# Study of Greenhouse Gas Emissions from Ships

Final Report to the International Maritime Organization

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Carnegie Mellon

DNV

# PREFACE

This study on greenhouse gas emissions from ships is a report delivered to the International Maritime Organization by the consortium run by MARINEK in partnership with Det Norske Veritas, Econ Centre for Economic Analysis, and Carnegie Mellon University.

The objective of the study has been to undertake an examination of greenhouse gas emission reduction possibilities through different technical, operational, and market-based approaches.

Execution of the work has primarily been based on fact finding and application of existing analytical tools and methods. It is emphasised that it was not within the scope of the work to undertake new research on the various areas, but rather to provide a state-of-the-art report on the subject.

Available information has been compiled and presented in way that the consortium believe will be valuable for the Marine Environmental Protection Committee, in considerations and development of a policy document on greenhouse gas emissions from ships.

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Norwegian Marine Technology Research Institute - MARINTEK
Trondheim, Norway, March 2000

Contributions to this draft report have been organised and managed by members of the consortium represented by: Kjell Olav Skjølsvik, Aage Bjørn Andersen, James J. Corbett, John Magne Skjelvik
MT Report: MT00 A23-038, Trondheim, Norway, March 2000.

## LIST OF ABBREVIATIONS

| | |
|---|---|
| CDM | Clean development mechanisms |
| CICERO | Centre for International Climate and environmental Research |
| $CO_2$ | Carbondioxide |
| DNV | Det Norske Veritas |
| DOT | U.S. Department of Transport |
| ECMT | European Conference of Ministers of Transport |
| ECON | Econ Centre for Economic Analysis |
| EEA | European Environmental Agency |
| EIA | Energy Information Administration |
| EPA | U.S. Environmental Protection Agency |
| GDP | Gross domestic product |
| GHG | Greenhouse gas |
| HFO | Heavy fuel oil |
| IBIA | The International Bunker Industry Association Ltd. |
| ICS | International Chamber of Shipping |
| IEA | International Energy Agency |
| IMO | International Maritime Organisation |
| IPCC | Intergovernmental Panel on Climate Change |
| ISO | International Organisation for Standardisation |
| JI | Joint implementation |
| LMIS | Lloyd's Maritime Information Services |
| MARINTEK | Norwegian Marine Technology Research Institute |
| MDO | Marine diesel oil |
| MEPC | Marine Environmental Protection Committee |
| $NO_x$ | Nitrogen Oxides |
| NMVOC | Non-Methane Volatile Organic Compounds |
| OECD | Organisation for Economic Co-operation and Development |
| UNCTAD | United nations Conference on Trade and Development |
| UNEP | United Nations Environment Programme |
| UNFCCC | United Nations framework Convention on Climate Change |
| VOC | Volatile Organic Compounds |

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# 1. EXECUTIVE SUMMARY

## 1.1. Introduction

In joint effort by:

- MARINTEK, Norway,
- Carnegie Mellon University, United States,
- Det Norske Veritas, Norway, and
- ECON, Center for Economic Analysis, Norway,

a study was performed for the International Maritime Organisation (IMO) to undertake an examination of greenhouse gas emission reduction possibilities through different technical, operational and market-based approaches.

## 1.2. Organisation of the work

The report from the study was organised as shown in Figure 1-1.

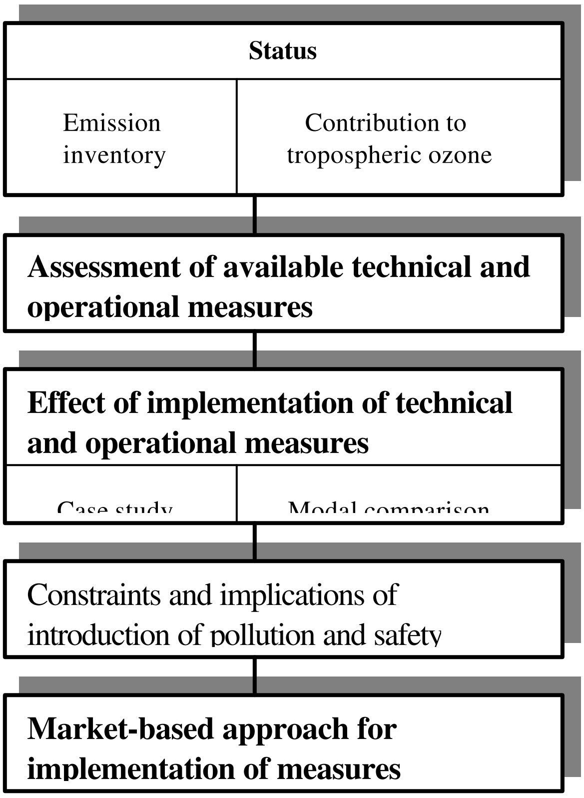


**Figure 1-1 – Organisation of the work**

## 1.3. Conclusions

The following conclusions were derived from the study:

- The world consumption of marine bunker fuel was established by use of different sources. The different sources are inconsistent and indicate a number of errors in the system for reporting the consumption of marine bunkers. In order to improve the estimates of emissions from ships based on a fuel consumption methodology, the bunker consumption statistical reference material should be improved.

- Statistical emission models and fuel consumption methodologies may be applied when emissions to air from ships are estimated. Both methodologies have documented weaknesses due to uncertainties related to statistical data material and emission factors presently adopted.

- The impact of ship $NO_x$ emissions on local and regional air quality (pollution) will continue to be the dominant policy driver, and may motivate additional domestic and international policy action. However, as scientific research furthers the understanding of global climate effects, policy decisions may increasingly focus on these global issues. Improved assessments of global climate impacts from shipping will need to include effects of $CO_2$, $NO_x$, and $SO_x$ emissions from ships. The research needed includes additional long-term field campaigns to measure $O_3$ and $NO_x$ in the remote marine boundary layer and troposphere.

- A potential for reduction of GHG emissions through technical and operational measures has been identified. Measures related to hull and propeller are identified as general measures for energy savings. Measures related to machinery are identified in a variety of options. The various options have varying effect on reduction of different components of emissions, which implicate that reduction of one component may be a trade-off with regards to increased emissions of another component.

- Technical and operational measures have a limited potential for contributing to reduced emissions from ships. If the increase in demand for shipping services and market requirement for increased speed and availability continues, technical measures alone will not be able to prevent a total growth in emissions from ships.

- Shipping has been confirmed to be a significant contributor in the development of environmental sustainable transport. Although emission for some components may be above the level for other means of transportation, the energy consumption is still a strong factor promoting seabourne transportation in an inter-modal transportation chain.

- Shipping is a small contributor to the world total $CO_2$ emissions (1.8% of world total $CO_2$ emissions in 1996). This implies that a 10% reduction in emissions from shipping represents less than 0.2% reduction of the world total emissions. The report documents areas where shipping may contribute to moderate reductions of emissions with moderate costs. Significant reductions will represent a cost that should be related to the total gain of the reduction in comparison with abatement cost level in other sectors.

- Significant potential for reduction of emissions from shipping based on operational measures has been identified. Based on the market mechanisms in shipping, implementation of the defined operational measures will most likely require participation from others than the ship owners.

- Technical measures can be easier to implement and enforce through international standards than operational measures, and implementing these measures primarily through new vessel construction may be more feasible for the industry than retrofitting existing ships.

- Based on an assessment of alternative policy instruments, and in the light of the ongoing ratification process of the Kyoto Protocol, the following strategy for policy implementation for IMO to curb GHG emissions could be feasible:

  1. Explore the interests for entering into voluntary agreements on GHG emission limitations between the IMO and the ship owners, or to use environmental indexing.
  2. Start working on how to design emission standards for new and possibly also for existing vessels.
  3. Pursue the possibilities of credit trading from additional abatement measures implemented on new and possibly also on existing vessels.

- A set of comprehensive and detailed regulations ensures necessary minimum protection of crew, passengers, environment, and the ship. As a part of the process of introducing new amendments, unintentional interrelations should be carefully considered, in order to avoid inconsistencies between the objectives of the safety and environmental regime.

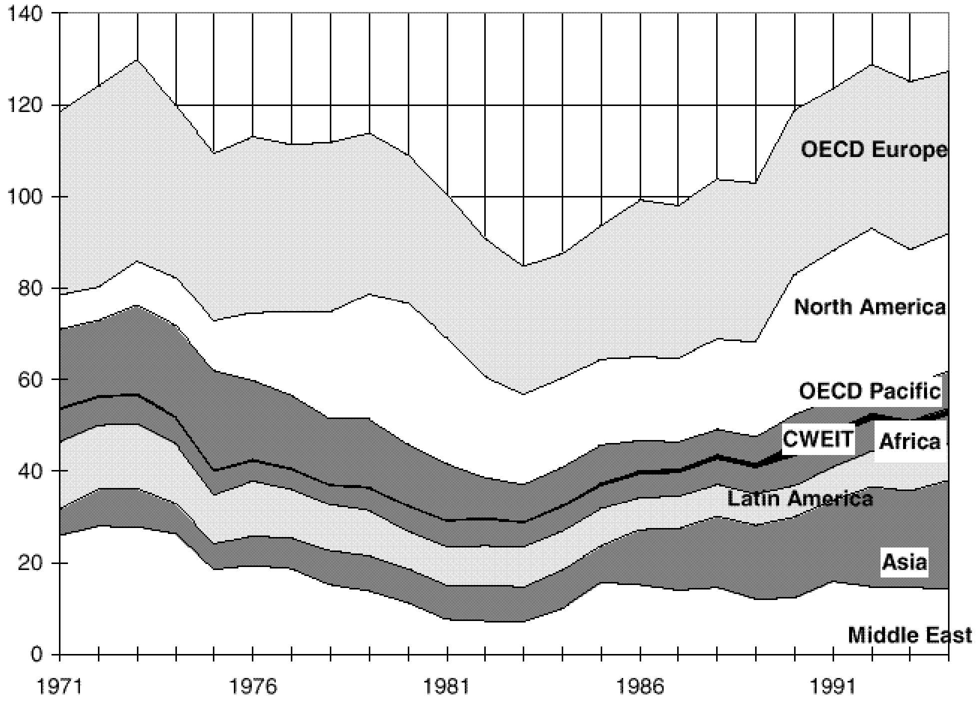
## 1.4. 1996 marine emissions

### 1.4.1. Emission inventory

Air pollution from marine engines in terms of exhaust emission amounts was established by use of emission models. These models are based on actual emission factors adopted from onboard engine measurements or theoretical factors arrived from the respective chemical reaction equations and combined with actual fuel consumption (based on international marine bunker fuel sale figures). International marine emissions were estimated by using:

- A fuel-consumption methodology.
- A statistical emission model.

The marine bunker supply was mainly collected from energy databases publish by the Energy Information Administration (EIA), the International Energy Agency (IEA), and United Nations Framework Convention on Climate Change (UNFCCC). An emission inventory for ships in international trade for the base year 1996 was established.



Source: IEA Statistics

**Figure 1-2 -World Sales of marine bunker fuel (in million tonnes) for 1971-1994, by regions (UNFCCC, 1997/IEA statistics).**

Different sources of marine bunkers supply world-wide have been evaluated and discussed. A number of inconsistencies have been found and discussed. Total world-wide marine bunker sales in the period 1990 – 1996 lies in the range of 120 Mton to 147 Mton.

Based the on assumptions and modifications described in the report, the 1996 world –wide international marine bunker sales may be estimated to be 138 Mton, and separated as:

Distillate fuel: 38 Mton
Residual fuel: 100 Mton

Based on the fuel-consumption methodology, the emissions to air were established as shown in Table 1-1.

**Table 1-1 Marine emission in 1996 using fuel consumption methodology based on different emission factors.**

| **Gas component** | | ***Supply 138 (Mton)*** | | | *Range (Mton)* |
|---|---|---|---|---|---|
| | | Low[2)] | CORINAIR[1)] | High[3)] | |
| CO | | 0.7 | 1.00 | 1.1 | 0.7-1.1 |
| NMVOC | | - | 0.33 | - | - |
| $CH_4$ | | - | 0.04 | - | - |
| $N_2O$ | | - | 0.01 | - | - |
| $CO_2$ | | 435.9 | 437.50 | 438.2 | 436-438 |
| $SO_2$ | *Residual* | 5.0 | 5.40 | 7.0 | 5-7 |
| | *Distillate* | 0.2 | 0.40 | 0.8 | 0.2-0.8 |
| | *Total* | 5.2 | 5.80 | 7.8 | 5.2-7.8 |
| $NO_x$ | | 10.1 | 10.30 | 11.4 | 10.1-11.4 |

[1)] Using “CORINAIR” emission factor, [2)] Using “Low” emission factor, [3)] Using “High” emission factor

The marine emissions were found to represent 1.8% of the global emissions of $CO_2$ in 1996 (based on UNEP figures in Global Environmental Outlook 2000).

Based on the statistical emission model, distributions of emissions on ship types were established. Results from the statistical emission model are given in Table 1-2.

Comparisons of the results as given in Table 1-1 and Table 1-2 indicate approximately 10% lower results for $CO_2$ from the statistical model. The main reason for this is that only main engines are represented in the statistical model.

**Table 1-2 - Model emission results 1996 by statistical emission model, main engine(s), separated by vessel type, using the "CORINAIR" emission factors.**

| Ship type | $NO_x$ (Mton) | CO (Mton) | NMVOC (Mton) | $SO_2$ (Mton) | $CO_2$ (Mton) |
|---|---|---|---|---|---|
| Liquid gas tanker | 0.29 | 0.03 | 0.01 | 0.20 | 13.40 |
| Chemical tanker | 0.32 | 0.03 | 0.01 | 0.20 | 14.20 |
| Oil tanker | 2.00 | 0.18 | 0.06 | 1.44 | 93.20 |
| Bulk Carrier | 2.60 | 0.22 | 0.07 | 1.58 | 96.00 |
| General cargo | 1.77 | 0.19 | 0.06 | 0.70 | 81.54 |
| Container | 1.63 | 0.15 | 0.05 | 0.89 | 64.39 |
| RO-RO cargo | 0.66 | 0.07 | 0.02 | 0.24 | 30.85 |
| Passenger | 0.29 | 0.03 | 0.01 | 0.11 | 13.37 |
| Refrigerated cargo | 0.27 | 0.03 | 0.01 | 0.11 | 12.34 |
| Sum | *9.82* | *0.93* | *0.30* | *5.46* | *419.30* |

In order to quantify the air pollution from marine engines, in terms of exhaust discharge within geographical regions, it is instructive to use a geographical emission model. These models are based on vessel traffic density within a number of chosen pollution areas, described below. It is evident that there are a smaller number of areas with high traffic density.

The conclusion is clear, at a given time most vessels are relatively near shore. Consequently the main amount emitted is along the coast mainly:

- In the Northern Hemisphere
- Along the west and east cost of United States
- In northern Europe
- The North Pacific

### 1.4.2. Impact of international shipping - $NO_x$ and tropospheric ozone

The impact of ship $NO_x$ emissions on local and regional air quality (pollution) will continue to be the dominant policy driver and may motivate additional domestic and international policy action. However, as scientific research furthers the understanding of global climate effects, policy decisions may increasingly focus on these global issues.

Reduction in $NO_x$ emissions motivated by air quality concerns, either through international standards such as MARPOL Annex VI or through domestic policy efforts, will tend to reduce the net warming effect due to tropospheric ozone and $CH_4$. If these $NO_x$ reductions are greater than corresponding increases in $CO_2$ emissions (that may result from decreased fuel efficiencies in the engine), then the combined effect of $NO_x$ control could reduce the global warming impact of international shipping. In total, the current net radiative forcing from ships (including $CO_2$, ozone, $CH_4$, and aerosols) is probably small or slightly negative.

Accurate estimates of radiative forcing due to $NO_x$ from international shipping cannot be made from currently available data. However, an indirect estimate of radiative forcing due to $CO_2$ emissions from ships indicates that ships may account for 1.8% of current IPCC estimates. $NO_x$ emissions are highly likely to produce non-zero, positive forcing effects that will contribute to global warming and that could be in the same range as (or larger than) direct forcing from $CO_2$.

Improved assessments of global climate impacts from shipping will need to include effects of $CO_2$, $NO_x$, and $SO_x$ emissions from ships. The research needed includes additional long-term field campaigns to measure ozone and $NO_x$ in the remote marine boundary layer and troposphere. Field research should also investigate the chemical composition and physical dynamics of ship emissions to investigate the small-scale nature of ship plumes and the larger-scale effects as the plume gases disperse and react. This work would build upon the important ship-board emissions characterisations performed 5-10 years ago as part of the Lloyd's Marine Exhaust Emission Research Programme, and research such as the Monterey Area Ship Tracks (MAST) Study of in-situ plume effects.

## 1.5. Assessment of technical and operational measures for reduction of GHG emissions

Following the status of amount and effect of emissions, both technical and operational measures for reduction of emissions were considered. The assessment of various options was based on both a short-term and long-term perspective.

In the context of this report, short term is closely connected to available technology. When technical options for reductions of emissions were analysed, the effect over time was considered in relation to the development of the fleet during the same period. With a long useful life (20 years+) for each ship, the replacement time for the entire world fleet is significant. Due to the long design and construction period for an innovative ship design and the size of the existing fleet if modifications were to be performed, the time for implementation of new technologies will be several years.

### 1.5.1. Applying state-of-the-art knowledge

Energy savings that can be obtained by applications of current technologies within hydrodynamics (hull and propeller) and machinery for new and existing ships was considered.

Due to the different applicability of different alternatives, new and existing ships were treated separately.

The identified potential for energy savings by improved hull design was based on MARINTEK's database of model test results. Efficiency and applicability of various propulsor alternatives was assessed as a basis for identifying a potential energy saving due to choice of propellers for new ships.

Emission reduction measures related to engine combustion processes were considered, with main focus on $CO_2$ and $NO_x$ reduction. Reductions of CO, HC and $SO_2$ emissions are however also addressed to a limited extent in the main report.

It is difficult to discuss reductions of $CO_2$ emissions from machinery isolated, without also considering the $CO_2/NO_x$ relationship. Measures that aim to reduce $NO_x$ emissions often have an influence on $CO_2$ emissions and vice versa, with a trade-off between the two. In addition, there is a great focus on $NO_x$ emissions from the marine sector, hence this relationship is discussed in the report. Table 1-3 shows the various measures discussed in the report.

**Table 1-3 – $CO_2$ reduction potential by technical measures**

| **Measures, new ships** | **Fuel/$CO_2$ saving potential** | **Combined 1)** | **Total 1)** |
|---|---|---|---|
| Optimised hull shape | 5 - 20 % | 5 – 30 % | 5 – 30% |
| Choice of propeller | 5 - 10 % | | |
| Efficiency optimised | 10 – 12 % 2)<br>2 - 5 % 3) | 14 – 17 % 2)<br>6 - 10 % 3) | |
| Fuel (HFO to MDO) | 4 – 5 % | | |
| Plant concepts | 4 - 6 % | 8 – 11 % | |
| Fuel (HFO to MDO) | 4 – 5 % | | |
| Machinery monitoring | 0.5 –1 % | | |
| **Measure, existing ships** | **Fuel/CO2 saving potential** | **Combined 1)** | **Total 1)** |
| Optimal hull maintenance | 3 – 5 % | 4 - 8 % | 4 – 20 % |
| Propeller maintenance | 1 – 3 % | | |
| Fuel injection | 1 – 2 % | 5 - 7 % | |
| Fuel (HFO to MDO) | 4 – 5 % | | |
| Efficiency rating | 3 – 5 % | 7 - 10 % | |
| Fuel (HFO to MDO) | 4 – 5 % | | |
| Eff. rating + TC upgrade | 5 – 7 % | 9 - 12 % | |
| (HFO to MDO) | 4 – 5 % | | |

1) Where potential for reduction from individual measures are well documented by different sources, potential for combination of measures is based on estimates only

2) State of art technique in new medium speed engines running on HFO.

3) Slow speed engines when trade-of with NOx is accepted.

The term operational control is used in this context to consider alternatives to technical solutions to obtain reduced greenhouse gas emissions. As emissions are related to the consumption of fuel, the various options considered were evaluated according to influence on fuel consumption. Operational measures considered are shown in Table 1-4.

**Table 1-4 – $CO_2$ reduction potential by operational measures.**

| Option | Fuel/$CO_2$ saving potential | Combined1) | Total1) |
|---|---|---|---|
| **Operational planning / Speed selection** | | 1 - 40 % | 1 - 40 % |
| Fleet planning | 5 - 40 % | | |
| "Just in time" routing | 1 - 5 % | | |
| Weather routing | 2 - 4 % | | |
| **Miscellaneous measures** | | 0 – 5 % | |
| Constant RPM | 0 - 2 % | | |
| Optimal trim | 0 - 1 % | | |
| Minimum ballast | 0 - 1 % | | |
| Optimal propeller pitch | 0 - 2 % | | |
| Optimal rudder | 0 - 0.3 % | | |
| **Reduced time in port** | | 1 – 7 % | |
| Optimal cargo handling | 1 - 5 % | | |
| Optimal berthing, mooring and anchoring | 1 - 2 % | | |

1) Where potential for reduction from individual measures are documented by different sources, potential for combination of measures is based on estimates only

### 1.5.2. Long-term considerations

The main innovation in ship design during the recent years has been towards increased ship size and increased transportation speed.

Considering hull and propulsion designs, only a breakthrough in viscous resistance reduction that can significantly impact the resistance of a conventional surface ship, while selection of speed will dominate the power consumption also in the long-term perspective.

It is foreseen that diesel engines will play a major role in ship machinery over the next twenty years. Research and development will continue to make it even cleaner and more efficient. However, an efficiency improvement of the same scale as obtained in the past twenty years is not realistic.

Efforts are foreseen to be in the areas of improved and more sophisticated injection systems, better charge-air systems, better utilisation of the exhaust waste heat, and improved $NO_x$ reduction methods. Improving engine reliability will also be focused even more, as a consequence of the shipowner requirements.

The development of different kinds of propulsion trains (based on electrical power distribution - the power plant concept), steadily open for specialised solution dedicated the type of ship and operation, is expected to continue.

With respect to the alternatives to diesels, strong efforts will be made from the gas turbine manufacturer to capture a greater part of the marine merchant market. To better compete, the overall efficiency will be improved ”combustion wise” and complete integrated power plant packages, energy optimised, will be further developed.

The development of emission friendly alternatives as i.e. fuel cells will continue. Hopefully the results from the great efforts done on fuel cell for the automotive industry will benefit the marine industry. However, the demand for constantly higher speed and more power even create greater challenges for applicability with respect to power density. The main challenges to overcome with the fuel cell are the low power density and the hydrogen logistics.

## 1.6. Effect of technical and operational measures

### 1.6.1. Case study

A case study of the effect of implementation of different technical measures for the world-fleet, in a 20-year time window, was performed. The case study results were compared with projected growth of shipping activity and corresponding growth in fuel consumption and emissions.

The primary reason for a case study with a time window of 20 years is the slow pace of introduction of new measures in a large world-wide fleet. A short-term analysis (5-10 years) is considered to provide information of limited value, owing to the fact that the replacement ratio of the fleet is low, and implementation of technical measures on existing ships will require a significant effort over time due to the large amount of vessels. As the uncertainties related to results increases with increasing length of projection, the upper limit for reasonable confidence in the results was chosen to be 20 years. In order to limit the model, results for year 2010 and 2020 are presented.

Within the framework of the defined scenarios a set of case studies, considering alternative measures for reduction of the fuel consumption or improved efficiency was performed. The world fleet consists of a large variation of ship types and sizes. In order to simplify the presentation and assessment of the potential of different technical or operational measures for improvement, only four ship categories were considered. Within the framework of the defined scenarios, case studies on the category tank, bulk, container, and general cargo were performed. The categories were selected based on their contribution to the overall emissions presented in 1.3 above (see Table 1-2).

Realistic models for development of the world fleet and effect of implementation of alternative measures were established based on input from ship and market statistics.

The case studies for the four case ships were used to quantify the effect of implementation of various measures aiming to reduce the emissions from the machinery from the world fleet. Based on the two scenarios developed, the case ship studies were combined to quantify the effect of the measures on the world marine fuel consumption and corresponding emissions. The chosen measures will in generally have similar impact on emissions of most components, but is only illustrated for $CO_2$ in the table below. For the remaining part of the world fleet not covered by the case study, the results indicate that a similar effect of the various measures is applicable also for these segments.

**Table 1-5 – Results from case study.**

**Estimated potential for reduction of emissions from world fleet**

| Reduction measures | Reduction of $CO_2$ emissions by implementation of measures on world fleet. [1] | |
|---|---|---|
| | **2010** | **2020** |
| M1. Efficiency rating ME, existing ships | 2.3% | 2.3% |
| M2. Efficiency optimised ME, new ships | 1.9% | 3.2% |
| M3. Stepwise switch from HFO to MDO. | 1.6 % | 3.0 % |
| H1. Optimal hull shape, new ships | 6.4% | 11.6% |
| H2. Propulsion system, new ships | 3.1% | 5.8% |
| H3. Maintenance (hull/propeller), existing ships | 2.3% | 2.3% |
| **Theoretical max. from technical measures** | **17.6%** | **28.2%** |
| O1. Speed reduction of 10% | 23.3% | 23.3% |
| O2. Weather routing | 0.8% | 0.8% |

**Estimated world fleet fuel consumption (no measures applied)**

**Scenario 1 - No measures**
**Annual growth of fleet 1.5%**

| | **2010** | **2020** |
|---|---|---|
| Est. fuel cons. (ME) | 165.8 Mt | 192.5 Mt |
| Increase from 2000[2] | 19% | 38% |

**Scenario 2 - No measures**
**Annual growth of fleet 3.0%**

| | **2010** | **2020** |
|---|---|---|
| Est. fuel cons. (ME) | 203.1 Mt | 256.62 Mt |
| Increase from 2000[2] | 36% | 72% |

[1] Comparison with base line fleet development when no measures are applied.

[2] Based on modelled growth of fuel consumption

Denomination M - machinery measure, H - Hull/propulsion measure, O - Operational measure

The theoretical maximum when implementing all technical measures considered for the entire fleet is a 17.6% reduction of the emissions in 2010 and 28.2% in 2020. Compared to the two scenarios these values are below the lower boundary for projected growth of fuel consumption and corresponding emissions.

The case scenario performed illustrates how the potential for various technical measures for reduction of $CO_2$ emissions can not be projected to apply proportionally when implemented for the entire fleet. Although the potential for a single technical measure may be significant, the effect on an aggregated level is reduced due to the applicability for different categories of ships. It further illustrates the need for long-term perspective in order to obtain quantifiable end results, due to the long period of time needed for effect of implementation of measures for new ships.

The case study indicates that the effect of technical measures will be different for different shipping segments. Technical measures may compensate growth in emissions due to growth of the fleet to a certain level, and for certain types of ships, but limitations in reductions of emissions by introduction of technical measures have been identified.

Reduction of speed in general was identified as the single measure that results in highest reduction of $CO_2$ emissions. This measure was further investigated and illustrated in the modal comparison (see 1.6.2 below).

Implementation of new and improved technology was identified as the second best approach to reduce the emissions.

The results from the case study were based only on a technical approach to the task of reducing greenhouse gas emissions from ships. Economical or trade related issues were not properly dealt with, and will affect the above conclusions. Applicability of several measures will have to be considered based on more thorough market analysis.

### 1.6.2. Modal comparison

Clearly, the importance of international maritime transportation to global trade is undisputed, particularly for bulk commodities and raw materials. Even for general and containerised cargoes, the tonne-km of cargo moved annually by international shipping exceed the combined total for the United States and Europe. However, this modal analysis demonstrates that international shipping represents one part of a global transportation system in which other modes (truck and rail) are more often partners than competitors. Further, effects from operational measures not properly presented by the case study are illustrated.

To identify explicitly the most important energy and environmental performance factors for international shipping, a Freight Transportation Model was developed. The idealised Freight Transportation Model defines an equal amount of cargo to be moved by each mode (ship, rail, and truck) across the same distance. It does not specify one type of cargo, but rather an equal tonnage of cargo that could be carried by each mode. By defining an equal tonnage of cargo and an equal distance, the tonne-km in the denominator are identical for all modes and all modes of freight transportation can be compared directly.

The Model estimates explicitly the energy-use and emissions during "open-ocean" or "highway" or "line-haul" transit, and estimates separately the average energy-use and emissions during manoeuvring, docking, and cargo transfer operations for each mode.

Four types of ships are modelled: 1) oil tanker; 2) bulk carrier; 3) container; and 4) general cargo. This Model use the same baseline characteristics assumed for the case-average ships presented in the case study.

Using the Freight Transportation Model presented in the main report, a modal comparison of energy and environmental performance was made. Ships generally compare well with other modes of freight transportation, but these comparisons vary significantly by type of pollutant. Moreover, the fuel consumption rates and emissions from ships are different for different types of ships. Wet and dry bulk carriers, which are larger and generally slower, perform better than general cargo and container ships. Rail and truck modes differ in terms of energy intensity and $CO_2$ emissions, but their $NO_x$ emissions at average capacity factors are nearly identical.

Optimising capacity factors and reducing average turn-around times by improving manoeuvring and cargo handling operations can provide significant reductions in energy intensity and emissions. These improvements apply to all modes, but the potential may be greatest for ships. The analyses performed with the Freight Transportation Model confirm the potential for reduced emissions by operational control as indicated in the case study.

## 1.7. Implications of safety and pollution prevention initiatives

An assessment on the regulative measures related to maritime safety revealed a number of ten international conventions, agreements, regulations and standards. SOLAS is recognised as the most important international regulative frame dealing with these topics. SOLAS, its main area of application and its development to date, have been assessed in order to define restraints likely to impact the potential of reducing GHG emissions from international shipping.

Similarly, an assessment identified five international conventions defining technical and operational constraints provided to ensure environmentally safe operations. MARPOL is the major tool conducting the extent of such constraints. An assessment of MARPOL regulations was undertaken in order to identify requirements, recommendations or standards violating the potential of reducing the GHG-emissions from international shipping.

Some specific characteristics with reference to initiatives and measures of both safety origin as well as that from the pollution prevention aspect were identified and grouped. The potential of these category groups impacting the fuel consumed by ships was been considered. New initiatives at present being debated were also evaluated. This includes that of regulating ballast water voyages and the proposed ban on the use of Tributyltin.
The different categories selected are shown in Table 1-6.

**Table 1-6 - Measures and initiatives affecting GHG emissions from international shipping, categorised by groups**

| No.: | Category I | Category II | Category III | Category IV |
|---|---|---|---|---|
| Type: | Measures limiting cargo carrying capacity | Measures introducing additional energy consumers | Measures effecting general efficiency | Misc. |
| Impact potential: | High | Minor | Medium | Minor |
| New initiatives | Ballast water management | | Tributyltin ban | |
| Impact potential | Medium | | Minor | |

Initiatives reducing a vessel's ability to utilise actual cargo carrying capacity (Category I) are initiated on both safety grounds as well as from a pollution prevention stand. Regulations in MARPOL, Annex I will in effect impose a ban of carrying oil cargo in vessels other than those built with double hull after reaching thirty years of age. The void space between the hulls represents empty space travelling and does represent a fuel penalty. Among category I initiatives, double hull requirement hold the highest penalty potential. Potential fuel penalty carried by category I measures are considered high in comparison with the other categories.

Measures represented in category III include those with impact on the routing patterns of the ship. These might initiate the vessel to obtain a lane that does not represent optimum efficiency. The introduction of restrictions in an area might cause the operators to avoid these either by de-routing and consequently increase fuel consumed or re-load cargo onto other means of transport that might represent a lesser efficiency (land based transport alternatives). However, routing as such do carry a potential of improving fuel efficiency as well (for example weather routing). The potential of measures falling into category III might cause a significant increase in fuel consumed in transporting goods even though requiring a set of circumstances to be present. The potential fuel penalty can be considered medium. Of measures with medium impact on fuel penalty, SOLAS regulations regarding routing/vessel traffic services, and MARPOL regulations for special areas were identified.

## 1.8. Market-based approach for implementation of abatement measures

The different alternative incentive regime options that exist for curbing emissions from ships were assessed. Alternative instruments were assessed related to their possible effects on the different GHG emissions abatement measures, and the prospects of implementing the instruments world wide or at least among Annex I-countries (i.e. industrialised countries committed to emissions targets according to the Kyoto Protocol).

Implementing policy instruments to limit GHG emissions from international shipping industry should contribute to global, cost-effective emission reductions. Thus, abatement measures in the shipping industry should only be implemented if the marginal costs are equal to or lower than the marginal abatement costs in other sectors.

Regimes addressed were:

- Environmental indexing.
- A voluntary agreements programme.
  Voluntary agreements were not found to be a viable approach to obtain significant global GHG emissions from international shipping.
- Carbon charges on bunker fuels.
  Common carbon charges were not found to be a viable option.
- Emission standards. Emission standards are considered to a feasible option. However, it should be carefully concerned whether such measures are cost effective to reduce GHG emissions.
- Emission trading. Allocation of emissions allowances to ship owners was not found to be a viable option. A system for creating emission credits may however be a possible way of including international shipping in a general emission trading system.

The case study and modal comparison performed show that there are several technical and operational measures that could be implemented to limit GHG emissions from ships. Reduction of speed is identified as the single measure that results in highest emissions reductions. Implementation of new and improved technology is identified as the second best approach to reduce emissions, in terms of technical emissions reduction potential.

However, our forecasts indicates that total emissions from international shipping will increase even if most of the identified measures are implemented, due to expected growth in the world economy and thus expected increase in demand for international freight services. Taking into account the conclusion of the assessment of market-based approaches there seems to be no feasible effective policy instruments that could lead to reduced speed, it seems inevitable that total emissions from international shipping will increase in the years to come.

This is in line with forecasts for other transport modes. OECD, 1999 indicates a similar development for $CO_2$ emissions from land-based transport and aviation. Our analysis shows that sea transport is the most GHG benign freight transport mode. It is also our understanding that there may be more technical options for GHG emission reductions in international shipping than in most other transport modes. Technical improvements on hull and machinery on new ships could lead to emission reductions, and thus reduce the growth in future emissions.

The different transport modes are closely inter-linked, and dependent on each other. Thus, measures to curb GHG emissions should be co-ordinated between the different transport modes, to avoid policies that are not cost effective and only contributes to move transport from one mode to another with no effects on overall, global emissions.

On this background, and in the light of the ongoing ratification process of the Kyoto Protocol, the following strategy for policy implementation for IMO to curb GHG emissions could be feasible:

1. Explore the interests for entering into voluntary agreement on GHG emission limitations between the IMO and the ship owners.
2. Start working on how to design emission standards for new and possibly also existing vessels.
3. Pursue the possibilities of credit trading from additional abatement measures implemented on new and possibly also existing vessels.

This could be a strategy that could meet several outcomes of the ratification process of the Kyoto Protocol, and in the short-term contribute to implementation of some of the cheapest abatement measures on new and existing ships. It will also ensure co-ordination with the use of policy instruments towards other transport modes to curb emissions.

# 2. INTRODUCTION

## 2.1. Background

Ship transportation is generally an environmentally friendly means of transportation. However, the relative share of emissions from shipping has increased during the past years compared to land transportation and other industries. This is due to the significant improvements that have taken place in these industries.

From the tender document, we quote:

> "The shipping industry work for unified rules world-wide. Regional and national port state regulations are feared to result in changed competition conditions and a shift towards other transportation means. Independent flag-state regulations result in additional economic costs for shipowners and a transfer of ships to other flags. However, the shipowners associations generally welcome incentives that give credit to high quality operators.
>
> When governments adopted the UNFCCC in 1992, they recognised that it would be a launching pad for stronger action in the future. By establishing an ongoing process for review, discussion, and information exchange, the Convention makes it possible to adopt additional commitments in response to changes in scientific understanding and political will.
>
> The third conference of parties to UNFCCC was held in December 1997 in Kyoto, Japan. The conference resulted in a consensus decision (1/CP.3) to adopt a Protocol under which industrialised countries will reduce their combined greenhouse gas emissions by at least 5% compared to 1990 levels by the period 2008 – 2012.
>
> Article 2, paragraph 2 of the Kyoto protocol states: "The parties included in Annex I shall pursue the limitation or reduction of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organisation and the International Maritime Organisation, respectively.".
>
> As mandated by resolution 8, adopted by the Conference of parties to MARPOL 73/78, and by the Kyoto Protocol to UNFCCC, the Marine Environment Committee of IMO at its 42nd session, agreed to invite the Secretariat of IMO to undertake a study concerning greenhouse gas emissions from ships by engaging a consultant qualified in the relevant subject areas.
>
> IMO intends to engage the services of a consultant firm to undertake a study on greenhouse gas emissions from ships. The principal purpose of the study is to examine possible greenhouse gas emissions reductions through different technical, operational and market-

> based approaches in accordance with Conference resolution 8, adopted by the Conference of parties to MARPOL 73/78.
>
> The outcome of the study will form the basis for the MEPC's considerations and development of a policy document on greenhouse gas emissions from ships which should be forwarded to the Secretariat of UNFCCC."

The study as documented by this report has been executed by a consortium consisting of The Norwegian Marine Technology Research Institute (MARINTEK, Norway), Det Norske Veritas – (DNV, Norway), ECON Centre for Economic Analysis (ECON; Norway) and Department of Engineering and Public Policy, Carnegie Mellon University (CMU, USA). The partners have previously worked excellent together in other national and international projects.

## 2.2. Scope of work

### 2.2.1. Objective

The primary objective of this study was to examine the potential for reduction of greenhouse gas emissions through different technical, operational, and market-based approaches. Reductions based on current technology available in the market as well as the potential for reductions by utilisation of new technological solutions have been considered.

As a reference for the work, an inventory analysis has been performed in order to quantify the base level with regards to emissions from ships. This serves both as a reference for comparison and a guideline with regards to magnitude of different component and sources of emissions.

Furthermore, operational initiatives for reducing the emissions by means of more efficient and improved maintenance, weather and current routing, speed reductions, etc. have been be considered.

Relative emissions from ships (kg/tonne-km) are very sensitive to capacity utilisation of the vessel, and thus to transport efficiency. The potential for reduced emissions through various market-based approaches like e.g. vessel route planning for increased transport efficiency has been evaluated.

### 2.2.2. Limitations

The study has been based on fact finding and application of existing analytical tools and methods. It is emphasised that it was not within the scope of the work to undertake new research on the various areas, but rather to provide a state of the art report on the subject.

It is clear from the work with the report, that data from different sources are not in compliance on different topics covered by this report. Variation or dissimilarities in the sources applied during the work has been commented upon and identified. It has not been within the scope of work for this report to eliminate the various uncertainties that were identified, but rather to identify the consequence of uncertainty and need for improvement.

Emissions to air from ships may be considered as a very wide topic. In this report it has been necessary to limit the work to focus on international shipping. The primary reasons for focusing on international shipping is available statistics on ships and consumption, hence data in this report is in general related to international transport and sales of international bunker. In this report emissions from consumption of marine bunkers have been the primary focus. This is based on existing knowledge on components of emissions to air from international shipping.

## 2.3. Organisation of the work and the report

The report covers the current status on green house gas emissions, measures for reductions and how reductions may be obtained.

In order to quantify air pollution from marine engines in terms of exhaust gas emission, it is instructive to use an emission model. These models are based on actual emission factors recorded from onboard measurements or theoretical factors arrived from the chemical reaction equations, combined with the actual fuel consumption.

In this report the emissions to air in terms of exhaust gas emissions have been established for the world international fleet for the base year of 1996. In chapter 3 of the report the calculation is presented.

Although $NO_x$ and ozone are local and regional air pollutants that also produce global climate change, the local and regional air-pollution problem is quite different from the global climate-change problem. The first part of chapter 4 describes the differences between the air-quality concerns and the global climate concerns surrounding $NO_x$ and ozone. The remaining sections focus entirely on the global effects

Following the status of amount and effect of emissions, the alternatives for reduction are considered in chapter 5. Different technical and operational measures for reducing the total emissions to air are considered. The assessment of various options is based on both a short term and long term perspective.

In the context of this report, short term is closely connected to available technology. When technical options for reductions of emissions are considered, the effect over time must be considered in relation to the development of the fleet during the same period. With a long useful life (20 years+) for each ship, the replacement time for the entire world fleet is significant. Due to the long design and construction period for an innovative ship design, and the size of the existing fleet if modifications were to be performed, the time for implementation of new technology will be several years.

During the work with the report it became clear that a quantification of the effect of the alternative measures for reduction was necessary. In order to consider the overall effect of different options for reduction it was found beneficial to consider the effect of reduction measures compared to "base-line" emission figures as derived from the study in chapter 3. In the report this is done through a case study of the effect of various alternatives for emission reduction.

In chapter 6 of the report a case study with two alternative scenarios for growth in marine bunker consumption has been performed. The case study applies different measures for reduction of emissions from diesel engines, in order to quantify the overall effect of full implementation of various measures. In order to visualise the effect of different measures four case ships were defined, and used throughout the assessment.

In order to investigate the potential for reductions by applying operational measures, a modal comparison study is also presented in chapter 6. This study visualises the effect and importance of logistics, choice of speed and turn around time when performing a ship operation.

