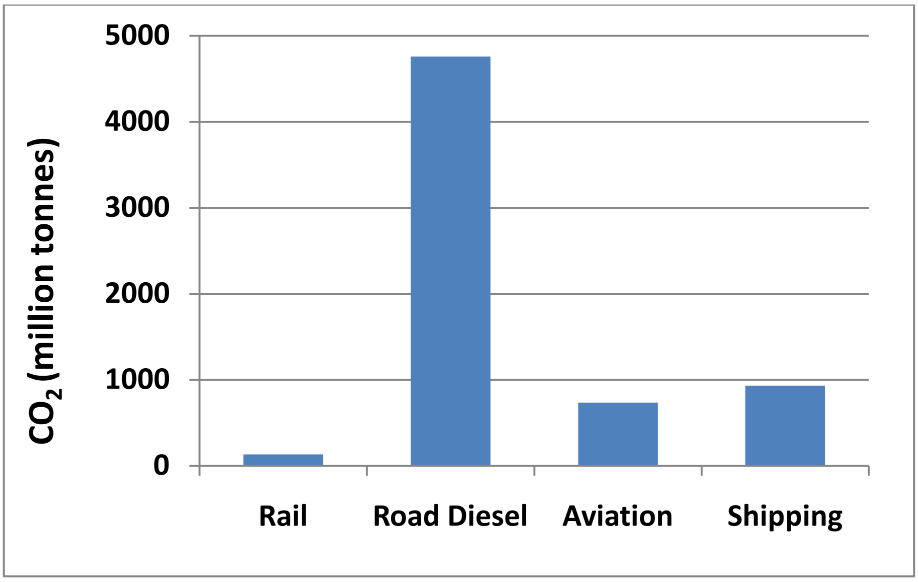

Figure 2 2005 Global Transport CO_2 emissions (IMO 2009) – excludes automobiles – goods transport only. Data taken from 2nd IMO Greenhouse Gas Study 2009.[8]

[8] Øyvind Buhaug et al, *Second IMO GHG Study 2009* International Maritime Organization (IMO) London, UK, April 2009.

6.1 Particulates – Global Cooling from Shipping?

Radiative forcing is an indication of the contribution to global warming. Positive forcing indicates warming, negative forcing indicates cooling. There are both cooling and warming effects from ship emissions, as illustrated in Figure 3.

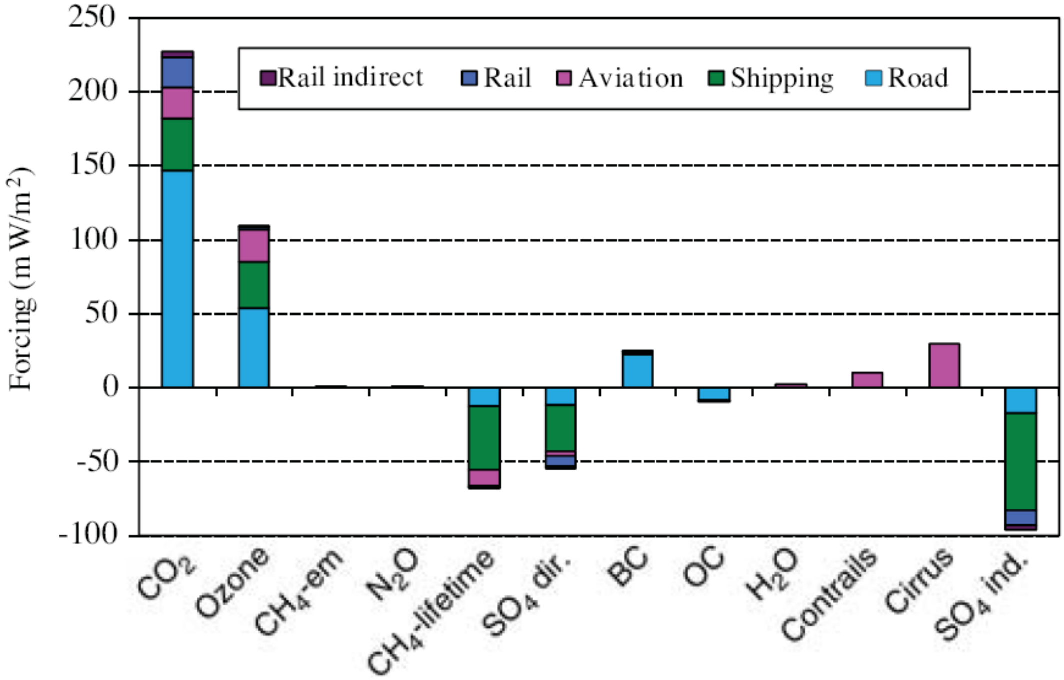

Figure 3 Radiative Forcing for 2000 Due to Transport, from Fuglestvedt al.[9]

- **Ozone: ozone in the lower atmosphere**
- **CH_4-em: emitted CH_4 - much smaller than naturally occurring CH_4, which is partially removed by reactions arising from NOx emissions**
- **CH_4-lifetime: reduction in naturally occurring CH_4**
- **SO_4 dir: direct scattering from sulphate particles**
- **SO_4 ind: increased scattering from clouds due to sulphate particles**
- **Contrails: vapour trails from aircraft**
- **Cirrus: impact of aviation vapour trails on cirrus cloud formation and properties.**
- **BC: black carbon**
- **OC: organic carbon**

The overall impact of ship emissions depends on the balance of cooling and warming effects.

- NOx emissions lead to increased ozone in the lower atmosphere (warming) and oxidation of methane (cooling).
- Sulphate and organic carbon aerosols (nuclei mode hydrocarbon particulates) scatter solar radiation (cooling).
- Sulphates also increase cloud reflectivity (albedo) (cooling).
- Black carbon absorbs radiation (warming).
- Black carbon on snow is important (warming) and needs further assessment.

Fuglestvedt et al[10] claim net cooling for shipping. Bows pointed out that their methodology was flawed as they did not account for cumulative effect of CO_2.[11] That is, CO_2 that has accumulated goes on accumulating, but

[9] Jan Fuglestvedt et al, 'Climate Forcing from the Transport Sectors' (2008) 105(2) *Proceedings of the National Academy of Sciences* 454.

other pollutant concentrations remain steady. The sulphate particulates have a relatively short lifetime in the atmosphere in terms of global warming.

6.2 Reducing Greenhouse Gas Emissions from Shipping

Numerous measures are available for reducing ship greenhouse gas emissions.

6.2.1 Speed Reduction

Speed reduction is an operational measure which offers significant CO_2 reductions. A 10% speed reduction gives 20+% reduction in fuel consumption over the same distance. Engines can be derated to optimise operation at reduced speeds by measures such as increasing compression ratio or turbocharger boost pressure to recover cylinder pressures when less fuel is injected per cycle. Classification Society Germanischer Lloyd have recently suggested that container ship speeds of 12 to 14 knots would be optimum.[12] The present norm is 20+ knots. This reduced optimum speed would save fuel costs and emissions as well as absorbing overcapacity in the fleet.

6.2.2 Other Measures

Other measures include:

- Alternative energy sources such as gas, wind, second/third generation biofuels (algae, lignocellulosic (eg from wood), pyrolysis oil, synthetic diesel, biomethane)
- Improved hull and propeller efficiency
- On-board energy efficiencies
- Weather routing
- New aftertreatment technologies, for example CSNOx by Ecospec, which is promoted to remove 74% of CO_2 from exhaust as well as 93% of SOx, 82% of NOx. It is not yet proven.

6.2.3 Emissions Trading/Carbon Tax.

Various alternatives are being actively considered.[13] The Australian Shipowners Association along with similar associations from a number of countries have proposed a global cap and trade system for international shipping.[14]

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[10] Ibid.
[11] Catherine Brahic, 'Transport Emissions Study Misleading Say Experts' *New Scientist* (2008) http://www.newscientist.com/article/dn13157-transport-emissions-study-misleading-say-experts.html>.
[12] 'Class proposes even slower speeds' *The MotorShip* (England) January 2010.
[13] Øyvind Buhaug et al (2009) above n 8.
[14] Australian Shipowners Association, Royal Belgian Shipowners’ Association, Norwegian Shipowners’ Association, Swedish Shipowners’ Association, Chamber of Shipping of the UK, 'A Global Cap and Trade System to Reduce Carbon Emissions from International Shipping' (The Chamber of Shipping, London, September 2009).

7 Conclusions

Ship engine exhaust emissions are known to have adverse impacts in areas of high shipping activity in other parts of the world. A considerable effort is underway globally to reduce these emissions and significant advances have been achieved.

A few individual studies have been made of air quality emissions from shipping in and around Australian ports. There is a need for an overarching study to quantify the significance of impact of ship emissions on air quality in Australia. Such a study will:

- Inform government policy. Shipping offers a relatively low greenhouse gas option for domestic transport compared with road or rail. Options include encouragement of domestic shipping and provision of incentives for uptake of alternative fuels such as low sulphur distillate or LNG.

- For the shipping industry, provide a sound basis for arguing the benefits of shipping and for investment planning.

Appendix

Nomenclature

CO_2	Carbon dioxide
CH_4	Methane
CO	Carbon monoxide
ECA	Emissions Control Area
EGR	Exhaust Gas Recirculation
IMO	International Maritime Organisation
LNG	Liquefied natural gas
NOx	Oxides of nitrogen
N_2O	Nitrous oxide
PM	Particulate matter
SCR	Selective Catalytic Reduction
SO_2	Sulphur dioxide
SOx	Oxides of sulphur
VOC	Volatile organic compounds (Hydrocarbons)