In chapter 7 the different existing safety and environmental regulations were assessed, with the objective to identify interrelations and effects on GHG emissions from ships.

Following the assessment of alternative technical and operational measures to reduce emissions, alternative methods for implementation have been considered. In chapter 8 a market-based approach with the aim to obtain reduction in greenhouse gas emissions from ships are considered.

# 3. INTERNATIONAL MARINE BUNKER CONSUMPTION AND EMISSIONS FROM SHIPS

Fuels supplied to ships engaged in international operations irrespective of the flag of the carrier, is referred to as *International Marine Bunkers.* International Marine Bunkers consists primarily of residual and distillate fuels. The Revised 1996 IPCC (Intergovernmental Panel on Climate Change) guidelines [IPCC, 1997] requested countries to estimate emission from international bunker fuel separately and to exclude these emissions from national totals. The emissions are reported according to IPCC table 7A- *Summary Report for National Greenhouse Gas Inventories* of the revised 1996 guidelines. The revised 1996 IPCC guidelines incorporating separate reporting of bunker fuels were selected by the UNFCCC Parties as the required reporting approach under the treaty and that decision was reaffirmed at the time of the adoption of the Kyoto Protocol [UNFCCC Decision 2/CP.3, paragraph 1].

Marine bunkers are a common term adopted for marine fuels combusted in ships' engines. Such fuel oils are normally used for the main engines propelling the vessel. Lighter fuels, diesel oils and gas oils, are usually used for the auxiliary engines that provide for lighting, pumping, cargo handling, etc.

The exhaust gas emission composition from marine diesel engines comprises of nitrogen, oxygen, carbon dioxide and water vapour mixed with smaller quantities of carbon monoxide, oxides of sulphur and nitrogen, partially reacted and non-combusted hydrocarbons as well as particulate matter. The amount of gases emitted from marine engines into the atmosphere is directly related to total fuel oil consumption.

In order to quantify air pollution from marine engines in terms of exhaust gas emission, it is instructive to use an emission model. These models can adopt actual emission factors recorded from onboard measurements, or they can use theoretical factors arrived from the chemical reaction equations. In combination with actual fuel consumption (International Marine Bunkers), an emission inventory can be produced.

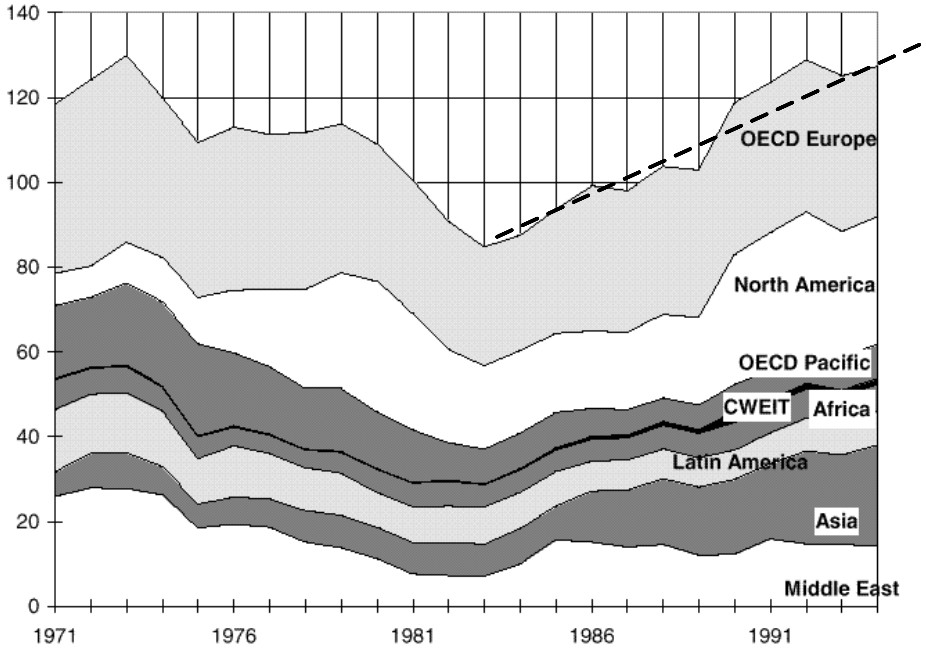
This study has identified sources on bunker fuel statistics, evaluated these and made some conclusions as to their validity. Based on this, a global marine fuel 1996 inventory has been established. Further the DNV's statistical emission model representing the world fleet of internationally trading vessels has been adopted for the purpose of verifying bunker supply data and hence, the emissions inventory. This task also provides an emission breakdown into vessel types. Finally, a global emission distribution assessment has been undertaken, based on the marine fuel 1996 inventory and by applying trade data.

## 3.1. ASSESSMENT OF MARINE BUNKER SUPPLY DATA

The marine bunker supply was mainly collected from energy databases publish by the Energy Information Administration (EIA), the International Energy Agency (IEA) and United Nations Framework Convention on Climate Change (UNFCCC).

### 3.1.1. World wide marine bunker sales

The total world bunker sales in million metric tons (Mton), separated by regions are present in Figure 3-1 (1971 to 1994) and Figure 3-2 (1995). The main bunker sales regions are Europe (OECD), North America, Asia and Middle East, supplying approximately 80% of the bunker usage world-wide.



Source: IEA Statistics

**Figure 3-1 World Sales of marine bunker fuel (in million tonnes) for 1971-1994, by regions (UNFCCC, 1997/IEA statistics).**

As illustrated by Figure 3-1, world bunker demand has grown rapidly since its low point in 1983 (85 Mton), at about 5 Mton per year to 1992 with a slight reduction in 1993. Demand in 1994 is about the level of the early 1970s. Using a growth rate of 4 Mton per year, gives in 1997 (or 1998) approximately 140 Mton (see trend-line in Figure 3-1). This volume (sales) is in good agreement with reported 1998 sales (merchant shipping) by the International Chamber of Shipping [MEPC, 1999].

By comparing figures published by EIA, IBIA (International Bunker Industry Association Ltd), CONCAWE and IEA (reported sales, Table 3-1), it becomes clear that there are discrepancies in reported bunker sales. However, the bunker sales in the period 1990 to 1996 seems to be in the range of 120 to 147 Mton and approximately 70% to 80% are residual bunkers. Some of the differences in the reported sales may be explained by different fuel categories being included (domestic, naval, and international marine bunker).

**Table 3-1 World-wide marine fuel bunker supply.**

| Year | Data source | Publication | | Marine bunker (Mton) | | Sum (Mton) |
|---|---|---|---|---|---|---|
| | | By | Year | Residual | Distillate | |
| 1990 | NSA 1) | UNFCCC | 1996 | 100 | 40 | 140 |
| 1990 | CONCAWE 2) | Corbett | 1999 | 100 | 40 | 140 |
| 1992 | EIA 3) | Corbett | 1999 | 110 | 30 | 140* |
| 1993 | EIA 3) | Corbett | 1999 | 109 | 38 | 147* |
| 1994 | IEA | UNFCCC | 1997 | - | - | ≈127** |
| 1995 | IBIA | IBIA | 1999 | - | - | 140 |

1) NSA-Norwegian Shipping Academy (Liddy, J.P. Bunker fuels – A global View towards Year 2000, 1992)

2) CONCAWE, The European environmental and refining implications of reduction of sulphur content of marine bunker fuels, CONCAWE Air Qual. Manage. Grup, Brussels, Belgium, 1993

3) Reported by: Maloney, M. J., World Energy Database, Energy Inform. Admin. (EIA), Washington D.C. 1996

* EIA definition: "bunkers": Fuels supplied to ships and aircraft in international transportation, irrespective of the flag of the carrier, consisting primarily of residual, distillate, and jet fuel oils (http://www.eia.doe.gov/emeu/iea/glossary.html).

** IEA definition: "International marine bunkers" cover those quantities delivered to sea-going ships of all flags, including warships. Consumption by ships engaged in transport in inland and coastal waters is not included (http://www.iea.org/stats/defs/origins/marine.htm).

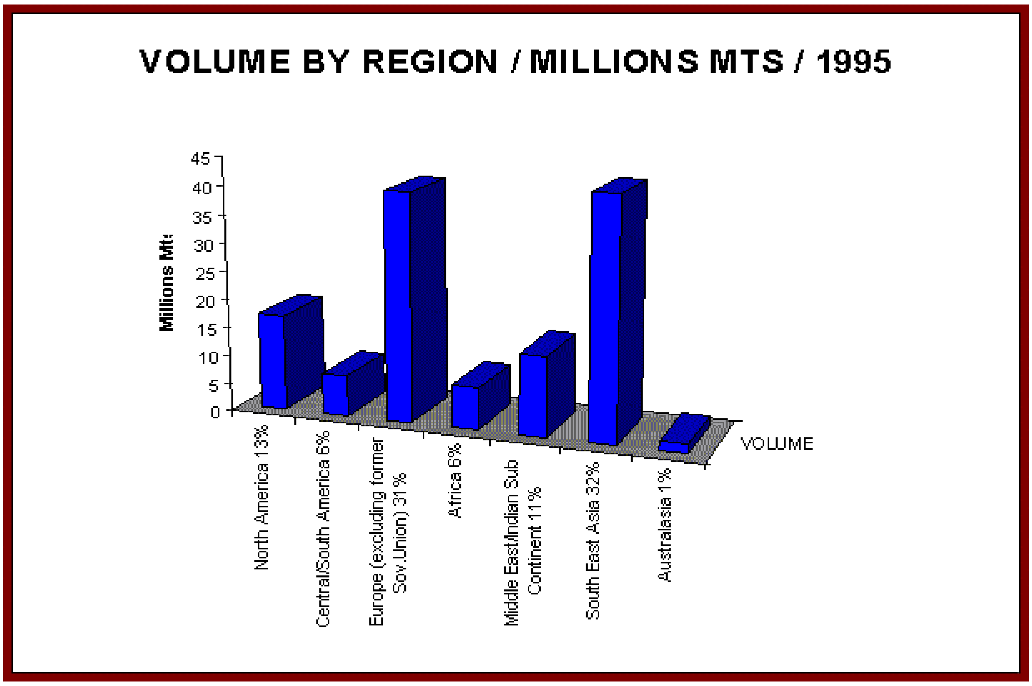


**Figure 3-2 The annual volume marine bunkers supplied world wide 1995 (IBIA, 1999).**

### 3.1.2. OECD and Russia

The reported 1993 and 1996 OECD international bunker supply numbers provided by EIA (1999) and IEA (1999 (1)), is presented in Table 3-2. The data show good agreement in the reported sales, with the OECD countries, supplying approximately 60% of the bunker usage world-wide.

The reported 1993 OECD bunker supply numbers provided by EIA (1999), UNFCCC (1999) and IEA (1999 (2)), and given by country is presented in Table 3-4. The data shows that, with the exception of the United States (UNFCCC), there is good agreement in the reported sales for most of the OECD counties. The main bunker selling OECD countries are United States, Netherlands and Japan. The reported sales in Table 3-4, seems also to be in agreement with a recently publish European greenhouse gas inventory (EEA, 1999; year 1990 - 1996).

**Table 3-2 EIA and IEA fuel bunker's supply (OECD countries)**

| Year | Data source | Publication | | International bunkers (Mton) | |
|---|---|---|---|---|---|
| | | By | Year | Marine | Civil aviation[1)] |
| 1993 | IEA | IEA | 1999 (1) | 77 | - |
| 1993 | EIA[2)] | EIA | 1999 | 74 | - |
| 1996 | IEA | IEA | 1999 (1) | 77 | 45 |
| 1996 | EIA[2)] | EIA | 1999 | 74 | - |

[1)] Deliveries of aviation fuels to international civil aviation. For many countries, this excludes fuel used by domestically owned carriers for their international departures.
[2)] Using 1 Barrel = 158.9873 litre

A problem that became apparent when comparing these data sets was that EIA and IEA define "International bunkers" differently; IEA gives the fuel consumption of marine international bunkers including consumption by warship, while EIA includes some international jet fuel in its figures for world fuel consumption from international bunkers. It should be noted that relative few countries have large navies, consequently this does not represent a large source of error. Table 3-2 shows that international civil aviation represents approximately 60 % (45 Mton) of international marine bunkers according to the IEA data (only OECD countries). These results indicate that international aviation may not be included in the EIA data.

Table 3-3 shows a deviation between the United States sources by a factor of 2 (approximately). But if the international aviation reported by UNFCCC (1999) or Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (EPA, 1999) is included, then the sum is in the category of 28-33 Mton. The Russian 1994 consumption was calculated to be 13 Mton based on EIA data, but to be 2.2 Mton using the 1994 UNFCCC (1999) data. Based on this, it may be concluded that:

International aviation bunker is probably included in the United States sales reported by IEA (EIA data include international aviation). The United States sales reported by EIA may not be used in the marine fuel inventory, without reducing the sales.

The Russian sales reported by EIA may not be used in an international marine fuel inventory without comparisons/ adjustments according to other sources.

**Table 3-3 United States bunker supply from different sources.**

| Reference year | Data Source | Publication | | International bunkers (Mton) | |
|---|---|---|---|---|---|
| | | By | Year | 14-18 | 28-33 |
| 1995, 1996 | FTD[1)] | EPA | 1998 | × | |
| 1995 | IBIA | IBIA | 1999 | × | |
| 1994, 1995, 1996 | UNFCCC[2)] | UNFCCC | 1999 | × | |
| 1993,1996 | EIA[3)] | EIA | 1999 | | × |
| 1993, 1994 | IEA | IEA | 1999 | | × |

[1)] FTP-Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 1998)

[2)] GHG-database on the Internet (covert to fuel consumption by $CO_2$ emission)

[3)] Include international aviation

### 3.1.3. Verification of the 1993 EIA bunkers supply, OECD countries

If international aviation sales are included in the reported 1993 OECD bunker supply numbers provided by EIA (according to EIA's definition of international bunkers), there has to be a deviation between reported sales by EIA and sales by UNFCCC (1999) and IEA (1999) (since UNFCCC and IEA separately report International aviation sales). However, by comparing the EIA bunkers data with UNFCCC (1999) and IEA (1999) data in Table 3-4, it is clear that international aviation is not included in the EIA data (except for United States, as discussed above).

A close to 1:1 statistical relationship between EIA and IEA (1993 OECD, Table 3-4) residual and distillate bunker sales was calculated by correlation analysis (correlation coefficient close to 1, United States not included). The results (only OECD) indicate good agreement in the reported supply numbers by IEA and EIA and small consumption by warships (mainly distillate, included in the reported IEA numbers of international marine bunkers).

Based on these results (only OECD countries), it is possible to estimate international marine bunkers supply using the EIA data, if the United States and Russian sales are reduced according to other sources.

**Table 3-4 Comparison of 1993 bunkers supply, reported by EIA (1999), UNFCCC (1999) and IEA (1999 (2)).**

| OECD | Distillate fuel (Mton) | | Residual fuel (Mton) | | SUM (Mton) | | UNFCCC[2] (Mton) |
|---|---|---|---|---|---|---|---|
| | EIA[1] | IEA | EIA[1] | IEA | EIA | IEA | |
| **Australia** | 0.10 | 0.10 | 0.51 | 0.51 | 0.61 | 0.61 | 0.60 |
| **Belgium** | 0.70 | 0.65 | 3.73 | 3.75 | 4.43 | 4.40 | 4.50 |
| **Canada** | 0.09 | 0.09 | 0.48 | 0.48 | 0.57 | 0.57 | 0.60 |
| **Denmark** | 0.46 | 0.45 | 0.91 | 0.92 | 1.37 | 1.37 | - |
| **Finland** | 0.15 | 0.14 | 0.40 | 0.40 | 0.55 | 0.54 | - |
| **France** | 0.34 | 0.34 | 2.16 | 2.17 | 2.50 | 2.51 | 2.50 |
| **Germany** | 0.55 | 0.49 | 1.72 | 1.73 | 2.27 | 2.22 | 2.20 |
| **Greece** | 0.77 | 0.72 | 2.43 | 2.44 | 3.20 | 3.16 | 3.10 |
| **Ireland** | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.03 | - |
| **Italy** | 0.61 | 0.56 | 1.88 | 1.89 | 2.49 | 2.45 | - |
| **Japan** | 0.41 | 0.38 | 6.33 | 6.36 | 6.74 | 6.74 | 7.00 |
| **Netherlands** | 2.02 | 1.88 | 9.99 | 10.04 | 12.01 | 11.92 | 11.90 |
| **Norway** | 0.22 | 0.22 | 0.29 | 0.29 | 0.51 | 0.51 | 0.50 |
| **Portugal** | 0.08 | 0.07 | 0.25 | 0.25 | 0.33 | 0.32 | - |
| **Spain** | 0.76 | 0.74 | 2.74 | 2.76 | 3.50 | 3.50 | - |
| **Sweden** | 0.18 | 0.17 | 0.75 | 0.75 | 0.93 | 0.92 | - |
| **Switzerland** | 0.02 | 0.02 | 0.00 | 0.00 | 0.02 | 0.02 | - |
| **Turkey** | 0.06 | 0.06 | 0.04 | 0.04 | 0.10 | 0.10 | - |
| **United Kingdom** | 1.22 | 1.19 | 1.32 | 1.32 | 2.54 | 2.51 | 2.10 |
| **United States[3]** | 6.67 | 7.15 | 23.05 | 25.74 | 29.72 | 32.89 | **21.40** |
| **Total** | **15.41** | **15.41** | **58.99** | **61.84** | **74.42** | **77.29** | - |

[1] Reported in Barrels

[2] Reported as emitted $CO_2$, converted to fuel consumption

[3] Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 1998), reported in 1993: Residual 19.1 Mton; Distillate 1.9 (EPA, 1999)

### 3.1.4. Uncertainty

The comparison includes some uncertainties due to the average fuel densities used, since the data from EIA is reported in thousand barrels (petroleum) per day while the IEA reported in Mton (annual). In the conversion from barrels to million ton (Mton), the following average densities were used based on the DNV oil database (VPS, 1999):

- Residual fuel: 971 kg/m$^3$ (ISO 8217: max. spec limit of 991.0 kg/m$^3$ at 15 °C)
- Distillate fuel: 862 kg/m$^3$

### 3.1.5. Conclusion

Different sources of marine bunkers supply world-wide have been evaluated and discussed. A number of inconsistencies and error sources have been found and discussed.

Total world-wide marine bunker sales in the period 1990 – 1996 lie in the range of 120 Mton to 147 Mton.

The reported 1993 international marine sales by OECD countries provided by EIA and IEA was nearly the same, i.e. 74 Mton and 77 Mton respectively (residual and distillate). However the world-wide sales in 1993 reported by EIA and IEA, do not correspond particularly well, i.e. 147 Mton and 125 Mton respectively. These results indicate that non-OECD countries mainly cause the difference in reported sales. As an example, the Russian 1994 bunker sales reported by EIA are approximately 6 fold higher, compared with the 1994 UNFCCC numbers. However, the United States (1993) bunker sales reported by EIA and IEA include international aviation.

These results show that it is possible to estimate world wide international marine bunkers using the EIA data if the United States and Russian sales are reduced according to other sources.

## 3.2. MARINE FUEL INVENTORY BY EIA DATA, 1996

Different sources of marine bunkers supply world-wide have been evaluated and discussed in above. The assessment of marine-bunker data illustrates that it is possible to estimate international marine bunkers using the EIA data.

### 3.2.1. Treatment of the EIA data

Our marine fuel inventory uses a modified 1996 EIA bunkers data set [EIA, 1999], based on the following assumptions and modifications:

The United States bunker sales reported by EIA include international aviation, and is reduced according to the United States 1996 sales reported by Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census [EPA, 1999], i.e.:

- Residual = 12.5 Mton
- Distillate = 1.6 Mton

The Russian bunker sales reported by EIA are too high (13 Mton only residual fuel) and are reduced according to1990 UNFCCC (1999) numbers (3.0 Mton) assuming the following distribution (assuming residual fuel oil accounts for 80 % of the sale, see Table 3-1 and [UNFCCC, 1997/IEA statistics; Wright, 1996]:

- Residual = 2.4 Mton
- Distillate = 0.6 Mton

The Saudi Arabia and Hong Kong bunker sales reported by EIA may include some international aviation or other source in the reported sales, based on:

- An analysis between the relation of distillate and residual fuel 1996 data. Figure 3-4 shows that Saudi Arabia and Hong Kong (tow triangle points) differ from the other observations.
- An analysis of the time variation of the sales by four countries, i.e. Japan, Netherlands, Saudi Arabia, and Hong Kong. Figure 3-3 illustrates an approximately constant bunker sales from 1990 to 1996 by Japan and the Netherlands, while Saudi Arabia (1990 to 1996) and Hong Kong (1992 to 1996) have in the same period an incredible increase in the sales of distillate. This study, therefore, replaces the Saudi Arabia and Hong Kong distillate 1996 sales with the 1990 figures (Japan and the Netherlands sales was approximately the same in 1990 and 1996).

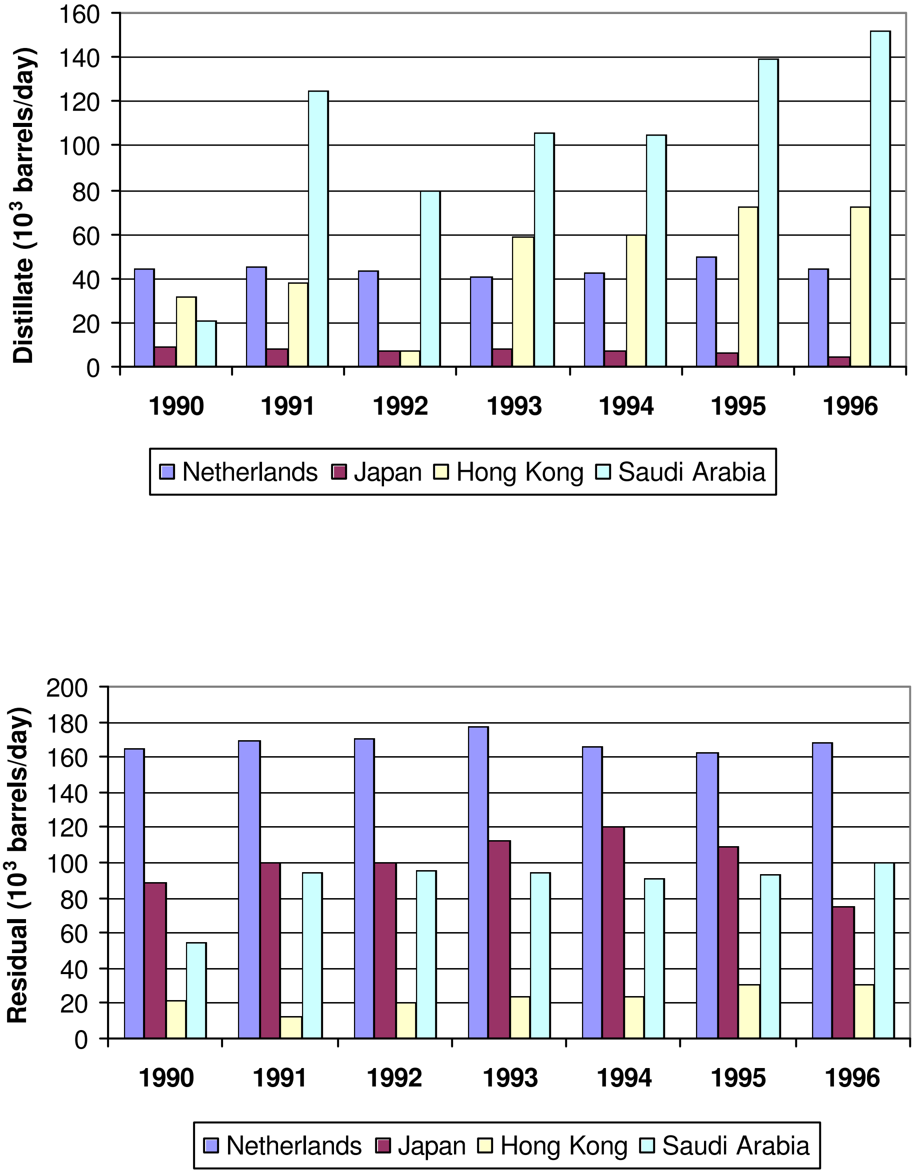


**Figure 3-3 Distillate (upper) and Residual (lower) 1996 sales by Netherlands, Japan, Hong Kong and Saudi Arabia, 1996 (EIA, 1999).**

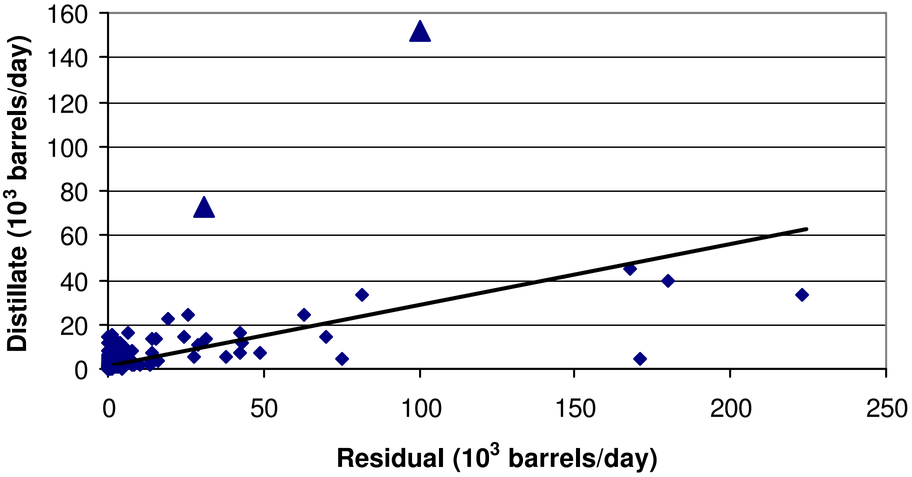


**Figure 3-4 The relation between distillate and residual fuel, all countries, 1996 data. Upper Triangle indicates Saudi Arabia and lower Hong Kong (EIA, 1999).**

### 3.2.2. Estimate of international marine supply

Based the on assumptions and modifications described above, the 1996 world–wide international marine bunker sales may be estimated to be 138 Mton, and separated as:

- Distillate fuel: 38 Mton
- Residual fuel: 100 Mton

A breakdown of the annual international marine bunker sales (138 Mton) is made by country. Table 3-5 shows the countries with the highest marine sales, supplying approximately 80% of the bunker usage world-wide. The United States was in 1996 the largest seller of international marine bunkers, followed by Singapore and Netherlands.

These results are in agreement with bunkering ports statistic found by Det Norske Veritas [DNV, 1997] based on fuel oil statistics (not including Russia). Singapore, Rotterdam, Antwerp, Fujairah (United Arab Emirates), Houston, New Orleans, Panama Canal, Los Angeles, New York, and Tokyo are the major volume bunkering ports in the world.

This may also be illustrated by information on “major” ports (Fairplay, 1998) combined with the following trade area/rout information:

- Vessel traffic density (major trade area) based on weather observations from ships in 1996 (NOAA, 1999), Figure 3-8.
- Major Seaborne Crude Oil Trade presented in
- **Figure 3-5**, and the most important sea routes (Kunnskapsforlaget, 1988).

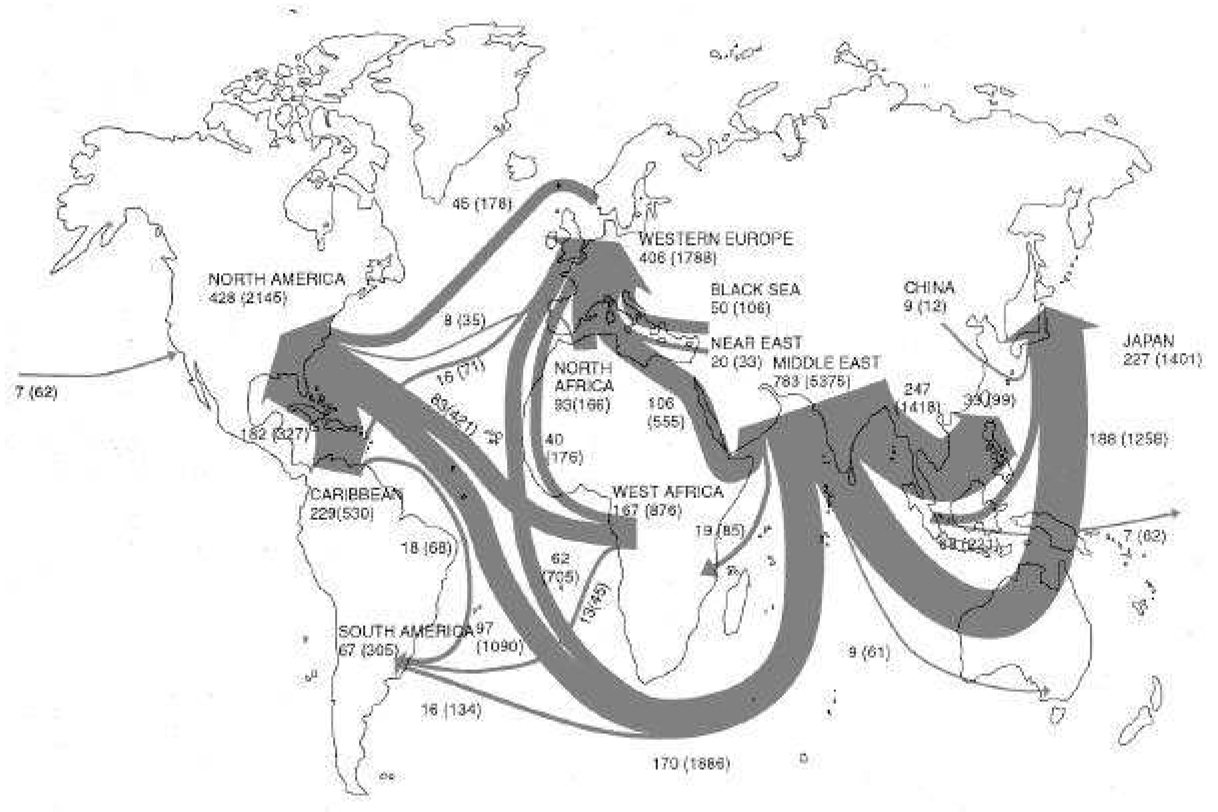


**Figure 3-5 Seaborne Crude Oil Trade (1997), million metric tonnes and billion tonne-miles (parenthesize). Source: Fearnleys.**

Table 3-5 Largest marine bunker seller by countries 1996 (EIA, 1999).

| Countries | International marine bunkers | | % sales total |
|---|---|---|---|
| | % sales residual | % sales distillate | |
| **United States*** | 12.6 | 4.3 | 10.1 |
| **Singapore** | 10.2 | 5.1 | 8.6 |
| **Netherlands** | 9.5 | 5.8 | 8.4 |
| **United Arab Emirates** | 9.7 | 0.6 | 6.9 |
| **Saudi Arabia*** | 5.7 | 2.7 | 4.8 |
| **Korea, South** | 4.6 | 4.4 | 4.5 |
| **Spain** | 3.6 | 3.2 | 3.4 |
| **Belgium** | 4.0 | 1.9 | 3.3 |
| **Japan** | 4.3 | 0.6 | 3.1 |
| **Hong Kong*** | 1.8 | 4.1 | 2.6 |
| **Greece** | 2.4 | 2.1 | 2.5 |
| **South Africa** | 2.8 | 1.0 | 2.3 |
| **Russia*** | 2.4 | 1.6 | 2.2 |
| **United Kingdom** | 1.5 | 3.2 | 2.0 |
| **France** | 2.4 | 1.0 | 2.0 |
| **Italy** | 1.8 | 1.7 | 1.8 |
| **Taiwan** | 2.2 | 0.7 | 1.7 |
| **Brazil** | 1.1 | 2.9 | 1.6 |
| **Egypt** | 1.7 | 1.5 | 1.6 |
| **Germany** | 1.4 | 1.8 | 1.5 |
| **Netherlands Antilles** | 1.6 | 0.7 | 1.3 |
| **Denmark** | 0.9 | 1.8 | 1.1 |
| **Venezuela** | 0.8 | 1.8 | 1.1 |
| **China** | 0.4 | 2.1 | 0.9 |
| **Panama** | 0.8 | 0.9 | 0.8 |
| **Sweden** | 0.9 | 0.5 | 0.8 |
| **Indonesia** | 0.1 | 2.0 | 0.7 |
| **Angola** | 0.4 | 1.1 | 0.6 |
| **Other** | **8.7** | **39.0** | **17.9** |

* Modified, see section 3.2.1.

### 3.2.3. Conclusion

An assessment based on several assumptions and modifications indicates the world international marine fuel sales as being 138 Mton in 1996. A breakdown of annual international marine bunker sales (138 Mton) shows that United States is (1996) the largest seller of international marine bunkers, followed by Singapore and the Netherlands.

### 3.2.4. CALCULATING MARINE 1996 EMISSIONS TO AIR

In order to quantify the air pollution from marine engines in terms of exhaust-emission amounts, it is instructive to use emission models. These models are based on actual emission factors adopted from onboard engine measurements or theoretical factors arrived from the respective chemical reaction equations and combined with actual fuel consumption (based on international marine bunker fuel sale figures). International marine emissions are estimated by using:

- A fuel consumption methodology described below.
- A statistical emission model described in Appendix A, with results given below.

### 3.2.5. The fuel consumption methodology

The specific emissions rate for: $NO_x$, $SO_2$, $CO_2$, CO and NMVOC may be calculated by the following general equation, adopted from Marintek/DNV study (Klokk, 1996) and (DNV, 1998 (1)):

$$M_{(g)} = B \cdot \sum_{i=1}^{n} (E_{i(g)} \cdot \alpha_i) \tag{1}$$

Where:

**$i$** = For $NO_x$ calculation: engine type (1=slow speed, 2=medium speed, 3=other);
for $SO_2$, calculation: fuel type (1=residual, 2= distillate);
for $CO_2$, CO, and NMVOC calculation: fuel type (1=residual+ distillate)

**$g$** = Individual exhaust gas component ($NO_x$, $SO_2$, $CO_2$, CO, and NMVOC)

**$M_{(g)}$** = Emissions rate (kg pollution) for the individual exhaust gas component $g$

**$E_{i(g)}$** = Fuel- or engine-based emission factors (kg pollution per kg fuel)

**$B$** = Annual international marine bunker consumption (kg fuel)

$\alpha_i$ = For $NO_x$ calculation: fraction of total installed engine effect world-wide with a specific engine type (slow =1, medium=2, other=3);
for $SO_2$ calculation: fraction distillate and residual fuel;
for $CO_2$, CO, and NMVOC calculation: equals **1**

A comparative method is described in a recent publication by Corbett (1999). The fuel based method is also described in *Atmospheric Emission Inventory Guidebook* (EMEP/CORINAIR, 1999).

Calculation of emissions by equation (1) is made for the 1996 supply case, i.e. annual international bunker sales of 138 Mton (*B*), using the emission factors given in Table 3-6 ($E_{i(g)}$). Emission factors used in the calculations, named "CORINAIR", are based on the emission factors presented in the *Atmospheric Emission Inventory Guidebook 1999* from

EMEP/CORINAIR [CORINAIR, 1999]. Appendix 1 gives the minimum and maximum emission factors labeled “Low” and “High” in Table 3-6.

The fraction ($\alpha_i$) of distillate and residual fuel is based on the 1996 supply cases, i.e. 38 Mton and 100 Mton respectively.

The distribution of total installed commercial machinery capacity is estimated to 63 % slow speed ($\alpha_1$), 31% medium speed ($\alpha_2$) and 6 % other engine ($\alpha_3$), using an statistical approach based on the:

- World Fleet Statistic [Lloyd’s, 1996]
- Installed engine effect as a function of DWT, ship type, and size [DNV, 1998].
- Engine distribution (slow, medium, other) according to ship type and size [DNV, 1998].

Based on the statistics of sulphur content in the main supplying ports [DNV, 1997]; minimum and maximum residual sulphur content is given in Table 3-6 (in parentheses). The minimum and maximum sulphur content of distillate fuel is assumed to be 0.3% (by wt) and 1% (by wt) respectively. Other investigations have used an average of (by wt):

- 0.3%, recently EPA study (1999)
- 0.5%, previous Lloyd’s investigations (1995)
- 2.0%, recently publish work by Corbett (1999)

Table 3-7 give emissions based on the 1996 EIA bunker supply data (138 Mton), using “Low”, “CORINAIR” and “High” emission factors. The “Range” column illustrates the uncertainty in the emitted amount of a gas. The total emission volume is further distributed on geographic regions in section 3.3.

**Table 3-6 Emission factors used in the calculations (EMEP/CORINAIR, 1999 and Appendix 1.**

| **Gas component** | | **CORINAIR factor** (kg emitted/tonne fuel) | **Low factor** (kg emitted/tonne fuel) | **High factor** (kg emitted/tonne fuel) |
|---|---|---|---|---|
| CO | | 7.4 | 5 | 8 |
| NMVOC | | 2.4 | - | - |
| $CH_4$ | | 0.3 | - | - |
| $N_2O$ | | 0.08 | - | - |
| $CO_2$ | | 3,170 | 3,159 | 3,175 |
| $SO_2$ | | | | |
| $SO_2$ | *Residual* | 20×S<br>(S= 2.7 %) | 20×S<br>(S= 2.5 %) | 20×S<br>(S= 3.5 %) |
| | *Distillate* | 20×S<br>(S= 0.5 %) | 20×S<br>(S= 0.3 %) | 20×S<br>(S=1.0 %) |
| $NO_x$ | *Slow speed* | 87 | 85 | 96 |
| | *Medium speed* | 57 | 56 | 63 |

S- sulphur content of oil fuel (% by wt)

**Table 3-7 Marine emission in 1996 based on different emission factors.**

| Gas component | | *Supply 138 (Mton)* | | | *Range (Mton)* |
|---|---|---|---|---|---|
| | | Low[2)] | CORINAIR[1)] | High[3)] | |
| CO | | 0.7 | 1.00 | 1.1 | 0.7-1.1 |
| NMVOC | | - | 0.33 | - | - |
| $CH_4$ | | - | 0.04 | - | - |
| $N_2O$ | | - | 0.01 | - | - |
| $CO_2$ | | 435.9 | 437.50 | 438.2 | 436-438 |
| $SO_2$ | *Residual* | 5.0 | 5.40 | 7.0 | 5-7 |
| | *Distillate* | 0.2 | 0.40 | 0.8 | 0.2-0.8 |
| | *Total* | 5.2 | 5.80 | 7.8 | 5.2-7.8 |
| $NO_x$ | | 10.1 | 10.30 | 11.4 | 10.1-11.4 |

[1)] Using “CORINAIR” emission factor, [2)] Using “Low” emission factor, [3)] Using “High” emission factor

### 3.2.6. Statistical emission model representing the merchant world fleet

The merchant world fleet can be divided into ship types according to the World Fleet Statistic [Lloyd’s, 1996], seen in Figure 3-6. The World Fleet Statistics is an annual summary of the changing composition of the world fleet of propelled sea-going merchant ships of 100 gross tonnage and above.

The total number of commercial vessels in 1996 was 43,325 (excluding fishing vessels), with a total of 722.2 million DWT. Cargo vessels accounting for about 95% of the tonnage, and are responsible for the majority of international marine bunker consumption. The highest numbers of vessels are in the General Cargo category, however the largest vessels are Bulk Carriers and Oil Tankers (Figure 3-7).

A breakdown of the world fleet according to ship type, ship size and engine type is made on three levels (shown in Appendix 1). Level three consists of the fraction of vessel with engine type *s* for a ship type *i* and of size x (*k*). Knowing the fuel consumption emissions factors (Table 3-6), the emissions rate for $NO_x$, $SO_2$ $CO_2$, CO and NMVOC may be calculated on four levels, using the equations in Appendix 1.

The amount of exhaust gas emitted from the main engine(s) is seen in Table 3-8, using the “CORINAIR” emission factor. The model estimates the fuel consumption (annual, 1996) to about 132 Mton usage (main engine(s)). Using the assumption that auxiliary engines consume 10% of the main engine(s), the total commercial consumption is about 145 Mton, which is approximately the same as the value calculated by EIA fuel data, and in correspondence with the conclusion.

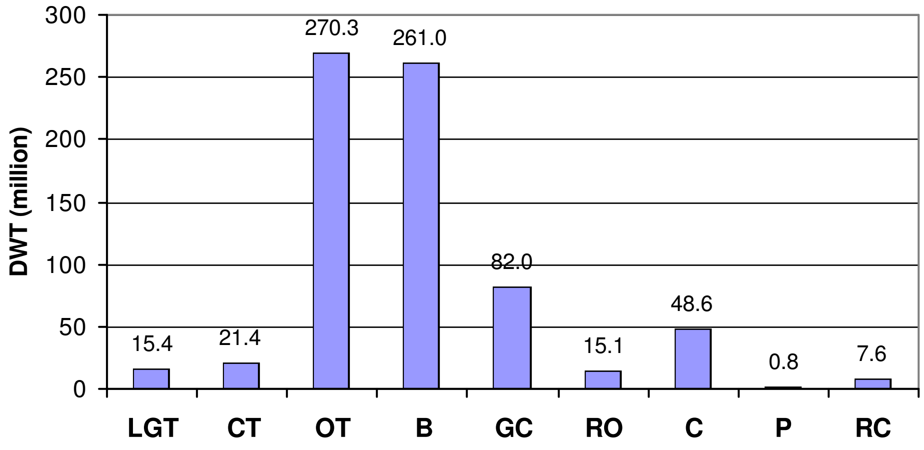


Figure 3-6 Total DWT for each ship type category. (LGT= Liquid gas tanker, CT= Chemical tanker, OT= Oil tanker, B= Bulk , GC= General cargo, RO= RO-RO cargo, C= Container, RC= Refrigerated cargo, P= Passenger)

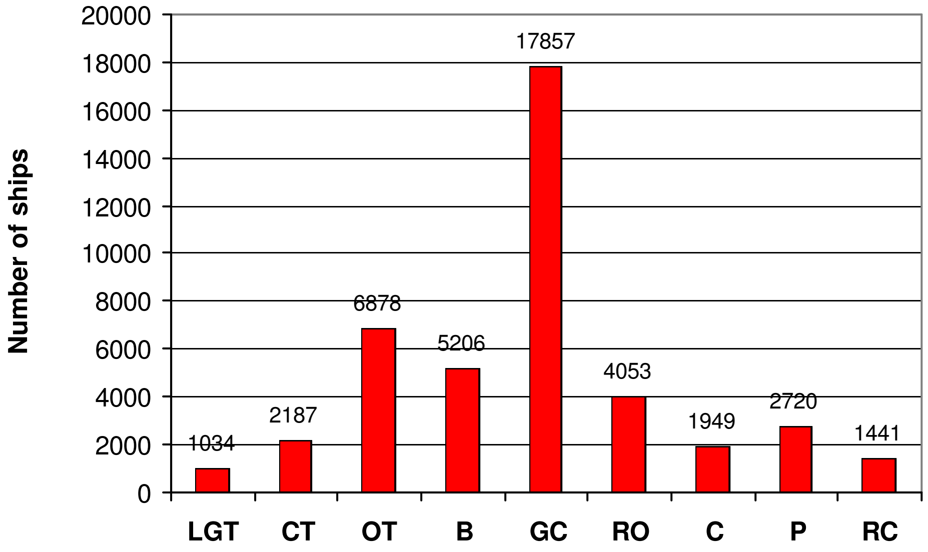


Figure 3-7 - Number of ships in each ship type category.

**Table 3-8 Model emission results 1996, for main engine(s), separated by vessel type, using "CORINAIR" emission factors.**

| Ship type | $NO_x$ (Mton) | CO (Mton) | NMVOC (Mton) | $SO_2$ (Mton) | $CO_2$ (Mton) | Supply (Mton) |
|---|---|---|---|---|---|---|
| LGT | 0.29 | 0.03 | 0.01 | 0.20 | 13.40 | 4.20 |
| CT | 0.32 | 0.03 | 0.01 | 0.20 | 14.20 | 4.50 |
| OT | 2.00 | 0.18 | 0.06 | 1.44 | 93.20 | 29.40 |
| B | 2.60 | 0.22 | 0.07 | 1.58 | 96.00 | 30.30 |
| GC | 1.77 | 0.19 | 0.06 | 0.70 | 81.54 | 25.70 |
| C | 1.63 | 0.15 | 0.05 | 0.89 | 64.39 | 20.30 |
| RO | 0.66 | 0.07 | 0.02 | 0.24 | 30.85 | 9.70 |
| P | 0.29 | 0.03 | 0.01 | 0.11 | 13.37 | 4.20 |
| RC | 0.27 | 0.03 | 0.01 | 0.11 | 12.34 | 3.90 |
| Sum | *9.82* | *0.93* | *0.30* | *5.46* | *419.30* | *132.30* |

### 3.2.7. Comparison with other marine inventories

The estimated amount of emitted gases in this study (fuel based and statistical model) is compared with other global investigations given in Table 3-9, reported in Corbett (1999) and UNFCCC (1997). Table 3-9 indicates that though there are few marine global studies, the estimated emissions seem to correspond well. However, the $SO_2$ emissions vary, depending on the chosen sulphur content (residual and distillate), the relationship between residual and distillate fuel consumption and the amount of fuel burned.

**Table 3-9 Comparison of global inventories for ship emission.**

| Source | Year | $C^*$ (Mton) | $SO_2$ (Mton) | $NO_x$ (Mton) |
|---|---|---|---|---|
| **Present study, fuel based** | 1996 | 117 (138) | 5.8 (5.2-7.8) | 10.3 (10.1-11.4) |
| **Present study, statistical model**¹⁾ | 1996 | 112 | 5.5 | 9.8 |
| **UNFCCC, 1997** | 1994 | 109 | 7.5-11.5 | 9.3 |
| **Corbett, 1999** | 1992/1993 | 123.6 | 8.5 | 10.12 |
| **Corbett, 1999/EDGAR**²⁾ | 199? | 149.2 | - | - |
| **Range** | | 109-149 | 6.1-11.5 | 9.3-11.9 |

* Emitted amounts of carbon, approximately 85 % (carbon content by weight) of marine fuel consumption

1) Only main engine(s), not included in "Range" (last row)

2) Reported in Corbett (1999), based on Oliver et al. 1996 (Emissions Database for Global Atmospheric Research (EDGAR), rep. 771060 002, Nat. inst. on Publ. Health and Environ. (RVIM) Bilthoven, Netherlands, 1996).

### 3.2.8. Conclusion

The results derived from this model, support the findings in the statistical assessment of international fuel sales. The model gives a distribution of sources as a function of ship types. Tankers and Bulk carriers are by number not dominant, but due to their size, of significant importance.

## 3.3. GEOGRAPHICAL DISTRIBUTION OF MARINE EMISSIONS IN 1996

In order to quantify the air pollution from marine engines, in terms of exhaust discharge within geographical regions, it is instructive to use a geographical emission model. These models are based on vessel traffic density within a number of chosen pollution areas, described below. It is evident that there are a smaller number of areas with high traffic density (as shown in Figure 3-8). The geographical areas are classified according to traffic density (Table 3-10).

### 3.3.1. Calculation method

The calculations of the distribution of global 1996 marine emissions is performed by using the following equation for emission of exhaust compounds:

$$M_{(g)_j} = \frac{S_j}{A_j}\left(\frac{M_{(g)}}{S}\right) \qquad \textbf{(2)}$$

Where:

$j$ = Individual pollution area (Figure 3-9 & Table 3-10)

$g$ = Individual exhaust gas component ($NO_x$, $SO_2$, $CO_2$, CO, and NMVOC)

$M_{(g)}$ = Emissions rate (kg pollution) for the individual exhaust gas component $g$ (Table 3-7)
$M_{(g)j}$ = Emissions rate (kg pollution/$m^2$) for the individual exhaust gas component $g$ in area $j$
$S$ = Average number of ships on voyage in all area at a given time (Table 3-10)
$S_j$ = Average number of ships on voyage in area $j$, at a given time (Table 3-10)
$A_j$ = Size of the area $j$ in $m^2$ (Table 3-10)

A comparative method is also described in recent published work (Corbett, 1999).

### 3.3.2. Data input

Table 3-10 presents the input data to the calculations, separated on regions. The following geographical information sources was used to estimate the traffic density and the pollution areas, given in Table 3-10:

- Vessel traffic density 1996 (Figure 3-8), based on The Comprehensive Ocean-Atmosphere Data set (CODAS) (NOAA, 1999), encompassing about 10 % of the world fleet (Corbett, 1999).
- Major Seaborne Crude Oil Trade presented in
- Figure 3-5, and the most important sea routes (Kunnskapsforlaget, 1988)

**Table 3-10 Estimated traffic density 1996, individual regions.**

| Traffic density | Area size ($10^6$ $km^2$) $A_j$ | Number of ships* $S_j$ |
|---|---|---|
| **Low** | 255.0 | 5 |
| **Medium** | 67.6 | 75 |
| **High** | 17.4 | 150 |
| **Extra high** | 2.3 | 300 |

* Average number of ships

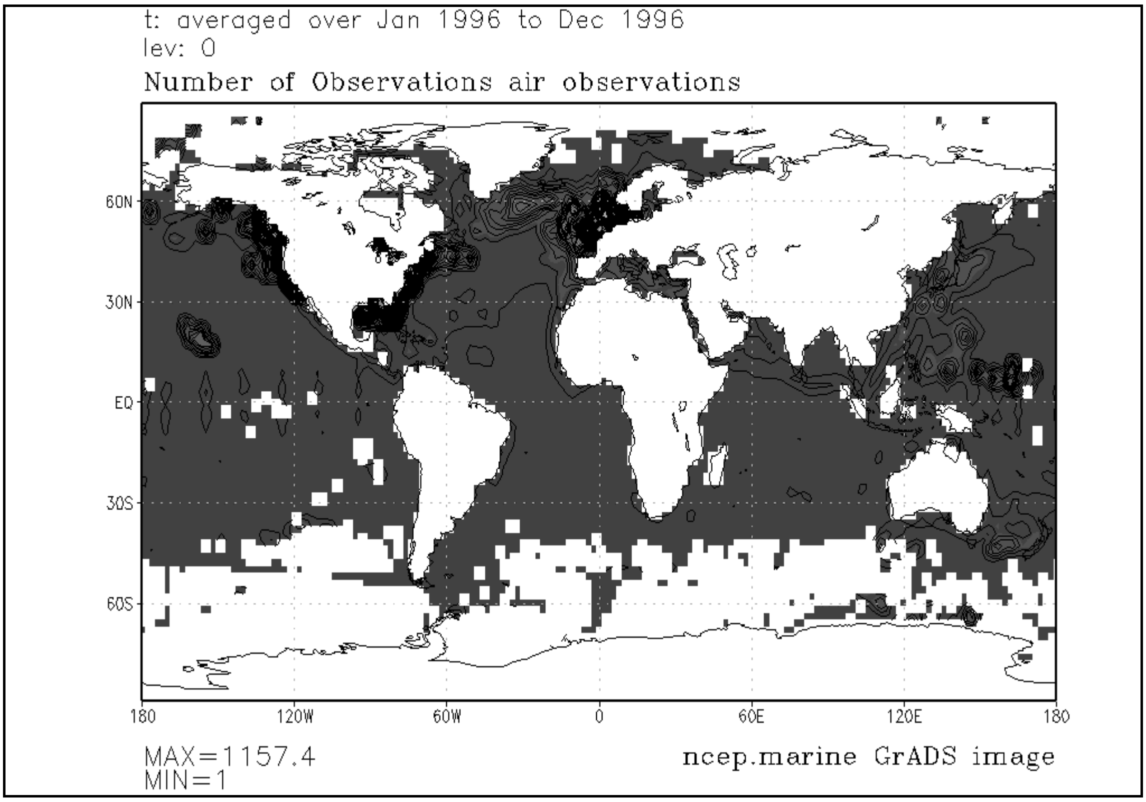


**Figure 3-8 Vessel traffic densities in 1996, based on The Comprehensive Ocean- Atmosphere Data set (CODAS) (NOAA, 1999).**

### 3.3.3. Results

The estimated annual (1996) concentrations (mg/m$^2$ y) in the pre-defined regions (Table 3-11) are connected to the colours in Figure 3-9. Table 3-11 shows that a major part of exhaust gases are emitted in the Northern Hemisphere, along the west and east cost of United States, North Pacific and northern Europe. Approximately 80 % are emitted near the cost and about 20 % in area of low and medium traffic density, often away from the coast. These results are also in agreement with the investigations of Corbett (1999), who used a more detailed calculation method (higher grid resolution etc).

The results can be used as an estimate of the global distribution of emissions from marine exhaust gases. However, it should be noted that:

- The calculation method is based on a simple approach
- The CODAS data set only covers 10% of the world fleet
- The used traffic density may include some domestic activity near the coast

The environmental impact of emissions to air for some emission components (NO$_x$, SO$_x$), will depend upon the existing background concentrations in the area. An area experiencing low background levels (low traffic density) might be more vulnerable for an increased "load" than identical increase in an already polluted area [Isaksen, IPCC 1999]. Hence, assessments looking at increased traffic density in such low load areas will require a more detailed and advanced approach.

**Table 3-11 Geographical distribution of the 1996 emissions, connected to colour in Figure 3-9.**

| Pollution Area | $CO_2$ | | $NO_X$ | | $SO_2$ | | Fraction (%) |
|---|---|---|---|---|---|---|---|
| | (Mton) | $mg/m^2y$ | (Mton) | $mg/m^2y$ | (Mton) | $mg/m^2y$ | |
| **Low** | 4.1 | 16 | 0.1 | 0.4 | 0.1 | 0.2 | 0.9 |
| **Medium** | 61.9 | 916 | 1.5 | 22 | 0.8 | 12 | 14.2 |
| **High** | 123.8 | 7115 | 2.9 | 168 | 1.6 | 94 | 28.3 |
| **Extra high** | 247.6 | 105604 | 5.8 | 2486 | 3.3 | 1400 | 56.6 |
| **Sum** | 437.5 | | 10.3 | | 5.8 | | 100.0 |

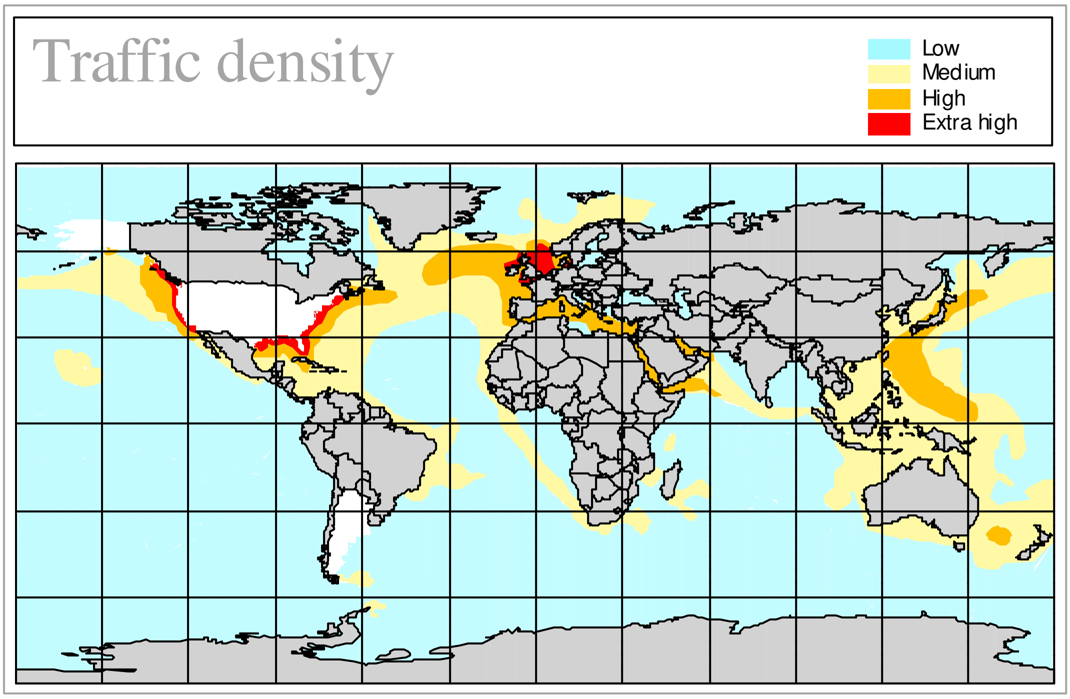


**Figure 3-9 Estimated traffic density based on data from 1996.**

### 3.3.4. Conclusion

Corbett (1999) concludes that nearly 70% of ship emissions occur within 400 km of land. Oftedal (1996) reported 74-83% of the ships was within 200 n. miles of land (based on IMO document: BCH24/inf.28 and MEPC 38/inf.12) at all time. The conclusion is clear, at a given time most vessels are relatively near shore (Table 3-11 and Figure 3-9). Consequently the main amount emitted is along the coast mainly:

- In the Northern Hemisphere
- Along the west and east cost of United States
- In northern Europe
- The North Pacific

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# 4. Impacts of International Shipping - $NO_x$ and Tropospheric Ozone

## 4.1. Introduction

Although $NO_x$ and ozone are local and regional air pollutants that also produce global climate change, the local and regional air-pollution problem is quite different from the global climate-change problem. The first part of this chapter describes the differences between the air-quality concerns and the global climate concerns surrounding $NO_x$ and ozone. The remaining sections focus entirely on the global effects.

### 4.1.1. Local and Regional Effects of Ozone[1]

Unlike most traditional air pollutants, ozone ($O_3$) is not emitted directly into the atmosphere. Instead, it is formed in the atmosphere through a series of complex photochemical reactions. Thus, it is referred to as a secondary pollutant, as opposed to a primary pollutant that is directly emitted. In the troposphere, ozone is formed through reactions of volatile organic carbon (VOCs) and $NO_X$ in the presence of sunlight.[2] However, this simple description belies the complex chemistry that is actually involved. Ozone is only formed via the photolysis of nitrogen dioxide ($NO_2$). Instead of actually playing a molecular role in the chemical reaction that directly forms ozone, the presence of VOCs affect the efficiency with which $NO_X$ forms ozone.

VOCs affect the formation of ozone through a chain of oxidation reactions. These chain reactions consume VOCs while recycling NO to $NO_2$, which is then available to produce more ozone. In many areas, there may be hundreds of different species of VOCs as a result of pollution or naturally occurring processes (e.g., from forests). Each of these species follows a different reaction pathway at a different rate and produces different products. VOC species that have been observed in ambient air can be divided roughly into three equally sized groups: For one third, including the simplest organic compounds, the reaction pathways, rates, and products are well characterised. For the second third, the reaction pathways and products are known, but the rates and product yields are not. For the last third, including most aromatic compounds, scientists can only make educated guesses as to the reaction pathways, rates, and products, although research continues to make progress in this area.

The formation of ozone via the photolysis of $NO_2$ competes with the formation of nitric acid, peroxyacetylnitrate (PAN), and other organic nitrates, which eventually remove nitrogen from the ozone-formation cycle. Ozone is also eventually removed from the troposphere by photolysis, reaction with NO or VOCs, or surface deposition. Thus, the formation of ozone is

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[1] Parts of this discussion are excerpted from Transboundary Environmental Assessment: Lessons from the Ozone Transport Assessment Group [*Keating and Farrell*, 1999].

[2] Stratospheric ozone is formed by the photolysis of oxygen caused by the absorption of solar radiation.

dependent on the fate of $NO_X$, which is in turn dependent on the quantity and composition of the VOCs present.

The relationship between ozone formation and the initial concentrations of $NO_X$ and VOCs is highly nonlinear and varies during the year. An ozone isopleth diagram, such as Figure 4.1, best describes this relationship. Initial concentrations of $NO_X$ are plotted along the vertical axis and initial concentrations of VOCs are plotted along the horizontal axis. The series of curves show different maximum ozone concentrations associated with each combination of $NO_X$ and VOC.

For example, at Point A in Figure 4.1, ozone formation is VOC-sensitive; a change in VOC will significantly change the ozone level. However, the opposite is true at Point B, which is $NO_x$-sensitive. It is important to realize that these diagrams differ for each location in the atmosphere and vary with meteorological conditions and changes in the distribution and composition of emissions. Thus, the control recommendations that are inferred from such a diagram are only valid for the conditions under which the diagram was constructed.

Figure 4.2 shows that, in general, ozone formation in marine regions is more sensitive to the presence of $NO_x$ than of VOCs ($NO_x$-sensitive). The implication that ocean regions are not VOC-sensitive is illustrated by the fact that increasing VOCs by a factor of ten while holding $NO_x$ relatively constant (moving from the “marine box” to the “remote tropical forest” box) does not change the typical concentrations of ozone. However, urban regions with the same VOCs as the remote tropical forest regions but increased $NO_x$ concentrations show significantly higher concentrations of tropospheric ozone (see Figure 4.2). It appears that the naturally-occurring VOC concentrations over ocean regions may be sufficient to react with additional $NO_x$ concentrations in shipping lanes to produce higher ozone concentrations in those regions. As discussed in 4.2.2 and in Appendix A2, this appears to be confirmed by model predictions of nitrogen and tropospheric ozone concentrations attributable to international shipping.

While stratospheric ozone protects the surface of the earth from harmful ultraviolet radiation, tropospheric ozone is a powerful oxidant that damages human lung tissue, vegetation, and other materials.

Short-term exposures (1 hr to 8 hr) to high concentrations can cause a range of acute adverse human health effects from irritation and shortness of breath to decreased immune functions and increased inflammation and permeability of lung tissue. Young children, the elderly, and individuals with preexisting respiratory disease are at particular risk of serious acute adverse effects from ozone exposure. The chronic human health effects of ozone exposure are less well known, but there is the possibility of irreversible morphological changes of the lung, genotoxicity, and carcinogenicity.

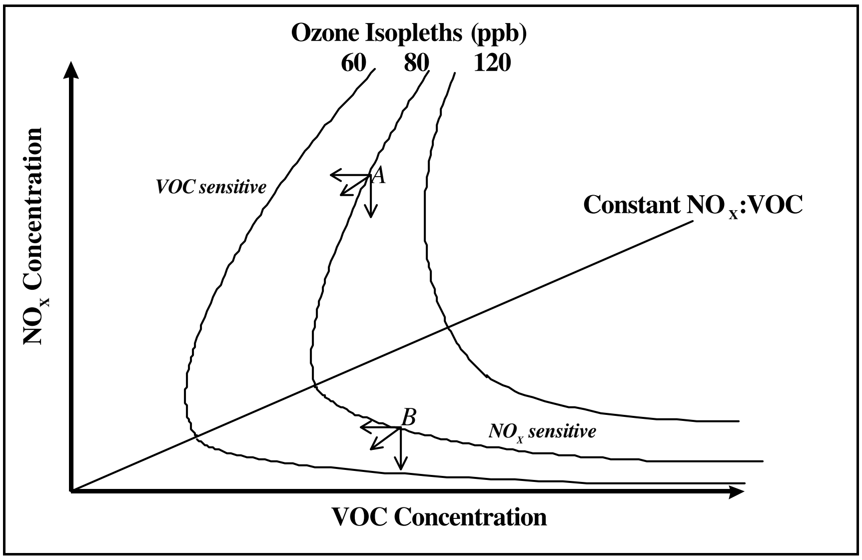

**Figure 4.1. An idealised example of the relationship between ozone and its precursors [*Keating and Farrell*, 1999]**

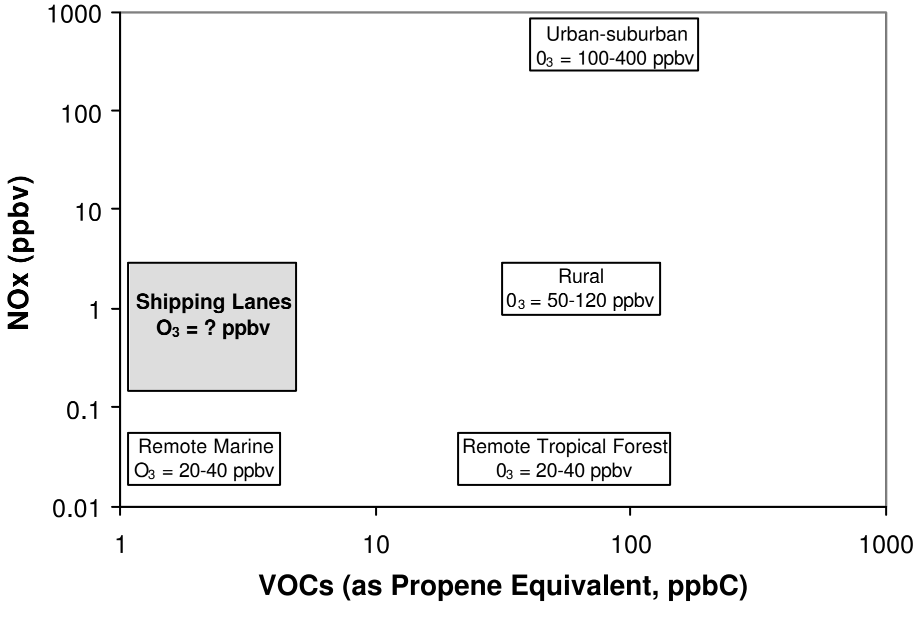

**Figure 4.2. Ranges of VOC, $NO_x$ and ozone concentrations in the atmospheric boundary layer for four regions of the atmosphere [*National Research Council*, 1991], with placeholder box for ozone in shipping lanes produced from $NO_x$ from ships.**

The adverse effects of ozone exposure on vegetation include leaf yellowing, premature senescence, reduced growth, and increased susceptibility to pests and other risks. These effects occur with agricultural crops and other vegetation. While the magnitude of the concentration is often more important than the duration of exposure for human health effects, both are important with respect to impacts on plants. A variety of metrics has been proposed for measuring ozone exposures to plants. Most involve counting the number of hours that exceed a threshold concentration during summer daylight (concentration hours). Exposure to ozone also leads to the oxidation and deterioration of many important materials including paint, textiles, rubber, and plastics.

These concerns were the primary motivation for domestic and international (e.g., transboundary) policy attention on $NO_x$ and ozone. In fact, the realisation that $NO_x$ from ships contributed significantly to air quality problems in regions with heavy ship traffic motivated action at IMO that resulted in MEPC Annex VI.

### 4.1.2. Global Climate Change Effects From Ozone

Global climate change is a long-term effect on the global energy balance. In this regard, the dimensions, impacts, and concerns are very different than the air pollution problem. Nonetheless, ozone has been shown to play a very important role in the energy balance. This is largely because conditions for its production are often present and its potential to trap energy in the atmosphere is significant, although it is a short-lived chemical.

In general, long-lived warming gases, primarily $CO_2$, dominate the greenhouse effect. The increasing usage of fossil fuels that began in the latter half of the 18th century with industrialisation has led to higher concentrations of $CO_2$ and other trace greenhouse gases in the atmosphere. The long-term rise in atmospheric $CO_2$ closely follows the increase in anthropogenic $CO_2$ emissions. These emissions are a direct result of fossil fuel combustion, of which international shipping accounts for approximately 1.8% (see Chapter 3).

Radiative forcing is a measure of the importance of a potential climate change mechanism. It expresses the perturbation or change to the energy balance of the Earth-atmosphere system in watts per square meter ($W\ m^{-2}$). Positive values of radiative forcing imply a net warming, while negative values imply cooling.

Carbon dioxide is the single most important trace constituent from the standpoint of global climate change, because its impact on the energy balance (greenhouse effect) is second only to that of water vapour. However, other pollutants emitted from ships can contribute to the greenhouse effect. In addition to $CO_2$, ozone is considered an important greenhouse gas. As was mentioned earlier, ships do not directly produce ozone during engine combustion, but they do emit ozone precursors, $NO_x$ and VOCs. Ozone's global warming potential occurs because it absorbs both incoming solar radiation in the ultraviolet and visible regions and terrestrially emitted infrared radiation in certain wavelengths. Stratospheric ozone absorbs more energy than it re-radiates, acting as a net source of warming, although it exerts both heating and cooling influences. For ozone in the troposphere, however, both direct solar absorption and infrared trapping warm the surface-troposphere system. Ozone resulting from ship emissions – as the $NO_x$ from ships reacts with ship-based and biogenic ocean/coastal VOCs, or mix with land-based emissions and react – would contribute directly to the warming in the surface-troposphere system.

There is an important effect of shorter-lived aerosols and tropospheric ozone episodes on the global energy balance:

1. Aerosols can re-radiate sun's energy, causing temporary cooling effects that mask the long-term warming of GHGs. The magnitude of these short-term effects is uncertain and non-uniformly dependent upon local conditions, but the total effect could be as large as -0.8 W $m^{-2}$ [*IPCC*, 1995b; *Seinfeld and Pandis*, 1998]. The global effects of sulphur aerosol emissions from ships has been the focus of a recent study [*Capaldo et al.*, 1999], which estimated that the indirect forcing (cloud-based cooling effect) due to ship sulphur aerosols (-0.11 W $m^{-2}$) represented about 14% of the global estimate by IPCC. Additionally, under certain conditions the generation of nitrate aerosols from chemical transformation of $NO_x$ could also have a negative-forcing effect.

2. Tropospheric ozone episodes (3-17 days long) can absorb heat and contribute to global warming effect. Estimated by IPCC to be 0.4 W $m^{-2}$, or about 25% of the warming effect due to $CO_2$. These calculations also are considered uncertain, ranging between 0.1-0.7 W $m^{-2}$, and are non-uniformly distributed [*IPCC*, 1995b].

### 4.1.3. Summary of Recent International Aircraft Studies

Ships have never been explicitly considered in global calculations of global warming due to ozone formation. By analogy, it is instructive to review the studies that have been done on international aircraft.

Similar to international shipping, aircraft consume about 2% of world fossil fuels [*Brasseur et al.*, 1998; *Penner et al.*, 1999]. This means that the total annual $CO_2$ emissions from aircraft and ships are similar, and that the global radiative-forcing impacts due to $CO_2$ from these international sources would be similar. However, the estimated $NO_x$ emissions from aircraft (0.37-0.6 Tg N $yr^{-1}$) are 5 to 6 times lower than the $NO_x$ emissions from ships (~3 Tg N $yr^{-1}$) [*Brasseur et al.*, 1998; *Corbett and Fischbeck*, 1997; *Penner et al.*, 1999; *Seinfeld and Pandis*, 1998]. Moreover, emissions from aircraft occur at varying altitudes, with a significant fraction occurring during climb-cruise-descent periods (68% for short-haul routes and 98% for long-haul routes) in the upper troposphere (9-13 km) and lower stratosphere [*Brasseur et al.*, 1998; *Penner et al.*, 1999]. This is an important difference from coastal (and perhaps open-ocean) regions, since $NO_x$ emissions directly to the upper troposphere tend to produce ozone more efficiently than $NO_x$ released at the surface, and since radiative effects are more sensitive to ozone near the tropopause. $NO_x$ aircraft emissions are 10-20 times more efficient in terms of ozone radiative perturbation at these altitudes than at the earth's surface [*Brasseur et al.*, 1998]. However, determining whether this general altitude difference in ozone radiative perturbation between $NO_x$ emissions at the earth's surface is roughly equal over both land and ocean regions require additional data not addressed in the aircraft studies.

A Special Report of IPCC Working Groups I and III [*Penner et al.*, 1999] estimated that radiative forcing due to ozone from aircraft $NO_x$ emissions may contribute an estimated 0.022 W $m^{-2}$ (warming effect). This estimate is larger than the 0.018 W $m^{-2}$ estimated for $CO_2$ from aircraft. The impact of $NO_x$ emissions on methane ($CH_4$) is estimated to be about –0.007 W $m^{-2}$ (cooling effect). Thus, the net radiative forcing estimated for aircraft by these three effects is roughly 0.033 W $m^{-2}$, dominated by the secondary effects of NOx emissions on ozone and $CH_4$. (The total forcing estimate reported in the IPCC study suggested that aircraft contribute a net warming effect of ~0.05 W $m^{-2}$.)

Ships annually emit 5 to 6 times more $NO_x$ than aircraft, although ship emissions occur in the marine boundary layer near the earth's surface where the resulting ozone radiative perturbation may be 5-10% as effective as ozone from $NO_x$ emitted at altitude. These facts could imply that the radiative impact from ships can be estimated proportionally from the IPCC aircraft study, but the problem is more complicated. There are a number of scientific reasons to avoid making direct comparisons with international shipping, including atmospheric circulation and chemical reactions that vary greatly across longitudinal, latitudinal, and vertical dimensions. However, the results from the aircraft study suggest that it is important to consider whether secondary $NO_x$ impacts on ozone and $CH_4$ could also be important components in determining the radiative-forcing contribution of international shipping.

## 4.2. How Do International Ships Affect Climate and Tropospheric Ozone?

In order to estimate the global radiative forcing from a single source, four modeling steps are needed (see Figure 4.3). First, the emissions must be estimated, and in the case of short-lived species, the geographic distribution of these emissions must be determined. Second, the emission flux must be translated into an atmospheric concentration for primary emissions. Third, the proper chemical reactions must be included to model the transformation of primary emissions into their secondary forms (where applicable). Both of these steps require that attention be paid to atmospheric flow dynamics and meteorology in addition to chemistry. Fourth, the output of these models must be entered into a radiative transfer model that integrates the various wavelengths of energy absorbed or emitted by different species on a global scale.

### 4.2.1. Modelling Challenges

Each of the steps in Figure 4.3 requires careful calculations and interdisciplinary expert collaboration. (For example, the IPCC report on aviation took three years to complete and included 107 lead authors from 18 countries, 100 contributing authors, and 150 reviewers.) Chapter 3 of this report provides a detailed inventory of the emissions from ships, but that is only the first step. The calculations for $CO_2$ are relatively straightforward, given that this most-important greenhouse gas has a lifetime range of 50-200 years [*IPCC*, 1995a]. (This is because anthropogenic $CO_2$ added to the atmosphere is removed by reservoirs having a range of turnover times [*Seinfeld and Pandis*, 1998].) Therefore, $CO_2$ becomes generally well mixed throughout the atmosphere, which allows for calculating radiative-forcing estimates without as much attention to local variability. The IPCC estimates that global forcing due to $CO_2$ emissions from human activity is 1.517 W $m^{2}$ [*IPCC*, 1995b; *Seinfeld & Pandis*, 1998].

The contribution of $CO_2$ emissions from international shipping on global climate forcing can be calculated indirectly from the IPCC estimate, by estimating the cumulative fraction of anthropogenic $CO_2$ emitted by ships. Ships converted from sail to fossil fuel power in the early 19th century during the same general period that industrial uses of fossil fuels began to increase. Expansion of international steamships, beginning with the first coal-powered steamship crossing of the Atlantic in 1819, was rapid and parallels the increased use of combustion machinery in land-based industries [*Encyclopaedia Britannica*, 2000]. The relative energy consumption in the international shipping industry since 1850 can be assumed to be roughly constant, so the radiative forcing due to $CO_2$ from ships is estimated to be ~0.027 W $m^{-2}$ (1.8% of the IPCC estimate for all fossil fuels).

However, estimating the global climate forcing is more complicated for other emissions, especially nitrogen, sulphur, and particulate matter. Shorter-lived gases and aerosols are greatly affected by weather, sunlight, chemical reactions, thermodynamics, and fluid flow dynamics. Often, direct emissions react to form secondary species that have different lifetimes and may be affected differently by atmospheric processes. To estimate these effects, a globally resolved inventory of ship emissions must be added to a global chemical transport model that includes meteorological input and all other known sources of the related emissions. This model must be run to calculate the

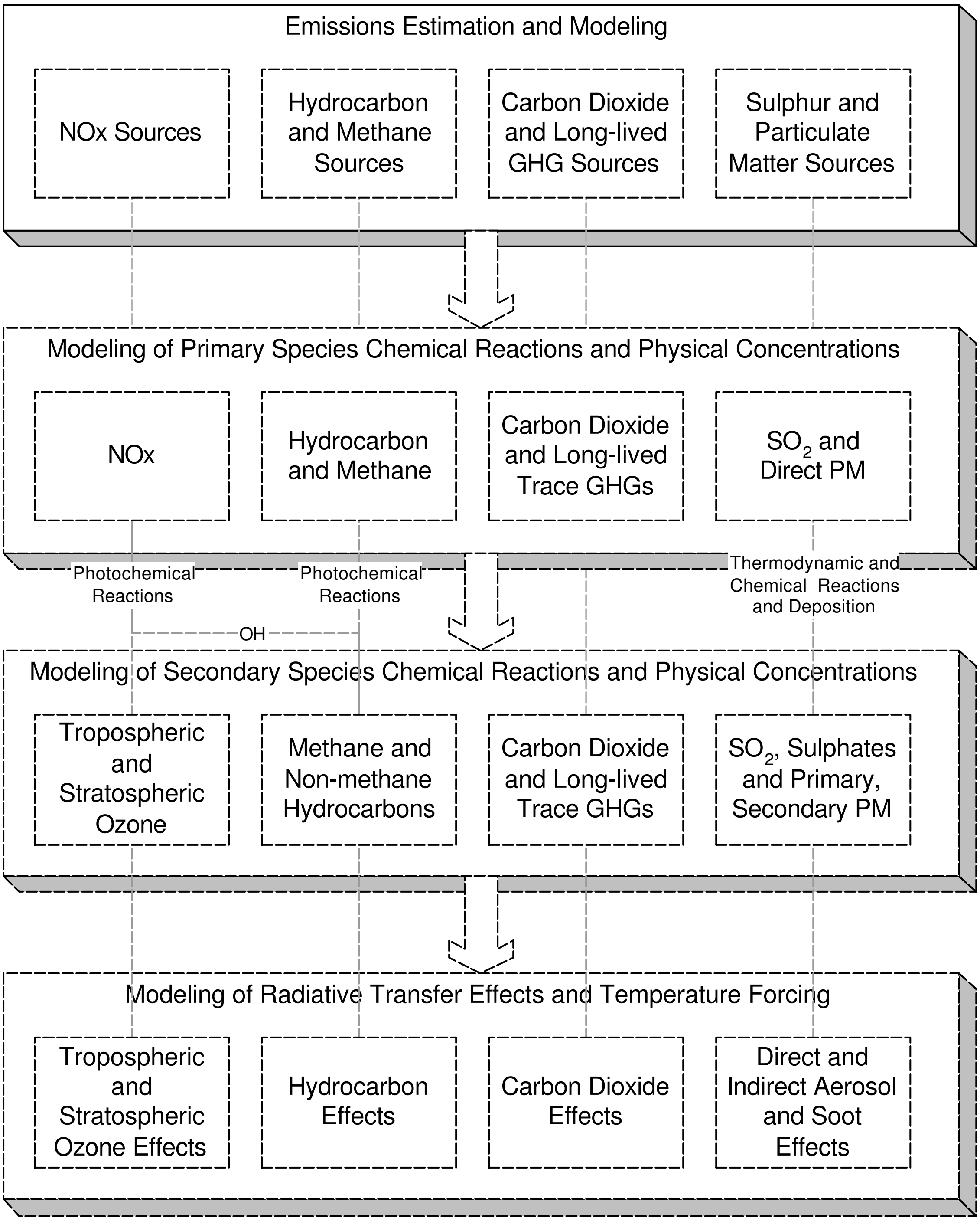

**Figure 4.3. General modeling process to estimate global climate forcing**

spatially resolved concentrations of primary and secondary species, followed by post-processing to attribute model results to each source category and calculate how much ship emissions contribute to regional concentrations. Lastly, a separate radiative transfer model must be used to calculate global climate forcing from the results of the global chemical transfer model, again followed by source-specific post-processing.

### 4.2.2. GCTM Predictions For NOx And Tropospheric Ozone From Ships

Researchers have begun to calculate these effects with better precision. Two studies are available that use a global chemical transport model to describe the chemical reactions of $NO_x$ emissions from international shipping, particularly focused on the resulting ozone concentrations. This section summarises the findings of these studies.

Studies have shown that emissions of trace gases from ships, such as nitrogen oxides ($NO_x$) and sulfur oxides, may significantly perturb the chemical composition of the marine boundary layer [*Capaldo et al.*, 1999; *Corbett and Fischbeck*, 1997; *Corbett et al.*, 1999]. Recent model calculations by Lawrence and Crutzen [*Lawrence and Crutzen*, 1999] indicate that emissions from ships can lead to surface $NO_x$ enhancements of over two orders of magnitude in open ocean regions where ship traffic is high. Lawrence and Crutzen further estimate that significant surface $NO_x$ enhancements (at least a factor of 2) occur over most of the North Pacific, North Atlantic, and Indian oceans, resulting in a significant enhancement of marine-boundary-layer ozone and hydroxyl radical concentrations in these regions.

In this study (derived from ongoing research [*Kasibhatla et al.*, submitted]), the impact of ship emissions on marine-boundary-layer $NO_x$ is re-assessed using a global chemical transport model. This study is distinguished from the Lawrence and Crutzen study in two important respects. Firstly, this analysis uses an updated inventory for $NO_x$ emissions from ships that is based on ship positions reports [*Corbett and Fischbeck*, 1997; *Corbett et al.*, 1999]. This updated inventory provides a more realistic geographical distribution of emissions compared to the inventory used in the Lawrence and Crutzen study. While the global magnitude of the ship $NO_x$ emissions used in the Lawrence and Crutzen study (3 Tg N $yr^{-1}$) is the same as in this study, ship emissions in the Lawrence and Crutzen study are confined to the main shipping routes. Secondly, Lawrence and Crutzen concluded that $NO_x$ observations in the marine boundary layer are too sparse to assess the accuracy of the model-predicted impact of ship emissions on $NO_x$.

The model results in this study are compared with recent measurements of $NO_x$ and reactive nitrogen (NOy) in the marine boundary layer of the central North Atlantic Ocean, which is the region where the modeled impact of ship emissions is largest. These comparisons are evaluated to assess whether the modeled impact of ship emissions is supported by measurements.

The global chemical transport model used in this study is the 11-level Geophysical Fluid Dynamics Laboratory model, as configured to simulate the global distribution of NOy compounds [*Levy et al.*, 1999]. The model explicitly simulates three NOy species, namely $NO_x$, nitric acid, and peroxyacetyl nitrate. Interconversions between these species are calculated using prescribed rates as described in Levy et al. [*Levy et al.*, 1999]. While the

NOy chemical scheme used is highly parameterized, the model has been shown to simulate successfully important features of the global $NO_x$ and NOy distributions [*Levy et al.*, 1999].

Two simulations, one excluding and one including ship emissions (hereafter referred to as the NOSHIP and SHIP simulations, respectively), have been performed to delineate the relative impact of these emissions on the $NO_x$ distribution. Both simulations include $NO_x$ emissions from land-based fossil-fuel combustion (22.4 Tg N $yr^{-1}$), biomass burning (7.8 Tg N $yr^{-1}$), biogenic processes (5.0 Tg N $yr^{-1}$), lightning discharges (4.0 Tg N $yr^{-1}$), aircraft fossil-fuel combustion (0.45 Tg N $yr^{-1}$), and stratospheric injection (0.64 Tg N $yr^{-1}$).

The SHIP run includes seasonally-varying emissions of $NO_x$ from ships [*Corbett and Fischbeck*, 1997; *Corbett et al.*, 1999]. The annual, global magnitude of this source is 3 Tg N $yr^{-1}$. The global distribution of the annual-average $NO_x$ emissions from ships used in this study is presented in Figure 4.4.

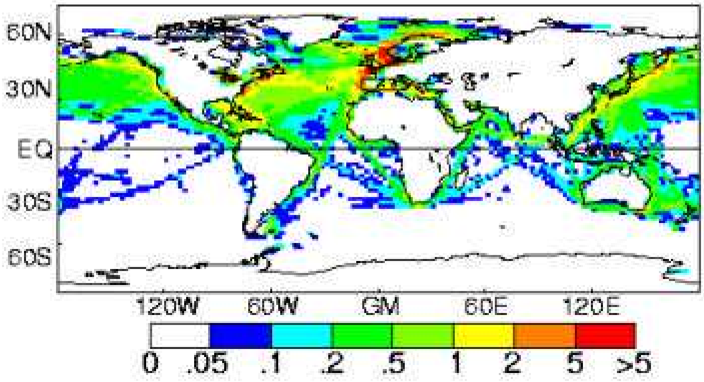

**Figure 4.4. Annual average emissions of NOx from ships ($10^{-12}$ kg N $m^{-2}$ $s^{-1}$).**

Monthly-mean $NO_x$ mixing ratios for January and July at the lowest model level from the SHIP simulation are shown in Figure 4.5. Also shown in Figure 4.5 are NOx ratio fields relative to the NOSHIP simulation results. The total $NO_x$ maps (top panels of Figure 4.5) show simulated surface $NO_x$ mixing ratios in excess of 100 pptv over most of the North Atlantic and North Pacific north of 20N, and over the northern Indian Ocean during January. In July, the surface $NO_x$ levels over these regions are generally lower owing to the shorter lifetime of $NO_x$ during summer. Nevertheless, surface $NO_x$ mixing ratios more than 100 pptv are simulated over most of the extratropical North Atlantic Ocean. During both January and July, simulated marine-boundary-layer $NO_x$ mixing ratios are highest (in excess of 200 pptv) over parts of the North Atlantic and the western North Pacific.

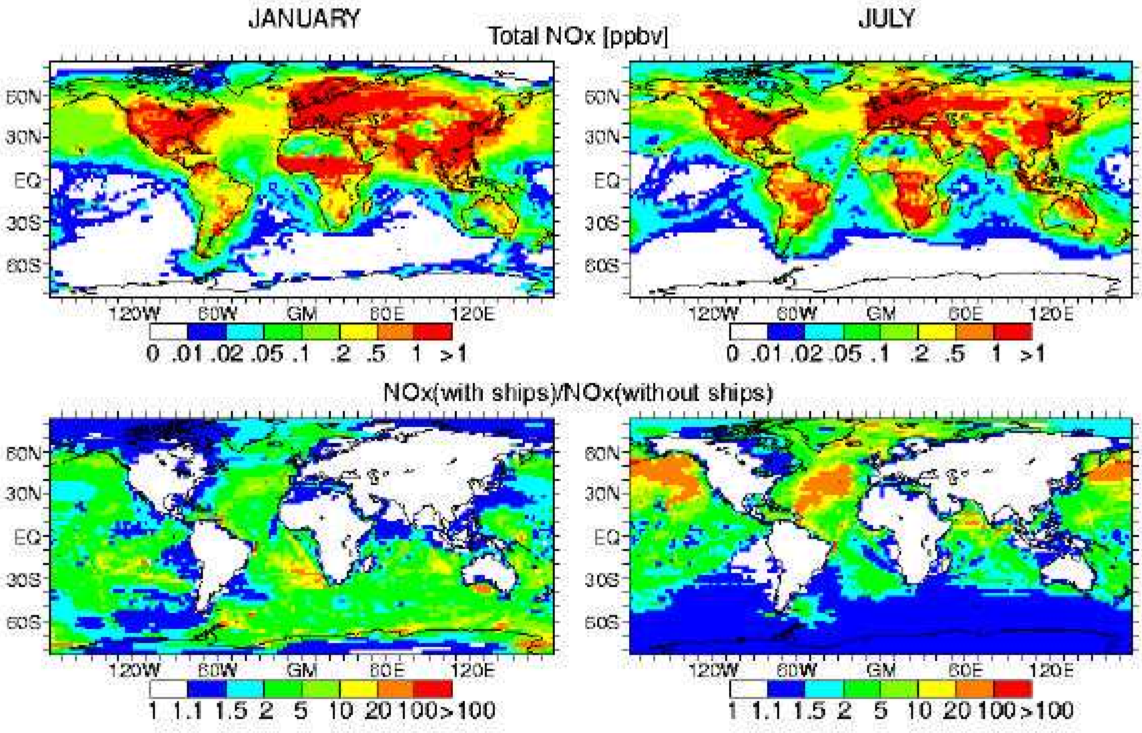

**Figure 4.5. Simulated monthly-mean NOx mixing ratios (ppbv) from the SHIP simulation (top) and the ratio of monthly-mean NOx mixing ratios from the SHIP and NOSHIP simulation at the lowest model level during January and July (bottom).**

Difference maps of $NO_x$ (not shown here) roughly reflect the distribution of $NO_x$ emissions from ships. Model results indicate that emissions from ships of the magnitude prescribed here can contribute as much as 200-500 pptv of $NO_x$ at the surface of the Northern Hemisphere midlatitude oceans. On a relative basis (bottom panels of Figure 4.5), the modeled impact of emissions from ships is particularly large over the central North Atlantic Ocean and over the midlatitude North Pacific Ocean during July. The combination of slower transport and shorter lifetime during the summer results in a much weaker contribution from adjacent continental regions, leading to the relatively high contribution of the in-situ $NO_x$ source from ships during this period.

As shown, the model predicts significant enhancements of these compounds over large regions, especially over the northern midlatitude oceans. This result is consistent with the Lawrence and Crutzen study, though the impacts predicted here are more widespread and the peak enhancements are not as large. However, recent measurements of NOy in the marine boundary layer over the central North Atlantic [*Peterson et al.*, 1998; *Ryerson et al.*, 1999] provide only limited support for the predicted enhancements in NOy. While NOy levels are generally well simulated at the Azores without ship emissions, the consistent under prediction of NOy in the NOSHIP simulation relative to the NARE 1997 data raises the possibility that about 150 pptv of NOy in central North Atlantic marine boundary layer may be due to ship emissions.

More significantly, the measurements do not support the large model-predicted enhancements of $NO_x$ by ship emissions. It is important to emphasize that the focus of this study is on the impact on model-resolved spatial scales of a few hundred kilometers. While the reasons for the over prediction of $NO_x$ are not obvious, one can speculate on various possibilities. It is possible that $NO_x$ in ship plumes is oxidized relatively rapidly (i.e., at a rate significantly faster relative to the prescribed oxidation rate in summertime midlatitudes that corresponds to a $NO_x$ lifetime of 0.75-1.0 days) on spatial scales not resolved by the model. It is worth noting that rapid $NO_x$-oxidation rates have been calculated in some studies of power-plant plumes, albeit in hydrocarbon-rich regimes [*Ryerson et al.*, 1998].

These results suggest there may be a gap in the scientific understanding of the chemical evolution of ship plumes as they mix into the background atmosphere in the marine boundary layer. In other words, even thought current research indicates that there is a significant global impact of $NO_x$ and ozone from international shipping, the magnitude of that impact cannot yet be confirmed with available data. The Lawrence and Crutzen study and this study highlight the need for measurements to elucidate certain aspects of marine-boundary-layer photochemistry. Long-term measurements of $NO_x$, NOy, and related species at locations such as the Azores, in concert with targeted field studies focused on understanding the chemical evolution of ship plumes as they mix into the background atmosphere, are needed. Such measurements will provide a better understanding of the impact of trace-gas emissions from ships in particular, and of marine-boundary-layer $NO_x$ and NOy budgets in general. Additional scientific research (both analytical modeling and experimental field measurements) will be needed to quantify accurately the contribution of ship $NO_x$ emissions to tropospheric ozone and global climate change.

These limitations show that a radiative transfer model cannot produce accurate estimates of the changes in radiative forcing due to international shipping until this discrepancy between model predictions and field observations is resolved. Potential sources of uncertainty include (in order of importance):

1. Model limits in resolution, averaging local chemical and physical processes over large regions (256 km by 256 km) and time periods. This may be addressed in global models using the same “plume-in-grid” approach that regional models are adopting to improve resolution and accuracy [*Gillani and Godowitch*, 1999; *Kumar and Russell*, 1996; *Odman and Russell*, 1991].

2. Inventory uncertainties, as discussed in Chapter 3. This includes uncertainties in the geographical distribution of ship traffic.

3. Reaction chemistry differences in remote ocean regions. While chemical reactions among NOx, VOC, and ozone are relatively well understood, these reactions can be highly non-linear depending on local conditions. It could also be possible that undetermined reactions occur between $NO_x$ and one or more remote-ocean chemical species, including VOC emissions from natural sources.

The results suggest that more scientific research may be necessary before developing international policies to reduce $NO_x$ emissions from international shipping for the purpose of global climate change mitigation. This report recommends that international policy makers continue to call for international research efforts that include field campaigns and improved modeling analyses.

### 4.2.3. Global Radiative Forcing From Ships

It is difficult provide quantitative bounds on the radiative forcing effect of $NO_x$ from ships without additional research findings. At a lower bound, current $NO_x$ emissions from international shipping will produce non-zero, positive radiative effects due to tropospheric ozone, contributing to global warming. It is plausible that the radiative effects due to tropospheric ozone are in the same range as the radiative effects from ship $CO_2$ emissions. A significant fraction of these ship emissions occur in remote ocean regions where there is no other anthropogenic source of $NO_x$ at the surface, but where there are biogenic sources of hydrocarbons (see Figure 4.2). The efficiency of ozone production from ship-emitted $NO_x$ in the open-ocean is likely to be higher than for similar magnitude emissions over land. If the radiative-forcing sensitivity to NOx in the remote ocean is more similar to that of the upper troposphere, then ship $NO_x$ emissions (which are several times greater than aircraft $NO_x$ emissions) could potentially result in global climate forcing larger than the IPCC estimates for aviation.

Also, it is likely that the magnitude of the cooling effect from $CH_4$ losses due to $NO_x$ from international shipping is less than the warming effect from ship-$NO_x$ produced tropospheric ozone. This means that on balance, $NO_x$ emissions from ships will produce a warming effect after combining the positive forcing due to tropospheric ozone and the negative forcing due to $CH_4$ destruction.

In total, the current net radiative forcing from ships (including $CO_2$, ozone, $CH_4$, and aerosols) is probably small or slightly negative. On a global-average basis, warming effects from direct $CO_2$ emissions and tropospheric ozone resulting from ship $NO_x$ emissions may be offset by cooling effects from $CH_4$ losses due to ship $NO_x$ emissions and indirect cloud effects from ship sulphur aerosol emissions. However, this may not be true locally, where tropospheric ozone and aerosols can dominate the smaller local effects of longer-lived species. In any event, it is important to note that these estimates are highly uncertain and significant gaps in scientific understanding must be resolved before relying on these initial conclusions.

Reduction in $NO_x$ emissions motivated by air quality concerns, either through international standards such as MARPOL Annex VI or through domestic policy efforts, will tend to reduce the net warming effect due to tropospheric ozone and $CH_4$. If these $NO_x$ reductions are greater than corresponding increases in $CO_2$ emissions (that may result from decreased fuel efficiencies in the engine, for example), then the combined effect of $NO_x$ control could reduce the global warming impact of international shipping. On the other hand, as $SO_x$ and PM emissions are reduced along with $NO_x$ over the next decades and as increased trade continues to require more energy for international shipping, the warming effects from long-lived GHGs such as $CO_2$ will begin to dominate. In other words, over the coming decades, $CO_2$ will become the most important greenhouse gas emitted by ships.

## 4.3. Conclusions

The impact of ship $NO_x$ emissions on local and regional air quality (pollution) will continue to be the dominant policy driver and may motivate additional domestic and international policy action. However, as scientific research furthers the understanding of global climate effects, policy decisions may increasingly focus on these global issues.

Reduction in $NO_x$ emissions motivated by air quality concerns, either through international standards such as MARPOL Annex VI or through domestic policy efforts, will tend to reduce the net warming effect due to tropospheric ozone and $CH_4$. If these $NO_x$ reductions are greater than corresponding increases in $CO_2$ emissions (that may result from decreased fuel efficiencies in the engine), then the combined effect of $NO_x$ control could reduce the global warming impact of international shipping. In total, the current net radiative forcing from ships (including $CO_2$, ozone, $CH_4$, and aerosols) is probably small or slightly negative.

Accurate estimates of radiative forcing due to $NO_x$ from international shipping cannot be made from currently available data. However, an indirect estimate of radiative forcing due to $CO_2$ emissions from ships indicates that ships may account for 1.8% of current IPCC estimates. $NO_x$ emissions are highly likely to produce non-zero, positive forcing effects that will contribute to global warming and that could be in the same range as (or larger than) direct forcing from $CO_2$.

Improved assessments of global climate impacts from shipping will need to include effects of $CO_2$, $NO_x$, and $SO_x$ emissions from ships. The research needed includes additional long-term field campaigns to measure ozone and $NO_x$ in the remote marine boundary layer and troposphere. Field research should also investigate the chemical composition and physical dynamics of ship emissions to investigate the small-scale nature of ship plumes and the larger-scale effects as the plume gases disperse and react. This work would build upon the important ship-board emissions characterisations performed 5-10 years ago as part of the Lloyd's

Marine Exhaust Emission Research Programme [*Carlton et al.*, 1995], and research such as the Monterey Area Ship Tracks (MAST) Study of in-situ plume effects [*Russell et al.*, 1999].

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# 5. TECHNICAL AND OPERATIONAL MEASURES FOR REDUCTION OF GREENHOUSE GAS EMISSIONS FROM SHIPS

## 5.1. Introduction

Following the assessment of the amount of emissions to air from shipping in chapter 3 and the effect on climate and ozone described in chapter 4, this chapter focus on alternatives for reduction of emissions to air from ships. In the following both technical and operational measures are presented.

The assessment of various options was performed with both a short term and long term perspective. In the context of this report, short term is closely related to availability of technical measures. As applicability of various measures may be different for new and existing ships, the discussion of the various technical alternatives was divided into one part concerning new ships and one part concerning existing ships.

## 5.2. Short-term considerations – applying state-of-the-art knowledge

### 5.2.1. Hull and propeller: new ships

This section focuses on the energy savings that can be obtained by application of current technology within hydrodynamics (hull and propeller) on new ships. Energy savings can then be easily converted into emission reductions.

International merchant shipping is a highly economically optimised business. Fuel cost is a major operating cost of most merchant ships. Ship designs are usually fairly well optimised with respect to maximum profitability. Thus, one should expect that there is not much efficiency to be gained by better design and selection of propulsion systems without changing the external economic conditions. Also in this section, measures that are not currently profitable will be discussed.

The energy savings obtained by different measures can be very accurately predicted for a specific ship. However, savings will in most cases vary between different ship categories and even between ships of the same category. Due to this, the general presentation presented in this chapter was supported by the case study presented in chapter 6.

### Hull Design

It is reasonable to expect that due to the significant effort put into hull optimisation for many years, there should be little potential left for improvement. Experience from work in the MARINTEK towing tank however indicates that reduction of power in the order of 20% may still be gained by relatively minor changes to the bow and/or stern on a vessel. From this experience, one might conclude that there is still a significant potential for power savings by good hull design, and that hull optimisation must be carefully performed by specialists for each new hull design.

To try to quantify a typical potential for energy savings by hull design, MARINTEK's database of model test results was used to estimate best and worst speed-power curve for typical categories of large contributors to $CO_2$ emissions identified in the emission inventory study in chapter 3. This was done by normalising results in the MARINTEK database for each of the ship category back to the size of a typical case ships (further described in chapter 6) and then drawing estimated best and worst curves as shown in Appendix 4. The results of this approach show very large potentials for reduction – in the order of 30%.

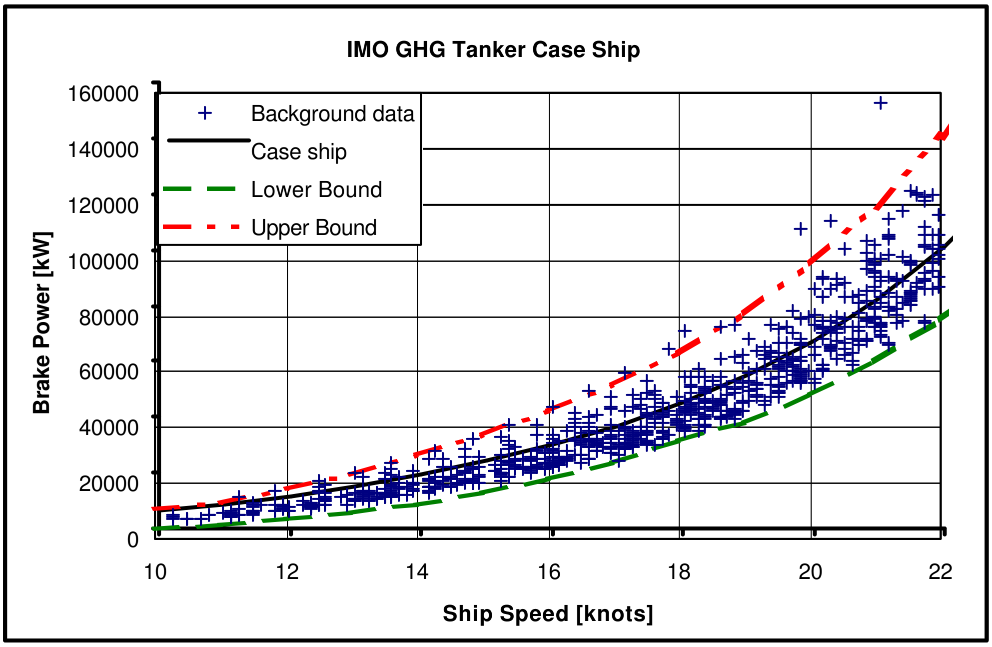


**Figure 5-1 - Example of speed-power curve for tanker case ship, included predicted best power level**

To exploit this potential one must have full freedom in selecting optimum main dimensions. This is not the case in practice, where limitations in harbours and canals usually restrict selection of main dimensions. Thus, 5 – 20% is considered more realistic, and in line with experience from work in the towing tank. The reference for this reduction is taken as the average of the fleet that is basis for the case-ship study.

The cost of optimisation the hull designs with respect to power consumption is mainly a fixed cost, fairly independent of the ship size. Thus, putting lots of effort into optimisation of hull designs is more profitable for large ships than for small ships. The cost of optimising the hull shape is in the range of 50.000 US$ to 200.000 US$. In addition to this a possible increase of building costs due to a more complex hull shape (more double curved surface for instance) has to be added.

### Propeller

The efficiency of a conventional screw propeller is dependent mainly on its main dimensions. The art of propeller design is primarily related to cavitation, noise and pressure pulses. For a new ship it must be assumed that the main dimensions are correctly selected, given the design restrictions. Typical design restrictions are limitations on diameter, cavitation and loading. Thus, in the present context, the question of power reduction by means of propeller selection is mainly a question of selection of propeller arrangement.

Table 5-1 lists the main types of unconventional propulsors for conventional ships, stating also the approximate gain in power, if full-scale tests have verified the model scale findings and the number of applications. Not all of these propulsive devices are suitable for all kinds of ships, and the gains in power are surely not additive in general. Note that waterjets are not mentioned, since they are relevant only for high-speed ships.

Low RPM propellers might be applied to many different types of ships. Low RPM propellers require larger diameter, something that might severely deteriorate ballast performance or it might be impossible due to other diameter restrictions. Low RPM propellers will sometimes require a reduction gearbox, where a conventional propeller could be directly coupled to the engine.

Contra-rotating propellers are most beneficial for relatively heavy-loaded propellers in single screw vessels (short propeller shaft is important), like container vessels, Ro-Ro and fast freight vessels. Main drawbacks of contra-rotating propellers are cost and gearbox problems.

The free rotating vane wheel uses the rotation of the propeller slip-stream to rotate the vane wheel. The vane wheel extends outside the ordinary propeller diameter, with the part extending outside the propeller acting as propulsor and the part inside the ordinary propeller diameter as turbine. The power gain numbers that are stated for the free rotating vane wheel is misleading, since an almost similar gain can be obtained by increasing the propeller diameter to the diameter of the vane wheel. Also, the very long and slender vane wings are prone to being damaged at sea.

Ducted propellers are “common practice” for vessels needing high thrust at low speed. Thus, in this context, a gain due to use of ducted propellers can hardly be taken into account.

Pre-swirl and post-swirl devices will work properly in many cases, but have not experienced a major commercial breakthrough since the gains are difficult to identify in practical applications.

**Table 5-1** - Comparison of unconventional propulsor performance with efficiency as claimed (from ITTC, 1990)

| Propulsor Type | | Power Economy (as claimed) % | | Number of applications at sea |
|---|---|---|---|---|
| | | Prediction on the basis of calculations and/or model tests | Full-scale test data | |
| Low RPM propeller | | 5~18 [Muntjewerf, 1983]<br>up to 15 [Pashin, 1986]<br>9~13 [Ciping, 1989] | | Many |
| Coaxial contrarotating propellers | | 12~13 [Glover, 1987]<br>13~15 [Pashin, 1986]<br>12~14 (Nakanishi, 1985]<br>15~20 [Shpakov, 1989]<br>7~11 [Sasaki, 1989] | 16 [Nakamura, 1989]<br>15 [IHI, 1989] | 2 [Nakamura, 1989], [IHI, 1989]<br>Many [Savikurki, 1988] |
| Propeller with a free-rotating vane wheel | | 9~12 [Muntjewerf, 1983]<br>11 [Beek van, 1985]<br>10 [Glover, 1987]<br>9 [Osborne, 1987]<br>8~9 [Stierman, 1986] | 6~8.5 [Kubo, 1988] | 59 [committee estimate] |
| Ducted propeller | Axisymmetrical duct | 5~12 [Glover, 1987]<br>10~20 [Pashin, 1986] | | Many |
| | Asymmetrical duct | Less than that of axisymmetric duct | | Many |
| | Duct in front of the propeller | 5~10 [Glover, 1987]<br>10~12 [Stierman, 1986]<br>10.5 [Osborne, 1987] | 5 [Szantyr, 1989] | |
| Preswirl devices | Radial reaction fins in front of propeller | 4~8 [Muntjewerf, 1983]<br>3~4 [Stierman, 1986]<br>3.7 [Osborne, 1987]<br>6 [Gearhart, 1988] | 7~8 [Takekuma, 1981] | |
| | Asymmetric stern | 1~7 [Nawrocki, 1988]<br>5~8 [Muntjewerf, 1983]<br>5~9 [Nonnecke, 1987] | | 30 [Nawrocki, 1988]<br>42 [Nonnecke, 1987] |
| Postswirl devices | Additional thrusting fins at the rudder | 4~5 [IHI, 1982]<br>1.6 [Osborne, 1987]<br>1~2 [Stierman, 1986]<br>4~8 [Zhang, 1985] | 8~9 [Ma, 1988] | |
| | Rudder bulb system with fins | 1.5 [Osborne, 1987]<br>2~3 [Stierman, 1986] | | |
| | Fins on prop. fairwater | 3~7 [Ouchl, 1989] | 4 [Ouchi, 1989] | 40 [Ouchi, 1989] |
| Flow smoothing devices | Wake equalizing duct | 1.5 [Osborne, 1987]<br>2~3 [Stierman, 1986]<br>5.8~7 [Guangyian, 1989] | | 350 [committee estimate] |
| | Guide vanes in front of the propeller | 3 [Osborne, 1987]<br>2~10 [Grothues-Spork, 1988] | 5~10 [Punson, 1985] | 30 [committee estimate] |

Flow-smoothing devices have little effect in general cases, but might be beneficial in cases where a "bad" hull design has led to poor propulsive performance, for instance due to restrictions on ship length.

From Table 5-1 and the discussion above, it is easy to conclude that a definitive number for power reduction by means of propulsion-system selection is hard to find without detailed investigations in each individual case.

Based on the above discussions, it is obvious that there is a significant potential for reduced fuel consumption by optimisation of hull shape and propeller type. The potential will vary with the category of vessel and type of trade.

**Table 5-2 – Energy-reduction potential for new ships – hull/propeller measures**

| Measure | Fuel/CO2 saving potential | Combined |
|---|---|---|
| Optimised hull shape | 5 - 20% | 5 – 30% |
| Choice of propeller | 5 - 10% | |

### 5.2.2. Hull and propeller: existing ships

#### Hull

The impact of hull maintenance on the GHG emissions is through the effect of hull roughness on ship resistance. Ship viscous (friction) resistance increases markedly with increasing hull roughness. Hull roughness tends to increase during the service life of a ship (see Figure 5-2) and might increase significantly between dockings, depending on the paint system applied. The increase in roughness depends not only strongly on how the ship is maintained, but also on operational area and operational profile. It is very difficult to obtain statistics on the current status regarding hull roughness and maintenance practises. What is considered typical roughness increase will be discussed, as well as what is obtainable by best practice. Then, the difference in terms of power consumption for the four case ships defined in this study will be computed.

Wen discussing hull roughness, the issue of antifouling paint systems is unavoidable. Modern self-polishing antifouling paint systems have significantly reduced the problem of increasing roughness between dockings, as long as maintenance intervals of the paint system are not exceeded. In fact, decreasing roughness in service has been reported, according to [Townsin, 1980]. However, how the hull maintenance is performed when in dock has been found to be very important. This is illustrated by Figure 5-2, where older ships obviously have been docked numerous times, and by Figure 5-3, which directly reports that for hulls that are initially fairly smooth, the roughness is typically increasing as a result of the docking. From this, one might conclude that in addition to use a self-polishing (or similarly effective) paint system, improved practice during hull maintenance must be introduced. In addition, re-blasting the hull should be performed with regular intervals.

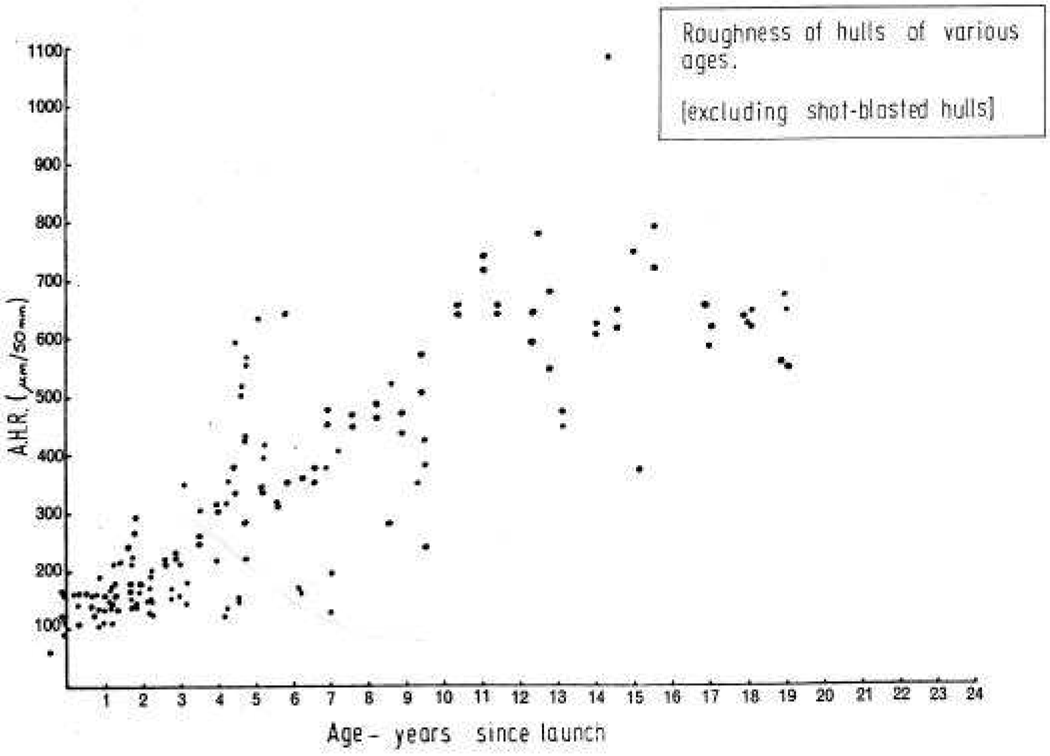


**Figure 5-2 - Roughness of Hulls of Various Ages, Excluding Re-Blasted Hulls [Townsin, 1980]**

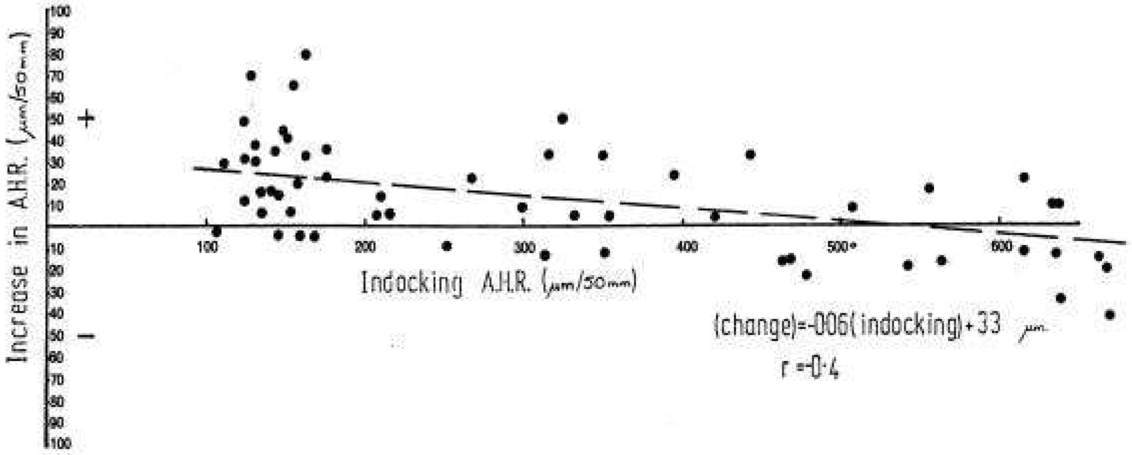


**Figure 5-3 - Change in Average Hull Roughness (AHR) Between Indocking and utdocking [Townsin, 1980]**

Based on this, it our opinion is that hull roughness can be kept at approximately the level of a new ship, which is assumed to be 150 µm, by application of best practice hull maintenance. The combination of typical drydocking workmanship, but use of self-polishing paint which is judged to be current common practice, the increase in roughness following dockings is assumed to be 30 µm. For a ten-year old ship, typically docked twice, this gives an additional roughness of 60 µm. Such a roughness increase implies an increase in power demand to maintain speed of 3-4%.

For the service life of a vessel, an increased hull roughness implies increased viscous resistance. As a consequence, there will be an increased power demand to maintain speed. Use of substandard paint systems, long periods in harbour, long stays in warm waters, and/or exceeding of the service life of the paint systems will increase roughness greater than 60 µm. A significant part of the world fleet will probably be in this category. Thus, it is proper to set the saving potential by perfect hull maintenance to more than the 3-4% given by the 60 µm roughness increase, and 5% is considered as a the more likely figure.

**Propeller**

Retrofit of propeller alternatives described in Table 5-1 on existing ships has been performed and may result in reduced fuel consumption. Although some references exist on results from retrofit on existing ships, it is difficult to establish general conclusions as in the case for new ships, and due to this retrofit has not been further investigated in this section.

Propeller roughness has been much less in focus than hull roughness, probably because the possible impact on fuel consumption is less. Grigson (1982) presents a method for calculation of increase of propeller blade drag due to roughness. Based on his method, it is possible to do a fairly good estimate of the increase in power, if the increase in roughness is known. There are however very few measurement data of increase of roughness in service. Thus, it is tempting to use Grigsons highly empirical estimate of 3% increase in power consumption due to a typically roughened propeller. To keep the propeller roughness increase at a low level the propeller roughness should be properly measured when the ship is docked, and the propeller polished if the roughness has increased above 0.2 mm. It is important to stress that an actual measurement needs to be carried out both before and after polishing. Visual observation is not sufficient. This is considered a cost-effective means of reducing power.

The measures considered most promising are given in Table 5-3 below. These measures could have been presented later in this chapter under operational measures, but are presented in this section as they were defined as technical rather than operational measures.

**Table 5-3 – Energy reduction potential for existing ships – hull/propeller measures**

| Measure | Fuel/$CO_2$ saving potential | Combined |
|---|---|---|
| Optimal hull maintenance | 3 – 5% | 3 – 8% |
| Propeller maintenance | 1 - 3% | |

### 5.2.3. Machinery: new ships

In the following the main focus is on $CO_2$ and $NO_x$ emission reduction measures related to engine combustion processes. Reductions of CO, HC and $SO_2$ emissions are however also addressed to a limited extent in separate section at the end of this part.

It is difficult to discuss reductions of $CO_2$ emissions isolated, without also considering the $CO_2/NO_x$ relationship. Measures that aim to reduce $NO_x$ emissions often have an influence on $CO_2$ emissions and vice versa, with a trade-off between the two. In addition there is a great focus on $NO_x$ emissions from the marine sector as reflected by chapter 4.

During discussion of short-term measures for new ships in the following, the reference is assumed to be modern turbocharged aftercooled machinery with the latest commercial available fuel injection system.

The different measures relevant for conventional diesel engines may be categorised according to effect on different exhaust gas components by applying the different measures. Measures listed in Table 5-4 are only briefly described below, while more detailed information may be found in Appendix 3.

**Table 5-4 – Alternative measures for diesel engines on new ships**

| Category | Measure |
|---|---|
| Reduced fuel consumption/$CO_2$ | - Efficiency optimised<br>- Machinery plant concepts |
| Reduced $NO_x$/Increased $CO_2$ | - Retarded timing |
| Reduced $NO_x$/Minor effect on $CO_2$ | - Low $NO_x$ combustion<br>- Water injection<br>- Water emulsion<br>- Humid Air Motor<br>- Exhaust Gas Re-circulation<br>- Selective Catalytic Reduction<br>- Miller Cycle |
| Other | - Fuel specification<br>- Machinery operation strategy<br>- Condition and efficiency monitoring |
| Reduction of HC and CO | - Reduced fuel consumption |
| Reduction of sulphur | - Seawater scrubber<br>- Fuel specification |

*Efficiency optimised (efficiency or economy rating):*
Efficiency or economy rating implies a set of combined measures of which increased compression ratio and redesign of fuel injection is of main importance. The fuel injections rate and fuel atomisation has to be improved by both a higher fuel nozzle opening pressure and injection pressure.

With efficiency rating utilising state of art techniques on new medium speed engines, a reduction of specific fuel consumption in the rage of 10-12 % can be obtained. On slow speed two-stroke engines a reduction in the range of 2-5% is possible. In the upper %-range higher $NO_x$ has to be encountered.

*Machinery plant concepts:*
When designing new ships today there are alternative options for configuration of the machinery plant. For some type of ships the traditional drive train with main engine connected to a fixed propeller has got a competitor in diesel-electric propulsion solutions. These multi-engine concepts offer a great deal of flexibility and possibilities to run with more optimal fuel consumption at the different operational conditions for a ship [Stenersen et al., 1996]. Considerable fuel saving could be expected on ships or trades with significant part load operations.

*Retarded timing:*

Retarding fuel injection timing is a commonly used method to reduce $NO_x$ from a diesel engine, which does not require costly modification on the engine. By retarding timing the premixed burning phase is shortened, combustion temperature and pressure reduced and thus resulting in reduced formation of $NO_x$ (the disadvantage is poorer fuel economy, and increased emissions of particulates and smoke).

*Low $NO_x$ combustion:*

This option includes adjustments and adaptations to existing engine designs with the purpose of reducing $NO_x$ emissions without suffering reduction in efficiency [Wärtsilä NSD, 1997]. With a retarded injection start combined with a shorter injection period (increased injection rate) the combustion can take place at a point optimal from engine efficiency point of view. By introducing low $NO_x$ combustion technique a positive effect is also obtained on efficiency and rate of $CO_2$ emissions [DNV, 1998].

*Water injection:*

Water may be injected into the cylinder through a combined diesel injector with a water nozzle included, or through a separate injection valve. Both solutions calls for additional water pump system as a high-pressure common rail pump. Water injection is available on a few types of medium speed marine engines. The installation cost is approximately 25 USD pr. kilowatt engine power. Operation and maintenance costs are approximately 4-5 % of fuel costs [Diesel & Gas Turbine, 1999].

*Water emulsion:*

By adding water to the fuel, $NO_x$ and particulate emissions can be reduced. One way to produce emulsion is by first pressurising the fuel and water mixture and then choking the flow. Emulsion may also be produced by the use of a mechanical homogenizer, ultrasound or steam injection. When it comes to the effects on the specific fuel consumption, the literature indicates a small reduction of the specific fuel consumption using emulsions with water contents up to approx. 20% and most effective at part load conditions. A higher water content is negative for fuel efficiency.

*HAM:*

The concept is called Humid Air Motor (HAM), and aims at increasing the specific heat capacity of the charge simultaneously as the oxygen concentration is reduced. The basic idea [Muntes Europa, 1998] behind the HAM concept is to use charge air with 100% relative humidity at a higher than normal charge air temperature. As steam has twice the specific heat capacity of dry air, the specific heat capacity of the cylinder charge is increased. At the same time, the steam occupies space that would normally contain oxygen, and the concentration of oxygen in the cylinder charge is reduced.

On new ships it is expected that the investment costs will be more or less the same as for a SCR installation. A retrofit on an existing ship is expected to be cheaper than an SCR retrofit. The running expenses in relation to a HAM installation is however far less than for a SCR installation [Bunes et al.,1998].

*Miller Cycle:*
By closing the inlet valves earlier, the temperature at BDC and during the hole combustion cycle can be reduced, and thereby also the NOx. It requires an efficient turbocharger with higher pressure ratio to feed the engine with the required amount of air. [CIMAC, 1998].

Adoption of the Miller Cycle requires another camshaft and in most cases also another turbocharger, compared to standard for the actual engine. The concept has not been adopted to any extent so far.

*EGR:*
By EGR a small portion of the exhaust gas is routed back into the charge air, thus increasing its heat capacity and lowering the oxygen concentration. This results in lower peak temperatures, and thus a reduction of $NO_x$ formation. Investment costs are in the magnitude of a water emulsion installation.

*SCR:*
In selective catalytic reduction (SCR) the $NO_x$ in the exhaust gasses is reduced to nitrogen ($N_2$) and water by the use of a catalyst and a reducing agent. This is one of the most efficient means found in the marked for reducing $NO_x$ content from exhaust gasses. At design load, 85–95% of the $NO_x$ may be removed from the exhaust gasses when applying this alternative.

Even with today's technologies, SCR systems are relatively large installations, but may replace the silencer. The investment costs of such an installation lies in the area of 50 % of the diesel engine for a 7 MW medium speed diesel engine. Both investment and operating cost have been reduced over the past 4-5 years, but has to be lowered even more to make SCR more attractive for ship use.

*Fuel specifications:*
Combustion properties of Light Fuel Oils are good, and the production of $NO_x$ is somewhat lower than that of the Heavy Fuel Oils. Less amounts of $SO_x$ is produced because of the lower sulphuric content. A change over from using HFO to MDO will reduce $NO_x$ formation [IMO 1989]. The $CO_2$ emissions will also be reduced in the range of 4-5 % by using MDO instead of HFO [The Motor Ship, 1999]. The reason for lower $CO_2$ emissions is mainly because of the lower Carbon/Hydrogen ratio of MDO.

However, it is no driving force a change over as long as the difference in price between the two is at the current level (80-110$ difference between IFO380 and MDO in January 2000 [Telemarine, 2000]), and present emission requirements can be meet even with HFO [Hennie et al. 1998].

*Machinery operation and strategies:*
The success of operational strategies is dependent of the overriding and main governing parameters for the specific trade as: cargo owners time schedule, fuel bill payer, fuel oil prices etc.

When looking at operating strategies that favours fuel economy, multi-engine plants are in favour as they open for more flexibility in operation adapted speed requirements, manoeuvring, stand-by etc. [Stenersen et al.1996]. A set of new cruise ship will even have combined gas turbine and steam turbine integrated electric drive system (GOGES), which will offer a thermal efficiency as high as 50% [Diesel & Gas Turbine, 1999].

*Machinery condition/efficiency monitoring*
Efficiency monitoring could incorporate more regular use of systems for monitoring machinery efficiency and planning related maintenance and adjustments based on an optimum time interval. This could reduce the specific fuel oil consumption for the diesel engine and hence the emissions level for $CO_2$. For the main engine it is normally today good routines for controlling the efficiency. The deviation in the main engine efficiency is seldom increasing above a level of 1 – 2 % from the normal range. The control is mostly performed at a periodic manner. By using an on-line system, which could catch any deviation more quickly, a potential increase in the average efficiency could possible be obtained. A possible figure could be in the range from 0.5 – 1 % in improvements.

*CO and HC*
It important to remember that a modern diesel engine basically has very low CO and HC emission, typically in the range of 0.1 - 0.2 g/kWh for both. Measures for reducing fuel consumption also have a positive impact on CO and HC emissions.
Measures for CO and HC reduction alone are not cost effective and difficult to justify. Reductions of emission of these components have to come as an extra profit of a $CO_2$ or $NO_x$ reduction measure.

*$SO_x$*
Sulphur from the fuel is during combustion transformed to $SO_x$ and particularly $SO_2$. The $SO_2$ emitted is fuel specific, meaning that reduction of sulphur in fuel gives a reduction in $SO_2$ from the exhaust. A scrubber could remove sulphur in the exhaust gases where the sulphuric compounds are absorbed by seawater. A seawater scrubber a described here is a rather costly and space demanding installation [Geist et al., 1997].

About 80% of the marine fuel consumption are HFO with a sulphur content varying from 2.5% to 4.5%. MDO contain less than 1.5% sulphur. For coastal water operation the use of MDO with low sulphur content (0.5%) is steadily increasing. If aiming for a significant reduction of the sulphuric effluent from shipping it seem clear that means like fuel taxation and legislation has to be used more actively [OECD, 1996].

Table 5-5, and Figure 5-4 summarise the reduction potential and the approximate cost of applying the different measures described above. Figure 5-5 shows the trade-off between measures for reduction of $NO_x$ and $CO_2$ emissions.

**Table 5-5 – Short term $CO_2$ and $NO_x$ reduction measures in new ships**

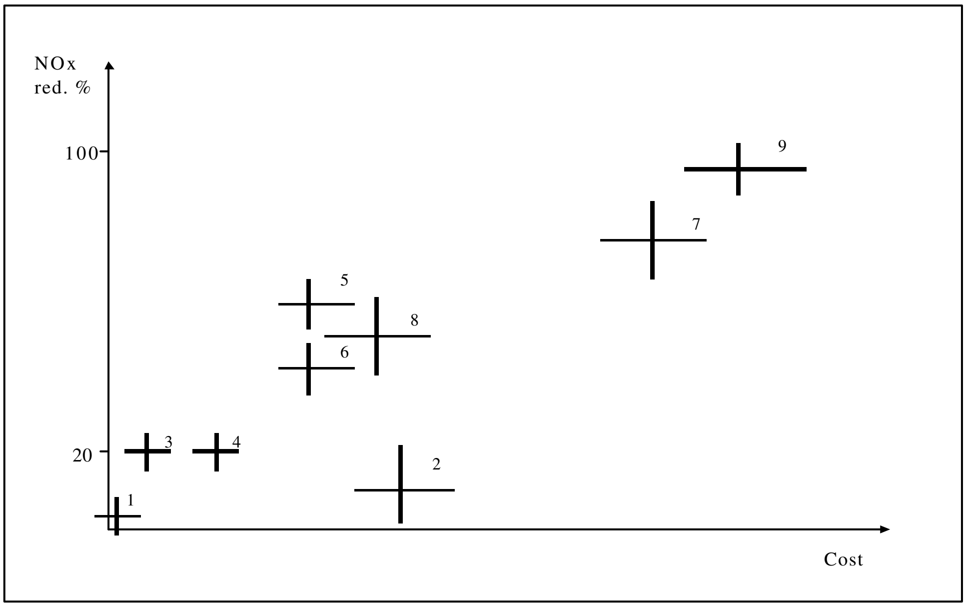
| Methods | | Reduction | | Cost | |
|---|---|---|---|---|---|
| | | $CO_2$ | NOx | Initial [1] | Operating [2] |
| 1 | Efficiency optimised [4] | 10-12% | | none | none |
| 2 | Plant concepts | 5 % | | 20% | none |
| 3 | Retarded timing | +10% | 10% | none | none |
| 4 | Low NOx combustion | 2-3% | 20% | none | none |
| 5 | Water injection | | 60% | 5% | none |
| 6 | Water emulsion | | 30% | 5% | 2% |
| 7 | HAM | | 60% | 20% | 10% |
| 8 | EGR | | 40% | 10% | 40% [3] |
| 9 | SCR | | 90% | 30% | 50% [3] |
| 10 | Fuel specification | | 10% | none | 40% |
| 11 | Machinery condition | 1% | 4% | 2% | |

[1] Extra cost relative to engine total cost

[2] Extra cost for fuel, water or urea

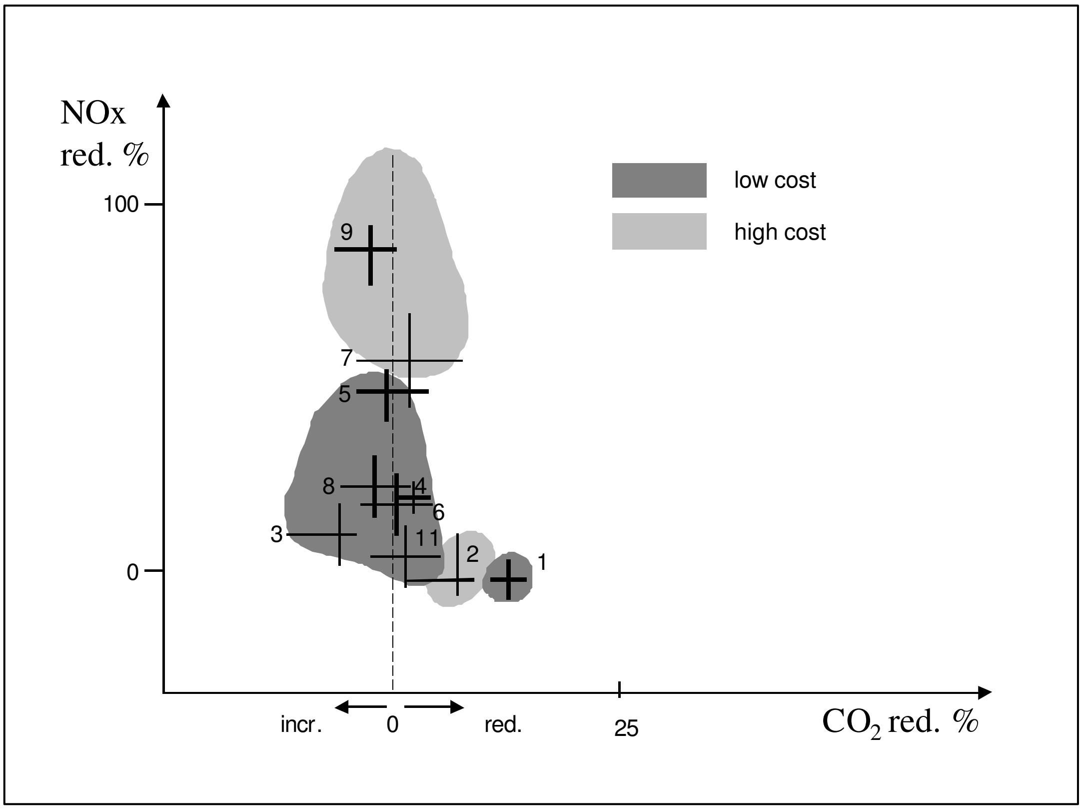
[3] For HFO machinery which has to switch to MDO, ekstra fuel cost is 40%

[4] For medium speed engines. Slow speed engined: 2-5 %. For highest percentage NOx increases.



* Numbers refer to type of measures in Table 5-5.

**Figure 5-4 - $NO_x$ reduction measures - cost comparison**



* Numbers refer to type of measures in Table 5-5.

**Figure 5-5 – $NO_x$ reduction measueres and $CO_2$ trade-off.**

Table 5-6 summarises the potential for fuel savings in new ships by machinery measures compared to existing marine engines 10-20 year old.

**Table 5-6 – CO2 reduction potential new ships - machinery measures**

| Measure | Fuel/$CO_2$ saving potential | Combined | Total |
|---|---|---|---|
| 1. Efficiency optimised | 10 -12 % [1)]<br>2-5 % [2)] | with 10.<br>14 - 17% | 14 - 23% |
| 2. Plant concepts | 4 - 6 % | with 1. + 10.<br>18 - 23% | |
| 10. Fuel (HFO to MDO) | 4 - 5 % | | |
| 11. Machinery monitoring | 0.5 -1 % | | |

[1)] State of art technique in new medium speed engines running on HFO.

[2)] Slow speed engines when trade-of with NOx is accepted.

### 5.2.4. Machinery: existing ships

It is assumed in the following that the engine onboard has a reasonable lifetime left and that engine modification can be justified compared to a new complete installation. As the reduction techniques in question are described in detail in Appendix 3 the next sections focus more on a possible applicability on existing ships of measures described above.

Efficiency improvement of machinery on existing ships can be divided into different categories. Improvements may vary from minor modifications to the most extensive, reflecting both the magnitude of improvement and the costs:

- Fuel injection can be modified so that the amount of fuel is injected over a shorter period of time. The cost involved by fuel injection modification is moderate. Fuel consumption can be reduced in the range about 2-4 g/kWh by applying this measure.
- A replacement of an old turbo charger with a new modern normally requires some adaptations for the new one to fit in. The effect on the engine overall efficiency is in the same magnitude as for the simple rate shaping described above. Retrofit of a turbo charger installation represents a significant cost, and hence the payback should be quite clear before applying this measure.
- Engine efficiency rating implies quite extensive modifications, including an engine upgrade with a set of changes. For implementation of this measure, the mechanical strength of the engine has to allow for increased peak pressure (10-15 bar).

Of the measures discussed in this part efficiency rating is the most extensive and thereby most expensive. Compared to the alternatives efficiency rating is found to be the measure that pays off with highest efficiency gain. A reduction in specific fuel consumption in the magnitude of 8-10 g/kWh may be achieved for medium speed engines. A slight increase in $NO_x$ has to be encountered.

*Timing retard:*
Retarded fuel injection timing is the simplest way to reduce $NO_x$ from a ship diesel engine. This measure can be implemented without hardware modification or extra cost. Retarded timing alone have a negative effect on fuel consumption (specific $CO_2$ increases). Reduction of the $NO_x$ emission level in the range of 6-8 g/kWh is possible, but at a cost of an increased fuel consumption of 5-7 g/kWh.

Most measures imply retrofit and engine modifications aiming for an improved combustion in order to reduce $CO_2$ and $NO_x$ emissions. The possible measures descried in the following are all primarily for $NO_x$ reduction and imply additional or modified equipment installed.

*Low $NO_x$ combustion:*
Some engine manufacturer can offer retrofit/upgrading packages for ”low $NO_x$ combustion” without increase of fuel consumption. A low $NO_x$ combustion upgrade on an existing engine implies to some extent engine component retrofit. The reduction of $NO_x$ emission is in the range of 4-6 g/kWh [Wärtsilä NSD, 1997].

*Water injection:*
Water injection to reduce $NO_x$ is an effective measure (50-60% $NO_x$ reduction) which can be retrofitted on existing engines. The main components are the combined injector, common rail water supply system and electronically control system. Retrofit cost figures are estimated to approximately 25 USD pr. kilowatt. The operating cost inclusive maintenance is about 4-5 % of fuel costs [Wärtsilä NSD, 1998, Diesel & Gas Turbine, 1999].

*Emulsion:*
Fuel emulsion (adding water in fuel) is a $NO_x$ reduction measure where the necessary equipment can be installed on existing engines. The reduction potential without penalty on fuel efficiency is in the range of 20-25%.

*Humid Air Motor (HAM):*
Implementation of the HAM technique on existing engines can result in up to 60% reduction of $NO_x$ emission level. The technique is however new and the long-term operational effect is not fully proven. In existing ship it is in most cases difficult to install the HAM equipment, mainly because of the rearrangement of the air supply system to the engine and the additional space required. Most engines have a turbo-charger and aftercooler system that is heavily integrated and matched for the specific engine. Engine manufacturers may be reluctant to modify this original integrated system solution [Bunes et .al, 1998, Munters Europa 1998].

*Miller Cycle:*
The Miller principle and measures as described on new engines are also valid for existing engines.

*Exhaust Gas Re-circulation (EGR):*
Several problems need to be addressed and solved before EGR will be an applicable measure for existing or new ships. The main challenge is the re-entrance of particulates damaging for the engine, especially when running on HFO and therefore very limited application is foreseen [EPA 1998, DNV, 1998].

*SCR:*

A properly operating SCR installation can remove up 95 % of $NO_x$ components from the exhaust. It can be installed on existing machinery as retrofit packages, which includes the reactor, urea storage/dosing and control system. For installation on an existing ship there are some practical limitations due to the need for space. Although the reactor can replace the exhaust silencer it can be rather costly to install. In addition to the space for the reactor, there is also need for storage space for urea.

*CO and HC*

Efforts on upgrading an existing engine normally also pay off with minor reductions on CO and HC emissions. In the overall perspective these gains are very small as the CO and HC emissions from the diesel combustion process are very low initially. Due to this reduction measures for CO and HC have not been further assessed in this report.

*$SO_x$*

The $SO_x$ emissions are related to the quality of the fuel. Only a dramatic turnover from high sulphur to low sulphur fuel oil can have a major impact on $SO_x$ emissions from the existing fleet.

**Table 5-7 - Emission reduction in existing ships - applicability**

| Methods | Applicability | Cost | Reduction potential |
|---|---|---|---|
| Efficiency rating | +++ | Small + | $CO_2$ 5-8 % [1)] |
| Retarded timing | +++ | Small | $NO_x$ 10%, $CO_2$ +10% |
| Low NOx comb. | ++ | Medium | $NO_x$ 30%, $CO_2$ 2-5 % |
| Water injection | + | Medium | $NO_x$ 60% |
| Water emulsion | + | Medium | $NO_x$ 25% |
| HAM | - | High | $NO_x$ 60% |
| EGR | - | Medium | $NO_x$ 20% |
| SCR | - | High | $NO_x$ 90% |

[1)] For medium speed engines. Potential on slow speed engines is lower, approx.2 %, 4-5% if trade-of with NOx is accepted.

| | |
|---|---|
| +++ | Easy to implement, not costly, no extra operating costs |
| ++ | Component retrofit, extra investments, no extra operating cost |
| + | Component retrofit, new systems, extra investments, add minor operating cost |
| - | New systems installed, extra space required, extra investments, add extra operating cost |

Figure 5-4 above compares $NO_x$ reduction measure and cost for new ships. The figure is to a large extent valid also for similar measures on existing ship machinery for the techniques that is possible to implement. The $NO_x/CO_2$ trade off (Figure 5-5) will also be valid for measures on existing machinery systems.

Table 5-8 summarises the potential for fuel savings on existing ships by machinery measures.

**Table 5-8 – $CO_2$ reduction potential in existing ships - machinery measures**

| Measure | Fuel/CO2 saving potential | Combined | Total |
|---|---|---|---|
| Fuel injection | 1 - 2% | 5 - 7% | 5 -12 % |
| HFO to MDO | 4 - 5% | | |
| Efficiency rating | 3 - 5% | 7 - 10% | |
| HFO to MDO | 4 - 5% | | |
| Efficiency rating + TC upgrade | 5 - 7% | 9 - 12% | |
| HFO to MDO | 4 - 5% | | |

### 5.2.5. Operational control

The term operational control is used in this context to consider alternatives to technical solutions to obtain reduced greenhouse gas emissions. As the emissions are related to the consumption of fuel onboard, the various options considered will be evaluated according to influence on fuel consumption.

As opposed to the evaluation of technical measures for reduction of emissions, the external factors affecting the various trades will be taken into consideration as far as possible when considering operational measures.

The operation of one ship or a fleet will be adjusted to the market situation. In a segment of the market, the supply and demand will correlate according to the governing market mechanisms for the segment. Based on historical data, the size of the fleet and the demand for tonnage has been found to be unbalanced for several commodities during several periods of time [Stopford, 1997].

In order to consider operational control in relations to the market demand for shipping services, the productivity of the fleet may be applied as measure for considerations on how operational control may reduce fuel consumption. If it is assumed that the productivity of a fleet segment should be equal or better than the present situation, the different factors affecting the productivity may be considered from a perspective where reduced emissions is the target for improvement. This assumption is applied based on the fact that shipping supply has limited influence on the demand. One simple reason for this is that changes in supply (measured in tonnage) will have a slow variation, while demand may fluctuate rapidly as an effect of external factors. The efficiency of the fleet will in this context offer a substantial flexibility in order to adjust to variations in demand.

Operational profile of a vessel or fleet will determine the operational efficiency in terms of transport work. The fleet productivity (P) for bulk transport may be expressed theoretically as [Wergeland, Wijnolst, 1996] :

$$P = f(A, CU, L, W, B_f, V)$$

Where

$A$ = Active part of fleet
$CU$ = Load factor, representing utilisation of capacity
$L$ = Average length of haul (loaded condition)
$W$ = Time not at sea (off-hire, loading/discharging)
$B_f$ = Ballast factor, relative time in ballast vs. in loaded condition
$V$ = Average speed

In the following, the various options for operational control will be discussed in accordance to their effect of reducing CHG emissions.

**Choice of speed**
For a given ship in a given condition, the fuel oil consumption, and thus the greenhouse gas (GHG) emission, will mainly be a function of the ship speed.

The fuel consumption per distance sailed will approximately increase proportionally with (at least) the square of the speed.

Limitations on speed selection
From the ship owner's point of view, planning of both fleet operation as well as the speed of each ship will be selected from economical considerations, dependent of the present and expected market situation (fleet planning is further discussed later on).

Optimal speed, from an economical point of view, may be defined as the speed that maximises the difference between income and expenses (per time unit) of the ship. Models for determination of optimal speed of a ship can for instance be found in [Ronen, 1982].

"Optimal speed", however, will not necessarily be identical as seen from the view of different participants in the transport chain. The cargo owner will normally consider the value of his cargo and the time of port arrival in relation to the transport cost. The ship owner must evaluate his income and costs, normally given by a contract. Contract forms and chartering conditions, however, will vary between different trades.

In a market with excess capacity of tonnage compared with the cargoes available, slow steaming can be favourable. However, before implementing "slow steaming", service level demands from the cargo owner must also be considered.

If the "optimal speed" (from an economical point of view) is close to the maximum speed of the ship (in a favourable market), the ship owner will normally select a "minimum time" strategy for the ship. In this case the ship will be operated at highest possible speed (only limited by technical and safety factors). To limit the ship speed in this case from an ecological point of view, this may only be achieved by means of law imposed speed limitations or penalty tax in relation to a high fuel consumption level.

If the optimal speed of the ship is lower than the maximum speed of the ship, the ship owner may select a "Just in time" or "Slow Steaming" strategy. In this case the ship will be operated at a reduced speed. From an economical point of view, slow steaming is normally of interest only if the number of ships, and then transport capacity, is high in relation to a given market.

For most ship engines, running at reduced speed / slow steaming may, however, cause problems. Such problems may be vibrations (critical RPM of engine / shaft) and accelerating sooting in the exhausted gas channel. Sooting problems are normally coincident with incomplete combustion and increasing GHG emission per fuel unit consumed. For ships permanently operating at slow speed, however, engine modifications / de-rating may be a solution.

**Weather routing**

Varying weather, current and depth conditions during a voyage affect the ship speed. Through routing techniques and/or fuel savings may, however, be gained. For such optimisations, a reliable weather and current forecast will be needed.

Weather routing decision support systems are available on the market. The systems may combine vessel information and weather forecast with the planned departure and position of the arrival port. Main parameters for the choice of a route are safety, avoidance of cargo damage, comfort of crew and passengers, limitation on time of arrival, maintenance work and economy. Weather routing decision support systems can only take into account a limited amount of these factors.

Factors affecting the benefits of using weather routing [Lepsøe, 1997]:

- The effect is reduced with increasing experience and knowledge of crew in the field of navigation.
- Studies indicate that the effect increases in areas with unstable weather, such as e.g. northern and southern parts of the Atlantic and the Pacific ocean, southern part of Indian ocean (particularly in the winter season)
- Type of trade. Vessels operating in the spot market will operate in various waters not well known or frequently visited by the crew
- Length of haul. The gain is reduced by reduced sailing distance.

The cost of installing a weather routing system is limited (USD 5.000-10.000). Weather forecast data are commercially available, and the main cost of applying a weather routing system is related to the purchase of these services. The benefit measured in reduction of time and/or fuel has been found to be in the area of 2-4%.

Ocean currents may also have significant impact on the fuel consumption. A study conservatively estimates that exploiting currents in the routing could reduce the annual fuel costs of the world commercial fleet on trans-Atlantic and trans-Pacific routes by $80 million [Lo, McCord, 1992]. These savings are given relative to routes where the ocean currents are ignored.

### Optimising operating parameters

There are different operating parameters that may be varied to contribute to reductions in GHG emissions.

Speed or power variation

Speed or power variations during a voyage will, compared to steady running, increase the fuel consumption. Steady conditions during a voyage will therefore be favourable. A steady RPM will normally be the simplest option to implement and also the most economical.

Steady power (minimum RPM variations) during a voyage will keep the total fuel consumption to a minimum. The saving potential is estimated to be 0,1 - 2 % of the total fuel consumption compared to normal practice with higher speed at the first part of the voyage.

To implement these savings, procedures for selection of RPM in relation to a given ETA (Estimated Time of Arrival) should be given more attention. Such procedures may, for example, be integrated as a part of a weather routing system. At least, education and motivation of the navigators must have priority.

Optimal trim

Other operational factors affecting the fuel consumption are optimal trim and propeller pitch. Optimal adjustment of the autopilot will, in addition, minimise the added resistance from use of rudder.

Optimal trim giving maximum speed at a given mean draft and engine power have a saving potential of 0,1 - 1 % of fuel consumption compared to normal practice. To implement this strategy, optimal trim conditions must be determined by ship model tank tests or full-scale measurements on board the ship.

Minimum ballast

Minimum ballast (decrease ballast and extra bunker to a minimum) may have a saving potential of 0,1 - 1 % of total fuel consumption compared to normal practice. To implement this minimum ballast strategy, propulsion efficiency and weather and stress dependent ship safety has to be taken care of. Improved procedures have to be implemented for practical utilisation of this potential.

Propeller pitch

Optimal propeller pitch on CP propellers may provide a saving potential of 0,1 - 2 % of total fuel consumption compared to normal practice. To implement these savings, optimal pitch conditions dependent on both draft, speed and weather conditions must be determined. Adjustments of propeller pitch may either be performed manually or by means of an automatic system.

Optimal rudder

Steady rudder / Minimum Rudder angle variations to keep total fuel consumption at a minimum (require autopilot adjustments) may provide a saving potential of 0,1 - 0,3 % of fuel consumption as related to normal practice. To implement these savings, optimal autopilot adjustments (dependent on both draft, speed and weather conditions) should be determined and followed up by changing conditions. A computer-based autopilot, based on multivariable controller principles, will normally give the best performance. An old fashion autopilot with low performance may, with advantage, be exchanged with a new and more efficient one.

### Time spent in ballast and utilisation of capacity

Time spent in ballast and utilisation of vessel capacity may influence total GHG emissions. The free market in shipping may, however, hamper reductions in GHG emissions. A typical example of this may be found in how the tank market operates. In a market with excessive supply of tonnage, vessels very often position themselves in long ballast trades to compete for new loads. This situation certainly affects the capacity utilisation of the tanker fleet in common and thus also the GHG emissions. This situation may theoretically be prevented by political market regulations, which in general may have many negative commercial effects, and will as such not be elaborated any more in this context. Several topics that contribute to improved utilisation of vessel capacity may be considered.

Improved fleet planning

Better utilisation of fleet capacity can often be achieved by improved fleet planning. An increased fleet utilisation will most often result in reduction in fleet fuel consumption and hence a reduction in the GHG emission. An example of this is the study performed on the operation of supply vessels outside the Norwegian Coast, where one by improved utilisation of the fleet managed to reduce the number of vessels involved in the operation by approximately 40 % [Fagerholt, Lindstad, 1999]. The reduction of $NO_X$-emissions is estimated to be in the same size of order.

Another example is given by Miller [Miller, 1987], where reductions of 5 - 15 % in fuel consumption were achieved for a specific shipping company through better planning of the ships' operation.

Pooling of cargo

Pooling of cargo for increased vessel capacity utilisation may also considerably influence the GHG emissions. Shippers actively co-operate to build up common logistics systems to reach the market, bearing in mind that more cargo opens new possibilities for increased logistics efficiency.

Among the various examples of the effects of cargo pooling, one may look at a Norwegian case that is documented. Land based industries (fertiliser, ferro products, aluminium and forest products) co-operate on building common logistics solutions for export of cargo from the

West Coast of Norway to the Continental, European and foreign markets. There is a considerable potential for increased logistics efficiency by these solutions, and thus also for reduced GHG emissions.

### Reduced time in port or off-hire

Time saved in port from more efficient cargo handling, mooring, berthing and anchoring may be used to lower the speed at sea accordingly and thus saving of fuel.

Cargo handling

Time saved in port due to efficient cargo handling may (among other options) be used to reduce ship speed at sea and thus save fuel and GHG emissions in the range of 1 - 5 % of total fuel consumption compared to normal practice. For cargoes with high handling complexity, special planning tools may be implemented. In most cases, however, systematic follow up of handling actions in relation to handling time, may be used for determination of more efficient procedures and development of new technology.

Reduced time in port may also contribute to improved ship utilisation and thus reduced emissions. In the EU 4FP project "Improved Port Ship Interface – IPSI", new technologies for Ro-Ro cargo handling were developed. A potential for a 75% reduction in time in port compared to conventional technologies was concluded. This highly influences the capacity utilisation of the vessel, and may as such also influence the total emissions [IPSI, 1996 – 1998]. The effect of reduced time in port is visualised in the modal comparison presented in chapter 6.

Anchoring and mooring

Time saved in port from efficient mooring, berthing and anchoring may also be used to reduce ship speed at sea and thus save fuel. Reductions in GHG emissions up to 1 - 2 % may be achieved compared to normal practice. The role of port facilities in reducing emissions, including requiring use of low-emission tugboats rather than having large ship engines running in port and other potential logistical efficiencies may provide significant contributions. The role of the port has not been addressed in this study.

### Maintenance

Through a more efficient maintenance, two main effects may be achieved, namely reduction of off-hire and keeping the efficiency of hull, propeller and machinery at a highest possible level.

Efficient maintenance and co-ordination with operational tasks, may be a very important contribution to the reduction of fuel consumption in two ways.

Reduced off hire and corrective maintenance actions delaying the ship will increase the ship availability and may give room for further reduction of fuel consumption and GHG emissions.

**Summary, operational measures**

To achieve fuel and GHG savings, relevant measures must be carried out. These measures may result in costs related to investments in both new equipment (sensors, automation, etc.), new procedures and routines (data collection, storage and handling), decision support systems as well as education and motivation of personnel.

Most measures discussed in this report may be applied on both existing as well as new ships. A minimum of technological changes is required.

Implementation of measures involves not only the ship and ship owner, but also the cargo owners, port authorities and operators, governmental and classification societies, etc.

**Table 5-9 – Summary of possible operational measures**

| Option | Fuel saving potential | Combined potential | Total potential |
|---|---|---|---|
| **Operational planning / Speed selection** | | 1 - 40 % | 1 - 40 % |
| - Improved fleet planning | 5 - 40 % | | |
| - "Just in time" routing | 1 - 5 % | | |
| **-** Weather routing | 2 - 4 % | | |
| **Miscellaneous measures** | | 0 – 5 % | |
| - Constant RPM | 0 - 2 % | | |
| - Optimal trim | 0 - 1 % | | |
| - Minimum ballast | 0 - 1 % | | |
| - Optimal propeller pitch | 0 - 2 % | | |
| - Optimal rudder | 0 - 0.3 % | | |
| **Reduced time in port** | | 1 – 7 % | |
| Optimal cargo handling | 1 - 5 % | | |
| Optimal berthing, mooring and anchoring | 1 - 2 % | | |

Table 5-9 provides a summary of the most relevant operational measures available and the potential for fuel savings. From the discussions above, it is clear that total effect from combination of different measures is difficult to predict or identify. In order to provide a better understanding and quantify some of the most obvious measures, a modal analysis is presented in chapter 6 illustrating the effect of different measures for different ship categories.

## 5.3. Long-term considerations – new and emerging technologies and trends

### 5.3.1. Hull and propulsion

### 5.3.2. Energy efficient hull/propulsive system/propeller design

The main innovation in ship design during the recent years has been towards larger and significantly faster ships for passenger and car transport as well as transport of high-cost manufactured goods. Such vessels have remarkably much higher fuel consumption per ton of cargo than conventional vessels. They are motivated by the need to fill the gap between air cargo and traditional shipping with respect to price and delivery time. This is illustrated in Figure 5-6. Neither the SeaLance nor the Fastship concepts have been built.

The Fastship concept is fairly close to realisation, while the SeaLance is much less developed, but still pretty typical of the current trends in fast sea transportation. SeaLand built eight of the SL-7 containerships in 1973, but soon laid up due to a combination of factors, one of them being excessive fuel cost.

The 5000 TEU ship is typical for state-of-the-art in conventional large fast container vessels. Note in particular the numbers for tonnes of fuel per TEU moved across the Atlantic by the different vessels. The fast conventional vessel uses 0.35 ton/TEU, while the Fastship uses 4.2 ton/TEU

**Table 5-10 -** Power, fuel consumption and cost of various fast transatlantic freight concepts (adapted from http://www.stud.uni-wuppertal.de/~ua0273/fastship.html)

| | SeaLance DK Group Inc. | Fastship Inc. | Aircargo | New 5000 TEU ship |
|---|---|---|---|---|
| Crossing time | 72 hours | 85 hours | 12 hours | 139 hours |
| Door to door time | 5 days | 5 to 7 days | 5 to 7 days | 7-20 |
| Speed [knots] | 46 | 37.5 | 450 | 23 |
| Power [MW] | 92.5 | 250 | | 49.8 |
| # of TEU (20’) | 1200 | 1432 | 15 | 5000 |
| Cargo Weight | Ca. 10.000t | Ca. 10.000t | 124t | 58.022t |
| Fuel per hour [ton/h] | 24 | 54 | | 9.4 |
| Fuel per trip [ton] | 1720 | 4600 | 70 | 1300 |
| Fuel per TEU [ton] | 1.9 | 4.2 | 6 | 0.35 |
| Fuel price $/ton | 190 | 190 | 211 | 130 |
| Fuel expense per voyage | 327.000$ | 874.000$ | 14.790 $ | 169.000$ |

**Figure 5-6 - Fastship artist impression (left), SeaLance trimaran concept (right)**

The impact of such extremely fast vessels on overall GHG emissions from international shipping is still very small, due to the very small number of such ships. However, it indicates in which direction the innovation in shipping is currently going towards higher speed, not towards lower fuel consumption. No energy saving device or concept can ever compensate for such an increase in speed. This also tells us that we can not use the current development trends and extrapolate into the future to make an analysis of what can be achieved in terms of energy efficient ships. Instead, we will try to analyse what is possible to obtain in terms of energy efficiency with known, but not applied technology.

In order to consider limitations in technological development, the nature of ship resistance is initially briefly described. A simple and common way of expressing ship resistance is:

Total resistance = Viscous Resistance + Residual Resistance

### Viscous Resistance

Viscous resistance is related to the skin friction between the hull and the water. It is commonly divided into a part dependent only on the speed and the area of the underwater part of the hull, and a part dependent on the three-dimensional shape of the hull. In addition, it is common to add a fraction dependent on the quality of the hull surface (a roughness correction). Then the viscous resistance can be written as:

$$C_V = \left(C_F + \Delta C_F\right) \cdot \left(1 + k\right)$$

$C_F$ is the resistance of a flat plate with the same area as the wetted part of the ship hull, while $k$ is the form factor, which means the addition to take the influence of the three-dimensional shape of the hull into account. $k$ has a value in the order of 0 to 0.2 for conventional hull forms.

The viscous resistance components in the preceding text are all expressed in the usual non-dimensional form, defined as:

$$C = \frac{R}{\frac{\rho}{2} \cdot V^2 \cdot S}$$

*R* is the resistance in physical units expressed by the resistance coefficient *C* by dividing by the water density ρ, the ship speed *V* and the wetted surface of the hull *S*. This way of expressing resistance components will be used throughout for all types of resistance components. The importance of the wetted surface and the velocity should be noted. This formulation is chosen because it gives a good representation of most resistance components.

If one accepts this description of the nature of ship viscous resistance, a number of conclusions can be drawn:

- Viscous resistance is roughly proportional to velocity squared
- Viscous resistance is proportional to the wetted surface of the hull
- Hull shape (form effect) is normally a small fraction of the viscous resistance, but might be large if a bad shape leads to excessive flow separation and vortex generation.

Thus, in order to reduce the viscous resistance, one must reduce speed, reduce wetted surface or change the basic frictional resistance (the friction line). Reducing the wetted surface significantly can only be done by lifting the hull partly or completely out of the water, either by static lift (air cushion) or by dynamic lift (planing hulls, hydrofoil, aerofoil). Reducing the wetted surface by lift is in practice only done for very high-speed vessels (above 40 knots, but less for small planing boats). Reducing the basic frictional resistance can be done by a number of different methods:

- Air lubrication in various forms
- Polymer injection in the water
- Special surface properties (shark skin)
- Special surface shape (wavy shape)
- Stepped hulls (high speed craft only)

At the moment, none of these methods are applied on merchant ships. Air lubrication has so far only been applied to very fast vessels (air cushion craft and SES). For conventional ships, no systems that give significant energy savings have been realised in full scale. Polymer injection is costly, and suffers many of the same problems as air lubrication. The surface properties methods are still on the basic research stage, stepped hulls are applicable only to high-speed craft.

### Residual Resistance

Residual resistance is mainly composed of wave resistance, but covers all resistance components not included in the definition of viscous resistance given above. Such components can be wave breaking resistance, spray, air resistance and so on. Air resistance is of minor importance for conventional merchant ships, but might be of significance for high-speed vessels (of the order of 20% of total resistance). Ignoring air resistance at the moment, residual resistance depends mainly on the speed and hull shape.

Residual resistance is usually presented as function of the non-dimensional Froude number $Fn = V/\sqrt{g \cdot L_{WL}}$ , where $V$ is speed in m/s, $g$ is acceleration of gravity and $L_{WL}$ is the waterline length. At equal Froude number, the ratio between inertia forces and gravitational forces will be the same. This means that for the same Froude number, ships of different size (but equal shape) will have the same wave pattern and the same residual (wave) resistance coefficient. The relation between residual resistance coefficient and Froude number is illustrated in Figure 5-7. It is seen that the residual resistance increases sharply as the Froude number increases from 0.3 to 0.5. This has a major impact on the ratio of residual to viscous resistance. Thus, for slow ships (Fn<0.2), residual resistance is of minor importance and so that hull shape optimisation in order to minimise wave resistance is less interesting.

For fast conventional ships, with 0.2<Fn<0.4, wave resistance is potentially prohibitively high so that minimising wave resistance becomes the most important factor for hull shape design.

It is found that viscous resistance accounts for approximately 70% of the resistance for the types of ships considered in the case study presented in chapter 6. Thus, reducing viscous resistance has clearly the greatest potential, but is at the same time considered most difficult at the current stage of technology. Since no practically attractive method for viscous resistance reduction exists at the moment, estimating future impact on GHG emissions is pure guesswork. A 50% reduction in viscous resistance implies a 35% reduction in power consumption at a fixed speed. For a container case ship a similar reduction in power is obtained by less than 3 knots speed reduction.

A 50% reduction in residuary resistance gives approximately 15% reduction in power consumption. For the container case ship this reduction corresponds to less than a knot reduction in speed. Only a submarine or an airship obtains a 100% reduction in residuary resistance.

From this, one can conclude that it is only a breakthrough in viscous resistance reduction that can significantly impact the resistance of a conventional surface ship, and that selection of speed is dominating the power consumption.

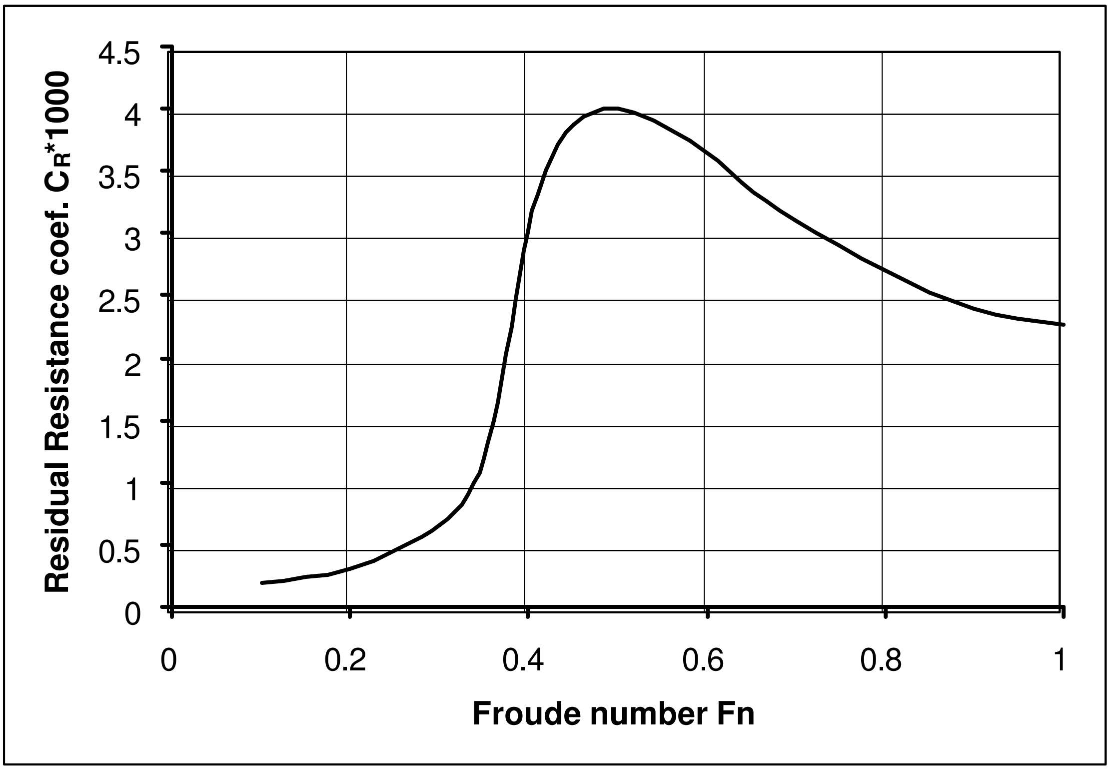


**Figure 5-7 - Principal sketch of relation between Froude number and Residual Resistance. The level of Residual Resistance Coefficient will vary several hundred % depending on actual hull form and ratio between displacement and wetted surface**

### 5.3.3. Supplementary propulsion systems

The efficiency of conventional well-designed propulsion arrangements range 50 - 70% as illustrated in Figure 5-8. The theoretical propulsive efficiency for a given propulsor load (thrust/area ratio) is typically in the range 50 - 97%. Thus, the theoretical maximum gain is in most cases limited to less than 20%, sometimes a bit more if it is possible to increase the propulsor working area ("propeller diameter") significantly. It should be noted that the theoretical maximum assumes no energy loss in the process of transforming the mechanical energy from the engine into momentum increase of the water, something that is not very realistic.

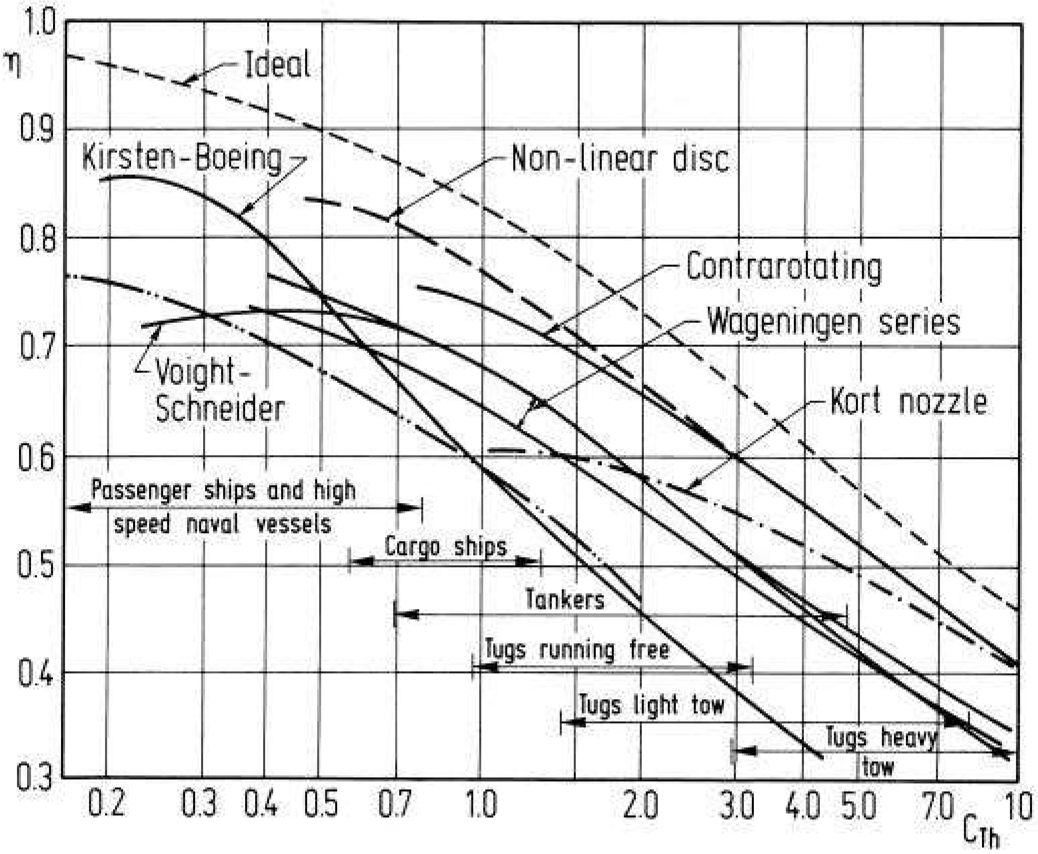


Figure 5-8 - Propulsive efficiency of different propulsion systems

It is clear that there is limited room for innovative solutions to revolutionise ship propulsion. There have been some original inventions over the years, like the Whale Tail Propulsion system and different versions of the paddle wheel. The possible advantage of those systems is that they apply a relatively larger propulsion area. Thus, they have a higher theoretical efficiency. However, they are mechanically more complex than the screw propeller, which adds weight and increase mechanical losses. The paddle wheels also have a lower efficiency converting mechanical energy into thrust. It seems unlikely that any of these inventions will have any impact on the energy consumption of the world fleet.

In the seventies and eighties there were several attempts to use sails and wind power as supplementary propulsion on fairly large merchant vessels. While upwards of 25 vessels, from 50 to 50,000 tons have either been retrofitted or studied for sail retrofit [Bergeson and Greenwald, 1982; Priebe, 1986], there is little or no commercial interest in sails as supplementary propulsion today. The reason for this is the same as it was 100 years ago; fuel oil is inexpensive, powered vessels are not labour intensive and powered vessels' performance is both reliable and repeatable. Currently envisioned concepts for sails as supplementary propulsion result in average fuel savings throughout a vessel's voyage on the order of 10-30% [Bergeson and Greenwald, 1982; MacAlister, 1982]. With anything near the current bunker price, this is not enough saving to warrant the investment, additional maintenance and crew requirements, as well as the restrictions the sailing gear will put on the use of deck space.

Wave propulsion is another supplementary propulsion system, where fixed or movable foils in the bow region provides a thrust produced by the vertical motion of the bow relative to the surrounding waves. This concept works well as long as the relative vertical motions are large, which is the case for relatively small vessels moving in head seas of suitable length and height. Thus, the number of ships where this concept would be applicable is small, and the gain for those ships is also small, since the period of time when the wave conditions are suitable is small.

### 5.3.4. Power plants

The diesel engine has during the last two decades been through a remarkable improvement of both specific power and efficiency. The need for more compact engines with lower fuel consumption has been the driving forces in the development.

This improvements has been possible because of a continuos improvement in the fields of:

- Design methods
- Materials
- Turbocharger systems
- Injection systems

In the nineties, development has also focused on $NO_x$ reduction, and most manufacturers can now cope with the proposed legislation requirements to $NO_x$ in the marine sector (IMO/MARPOL Annex VI).

A prediction of what type of marine machinery that will dominate 20 years ahead, are to a great extent dependant of the future external conditions (driving forces). These can be foreseen as:

- Fuel availability and price (especially on HFO)
- Rules and regulations
- Shippers/charterers requirements and profile
- Market demands (economic development)

The long-term development trends will to a great extend depend on what to be focused by the ” participants” involved in future marine development.

*Shipowners primary focus will be on:*

- increased reliability
- propulsion train redundancy
- arrangement and operating flexibility
- reduce operating cost
- reduced fuel cost (energy efficiency)
- lifecycle costs
- fitness to cargo owners strategies
- safe and reduced manoeuvring time

*Cargo owner focus:*

- Increased influence of hole transportation chain
- Prices pr. unit freight (area, ton, speed)
- Buying door to door freight
- Industrialised sea transportation

- Environmental aspect
- Reduced fuel cost (energy efficiency)
- Satellite communication for cargo handling and ship monitoring

*Shipbuilders focus:*

- Cost effectiveness in production/lead time
  - modularization
  - specialisation
  - flexibility
- New machinery arrangements
- Other prime movers

*Community focus:*

- Economic growth - more trade
- Environmental matters (reduction of)
  - $CO_2$
  - $NO_x$
  - $SO_x$
  - particulates
- Resources availability

*Engine suppliers focus:*
Areas where the technical development are focused at the moment (near future) can be summarised as in Table 5-11 below [The Motor Ship,1999 and MARPOWER -Thematic Network, 1998 and PRODIS-Thematic Network, 1999].

The development for more efficient and powerful engines will continue. However, it is not likely that the improvement seen in the last twenty years will continue with the same magnitude. Even a less extensive development from today's level is foreseen to require huge escalation in efforts. Shaft efficiency for a diesel engine has during the last twenty years moved from slightly above 40% up to close 50%. There is still a potential for increase but far from what seen.

When talking to the engine suppliers they are confident that the diesel engine will play a major role even in the next fifty years [The Motor Ship, 1999].

Future requirements to propulsion power redundancy, waste heat recovery (higher energy efficiency) and quality of fuel oil to be used can contribute to make "power plant" solutions in merchant shipping will be more attractive. In such plants the traditional diesel engine will meet more competition from the gas turbines [PRODIS-Thematic Network, 1999].

The diesel engine manufacturers will see gas turbine manufacturers that steadily will increase efforts to participate in a foreseen growing marine market.

**Table 5-11 – Engine development**

**Marine engines - technologies**

| Process segment | Influence on efficiency | Influence on emissions | Technology | Advantage | Disadvantage | Status |
|---|---|---|---|---|---|---|
| Air supply | High | Low | 2-stage turbocharger | | | Prototype |
| Charge condition, ignition, combustion | Low | High | HAM | Low NOx | | Prototype |
| | | | Emulsion | Low NOx | | |
| | | | Water inj. | Low NOx | | Commercial |
| | | | | | | |
| | | | | | | |
| Waste heat utilisation | High | Low | Hot comb. Combi-cycle | High plant eff. | | Prototype |
| | | High | STID | High eff, Low NOx | | |
| Expansion, charge exchange | High | Low | Miller Cycle | Low charge air temp. | | |
| Engine control | High | High | Common rail | Optimal running all loads | Complexity | Prototype/ commercial |
| The intelligent engine | | | Engine control | Optimal running all loads | Complexity | Prototype |

Combined plant:

Power station has for a long time used gas turbines in combination with steam turbine, so called Combi-Plants. By utilising the exhaust waste heat to produce steam for a steam turbine, the overall efficiency is increased considerably. Offshore platforms and even the new cruise ships have recently adopted this concept (COGES).

Even the diesel engine is now under development for running combined-cycle where the exhaust heat produces steam for a turbine (HOT Combustion). Plant efficiency between 55 and 60% is expected

These combined plants will be more attractive the bigger they are. It is difficult to set an exact MW limit, but looking at the new COGES cruise vessels, the plant is typically above 50MW. Thermal efficiency is here expected to be close to 45% [Diesel&Gas Tubine, 1999].

The progress made on generators, motors and power converters also urges for more extensive use of electrical power trains in ships. It also opens for combination of prime movers (diesels and turbines) and optimising of operation adapted the different operational modes.

For the case ship categories herein the diesel engine as prime mover will be dominating also the next twenty years. The fixed propeller drive will probably see more competition from the alternatives (SSP, Azipod, Compass etc).

Gas turbines:
An increased focus from the gas turbine manufacturer on the merchant marine marked is expected in the time to come. The "fight" between diesel and turbine suppliers will probably intensify and urge development for better energy efficiency.

Where power density (kW pr. ton or $m^3$ installation) is important, the gas turbine is favourable compared to the diesel engine. $NO_x$ emissions can be as low as 0.5-1.0 g/kWh using the latest low $NO_x$ techniques. These techniques are also foreseen developed and implemented for transient operated marine turbines. However, shaft efficiency is still not competing with the diesels. But development is going on for making more efficient marine turbines. Shaft efficiency in the range of 40-42 % is reported (Rolls-Royce WR21 propulsion module, turbine with recuperation).

A major drawback for the gas turbine is the requirement to fuel quality. In contrary to a diesel engine, the gas turbine cannot be run on HFO. But a future market switch from HFO to MDO driven by mechanism released by $SO_x$ emission limitations can contribute to outweigh some of the fuel quality drawback of the gas turbine.

Fuel cells (EEC 1994, CARB 1998):
Fuel cells are here discussed under "alternative prime movers", although it is just as much "alternative fuelling" as hydrogen is the fuel. The fuel cells in question all utilise hydrogen as working media in the cell itself. However, different fuels can be used/stored onboard (i.e. methanol, nat. gas etc.), but then a reformer is needed to separate and supply pure hydrogen to the cell.

Fuel cell drive concepts with highly efficient electric drive systems can provide a fuel-efficient, zero emission propulsion concept for the future. Fuel cells are up to three times as efficient as the internal combustion engine with mechanical transmission systems and therefore seem to be one of the most promising option for clean and low-noise propulsion of the future. Achievable fuel efficiencies range in the order of 40 % - 50 % for internal combustion engines and of 45 % - 75 % for methanol or hydrogen fuel cell powered electric drives.

Weight and volume are two significant limitations for the fuel cell technology, partly because of the low volume/energy ratio of hydrogen even in liquid phase. The limitation for applicability in larger scale is connected to more or less the same problems as for direct hydrogen use (storage, production and refuelling). In literature the fuel cell efficiency is normally reported as very high. These figures do not take into account the great energy losses (in the range of 40%) by making the hydrogen fuel. It is also so that fuel cells have their best efficiency in the load range around 30-50%, not as ideal for ship propulsion as for powering cars. Current fuel cells PEMFC for the transportation have a power density of 1200 W/m$^3$ and 700 W/ton and a lifetime of 4-5 years.

The actual types of cells for use in ships are the PAFC (Phosphoric Acid fuel cell) and the PEMFC (Proton Exchange Membrane fuel cell) cell, both utilising hydrogen as fuel.

The main challenges from now on for these alternatives are increase of power density (space and weight), fuel storage, complexity, investment cost, full load efficiency and lifetime. In parallel with fuel cell development and increased applicability, it is assumed that technology and availability for refuelling also will follow to meet market needs. A major question will also be how to make the hydrogen fuel in the future in the most efficient way.

When discussing fuel cells and emissions it is important not to forget the overall $CO_2$ account, included also from hydrogen production. If methanol is used as basis for hydrogen conversion, the fuel cell $CO_2$ benefit is significantly reduced. Technology on fuel cells using hydrogen as fuel has moved forward. There is still put great resources in the fuel cell development programs, and it is expected great improvements in unit/system capacity and costs. The driving force is the automotive industry.

In the near future it is foreseen pilot projects with fuel cells also in the marine sector, then probably in the auxiliary power systems. A prediction for the next two decades do not expect the fuel cell to play any major role as main power for ships.

### 5.3.5. Alternative fuels

#### Distillates

The marine fuel qualities available are:

- Marine Gas Oil (MGO)
- Marine Diesel Oil (MDO)
- Intermediate Fuel Oil (IFO)
- Heavy Fuel Oil or Residual Fuel Oil (HFO)

HFO is the dominating marine fuel. It comes out at the end of the processing line in a refinery and is highly sensitive to the crude oil quality and the refinery structure. Specifications have been developed to a quality level that is acceptable when aiming for a cheap fuel that does not restrict availability with the refinery structure and crude oil in use. As conversion plants, which enables to extract more light distillates from the crude, have been heavily introduced in the refineries for some years, the fuel oil quality has become poorer and an increasing proportion is slowly approaching the critical specification that can be accepted. Not only from an environmental point of view but also from what is acceptable for an engine.

HFO has to be treated onboard a ship. The required heating is normally taken from exhaust waste heat, while the sludge removal requires electrical power (minor). The quality of the exhaust from the ship is not effected significantly by this pre-treatment of fuel. The sludge represents a ”loss” of fuel and a disposal problem. The components removed because they are harmful to the engine will be emitted when the sludge is burned onboard (normally done). The alternative is disposal and burning ashore.
It is a pressure at the moment and probably even more in the future, both from environmental initiatives and also with respect to machinery reliability, to tighter restrictions on marine fuels of which the sulphur content is of most importance.

A global cap of 4.5% sulphur does not have any substantial effect on fuel availability. However, if demand for fuel oil with maximum 1.5% sulphur increases significant in the future, i.e. because of extension of ”$SO_x$ Emission Control Areas”, the picture will be more complex.

Desulphurization of oil is expensive and energy consuming. The refineries will have to decide upon a strategy by either invest heavily in residue upgrading plant or in a residue destruction plant. Future fuel oil demand and future quality requirements will be in favour of the former, for the latter the cost margin between residual and distillate will be important. A variety of refinery processing will emerge, but generally the oil companies foresee an accelerated tightening of fuel oil availability [CIMAC 1998].

What can be achieved by a change to lighter fuels? Assuming an annual marine fuel consumption of approximately 225 Mt in year 2020 and a 80% share of HFO, as today. A full replacement of this HFO by i.e. MDO will reduce $CO_2$ emissions by approximately 36Mt (total amount approximately 700Mt) and $SO_x$ by approximately 5.9 Mt a year (total amount approximately 9 Mt).

The price on marine bunkers vary over time, but for quite some time the price on HFO has been around 60 USD and for MDO 110 USD pr. ton. The difference in price itself illustrates the great future challenges for scenario where a change to distillates is foreseen.

### Reformulated

Reformulation of fuel normally involves the refining process itself, but also mixing of components and additives to obtain certain characteristics. Reformulation has to now mainly been applied to gasoline, and especially in the US, aiming for a more environmental friendly gasoline to reduce harmful exhaust emissions. The term ”reformulation” is also used on diesel fuel. So far this is mainly connected to fuel processing and treatment to obtain low or ultra low sulphur content (< 0.5%).

### Natural gas

Natural gas is an excellent fuel for combustion engines. It is also the biggest energy reserve known and will continue to grow in availability to the public world-wide.

Natural gas can be applied on ships and all the technique needed is available. The main challenges are connected to onboard storage of sufficient fuel, which in most cases should be LNG, and to the infrastructure of refuelling LNG, i.e. practical limitations in applicability.

As an example the case of a container ship with gas-diesel machinery may be considered. The gaseous fuel could be stored onboard in LNG tank containers. The space needed is 2.5-3 times more than conventional HFO storage. Gas fuel for a week at sea (assuming a 30MW powered ship with 150 hours running at 85% load) will typically require 70-80 units of 20' ISO tank containers filled with LNG. This is not realistic particularly because of refuelling/logistics. A piping system onboard will also be extensive and complicated. Emissions are reduced on the same trip with approx. 400 tonnes $CO_2$ , 27 tonnes $NO_x$ and 25 tonnes $SO_x$.

### 5.3.6. Future R&D on ship machinery

It is foreseen that the diesel engine will play a major role in ship machinery over the next twenty years. Research and development will continue to make it even cleaner and more efficient. However, efficiency improvements in the same scale as obtained in the past twenty years are not realistic.

Efforts are foreseen to be in the areas of improved and more sophisticated injection systems, better charge-air systems, better utilisation of the exhaust waste heat, and improved $NO_x$ reduction methods. Improving engine reliability will also be focused even more, as a consequence of the shipowners requirements.

The development of different kinds of propulsion trains (based on electrical power distribution - the power plant concept), steadily open for specialised solution dedicated the type of ship and operation, is expected to continue.

With respect to the alternatives to diesels, strong efforts will be made from the gas turbine manufacturer to capture a greater part of the marine merchant market. To better compete, the overall efficiency will be improved ”combustion wise” but also by offering complete integrated power plant packages, energy optimised.

The development of emission friendly alternatives as i.e. fuel cells will continue. Hopefully the results from the great efforts done on fuel cell for the automotive industry will benefit the marine industry. However, the demand for constantly higher speed and more power even create greater challenges for applicability with respect to power density. The main challenges to overcome with the fuel cell are the low power density and the hydrogen logistics.

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# 6. EFFECT OF IMPLEMENTATION OF TECHNICAL AND OPERATIONAL MEASURES

The initial chapters of the report describe the amount and effect of greenhouse gas emissions from ships, and provide a general description of technical and operational measures to reduce the emissions. Based on the above presentation, the most applicable or cost efficient means for reducing emissions, or the total effect of the various measures, is difficult to consider. Historical data provide clear indications of increased consumption of marine bunkers. As a consequence of the increased total consumption, emissions will increase compared with the figures for the base year of 1996 as presented in Chapter 3.

In order to quantify the effect of various measures, a selection of measures considered most relevant and applicable was chosen for further illustration. A case study was established primarily to quantify the effect of technical measures, while a modal comparison serves as an illustration of the potential of some operational aspects.

## 6.1. Scenario for future growth of GHG emissions from ships – A case study

### 6.1.1. Introduction

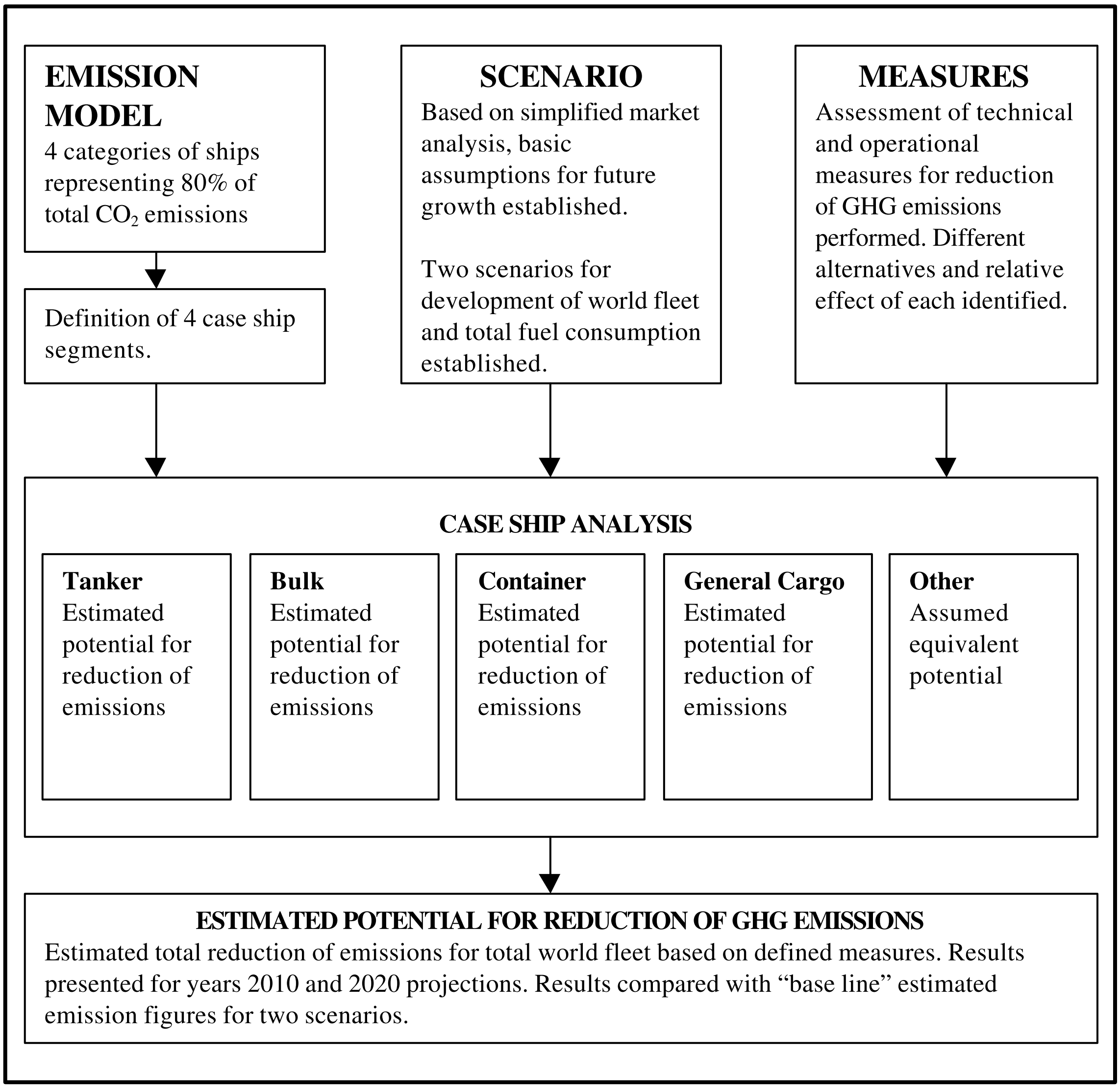
Two scenarios for growth of the world fleet were developed for comparison reasons for a case study. A scenario in this context is a set of assumptions related to the development of the consumption of marine bunkers for the next 20 years.

The primary reason for a case study with a time window of 20 years is the slow pace of introduction of new measures in a large world-wide fleet. A short-term analysis (5-10 years) is considered to provide information of limited value, owing to the fact that the replacement ratio of the fleet is low, and implementation of technical measures on existing ships will require a significant effort over time due to the large amount of vessels. As the uncertainties related to results increases with increasing length of projection, the upper limit for reasonable confidence in the results was chosen to be 20 years. In order to limit the model, results for year 2010 and 2020 are presented.

Within the framework of the defined scenario a set of case studies, considering alternative measures for reduction of the fuel consumption or improved efficiency was performed. The world fleet consists of a large variation of ship types and sizes. In order to simplify the presentation and assessment of the potential of different technical or operational measures for improvement, only four ship categories have been considered. Within the framework of the defined scenarios, case studies on the ship categories tank, bulk, container, and general cargo have been performed. The categories were selected based on their contribution to the overall emissions as presented in Chapter 3.

### 6.1.2. Methodology

The methodology used for the case study is illustrated in **Figure 6-1**.



**EMISSION MODEL**
4 categories of ships representing 80% of total $CO_2$ emissions

Definition of 4 case ship segments.

**SCENARIO**
Based on simplified market analysis, basic assumptions for future growth established.

Two scenarios for development of world fleet and total fuel consumption established.

**MEASURES**
Assessment of technical and operational measures for reduction of GHG emissions performed. Different alternatives and relative effect of each identified.

**CASE SHIP ANALYSIS**

**Tanker** Estimated potential for reduction of emissions

**Bulk** Estimated potential for reduction of emissions

**Container** Estimated potential for reduction of emissions

**General Cargo** Estimated potential for reduction of emissions

**Other** Assumed equivalent potential

**ESTIMATED POTENTIAL FOR REDUCTION OF GHG EMISSIONS**
Estimated total reduction of emissions for total world fleet based on defined measures. Results presented for years 2010 and 2020 projections. Results compared with “base line” estimated emission figures for two scenarios.

**Figure 6-1 – Schematic overview of case study and scenario assessment**

### Case ships to consider

Various options were considered for assessing of fleet growth and the corresponding effect on GHG emissions. In order to perform a quantitative presentation, it was found necessary to divide the fleet into segments, but at the same time limit the amount of information. To consider the total fleet in general terms was considered too coarse, while individual ship representation would require time and resources beyond the framework for the project. Based on the above, the combination of case ships and baseline scenarios was chosen in order to quantify the effect of various measures to reduce emissions.

A case ship is a hypothetical ship, representing a typical vessel in a specific ship category. The size of a case ships was selected based on the contribution from different tonnage groups to the total DWT of one segment. Main-engine effect was found by selecting relevant main dimensions for an actual ship of equivalent tonnage and then making an empirical resistance prediction based on the database from the MARINTEK towing tank. These results compared well with empirical data from DNV fleet information.

Based on the results from the calculation of emissions in 1996, the ship categories were selected from the main contributors to the overall emission level as shown in Table 6-1.

**Table 6-1 – Case ship description, based on Emission Inventory Analysis.**

| | Oil tanker | Bulk carrier | Container | General Cargo |
|---|---|---|---|---|
| DWT | 275,000 | 70,000 | 36,500 | 12,700 |
| Main engine type | Slow speed | Slow speed | Slow speed | Medium speed |
| Speed (knots) | 14 | 14 | 20 | 15 |

The four ship segments represent approximately 80% of the $CO_2$ emissions in 1996.

### Scenario for growth

In order to perform assessments of the potential of long- and short-term emission reductions, the technological alternatives must be combined with a forecast of the market.

As it is considered outside the scope of the report to perform a thorough market analysis, assumptions have been made based on available market information on supply and demand for shipping.

On the supply side, statistical data for some fleet categories was considered. Demand was based on the correlation between economic growth and corresponding world-fleet development.

Numerous attempts have been made to forecast market development for seaborne trade. In this report some very simple models were applied in order to quantify possible reduction of GHG emissions from shipping in a realistic framework. The market forecast was based on two basic principles:

1) World economic growth will continue
2) Demand for shipping services will follow the general economic growth.

Historical data demonstrates how seaborne trade follows the general economic growth.

Based on historical data, it is apparent that the volume of seaborne trade varies significantly both expressed by volume (tonnes) and transport performed (tonne-miles). The different sources considered confirm the difficulty in predicting the future market demand for shipping services based on historical data.

In this study, the main purpose was not to forecast the market development, but to consider possible future reductions of greenhouse gas emissions from ships. In order to do this, a baseline scenario was developed for comparison purposes. The baseline scenario was constructed using a combination of available information and some basic assumptions as presented below.

The following historical relations may be found by compiling information from various sources [ISL,1998], [UNCTAD],[IEA,1998]:

- The world average growth in GDP has been at an annual average of 3.2% during the period 1971 to 1995, while the growth during the last decade has been slightly lower.
- The magnitude of annual growth in seabourne trade varies between different sources. This is due to the use of parameters based on different scales of measure (tonnes or tonne-miles) and different time windows selected from the period 1970 to 1997. From a 20-year perspective, the growth has been found to be in the area 1.5-2.5%, dependent on scale of measure used. The growth during the last decade is found to be above 2.5% measured both in tonnes and tonne-miles.

The perspective in this report is long-term compared to general market analyses. The purpose of the report is to forecast development 10-20 years ahead, and hence short-term fluctuations (1-5 years) cannot be accounted for or anticipated. The figures used in this study related to fleet and market development should only be considered relevant as 10-year average values.

Based on the various sources as indicated above, the following assumptions were chosen for the baseline forecast scenarios:

- Continued annual world growth of GDP, 2000-2020, set to 3.1 %
- Annual growth of seabourne trade, 2000-2020, set to 1.5 %, and 3.0 % (low- and high-growth scenarios).

The predicted growth of GDP was based on the IEA world energy outlook [IEA, 1998]. Although it is assumed that seabourne trade is related to growth in GDP, the growth in world fleet is assumed to be somewhat lower (but in line with growth of seabourne trade). Total growth in GDP will not be followed by a proportional growth in seabourne trade, as many segments included in GDP do not contribute to increased trade (e.g., wholesale and retail, communication). Replacement of old tonnage with more efficient larger, higher speed vessels will also contribute to an expected lower growth of the world fleet.

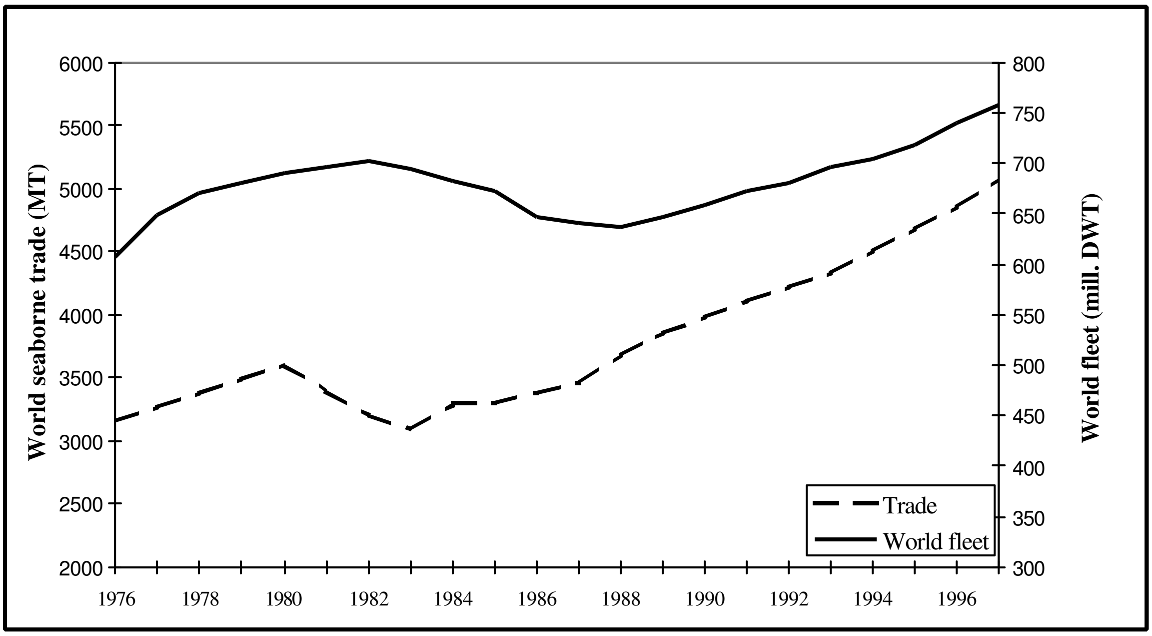


**Figure 6-2 – Correlation between trade and size of world fleet. Development of world trade and world fleet [ISL, 1998][Lloyds, 1998].**

## Measures considered

Based on the assessment in Chapter 5 of the different measures available, the measures given in Table 6-2 were chosen for illustration in the case study.

**Table 6-2 – Measures considered and percentage reduction of consumption from various measures applied for the case ships.**

| | % Reduction from measure | | | |
|---|---|---|---|---|
| **Measures for reduction of fuel consumption and $CO_2$ emissions** | Tanker | Bulk | Container | General Cargo |
| Machinery, efficiency rating existing ships | 3 | 3 | 3 | 3-7 [1)] |
| Machinery, eff. optimised, new ships | 4 | 4 | 4 | 4-8 |
| Switch from HFO to MDO [2)] | 4 | 4 | 4 | 4 |
| Hull, optimal design, new ships | 15 | 15 | 15 | 20 |
| Hull, optimal propeller design, new ships | 5 | 5 | 10 | 10 |
| Hull, improved hull and propeller maint. | 4 | 4 | 4 | 4 |
| Operational control, 10% reduced speed [3)] | Calc. | Calc. | Calc. | Calc. |
| Operational control, weather routing [4)] | 3 | 3 | 0 | 3 |

[1)] Relevant share assumed powered by medium speed ME with higher potential for reductions

[2)] Applied only on a relevant share of the different segments. In the model, 50% change from HFO to MDO assumed during 2000-2010, down to no use of HFO in 2020.

[3)] Calculated from speed/resistance curves established for each case ship

[4)] Applied only on a relevant share of each segment. Not applied on container.

## Basic assumptions applied

- The tanker and bulk fleet have a high average age. It is not taken into account the effect of unbalance between rate of newbuilding and scrapping. The increase in tonnage predicted in the case study does not reflect reduction in average age of fleet, only increase in tonnage. This means that if tankers are allowed to trade beyond 25-30 years of age, the picture will not be correct. Based on the rate of newbuilding and scrapping the last ten years [Lloyds, 1998], it is assumed in the case study that the age distribution will remain relatively constant during the forecast period.
- In the case study, the age profile of a case ship segment and the historical data on ratio of deliveries versus existing fleet have been taken into account when considering the effect of introducing various measures. Although a significant theoretical potential for further improvements has been identified, the effect of a measure must be related to the percentage of the fleet being renewed each year.
- There is an assumption in the forecast that tanker and bulk will see a reduced share of the total world tonnage. This is in line with trends in present statistics. No technology change towards alternative energy sources or significant shift in propulsion systems assumed in the forecast of fuel consumption. No emerging new techniques (i.e. fuel cells) foreseen to be of any significance in the period. The fuel consumption figures are proportional to the growth of the total fleet tonnage. Heavy fuel was assumed to be main fuel type within the time window of the case study unless otherwise stated.

- Different average annual growth was assumed between the fleet segments. This was based on the assumption that the biggest share of increased trade will be found among manufactured products which will be shipped by container vessels or vessels grouped as "others" above (RO-RO, general cargo). Historical data [Lloyds, 1999] confirm that the market share of total world trade has changed for the various commodities and categories of vessels.
- The increase in container fleet was not expected to continue in the same pace as the recent years. This assumption was based on the increased efficiency of the new tonnage introduced. Still the general expectation for the trade is a significant growth for a substantial period of time, and this is accounted for in the model.
- Latest engine technology is taken into use in newbuildings. Slow speed diesel engines were assumed to dominate the tank and bulk segment also in the time to come.
- The speed–power curve for each case ships was derived by searching the MARINTEK database of model tested ships for ships of the same category. Then, a speed–power curve was derived by averaging the resistance of a subset of ships with approximately the same main dimensions (L/B-ratio, B/T- ratio, $C_B$ etc.). The power consumption at the case ship speed was compared with the statistically derived engine power and fairly good agreement was found.
- For each case ship two additional speed–power curves were derived, based on the scatter plot of the speed–power data from the MARINTEK data base, one for the upper and one for the lower limit of power consumption. The scatter plot was produced after all the ships were scaled to the displacement of the case ship by keeping the Admirality number constant. This is the reason why for instance the tanker case ship plot (see Appendix 4) contain data for unrealistic high speeds – the high speed results originate from smaller ships being scaled to larger size, keeping the ratio between length and speed constant.

### 6.1.3. Results

The case studies for the four case ships was used to quantify the effect of implementation of various measures aiming to reduce the emissions from the machinery from the world fleet. Based on the two scenarios presented above, the case ship studies have been combined to quantify the effect of the measures on the world marine fuel consumption and corresponding emissions. The chosen measures will in generally have similar impact on emissions of most components, but is only illustrated for $CO_2$ in the table below. For the remaining part of the world fleet not covered by the study of the case ships, the results below indicate that a similar effect of the various measures is assumed applicable also for these segments.

**Table 6-3 – Results from case study – fleet total.**

| Estimated potential for reduction of emissions from world fleet | | |
|---|---|---|
| Reduction measures | Reduction of $CO_2$ emissions by implementation of measures on world fleet. 1) | |
| | **2010** | **2020** |
| M1. Efficiency rating ME, existing ships | 2.3% | 2.3% |
| M2. Efficiency optimised ME, new ships | 1.9% | 3.2% |
| M3. Stepwise switch from HFO to MDO. | 1.6 % | 3.0 % |
| H1. Optimal hull shape, new ships | 6.4% | 11.6% |
| H2. Propulsion system, new ships | 3.1% | 5.8% |
| H3. Maintenance (hull/propeller), existing ships | 2.3% | 2.3% |
| **Theoretical max. from technical measures** | **17.6%** | **28.2%** |
| O1. Speed reduction of 10% | 23.3% | 23.3% |
| O2. Weather routing | 0.8% | 0.8% |

| Estimated world fleet fuel consumption (no measures applied) | | | | | |
|---|---|---|---|---|---|
| **Scenario 1 - No measures**<br>**Annual growth of fleet 1.5%** | **2010** | **2020** | **Scenario 2 - No measures**<br>**Annual growth of fleet 3.0%** | **2010** | **2020** |
| Fuel cons. (ME) | 165.8 Mt | 192.5 Mt | Fuel cons. (ME) | 203.1 Mt | 256.62 Mt |
| Increase from 2000 2) | 19% | 38% | Increase from 2000 2) | 36% | 72% |

1) Comparison with base line fleet development when no measures are applied.

2) Based on model growth in fuel consumption

Denomination M - machinery measure, H - Hull/propulsion measure, O - Operational measure

The theoretical maximum when implementing all the considered technical measures for the entire fleet is a 17.6% reduction of the emissions in 2010 and 28.2% in 2020. Compared to the two scenarios these values are below the lower boundary for projected growth of fuel consumption and corresponding growth of $CO_2$ emissions. The fuel consumption increased by 46% during the period 1983 to 1993; hence, a growth in line with the scenarios has been experienced earlier during a period of 10 years.

The effect of the measures was found to be different for the different ship segments, and this is further described in Appendix 4.

The case scenario performed illustrates how the potential for various technical measures for reduction of $CO_2$ emissions can not be projected to apply proportionally when implemented for the entire fleet. Although the potential for a single technical measure may be significant, the effect on an aggregated level is reduced due to the applicability for different categories of ships. It further illustrates the need for long-term perspective in order to obtain quantifiable end results, due to the long period of time needed for effect of implementation of measures for new ships.

The case study indicates that the effect of technical measures will be different for different shipping segments. Technical measures may compensate growth in emissions due to growth of the fleet to a certain level, but limitations in reductions of emissions by introduction of technical measures have been identified.

Reduction of speed in general is identified as the single measure that results in highest reduction of $CO_2$ emissions. The reduction will be less if the transport capacity is kept constant, as number of vessels will increase. Even with increased number of vessels, reduced speed will result in reduced total consumption and emissions.

Implementation of new and improved technology is identified as the second best approach to reduce the emissions.

The results from this case study are only based on a technical approach to the task of reducing greenhouse gas emissions from ships. Economical or trade related issues are not properly dealt with, and will affect the above conclusions. Applicability of several measures will have to be considered based on more thorough marked analysis.

## 6.2. Comparison of freight transportation modes

### 6.2.1. Introduction

This chapter presents a comparison of international maritime transportation with other modes of freight transportation (truck and rail). Many previous studies exist that calculate these comparisons. Each of these studies tends to follow one of two approaches:

1. They calculate emissions by mode from national average data that may not represent specific regions or modal trade-offs [*Davis*, 1998; *International Chamber of Shipping*, 1997; *OECD and Hecht*, 1997; *Schipper and Marie-Lilliu*, 1999]; or
2. They develop a geographically-specific case study that may not be valid generally outside of the region considered [*Lipinski et al.*, 1999; *Newstrand*, 1992].

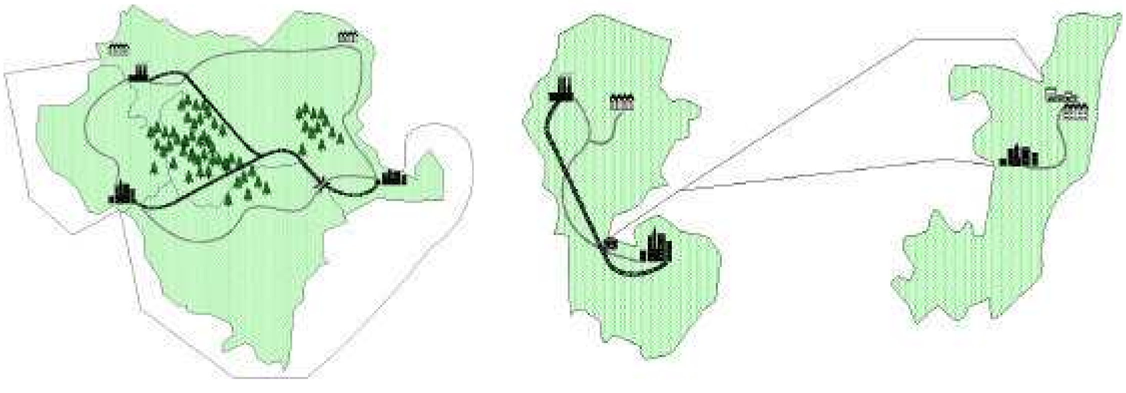
In fact, some studies contradict each other by ranking the modes differently. The analysis presented here attempts to resolve these two approaches by developing a common model that can address both approaches in one framework.

In addition, a comparison of international shipping with other modes of freight transportation in developed nations is presented. Modal shares (by tonne-kilometre) for national freight movement in Western Europe, the United States, and Central and Eastern European countries are reported. Total tonne-km in international shipping is presented by general category of cargo.

### 6.2.2. Methodology

International maritime shipping is a critical element in the global freight transportation system that includes ocean and coastal routes, inland waterways, railways and roads. In some cases, the freight transportation network connects locations by multiple modal routes, functioning as modal substitutes (see Figure 6-3a). In this case, the cargo shipper has some degree of choice how to move freight between locations. However, it is more common for international maritime transportation to function as a modal complement to other modes of transportation. International shipping connects roads, railways, and inland waterways through ocean and coastal routes (see Figure 6-3b).

To identify explicitly the most important energy and environmental performance factors for international shipping, a Freight Transportation Model was developed. The conceptual framework is shown in Figure 6-4.



(a) (b)

**Figure 6-3. Interdependence of Mulit-modal Freight Transportation System as (a) Potential Substitute Modes and (b) Complementary Modes**

This idealised Freight Transportation Model defines an equal amount of cargo to be moved by each mode (ship, rail, and truck) across the same distance. It does not specify one type of cargo, but rather an equal tonnage of cargo that could be carried by each mode. By defining an equal tonnage of cargo and an equal distance, the tonne-km in the denominator are identical for all modes and all modes of freight transportation can be compared directly.

The Model estimates explicitly the energy-use and emissions during "open-ocean" or "highway" or "line-haul" transit, and estimates separately the average energy-use and emissions during manoeuvring, docking, and cargo transfer operations for each mode.

Four types of ships are modelled: 1) oil tanker; 2) bulk carrier; 3) container; and 4) general cargo. This Model use the same baseline characteristics assumed for the case-average ships presented in the case study above.

Some assumptions are mode-specific. By setting the annual cargo movements by each mode equal, the Model includes an estimate of time and energy consumption associated with each "turn-around", i.e. terminal approach, cargo transfer, and departure. In this regard, each mode is unique. For example, the Model assumes mode-specific times for ship terminal loading/unloading that begin when the vessel passes the "arrival-buoy" and end when the vessel passes the "departure-buoy". For a truck, this would represent the period beginning when the vehicle leaves the highway to enter the surface-street traffic near the terminal and ending when the vehicle resumes highway driving. For rail, this represents the period off the main rail line and in the switchyard, while the engine is de-coupled and re-coupled to railcars.

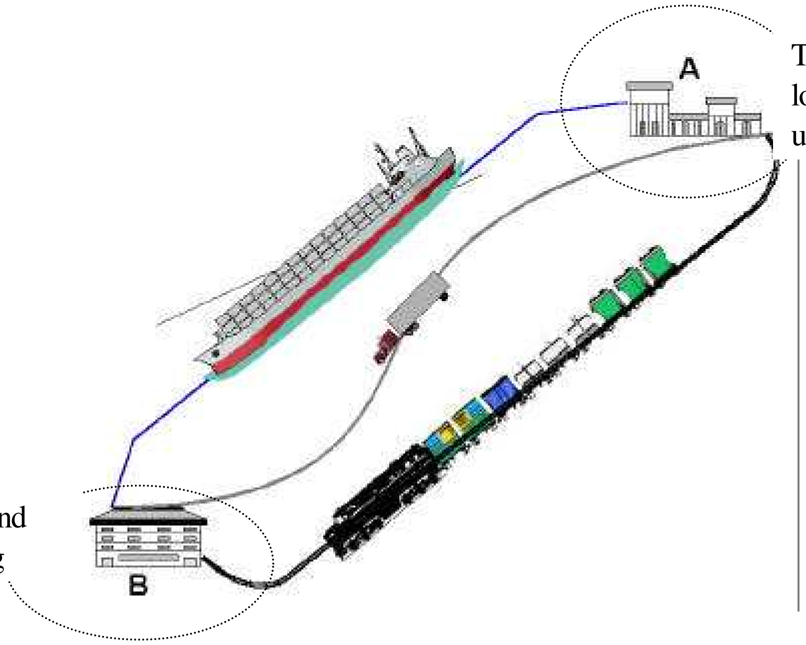
The Freight Transportation Model allows the distance between cargo movements (points A and B in Figure 6-4) to vary, but for baseline conditions a distance of 3,218 km (2,000 miles) was chosen. In the Model, 32.2 Million tonnes of cargo is moved by each mode in one year.

This tonnage is arbitrary, but roughly represents the amount of cargo moved in a moderately large port annually. Lastly, the carbon content of petroleum fuels (distillate and residual) is nearly constant [*Flagan and Seinfeld*, 1988; *Heywood*, 1988; *Lloyd's Register*, 1990; *Taylor*, 1995], well within the uncertainty bounds of the IPCC emission factor for $CO_2$ [*Houghton et al.*, 1996] as discussed in Chapter 1. Therefore, the Model applies the same emission factor for $CO_2$ across all modes. Table 6-4 summarises these common assumptions.

**Table 6-4. Common Model Assumptions across Modes**

| | |
|---|---|
| Cargo Movement Distance | 3,218 km (2,000 miles) |
| Cargo Total Movement | 32.2 Million Tonnes |
| $CO_2$ (kg/tonne fuel)$^{a)}$ | 3,170 |

a) Fuel-carbon content is nearly equal (within 2%) for diesel fuel used in truck, rail, and marine engines and for residual fuel used in marine engines. Uncertainty reported in emission factor (refer to DNV chapter) exceeds variation between transportation modes.



Terminal loading and unloading

Terminal loading and unloading

**Figure 6-4. Freight Transportation Model Design Framework: Each Mode Performs the Same Work in One Year (Equal Tonnage Moved Equal Distance)**

The Model calculations begin by estimating the cargo that can be carried on each case ship (or truck or train). Because DWT describes more than the cargo carrying capacity of a ship, the DWT reported in Lloyds was multiplied by 80% to obtain an estimate of the maximum cargo tons that could be carried; this is consistent with typical voyage estimating factors [*Packard*, 1991]. This value was multiplied by the capacity factor.

Rated vessel speed and the Model distance of 3,218 km (1,739 nautical miles or 2,000 miles) were used to estimate transit times. The slower average manoeuvring speed of 10 knots was applied during the assumed turn-around time in port. From this information, the number of hours per trip, annual number of trips per vessel, and number of ships required to move the total cargo in one year were calculated.

Engine power at cruising speed was used to estimate average daily fuel consumption during transit. Daily fuel-use during manoeuvring into and out of port regions was estimated as presented in Appendix 4. Total fuel consumed per trip was estimated by multiplying the daily fuel consumption for transit and turn-around periods by the amount of time spent underway and manoeuvring, respectively. The entire E3 duty cycle was not used in these calculations because turn-around performance was modeled separately. Similar procedures were used for rail and truck.

By multiplying the fuel consumed each trip by the annual number of trips per ship and by the number of ships required, the Model estimates the annual fuel consumption required to move the total cargo tonnage. Total fuel use divided by the total cargo moved results in an estimate of the annual energy intensity, measured as fuel use per ktonne cargo. From this value, conversions can be applied to estimate energy intensity in MJ per ktonne cargo, or to estimate emissions per ktonne cargo.

### 6.2.3. Results

The Freight Transportation Model can be used to compare modes while varying important input parameters such as capacity factor. Figure 6-5 shows that capacity factor has significant effect on the fuel consumption per ktonne cargo, and that the effect is greatest for trucks. This confirms the qualitative insights from previous analyses about the importance of capacity factor, presented in Section 5.1. Using average capacity factors, trucks consume more than twice as much fuel per ktonne as rail. (All model runs presented in this section use a cargo transportation distance of 3,218 km. The effect of changing transportation distance is discussed in Section 5.4.)

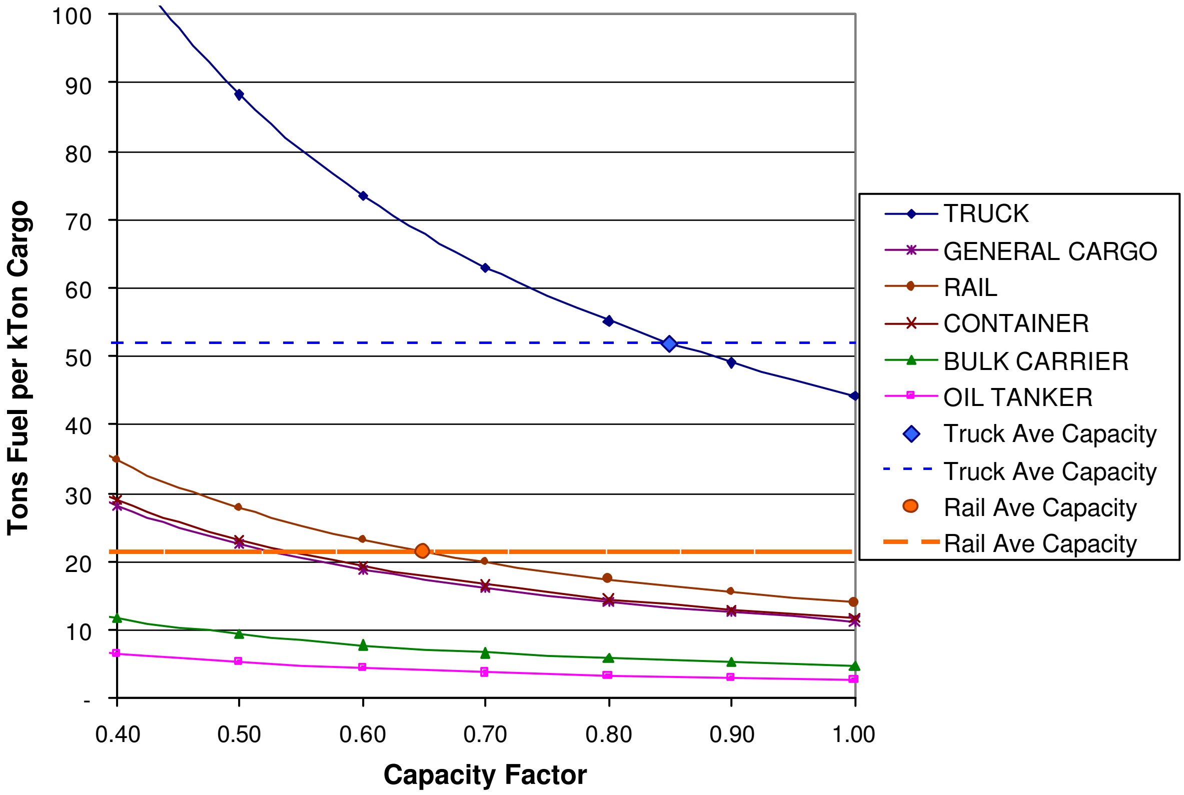


**Figure 6-5. Fuel Consumption by Freight Transportation Mode as a Function of Capacity Factor**

Figure 6-6 presents similar results for $CO_2$ emissions per ktonne cargo, including error bars representing the variability introduced by including different speed and power combinations. Three important points should be noted. First, even with error bars the truck mode produces the highest $CO_2$ emissions per ktonne cargo. Second, rail does not always perform significantly worse than ships, if different speed and power relationships are used for ships of the same type and size as the case-average container and general cargo ships. Third, bulk carriers and oil tankers in the case-average size ranges do perform significantly better than other ships, rail and truck.

When other pollutants are considered, the results can be different. $NO_x$ comparisons varied by capacity factor are presented in

Figure 6-7. Ships still perform better than truck or rail modes, but this difference is not always large. Because significant $NO_x$ controls have been required for trucks, their $NO_x$ performance improves relative to the other modes. Additionally, more fuel-efficient diesel engines in rail and marine applications tend to operate at higher temperatures and pressures than truck engines, and therefore produce more $NO_x$ for the same power. Most interestingly, under average truck and rail capacity factors (85% for truck and 65% for rail), the $NO_x$ performance of these modes is nearly identical.

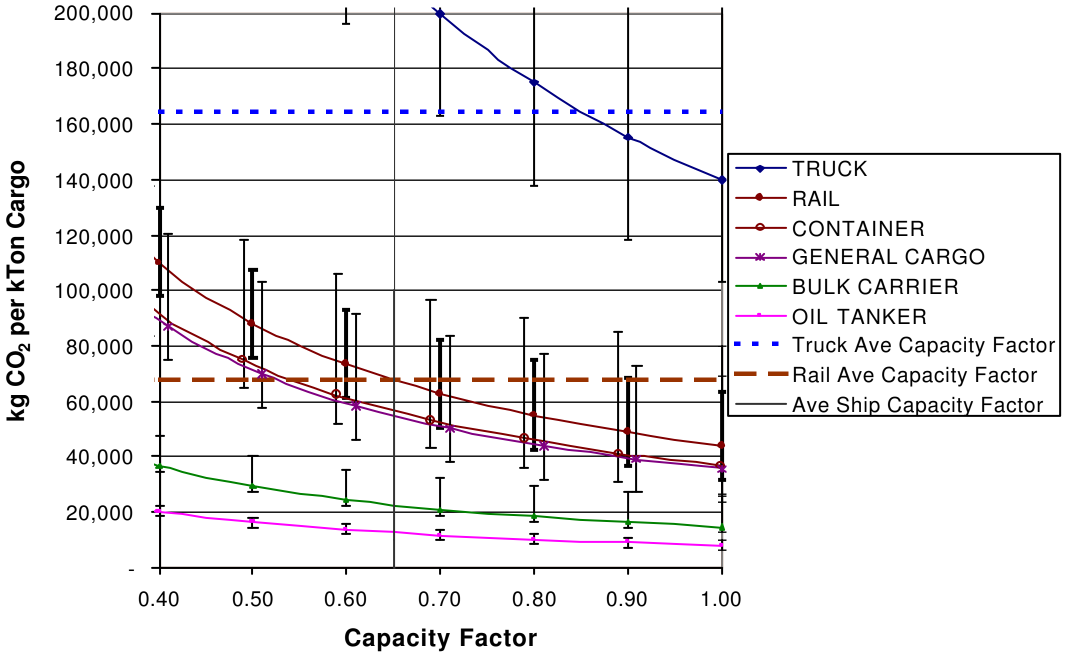


Figure 6-6. $CO_2$ Emissions Varied by Capacity Factor (with 5th and 95th percentile effects of variability shown)

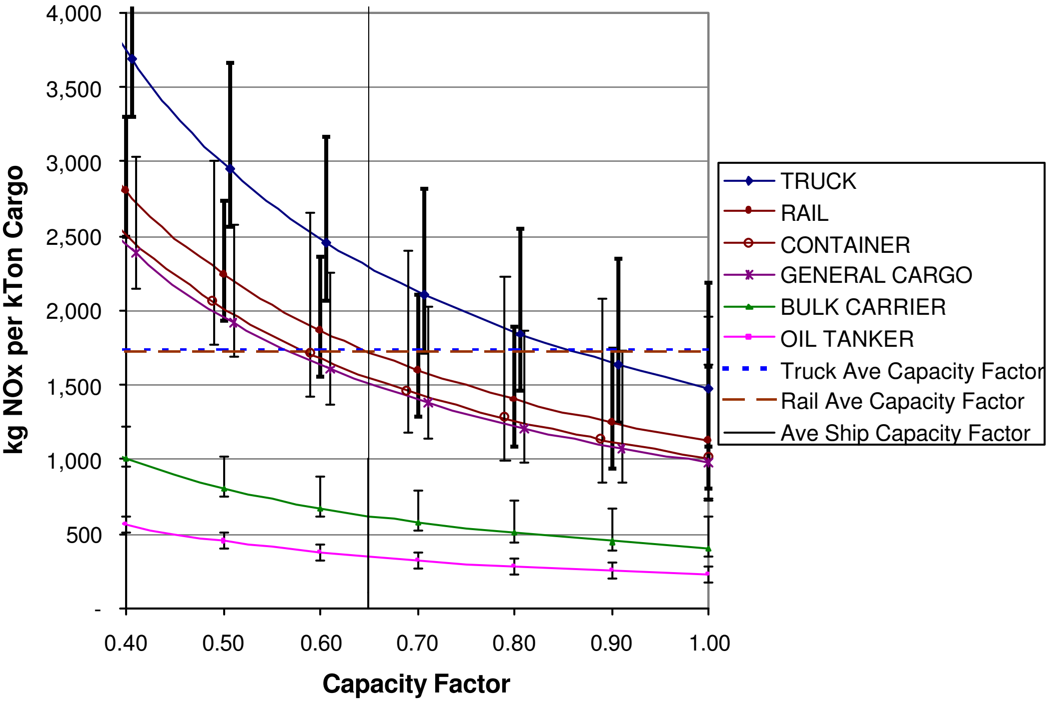


Figure 6-7. NOx Emissions Varied by Capacity Factor (with 5th and 95th percentile effects of variability shown)

Emissions differences between the modes are most noticeable for $SO_x$ (Figure 6-8). The fuel-sulphur contents for marine bunkers are much greater than distillate diesel fuels used by truck and rail modes. This results in $SO_x$ emissions per ktonne cargo that can be 6 to 26 times higher for ships than for land-based modes.

In summary, capacity-factor differences between the modes are significant, but modal differences between pollutants are much larger. The effects of changing capacity factors are not at all similar across pollutants. This is primarily due to modal differences in emission control, engine design, and fuel specifications. Under baseline model conditions, the $CO_2$ performance by ships is clearly better than other modes of freight transportation.

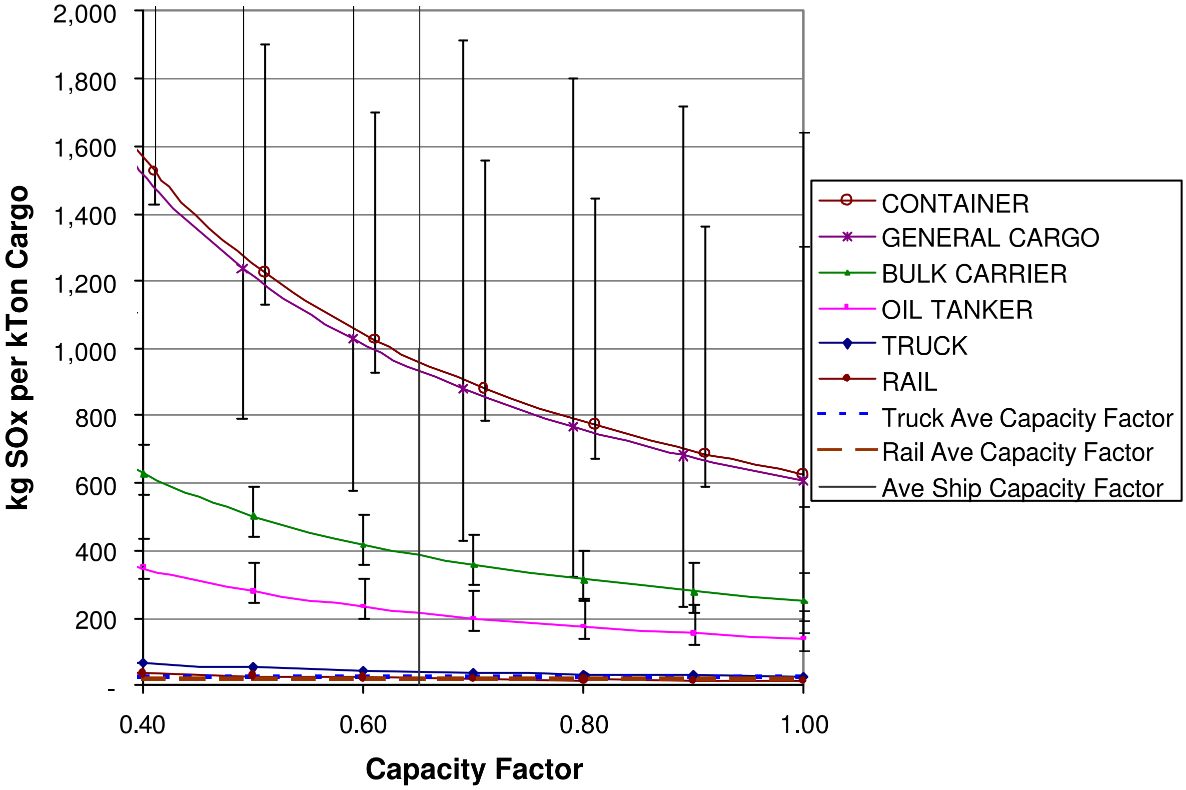


**Figure 6-8. SOx Emissions Varied by Capacity Factor (with 5th and 95th percentile effects of variability shown, dominated by fuel-sulfur content)**

One important input assumption is the turn-around time, because the corresponding energy use during this period can account for 4% to 15% of total energy use per trip for ships under baseline model assumptions. Reducing turn-around time – or at least minimising the energy used by ships during turn-around time – can reduce total energy and emissions intensities in two different ways. The reduced turn-around time per ship can result in more trips per ship per year, thus requiring fewer ships to perform the work. Alternatively, reduced turn-around time can be used to make transit-speed adjustments that maintain constant trip duration; this results in reduced power with the same number of ships performing the cargo movements. Each of these is discussed below.

A 25% reduction in turn-around time can reduce $CO_2$ emissions by 1% to 4%, depending on the mode. In general, when turn-around times are a larger fraction of total energy use for each trip, reducing turn-around times has a larger effect in reducing $CO_2$ emissions. (It should be noted that reduced turn-around times also reduce other emissions and improve overall energy performance.)

On the other hand, using these reductions to adjust transit speeds can provide additional reductions in energy use, $CO_2$ emissions, and emissions of other pollutants. Figure 6-9 shows that given the baseline assumptions, a container ship can reduce transit speed by approximately 1 knot over a 3,218 km (2,000 mile) transit with a 6 hour (25%) reduction in turn-around time. The potential for turn-around time adjustments to reduce transit speed is greatest for faster vessels. For the case-average general cargo ship, the same reduction in turn-around time for the same 3,218 km transit allows for less than 1 knot speed reduction, and for the case-average tanker and bulk carrier the speed reduction is about 0.5 knots.

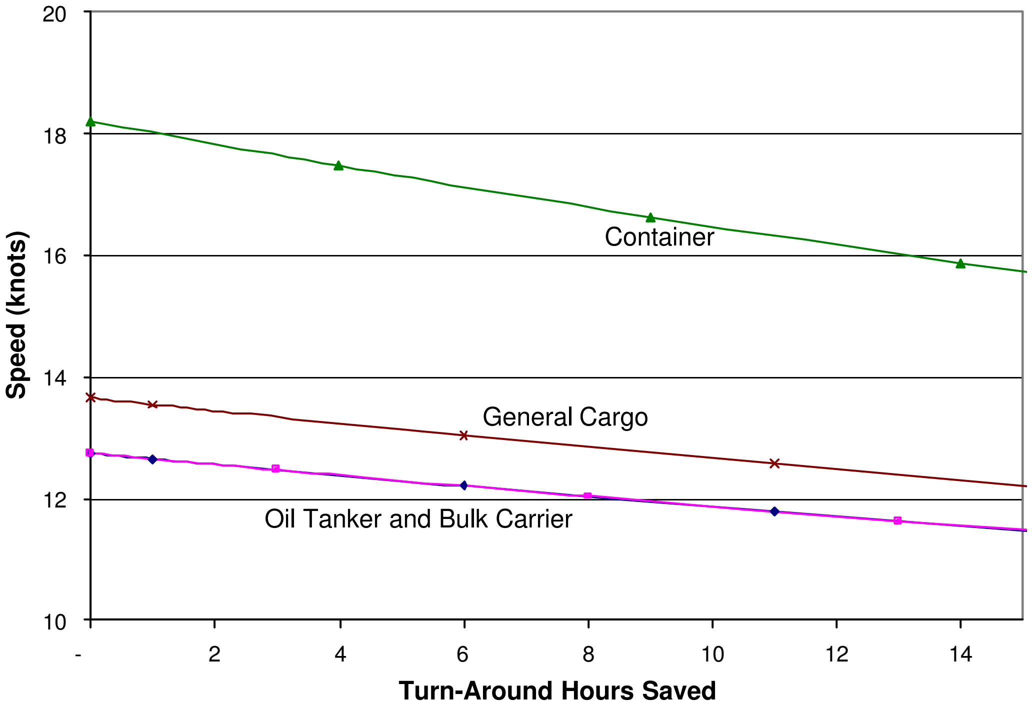


**Figure 6-9. Speed Adjustment Potential to Maintain Constant Total Trip Time with Reduced Turn-Around Time for Baseline Scenario Distance of 3,218 km (2,000 miles)**

The Freight Transit Model shows that these relatively small reductions in speed afforded by improved turn-around times have the potential to reduce emissions. Figure 6-10 compares the percent $CO_2$ reduction that results from reducing the required number of trips and ships with the percent $CO_2$ reduction from transit speed adjustments. While reducing turn-around time alone provides a modest reduction in emissions, additional reductions can be achieved by using these gains to reduce energy and emissions during transit. Under baseline model conditions, a 25% reduction in turn-around time with speed control can reduce $CO_2$ emissions by 14% to 17%, depending on ship type.

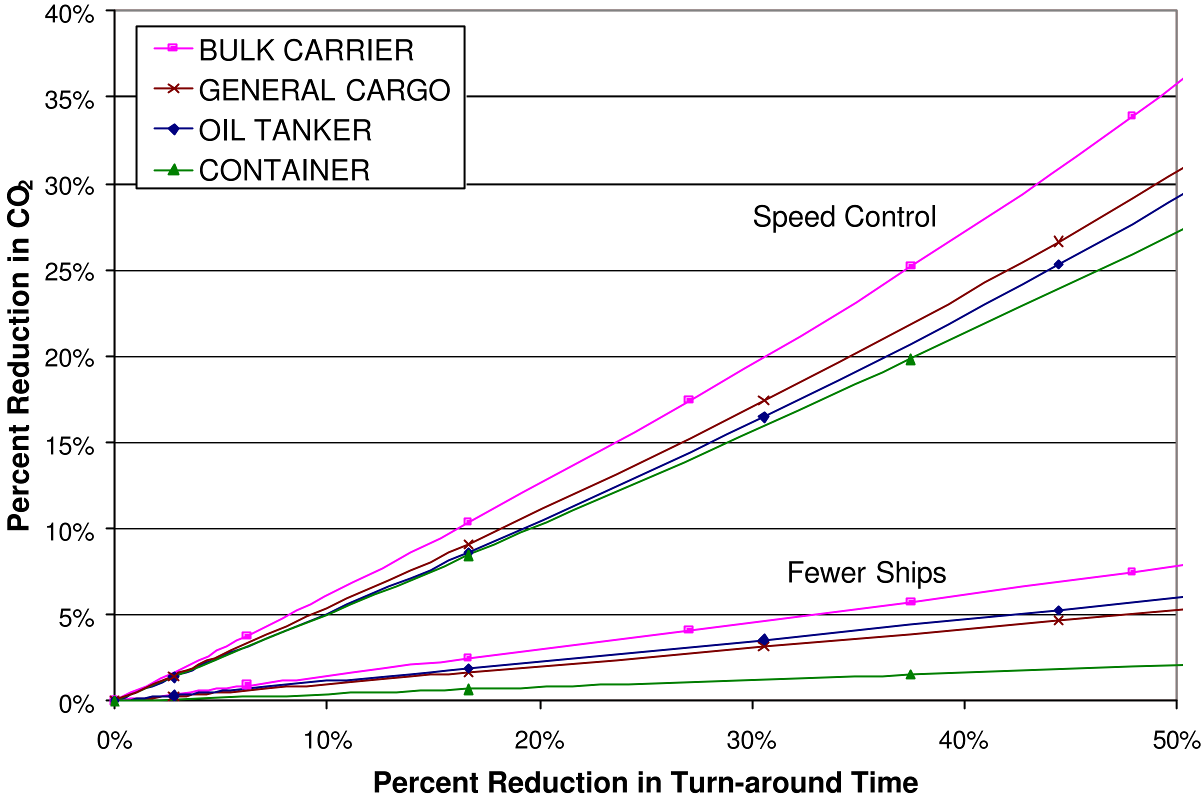


**Figure 6-10. Comparison of Percent Fuel Consumption Variability with Terminal Turn-Around Time for Scenarios With and Without Open-Water Transit Speed Reduction**

These results would be different under different model scenarios. Particularly, the transit distance has a significant effect on how much speed reduction can be achieved for a given reduction in turn-around time. To illustrate this, Figure 6-11 presents the same calculation for transit-speed reduction for three different distances. The baseline distance used in the model is 3,218 km (2,000 miles). For a distance of 805 km (500 miles), the same reduction in turn-around time can afford a much greater reduction in transit speed, because the turn-around time is a larger fraction of the total trip time. For a distance of 8,045 km (5,000 miles), the effect of reduced turn-around time on transit speed is much less.

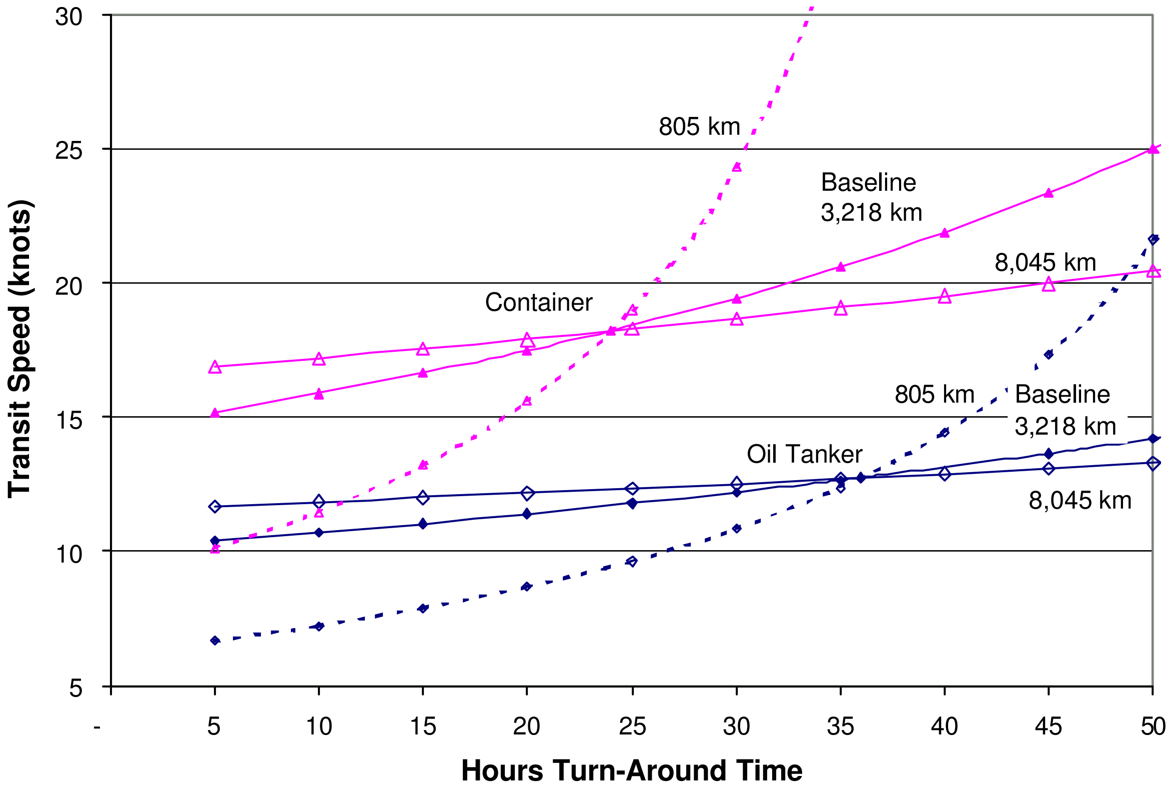


**Figure 6-11. Sensitivity of Transit Distance on Speed Adjustment to Maintain Constant Trip Time (Baseline Scenario is 3,218 km)**

As demonstrated, the turn-around time and resulting energy consumption are important factors in the overall energy and environmental performance of each mode. While the Model uses reasonable values for each mode, these may vary from port to port. Moreover, vessels different than case-average ships (e.g., mega-container ships or smaller coastal tankers) could require significantly different turn-around times than assumed here. Lastly, the average manoeuvring speeds during turn-around (terminal approach, docking and cargo transfer, and departure) vary from port to port, resulting in different energy and emissions performance even if the turn-around times are comparable. These regionally variable factors can be investigated with this Model.

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# 7. IMPLICATIONS OF INTRODUCING SAFETY AND POLLUTION PREVENTION INITIATIVES ON THE POTENTIAL OF GHG REDUCTION POTENTIAL

## 7.1. Introduction

An assessment on the regulative measures related to maritime safety has revealed a number of ten international conventions, agreements, regulations and standards (Table 7-2). SOLAS is recognised as the most important international regulative frame dealing with these topics. SOLAS, its main area of application and its development to date, have been assessed in order to define restraints likely to impact the potential of reducing GHG emissions from international shipping.

Similarly, an assessment has identified five international conventions defining technical and operational constraints provided to ensure environmentally safe operations. MARPOL is the major tool conducting the extent of such constraints. An assessment of MARPOL regulations have been undertaken in order to identify requirements, recommendations or standards violating the potential of reducing the GHG-emissions from international shipping.

Some specific characteristics with reference to initiatives and measures of both safety origin as well as that from the pollution prevention aspect have been identified and grouped. The potential of these category groups impacting the fuel consumed by ships have been considered.

New initiatives at present being debated have been evaluated. This includes that of regulating ballast water voyages and the proposed ban on the use of Tributyltin.

**Table 7-1 - Measures and initiatives affecting GHG emissions from international shipping categorised by groups**

| No.: | Category I | Category II | Category III | Category IV |
|---|---|---|---|---|
| Type: | Measures limiting cargo carrying capacity | Measures introducing additional energy consumers | Measures effecting general efficiency | Misc. |
| Impact potential: | High | Minor | Medium | Minor |
| New initiatives | Ballast water management | | Tributyltin ban | |
| Impact potential | Medium | | Minor | |

## 7.2. Development of regulative initiatives in international shipping

The implementation of new initiatives seen materialised in regulations, are often the results of policies reflecting local, national or regional priorities. An incident or the growing level of awareness among the public in general, is often the trigger initiating such processes.

Awareness on safety and environmental matters has steadily grown over the last few decades. The number of international conventions, amendments and codes developed during this period reflects this awareness.

Regulating an internationally moving industry efficiently seems impossible unless regulations are harmonised and developed from a mutual base. Therefore, local, national or regional initiatives are often brought forward to IMO in recognition that these might be more efficiently developed and implemented if made mandatory globally. However, sometimes the resulting framework following compromises adopted through the IMO process, might by some be considered insufficient and hence unilateral/ bilateral regimes might emerge. The process of reaching the required broad mutual views within the framework of the IMO is time consuming. The time-factor may act as a catalyst in promoting local, national or regional additional requirements.

International regulative initiatives and measures should as an overall rule always include an impact study. This should include the potential of such an initiative or measure introducing unintentional conflicts of interests. In the UNCLOS this is stated as an overlaying principle.

Equal requirements world-wide will rest upon the overlaying assumption that the required protection level is a global constant. This is not necessarily the case neither concerning safety nor the environment. Climatic-/ weather-related conditions, traffic density, the nature of goods carried, geographical particulars, etc. are components that will influence on these aspects and vary from one area to another. Variations promoting the need to implement particular constraints in particular circumstances need to be managed by international regulations. The following examples illustrate how this in effect can be seen done today.

| | |
|---|---|
| Safety: | requirements may refer to different ship types. |
| Environment: | stricter requirements may apply in defined areas (Special Areas, Particular Sensitive Areas). |

International regulations covering international shipping are often used as a base for national regulations. International Conventions and Codes including their amendments developed through IMO are therefore providing for national regulations.

## 7.3. International Conventions and Amendments

An overview of existing Conventions, Amendments and Codes of the IMO may be found in the IMO-Vega database (IMO/ DNV). In addition to the regulations of the Convention and Codes, this also include corresponding interpretations, guidelines and resolutions from IMO's Assembly, the Marine Safety Committee (MSC) and the Marine Environmental Protection Committee (MEPC).

Appendix 5 provides a comprehensive overview of Conventions, amendments and regulations listed in accordance to entry into force dates. Table 7-2 below provide a listing of international convention, agreement and, regulations addressing safety and environmental aspect of ship operations respectively.

**Table 7-2 - International regulative tools on maritime safety and pollution prevention**

| International Conventions – Safety | International conventions - Environmental |
|---|---|
| **International Convention for the Safety of Life at Sea (SOLAS), 1960 and 1974** | International Convention for the Prevention of Pollution of the Sea by Oil (OILPOL), 1954 |
| International Convention on Load Lines (LL), 1966 | International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties (INTERVENTION), 1969 |
| Special Trade Passenger Ships Agreement (STP), 1971 | Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LDC), 1972 |
| International Regulations for Preventing Collisions at Sea (COLREG), 1972 | International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78) |
| International Convention for Safe Containers (CSC), 1972 | International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC), 1990 |
| Convention on the International Maritime Satellite Organization (INMARSAT), 1976 | |
| The Torremolinos International Convention for the Safety of Fishing Vessels (SFV), 1977 | |
| International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), 1978 | |
| International Convention on Maritime Search and Rescue (SAR), 1979 | |
| International Convention on Standards of Training, Certification and Watchkeeping for Fishing Vessel Personnel (STCW-F), 1995 | |

The International Convention for the Safety of Life at Sea, (SOLAS), is the most important international convention dealing with maritime safety. Likewise, The International Convention for the Prevention of Pollution from Ships (MARPOL) is the most important instrument regulating the environmental impact from international shipping is that of MARPOL. The following two sections consider the content and the possible areas of conflict between initiatives aiming at reducing GHG emissions and the regulations of these two instruments respectively.

### 7.3.1. International Convention for the Safety of Life at Sea (SOLAS)

SOLAS cover a wide range of measures designed to improve the safety of shipping and was first adopted in 1914 following the loss of the S/S Titanic. The second and third editions were adopted in 1929 and 1948 respectively.

In order to keep pace with the change and technological developments of the shipping industry, the Convention has undergone continuos upgrading and renewal by the adoption of Amendments.

A completely new Convention was adopted in 1974 including all Amendments as agreed upon and in addition a new Amendment procedure designed to ensure that changes could be made within a specified (and acceptably short) period of time.

The objective of SOLAS is to specify minimum standards for the construction, equipment and operation of ships in order to assure a level of safety. Flag states are responsible for ensuring that ships under their flag comply with these requirements. A number of certificates are prescribed in the convention as proof that this has been done. Control provisions allowing contracting governments to inspect ships of other contracting nations if there are reasons to believe that the ship and its equipment do not comply with the requirements of the Convention follows.

In Appendix 5, a summary of the content of each chapter of the SOLAS Convention is given.

### 7.3.2. The International Convention for the Prevention of Pollution from Ships

MARPOL identifies a framework for the safeguarding of the environment from unacceptable impacts from international shipping. In its present form it consists of six annexes;

| | |
|---|---|
| Annex I | Regulations for the Prevention of Pollution by Oil |
| Annex II | Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk |
| Annex III | Regulations for the Prevention of Pollution by Harmful Substances in Packaged Form |
| Annex IV | Regulations for the Prevention of Pollution by Sewage from Ships |
| Annex V | Regulation for the Prevention of Pollution by Garbage from Ships |
| Annex VI | Regulations for the Prevention of Air Pollution from Ships |

MARPOL is a combination of three treaties;

- International Convention for the Prevention of Pollution from Ships, 1973,
- The Protocol of 1978
- The Protocol of 1997

MARPOL was initiated by the IMO Assembly in 1969 when it was decided to convene an international conference in order to develop international agreements for placing restraints on the contamination of the oceans, land and air caused by international shipping operations. This initiative materialised in the Protocol adopted in November 1973 (International Convention for the Prevention of Pollution from Ships, 1973).

MARPOL addresses all technical aspects of pollution from ships, with the exception of disposal of waste into the sea by dumping. It applies to ships of all types. However, it does not apply to pollution arising from exploration/ exploitation associated to sea-bed mineral resources.

Development milestones of MARPOL are identified in Appendix 5, together with a summary of content of each annex.

## 7.4. Interrelations - Safety and environmental protection measures versus GHG emissions

The comprehensive and detailed regulations ensuring necessary minimum protection of crew, passengers, the environment as well as the ship are interrelated in many ways. The effect of changes by introducing amendments within the safety regime may well be in disharmony with one or more objectives within the environmental regime and vice versa. Some examples of objective inconsistency may be obvious whilst the effect of others might involve complex mechanisms and may therefore not emerge as obvious.

The introduction of unintentional effects caused by the implementation of any measures should be considered (UNCLAS). In many cases, it is evident that the working groups of the MEPC and the MSC do consider such effects. One example is that of the discussions on measures preventing the transfer of unwanted harmful aquatic substances, when introducing the change of ballast water in open seas. The potential consequences on both strength and stability was forwarded to appropriate working groups and dealt with. However, it does not seem to be any standard mechanisms ensuring such considerations to be undertaken. As many cases might not occur obvious, this might be necessary.

### 7.4.1. Measures and effects

An assessment on regulative measures related to maritime safety has revealed a number of ten international conventions, agreements, regulations and standards (Table 7-2). SOLAS has been recognised as the most important international regulative frame dealing with these topics. SOLAS, its main area of application and its development to date, have been assessed in order to define restraints likely to impact the potential of reducing GHG emissions from international shipping. Similarly, an assessment has identified five international conventions defining technical and operational constraints provided to ensure environmentally safe operations. MARPOL is the major tool conducting the extent of such constraints. An assessment of MARPOL regulations have been undertaken in order to identify requirements, recommendations or standards violating the potential of reducing the GHG-emissions from international shipping.

#### 7.4.1.1. GHG reduction and preventing characteristics

Regulative constraints identified have specific characteristics allowing them to be grouped by categories. Such categories are presented in Table 7-3. Table 7-4 and Table 7-5 lists requirements of SOLAS and MARPOL respectively by category following the assessment carried out above.

**Category 1 Measures limiting cargo carrying capacity**
Initiatives reducing a vessel's ability to utilise actual cargo carrying capacity are initiated on both safety grounds as well as from a pollution prevention stand. Measures might impose operational limitations;

Loading restraints aiming at reducing stress imposed on the vessel structure or they can involve constructional features;
Securing cargo from entering the environment following an incident by requiring a double hull.

Regulations in MARPOL, Annex I will in effect impose a ban of carrying oil cargo in vessels other than those built with double hull after reaching thirty years of age. The void space between the hulls represents empty space travelling and does represent a fuel penalty. Among category I initiatives, double hull requirement hold the highest penalty potential. Potential fuel penalty carried by category I measures are considered high.

**Category II Measures introducing additional energy consumers**
Regulations of both SOLAS and MARPOL motivate for the implementation of additional functions resulting in more onboard equipment and hence an increase of items to be accounted for in the energy balance of the vessel.

Requirements on duplication of functions are thought to have a more significant impact on total power requirement than that of introducing new functions. However, technological advance has improved energy efficiency for a number of traditional shipboard functions. The introduction of new requirements might in some cases open for the use of more energy efficient solutions.

Taken into account the limited share of the ship total energy requirement underway represented by energy consumers other than main propulsion, it can be concluded that category II measures represent only minor potential fuel penalty impact.

**Category III Measures effecting general efficiency**
Identified measures represented in this category include those with impact on the routing patterns of the ship. These might initiate the vessel to obtain a lane that does not represent optimum efficiency. The introduction of restrictions in an area might cause the operators to avoid these either by de-routing and consequently increase fuel consumed or re-load cargo onto other means of transport that might represent a lesser efficiency (land based transport alternatives). However, routing as such do carry a potential of improving fuel efficiency as well (for example weather routing).

The potential of measures falling into category III might cause a significant increase in fuel consumed in transporting goods even though requiring a set of circumstances to be present. The potential fuel penalty can be considered medium.

**Category IV Miscellaneous measures.**
Some initiatives in the safety and environmental protection area does not fully comply with the specified categories defined above and have thus been given a separate category. Measures falling into this can be visualised from both SOLAS and MARPOL regulations.

Measures requiring or advising the vessel to use reception facilities might increase fuel consume due to a potential need to undertake energy-requiring onboard processing operations and to increase the length of a voyage. In addition, the vessel will carry additional weight over a longer distance and thus use more energy.
The required inert gas procedures introduce additional equipment and might be argued to belong to category II. However, since $CO_2$ (exhaust from machinery) is sometimes used for the purpose, it is listed under category IV.

The latest Annex of MARPOL is explicitly directed towards the protection from pollution to air emphasising on reducing the emissions of ozone depleting substances $NO_x$ and $SO_x$ among others. The two latter components origin from the combustion of fuel. As there are a combustion efficiency aspect related to the production of $NO_x$, one will expect the $NO_x$ limits drawn to impact the fuel consumption in an unfortunately manner. This is dealt with in depth elsewhere in this study.

Category IV measures are considered only to have a minor potential of impacting the level of fuel consumed.

**Table 7-3 - Categorisation of safety/pollution measures**

| I | II | III | IV |
|---|---|---|---|
| Measures limiting cargo carrying capacity | Measures introducing additional energy consumers | Measures effecting general efficiency | Misc. |

**Table 7-4 - Requirements sorted by category I and II**

| Category I | | Category II | |
|---|---|---|---|
| **SOLAS** | **MARPOL** | **SOLAS** | **MARPOL** |
| Strengthening requirements, passenger vessel/ cargo vessels.<br>Separation of spaces (subdivision/ stability),<br>Loading requirements/ cargo handling requirements.<br>Additional strength/ loading limitation requirements, for bulk carriers | Segregated ballast, hydrostatically balanced loading, double hull requirements, | Duplication of equipment, additional equipment (steering machinery, navigational aids, communication, monitoring & lightening | Waste treatment systems (crushers, incinerators, pumps, processing plants), |

**Table 7-5 - Requirements sorted by category III and IV**

| Category III | | Category IV | |
|---|---|---|---|
| **SOLAS** | **MARPOL** | **SOLAS** | **MARPOL** |
| Vessel Traffic Services (VTS), Routing, | Special Areas | Inert gas | Reception facilities, Reduction of $NO_x$, $SO_x$ Emission Control areas, ban on ozone depleting substances, |

## 7.4.2. Regulative measures under development

The debate considering the need to reduce the environmental burden represented by shipping is at the moment prioritising the topics of:

- Unwanted transfer of harmful organisms by vessels in ballast.
- Prohibiting the use of Tributyltin in antifouling paints.

#### 7.4.2.1. Ballast Water Management

The need to monitor and eventually enabling measures to be undertaken to avoid unwanted biological invaders into an area, is one of high priority. The current measure outlined in an IMO guideline (Ass.Res.A868(20)) advice vessels to re-ballast in open sea areas. Two methods, that of sequentially re-ballasting tanks and that of flushing through the tanks, are described. Both operations require depths of more than 500 m and can only be done at a distance of more than 250 nautical miles from shore.

Re-ballasting will incur an increase in power generated represented by additional pumping as well as by the potential need to leave optimum choice of lane.

At present, there are a number of uncertainties related to the future restrictions on ballast water management. Initial investigations reveal that numerous voyages does not represent a particular risk of transferring an unwanted species from one destination to another (DNV, 1999), and hence, there might be no risk reducing potential in requiring these to be re-ballasted or to be treated by any other method for that matter. From this, the obvious measure should be that of considering the risk represented by an actual voyage prior to any required treatment measure to be made. This will also help reducing the potential fuel penalty represented by ballast water requirements.

#### 7.4.2.2. Prohibiting Tributyltin in antifouling paints

A proposed ban on the use of Tributyltin (TBT) is currently being discussed within the MEPC. The introduction of a ban can be implemented as early as year 2003. No new ships will be treated with antifoulings containing TBT after the date of entry into force. A phase-out period of 5 years will ensure that no vessels will be coated with TBT-based products after year 2008.

Tributyltin (TBT) based antifoulings (self-polishing copolymer (SPC) paints) have since the mid 1970' provided efficient fouling protection allowing docking intervals of up to 5 years. The proposed ban on these products will result in the adoption of tin-free replacements. There have been consistent claims, in particular from the lobbying interests for tin-products, that these replacements will provide less efficient protection. Hence, the requirement of shorter docking intervals will emerge. Assuming that these products do provide less efficient protection, it is likely to assume further, that the TBT-ban will introduce a GHG-penalty due to the increase of fuel consumption in the period prior to docking.

**Replacement products:**

Options at present commercially available are:

- Products working on the conventional principle where TBT is replaced by for example Copper.
- Foul release coatings

Most manufacturers have available copper-based products. These are self-polishing paints and tend to indicate performance as good as tin-based products. They function on similar principals, but are more expensive. Copper products can offer the same docking intervals as TBT products.

Low surface energy absorbing surfaces, so called foul release coatings as distinct to antifouling coatings, offer a very smooth surface which fouling find it difficult to stock to. The vessel might foul when stationary, but once moving, the surface will clean itself. Not by self-polishing however, since this provide a non-stick surface. Test results from various manufacturers indicate high performance capability. The non-stick products have a duration considerable longer than the 5-year proposed interval. However, these products do carry considerable costs.

TBT-based antifoulings have proven to provide efficient long lasting protection against fouling allowing docking periods of up to 5 years. The introduction of tin-free substitutes has been attacked on the grounds that these products are inefficient causing fouling earlier in between docking intervals. Some claims have been made suggesting that;

- TBT-free paints require a higher docking frequency (every three years).
- Lacking efficiency leads to higher resistance and thus increased fuel consumption.
- Substitute products are considerably more expensive.

Most of the paint-manufacturers seem to disagree with these claims and are now pushing for the introduction of the ban.

Docking intervals are not only initiated due to the need to renew the antifouling system alone. Both owner policy as well as operational circumstances may determine another docking frequency pattern. Looking at actual docking frequencies reveal that in fact very few vessels at present (using TBT antifoulings) uses the 5 year window. It is likely that a substitute product will perform satisfactory within actual docking intervals (being closer to three than five years).

The ship resistance through water is sensitive to changes in level of fouling. Insufficient anti-fouling measures will lead to an increase of fuel consumption. This can be seen at a relatively early stage in the fouling process. Fuel penalties associated with hull fouling can reach considerable levels as shown in many case studies. Champ and Seligman (1996) estimated the world-wide annual fuel increase due to an assumed fouling protection deficiency to more that 7 Mton. This represents approximately 5 % of the annual sales of fuel to international shipping and is equal to Singapore's contribution alone. However, studies addressing this topic, will not provide necessary realism unless they consider the efficiency variations of the range of available substitute products. Furthermore, the likely future increase in efficiency for replacement products should also be included. Most manufacturers offer a range of alternatives and claim that alternatives as good as TBT are available.

Substitute non-TBT products vary in price according to type. In general they are more expensive than the conventional products. A figure of a 20% cost penalty is at present a reasonable estimate. However, the price gap between replacement products and the traditional TBT antifouling has narrowed and is continuing. A larger market will most likely accelerate this trend.

A number of States have already introduced restrictions on the use of TBT-based antifoulings. In the Table 7-6 below, these are listed. The type of restrictions made and also the number of nations requiring alternatives, suggests that there must be considerable operational experience on these alternatives. Some owners operating ships that never trade in these areas have converted to alternative non TBT products.

**Table 7-6 - Overview of restraints concerning the use of TBT**

| Country | Year | Regulations |
|---|---|---|
| Austria | | Banned the use of TBT antifouling paint in fresh water lakes. |
| Australia | 1989 | Prohibited the use of TBT-based paints on vessels less than 25 meters (m) in length.<br>Maximum leaching rate of 5 micrograms per square centimeter per day ($\mu g/cm^2/day$) for vessels greater than 25 m in length.<br>All dry-docks must be registered with the Environmental Protection Agency because of discharges.<br>All antifoulants must be registered. |
| Canada | 1989 | Prohibited the use of TBT-based paints on vessels less than 25 m in length, except for aluminium-hulled vessels. Maximum leaching rate of 4 $\mu g/cm^2/day$ for vessels greater than 25 m in length. All antifoulants must be registered. |
| Commission of the European Communities (EC)* | 1991 | Prohibited the use of TBT-based paints on vessels less than 25 m in length.<br>TBT antifoulants available only in 20 litre (L) containers. |
| Europe (non-EC members)* | Varies | Prohibited the use of TBT-based paints on vessels less than 25 m in length (most countries). |
| Hong Kong | | All TBT antifoulants must have a valid permit for import/supply. All antifoulants must be registered. |
| Japan | 1990<br>1992 | TBT banned for all new vessels.<br>TBT banned for all vessels. |
| New Zealand | 1989 | The application of TBT copolymer antifouling paint is banned with three exceptions: hulls of aluminium vessels, the aluminium outdrive, or any vessel greater than 25 m in length. The application of TBTO free-association paints is banned. Maximum leaching rate of 5 $\mu g/cm^2/day$ for vessels greater than 25 m in length. All antifoulants must be registered. Use of any organotin containing |
| South Africa | | Prohibited the use of TBT-based paints on vessels less than 25 m in length. TBT antifoulants available only in 20-L containers. All antifoulants must be registered. |
| United States | 1988<br>1990 | Prohibited the use of TBT-based paints on vessels less than 25 m in length, except for aluminium-hulled vessels.<br>Maximum leaching rate of 4 $\mu g/cm^2/day$ for vessels greater than 25 m in length.<br>All antifoulants must be registered.<br>TBT-based antifouling paints can only be applied by certified applicators. |

*: Finland, France, Germany, Ireland, The Netherlands, Norway, Sweden, United Kingdom and Switzerland have detailed regulations going further.

Assuming that TBT is banned and considering actual docking practice and the improvements seen on alternative products both considering their efficiency and their costs, it is unlikely that a fuel consumption penalty will emerge. However, if copper is subsequently banned, there may be some penalties incurring in terms of fuel consumption.

## 7.5. References

Reference is given to Appendix 5 for extensive reference material for SOLAS and MARPOL.

# 8. MARKET-BASED APPROACHES

## 8.1. Current status

### 8.1.1. Background

Greenhouse gas (GHG) emissions from international shipping and aviation are neither covered by the Kyoto Protocol, nor included in the national emissions inventories of Annex I parties to the United Nations Framework Convention on Climate Change (UNFCCC) or Annex B parties to the Kyoto Protocol. Annex I/Annex B parties consist of all developed countries plus the so-called "economies in transition" of central and eastern Europe, including Russia and Ukraine.

Although international shipping accounts for only about 2 percent of global $CO_2$ emissions from fossil-fuel use, this is a higher percentage than for many countries undertaking emission reduction obligations pursuant to the Kyoto Protocol. An underlying assumption of this analysis is that reductions in this sector could make a meaningful contribution to the global reduction of GHG emissions.

A secondary assumption is that there is in the international shipping industry considerable scope for GHG emission reductions at moderate cost, which would not substantially reduce the volume of sea transport. Sea transport is the most energy-efficient means of freight transport, with a $CO_2$ intensity two orders-of-magnitude lower than air freight. Efficiency improvements making sea freight transport even more commercially attractive than it is now, would be a gain for the global environment and the world economy.

### 8.1.2. Properties of the international shipping industry

Sea transport has a number of distinct characteristics that need to be kept in mind when seeking the most practical solution to global GHG emissions reduction:

- *It is difficult to define the nation or territory where «generation» of sea transport services takes place*. Sea transport and emissions in international sea, which is the focus of this report, take place outside national control. In contrast, the UNFCCC and Kyoto Protocol are based on responsibilities assumed exclusively by nation-states.
- *Often, it is difficult to determine the country of ownership of a vessel, or who is the real owner or responsible for its operation.* A ships country of registration has jurisdiction over it on the high seas and determines the technical standards that it must meet etc. [Michaelis, 1997]. The majority of the world's cargo-carrying capacity in deadweight tonnage (cargo capacity) terms is registered in non-Annex I countries. Ships are often operated on a charter or lease basis. In a "voyage charter" or "time charter",

the owner remains responsible for ship operation including costs, whereas in a “demise charter” the charterer takes responsibility for operating costs. Ships may also be operated by a ship management company on behalf of the owner. The form of operation has implications for the extent to which ship owners are concerned about energy efficiency. In this report, we use the term «ship owner» as a common expression for owner and/or operator.

- *The majority of the world’s bulk shipments either start or finish their journey in an Annex I country.* Only 16 percent of tons shipped in bulk carriers begin and end their journey in non-Annex I countries [OECD, 1997].
- *Bunker-fuel sales differs from the sales of other petroleum products in that bunker-fuel is commonly sold to ship operators by dealers independent of the major oil companies*. This has implications for the implementation of any bunker tax, as tax collection at the point of sale would be administratively complex.
- *The inherent mobility of ships implies that measures to reduce industry-wide emissions must be global in scope if they are to be equitable and avoid leakage and «free riders».* However, some actions taken by, for instance, Annex-I countries only, may have a significant impact on global emissions from ships.
- *Manifested mainly by IMO conventions, the international shipping industry has achieved some solutions to common safety and pollution problems.* These have, to a large extent, involved the adoption of global uniform (minimum) standards.

## 8.2. Environmental indexing

The idea of environmental indexing of ships is to use environmental criteria to give vessels an index indicating the environmental performance of the ship. The index given to a vessel can be used to differentiate taxes, port dues and charges, but also insurance rates and different financial conditions may be differentiated on the basis of an indexing system.

Indexing systems have until now only been introduced to a limited extent in some few countries. Some systems are specifically targeting a special type of pollution. The Swedish administration has introduced such a concept focussing on $NO_x$ and $SO_x$. Other systems are broader, i.e. the Norwegian concept. It should be noted that the complexity of these systems increases with the areas they cover.

For greenhouse gas emissions reductions it is of outmost importance to have an internationally harmonised system. This comprises both a consensus on the indexing criteria and on how to give ship owners the right incentives to improve their environmental performance. A voluntary environmental indexing concept would in many ways be similar to a voluntary agreements programme (see below), while a mandatory system would be similar to imposing emissions or energy efficiency standards (see below). It could therefore be difficult to see what role environmental indexing could play in the longer run. It should be further considered how environmental indexing could play a role in curbing GHG emissions from ships.

## 8.3. A voluntary agreements programme

### 8.3.1. What is a voluntary agreement?

Voluntary agreements, often also called “negotiated agreements”, between industry or a company and the government have become a popular policy tool in many countries’ energy-efficiency and climate-change policies since the adoption of the Kyoto Protocol in 1997.

Voluntary agreements can range from declarations of intent from a company/industry, to binding contracts with industry and a regulator with counter measures (penalties) specified in case of non-compliance (CICERO, 1999). Such agreements are not voluntary in a strict sense, since in most cases there is an implicit or explicit threat from the regulator to impose other policy instruments if the company/industry is unwilling to negotiate. Also, if the target is not met, the company/industry could meet other, stricter regulations such as emissions fees or the introduction of taxes.

Most agreements focus on reductions in relative emissions or energy efficiency. They often contain targets like $CO_2$ emissions or kW per produced unit, with no limits on companies or industry’s total emissions. Some agreements have targets for the implementation of special technologies, fuel switching, operational measures etc., without specifying any emissions or energy-efficiency targets. Few agreements have targets for total emissions.

### 8.3.2. The use of voluntary agreements

Several developed countries have voluntary agreements programmes either as part of or, in some cases, as the mainstay of their national climate-change programme under the UNFCCC. The most comprehensive use of agreements at present can be found in Germany and the Netherlands. In the case of Germany, the federal government entered into an over-arching agreement with the German federation of industry calling for industry to achieve an aggregate reduction in $CO_2$ emissions of 20 percent below the 1990 level by 2005. The agreement is predicated on an understanding that as long as steady progress toward the target is being made, the government will refrain from introducing new taxes or regulations and will resist initiatives for EU-wide co-ordinated taxes. This is one of the few examples of agreements limiting total emissions.

In the Netherlands, the agreements between industries and the government focus on improvements in energy efficiency, imposing rather strict targets for this, but with no targets on total emissions. In other countries, such as the US and Canada, voluntary agreements are less comprehensive and are characterised by voluntary actions taken by industry without any formal agreement with the government.

The European Commission, on behalf of the European Union (EU), in 1998 finalised an agreement with the European Automobile Manufacturers Association (ACEA). In this agreement, the manufacturers are committed to reduce emissions from new passenger cars by 25% between 1995 and 2008. This implies that new passenger cars on average can emit no more than 140 g $CO_2$/km in 2008. The agreement also contains some indicative targets for 2003. There is established a monitoring procedure administered jointly between the Parties, based on data from EU member states independent of the industry. In the case of non-compliance with the 2003 targets, EU will consider to make the targets legally binding. EU has also negotiated similar agreements with car producers in Japan and Korea. All these agreements could be seen as attempts to create some common emission standards for the future car fleet.

In addition, the European Commission is currently negotiating an agreement with the European Airline Association and the European Aerospace Industry Association on reducing $CO_2$ emissions. The EC is suggesting an annual reduction in fuel consumption or $CO_2$ emissions per passenger-kilometre of 4-5% by 2012, while the industry proposes a reduction of 1.1% [Ends Environment Daily, Friday 7, January 2000].

### 8.3.3. Voluntary agreements in the international shipping industry?

One could envisage a program in which ship owners would agree voluntarily to do one or more of the following:

- *Adopt emission or efficiency standards*, which could be differentiated according to ship size and type as well as other fairness and/or attainability criteria. The standards could be phased-in over time or go into effect at a prescribed future point in time. Each ship owner would have discretion to choose how to meet the standard, which could include changes in some operating procedures as well as improvements in technology or upgrades in equipment. The compliance test could be met by third part verification of overall emissions reductions or improved average efficiency.
- *Adopt certain approved practices and/or agree to take certain prescribed actions.* The compliance test would be met by demonstrating that action had been taken, not by proving that as a result of the action emissions had been reduced or efficiency improved.
- *Report emissions or efficiency levels, describe any actions being taken to improve them, and/or report any emission reductions or efficiency improvements being achieved.* The compliance test would be met by simply reporting the status of emissions, efficiency levels, actions taken, and/or results of actions taken.

The first of these approaches would be the most stringent, the third would be the least. The voluntary agreements programs of Annex I parties under the UNFCCC run the gamut of these alternatives, with the Dutch and German programmes being relatively more demanding and the Canadian and Australian programmes less so.

Compared to national industries, international shipping has weak incentives to enter into voluntary agreements with national (flag state) governments. Shipping faces no immediate threat of national policy instruments to curb GHG emissions, and companies can easily move to other countries if such measures are imposed in their host country. Besides, international shipping is not organised in a way that makes comprehensive voluntary agreements easy to negotiate for the whole shipping fleet.

Possibly, the IMO could be a counterpart for agreements on emissions reductions with each shipping company. This would imply a new role for the organisation. The extent to which there would be any signed agreements would depend entirely on each ship owners willingness to sign, as IMO would have no sanctions or threats towards those not signing. Some ship owners might be interested to commit themselves to emission reductions measures to obtain positive good-will from customers and the public at large, although this argument seems of less importance at the moment.

Agreements between some ports and ship owners on GHG emission reductions are also an option. Such agreements exist for some other pollutants. For instance in Oslo, the local port authority has agreed with nine ship owners currently entering the port to use low sulphur bunker fuel for their ships when sailing in the Oslo Port area. Similar agreements could, in principle, be established between several ports, for instance in Annex I-countries, on GHG emissions limitations.

It is also possible that some ship owners may wish to join efforts with some shipbuilders to develop more $CO_2$ benign ships.

To summarise, a voluntary agreement is a rather weak policy instrument to achieve substantial emission limitations. Some reductions may be achieved by local agreements etc. or agreements between Annex I-countries/IMO and ship owners, where Annex I-countries co-ordinate their efforts. To avoid free-riders such agreements would most likely have to be mandatory. Thus, they would have to be in the form of technical standards, a policy instrument that will be analysed later in this chapter.

## 8.4. Carbon charge on bunker fuel

### 8.4.1. Introduction

A carbon charge on bunker fuels would increase fuel costs for the vessels. Since emissions of $CO_2$ are connected to fuel consumption, carbon charges will give ship owners increased incentives to reduce fuel use and emissions.

Fuel costs are in many cases a large proportion of shipping costs and therefore play an important role in the decisions of ship builders and owners. The relative importance depends on the type of vessel and the type of trade in which it is involved. Wright (1996) indicates that fuel typically comprises 20-25% of overall capital and operating costs for container ships. According to Melissen et.al. (1993) fuel costs are a much smaller share (in the region of 10 percent or less) of overall costs for new bulk carriers, but a much larger share (over 30 percent) for a fully depreciated 15-year old steam turbine-powered tanker.

The fuel share of costs is strongly influenced by the vessel speed. Higher operating speeds effectively decreases the importance of capital costs (because the vessel can make more frequent voyages for a given capital investment) and increase the fuel costs (because energy use per kilometre increases with the square of speed).

Historically, bunker fuel demand has reacted to bunker fuel price changes. Bunker fuel demand declined briefly after the oil price rice in 1973, and again after a more extended period after the second oil price rice in 1979, [Michaelis, 1997]. It reached a low point in 1982, but has grown almost continuously since at over 3% per year.

### 8.4.2. Possible effects of a carbon charge

A carbon charge on bunker fuels might reduce bunker demand and associated $CO_2$-emissions through the following measures [OECD, 1997]:

- Reductions in the amount of maritime traffic
- Energy efficiency improvements in ship engines and ship design
- Changes in operating practices including load factors, routing and sailing speeds
- Switching to different vessel types
- Switching to alternative fuel

The last 4 measures will be discussed later in this chapter. Here we will look more closely into the possible effects on maritime traffic and some leakage effects of a carbon charge on marine bunker fuel.

There exists some literature on oil price elasticities for marine freight. The literature reports a wide range of numbers, depending on commodity and origin/destination of the cargo.

**Table 8-1 - Oil price elasticities for marine freight for different commodities and origins/destinations of the cargo**

| Coal | Iron ore | Liquid bulk | Grain |
|---|---|---|---|
| -0.06 to –0.24 | -0.11 | -0.21 | -0.02 to –1.64 |

Source: Oum et.al., 1990,

The interpretation of the elasticities is that a 1 per cent increase in fuel prices will lead to a reduction in the amount of for instance iron ore transport by 0.11 per cent. The numbers above indicates a large difference in the effects of a bunker fuel charge on short vs. long distance maritime freight.

Analysis in OECD, 1997 indicates that there is a strong negative correlation between the growth of non-bulk cargo transport and the oil price. The possible difference in effects of a charge between bulk commodities and container transport may be due to lack of transport alternatives for the former. For the majority of international trade, being it bulk or container transport, there is no real alternative to marine transport. However, high-value and time-sensitive consignments are increasingly shipped by air, and road and rail are serious alternatives for some international freight currently moved by sea. Thus, it is possible that a bunker charge, if not matched by similar charges for other transport modes, could reduce the price advantage of maritime transport relative to those modes [OECD, 1997]. If a bunker charge were to lead to a decrease in the share of freight carried by sea and an increase in road and air transport, this would most likely result in increased $CO_2$ emissions.

A bunker charge could easily be evaded by bunker suppliers and ship operators, unless it is globally implemented as part of a general carbon tax. Offshore bunker supply is already normal practice to avoid paying port fees or being constrained by loading limits in ports. According to OECD, 1997 the cost of bringing fuel from a port in Africa or the Middle East to northern Europe, or from Latin America to north America, is in the order of $10-15/tonne fuel. Thus, any carbon charge in excess of this level would provide an incentive for suppliers to transport untaxed fuel to supply points immediately outside the waters of Annex I countries. This could possible result in a net increase in greenhouse gas emissions if ships changed their sailing routes to buy untaxed bunker fuel. Today, ships already choose their bunker source on the basis of small price differentials. OECD, 1997 argues that even a $5/tonne bunker charge would introduce an incentive to bunker at ports of non-Annex I countries. This would mainly affect bulk carriers (i.e. about a quarter of the bunker fuel market) For container and other ships whose consignments are more time-sensitive, and which operate on very tightly defined schedules, there would be less opportunities to avoid a small charge.

Annex-I countries accounted for about 60 per cent of total bunker fuel sales in 1994, about the same as in 1971 [OECD, 1997]. A few countries account for the majority of Annex I country bunker fuel sales. The United States is the largest, supplying nearly a fifth of world demand, followed by the Netherlands, Japan, Greece, Belgium, and Spain. However, according to OECD (1997) these countries are not likely to feel most of the negative impacts of a bunker charge. Those countries competing in markets for agricultural and manufactured goods and relying on maritime transport for a large share of their exports and those exporting raw materials may face significant increased costs from a charge [OECD, 1997].

### 8.4.3. Implementation issues

There are several obstacles for the implementation of a carbon charge on bunker fuels. It would be necessary to reach an agreement between countries on implementing such a charge. Even if a charge only involved a small number of countries, it would be important for them to negotiate a range of issues with non-participating countries. Any Annex I country initiative would need to be negotiated in a wider international framework including developing countries. The negotiations would need to address issues such as the point of application of the charge, the question of which government would be responsible for collecting and disbursing the proceeds of the charge, and the question of transfers of revenue among countries.

If collection of revenue is done by states, emissions would have to be allocated among countries. The following possible allocation methods to Parties (nations) emissions inventories have been recommended for further consideration [OECD, 1997]:

- *Allocation of emissions to Parties according to where the bunker is sold.* This approach may seem as the most natural one to pursue.
- *Allocation of emissions to Parties according to the nationality of the transporting company, the country where the vessel is registered, or the country of the operator.* This approach would require a comprehensive investigation of what nation that would be the right one to allocate to.
- *Allocation of emissions to Parties according to the country of departure or destination of the vessel, or sharing of responsibility for emissions between the country of departure and country of arrival.* This approach would require managing bunker use at departure or arrival ports and levying port fees. It is not clear what the basis of allocations would be.
- *Allocation to Parties according to the country of departure or destination of passengers or cargo, or sharing of responsibility for emissions related to the voyage of passengers or cargo between the country of departure and country of arrival.* This approach would require calculating the bunker use for particular voyages and somehow allocating it among passengers and/or freight based on their origins and destinations.

All of the above allocation approaches raise questions of equity, political acceptability, and practical feasibility. It is highly unlikely that any method or formula for allocating bunkers and emissions could be agreed through the UNFCCC negotiating process. If this should be possible, it is likely that the Kyoto Protocol would have to be re-negotiated. National emissions inventories would be changed, and some countries would therefore require their emissions reductions obligations (“Assigned Amounts”) to be changed. Nationally based bunker charges then become impossible to implement.

One way to enhance the likelihood of gaining acceptance for a system of charges could perhaps be for the IMO to administer the system. Still, someone at the national level would have to collect the revenue in some ways. Besides, the UNFCCC Conference of the Parties, its members, and other stakeholders in the international climate change process may have different ideas regarding the use of proceeds. Obviously, a portion of the proceeds should be used by the IMO to finance the costs of operating the charge system. Another potential *internal* use (i.e. internal to the international shipping industry) could be to provide support for R&D aimed at improving design and operation of ships with respect to fuel efficiency and emissions profiles. External uses of proceeds could include contributions to UNFCCC programmes, e.g. ones aimed at helping developing countries mitigate or adapt to climate change. However, it is not easy to see how it should be possible to agree on such a common system for carbon charges.

Potential effects of a charge on international trade must also be addressed. The likely different impacts on bulk and non-bulk traffic and other effects on trade competitiveness implies that the World Trade Organisation would need to play an important role in the negotiations, which would complicate the whole process.

Another important obstacle against common carbon charges is the unwillingness in most countries to use $CO_2$ taxes as an instrument in their domestic GHG policy, especially towards energy intensive industries competing in international markets. Thus, it is hard to see many countries that would like to pursue the use of common carbon charges in international shipping. We therefore conclude that common carbon charges do not seem to be a viable option at present.

## 8.5. Common emissions standards

### 8.5.1. IMO's experiences with standards

International shipping has along with aviation substantial experiences in finding international solutions to common safety and pollution problems in the form of conventions through global uniform (minimum) standards.

In principle, IMO conventions and convention annexes on a global basis tackle analogue problems to $CO_2$ emissions. IMO member states, practically all the maritime nations, handle a number of IMO conventions *as flag states*. There are in many important ports a machinery for *Port State Control*. In several connections the authority from IMO conventions through port state control extends to ships also from countries that *have not ratified* the relevant convention, and even to territories *not members* of IMO. In addition to notifying the flag state, the port state may in many instances retain ships until serious deficiencies have been rectified. This may relate to ship safety matters, but may also extend to e.g. environmental aspects.

IMO has adopted a $NO_x$ Technical Code for engines installed on ships constructed on or after 1. January 2000 or engines which undergo a major conversion on or after the same date. The purpose of the Code is to establish mandatory procedures for the testing, survey and certification of marine diesel engines which will enable engine manufacturers, ship owners and Administrations to ensure that all applicable marine diesel engines comply with the relevant limits for emissions values for $NO_x$ as specified in regulation 13 of Annex VI to MARPOL 73/78 [IMO Briefing, 1999]. Regulation 13 specifies emissions limits for $NO_x$ from these engines, and presents some procedures for testing and certification. These standards could form a pattern for similar standards for GHG emissions.

### 8.5.2. Standards for reducing $CO_2$-emissions

#### *8.5.2.1. How could standards be designed?*

Because $CO_2$-emissions from ships are determined both by operational practises and the technical construction of the vessel, standards should ideally cover both. The operation of ships relevant to $CO_2$-emissions should measure actual fuel consumption and relate it to the transport work performed by the ship. Monitoring actual operational practice relevant to fuel consumption may be difficult and open to evasion. Part of the monitoring would be the difficult assessment of the denominator of the calculation, which is the transport work performed.

Should standards focus on GHG emissions/energy efficiency or technical solutions to reduce emissions? Even if the primary goal is to reduce emissions, standards will most likely be decided on the basis of available technology to reduce emissions, and should be based on what technical solutions that currently seems to be the most cost effective. Expected future technology development and implementation rates of new technology will also be of importance. Thus, it may seem rather peculiar to base standards on emissions, when technology is the driving factor.

It may also be easier to implement and control technology based standards. Generally, the degree of energy efficiency built into a ship would be embedded, the fuel efficiency and thus emissions at normal operating speed deteriorates very little over its lifetime, if well maintained. However, it may be necessary to control the vessel during its lifetime to ensure proper maintenance etc. We will look into this in more detail later in the chapter.

However, there are several advantages setting standards for emissions/energy efficiency, since this is the factor we want to improve. Emissions standards leave it to the ship owner to decide how to achieve the target, which could stimulate more cost effective emission reductions. The discussion in chapter 5 indicates that there are several technical options to choose among.

Thus, it will be necessary for ship owners to choose among different technology solutions to find an optimal mix, since several of the proposed measures are not additive and some may even be mutually exclusive. Besides, standards for emissions would be in compliance with the way the IMO $NO_x$ standards are set.

#### *8.5.2.2. Standards for existing ships*

New ships generally have lower energy intensity than the average for existing vessels of similar type. At the other end of the scale there are a number of vessels, mainly old, that are relatively energy intensive for their size and type. They account for a disproportionately high share of the GHG emissions from world sea transport. One could consider establishing a minimum standard that existing vessels would have to meet. This standard would have to be much less strict than a standard for new ships. The "cut off rate" for existing ships might e.g. intend to hit the 10 to 15 percent of fleet segments with the poorest energy efficiency.

Issuing a certificate for existing vessels would require other procedures, far more costly and less certain, than for new ships. The oldest vessels would not always be the ones to be hit by the requirements. Some old ships may come out favourably for instance due to low normal speed.

A number of existing vessels that would not meet certificate requirements sailing at normal speed, could still meet the requirements with the machinery "de-rated" so that only a reduced speed could be achieved, or other machinery modifications. This would often be a better proposition for their owners than scrapping. A measure where one consciously aims at obtaining slow steaming through de-rating of energy intensive, older vessels may possibly be the best solution available for existing vessels.

A certificate for existing ships, if successful, could lead to some accelerated scrapping, and thereby somewhat increased newbuilding demand, at least for a period. Such a certificate would, however, have a north-south profile that might make it less acceptable.

A certificate for existing ships that does not tighten requirements over time would only have effect over a few years, as most of the vessels hit by it would have been scrapped in a few years anyhow. Such a scheme might not be worth while setting up. If requirements were to be tightened over the years, it would create a permanent regime of forced obsolescence.

It is unlikely that a certificate for existing ships could become nearly as cost effective as a certificate for new constructions. Besides, it would be difficult to monitor and implement.

#### *8.5.2.3. Standards for new constructions*

Standards directed towards new constructions would be easier to define and monitor (control for evasion) than design standards for existing ships. Standards for new ships would only gradually have an effect on the average emissions level for the world fleet. A rough estimate is that approximately half the world fleet would be covered within ten years of introduction of standards.

If fuel consumption is used as a proxy for emissions, a standard based on fuel consumption per cargo ton-mile would have to be a function of ship size and type. This differentiation is probably the greatest challenge for standards-based approaches. The authority establishing the standard for fuel use/efficiency would have to have substantial ship design expertise as well as insight into the economics of sea transport. The design parameters involved in setting standards would include: engine power, hull shape, main engine efficiency, total propulsive plant efficiency, and overall vessel design speed. The time value of typical cargoes for a given ship type/size would have to be taken into account. In order not to discourage innovative design progress, the standard should relate to function and not specify technology. For each newbuilding the task of the ship owners and shipbuilders would be to meet or exceed the standard, combining various design parameters at their own discretion.

The IMO currently certifies ships with respect to other standards, so this approach would not be new. It is also normal practice for shipbuilders to guarantee the fuel efficiency of ships they deliver.

#### *8.5.2.4. Control of standards*

Design standards for new vessels could probably most easily be controlled and verified by independent verification bodies such as flag state maritime administrations and the classification societies, who usually follow the construction process. If a convention on design standards is ratified by all IMO member states, comprising nearly all maritime nations, this should be straightforward.

However, it may also be necessary to control the ships during their lifetime to ensure that the standards are maintained. Besides, not all countries are IMO members and all member states may not ratify the convention. In order for the standard to become global, port state control seems required, where the port state is authorised to control compliance with convention standards also for ships of other flags than those of ratifying IMO members. One may assume that the necessary administrative capacity for port state control exists in all Annex I countries. Since about nine-tenths of international voyages start or end in Annex I countries, administration this way of IMO-adopted measures to control GHG emissions should be good.

If the standards target the technological properties of the ship, few ships could be built without regard to such requirements even if they are only maintained by non-Annex I countries. Most ships must be able to trade to Annex I countries over their lifetime, e.g. through change of ownership. Even if a regulatory regime did not formally include non-Annex I parties, or if one could not reasonably expect them to abide by it, most international maritime transport could be covered. However, such a regime may lead to the construction of a "non-Annex I fleet" with relatively high emissions. The possibilities of such development should be further investigated.

Imposing design standards on new ships would involve a straightforward requirement that new constructions meet a specified emissions standard in order to be certified. The standard should be stricter than the reference case or baseline standard which is assumed would apply in the absence of any perceived need to address GHG emissions. This approach gives ship owners no incentives to improve efficiency beyond the fixed standards. Such incentives could be established by allowing ship owners to earn credits from exceeding the standards. This will be discussed in the next section.

## 8.6. Emissions trading

### 8.6.1. What is emission trading?

The Kyoto Protocol approves the use of the following three flexible mechanisms to reduce GHG emissions globally:

1. Cross-border emissions trading among Annex I countries, i.e. those countries subject to emissions reduction/limitation obligations, (pursuant to Article 17);
2. Joint Implementation (JI) emissions mitigation projects developed within Annex I (pursuant to Article 6); and
3. Mitigation projects through the Clean Development Mechanism (CDM) developed in countries outside Annex I (pursuant to Article 12).

Rules and guidelines for the use of these mechanisms are currently being negotiated. Preliminary plans call for open trading of emission permits (allowances and/or credits) in an open international market. Some parties (e.g. the EU), however, advocate restrictions on the use of the mechanisms, requiring that they should be supplemental to domestic actions.

An underlying assumption is that controls on emitters would underpin the system and give value to the emission reduction units. Another assumption is that Annex I parties will impose emission controls on companies operating within their borders or under their jurisdiction. Permit transactions between companies will involve additions to and subtractions from national emissions quotas (so-called Assigned Amounts in the Kyoto Protocol).

Annex I country governments may allocate or sell emissions allowances *ex ante* to their national emitters, who may trade them in advance of actual reductions. In contrast, credits are created *ex post* when an emitter emits less than allowed or when somebody invests in mitigation measures to be able to sell the credit obtained. After being certified by an independent agency, credits may be sold in the market.

Credits earned through CDM and JI projects are likely to be traded in the same international market as allowances. Credits will increase the Assigned Amounts of Annex I parties, thus helping them to meet their Kyoto obligations.

### 8.6.2. Ways of including international shipping in emissions trading

#### *8.6.2.1. Allocating emissions allowances to ship owners*

If emissions from international shipping were included in national emissions inventories, ship owners assigned to an Annex I country could be allocated for free or have to buy allowances along with other emitters and be allowed participating in the emissions trading. As shown in previous sections, allocating emissions from international shipping among countries seems impossible to achieve in the foreseeable future, and is inconsistent with the reporting process for international bunker fuels adopted by the UNFCCC.

Another approach could be to establish emissions allowances trading for sea and/or air transport *outside the Assigned Amounts of Annex I parties to the Protocol*, and under the auspices of IMO or others. This requires the establishment of a restriction (cap) on total emissions from international shipping. Ship owners could then be allocated for free or have to buy emission allowances to cover their emissions. Ship owners choosing to over-comply could sell surplus allowances in the international emissions trading market or in a special market limited to the international shipping and/or aviation industries. If international shipping is included in international emissions trading, a cap on emissions from this industry would have to be negotiated with the parties to the Kyoto Protocol. This would imply rather complicated negotiations, and it is not clear who should represent the shipping industry in these negotiations.

However, since this approach would imply limiting emissions and distributing allowances to each ship owner in advance of trading, it seems unlikely to be able to capture all emitters from the industry. If limited only to for instance the ships registered in Annex I countries, there would be an incentive to register ships in non-Annex I countries instead. The approach would also require difficult negotiations on the distribution of allowances among ship owners. Thus, this does not seem to be a viable approach.

#### *8.6.2.2. Credits from emissions reductions*

Alternatively, ship owners could be allowed to earn credits for reducing emissions below a baseline, similar to investments in emissions abatement measures in developing countries through the CDM mechanism. This is a much easier way of including international shipping in emissions trading than through allocating allowances. The possibility to sell credits in an international emission trading market may give ship owners a strong incentive to reduce emissions.

A baseline is a reference case, «counter-factual», or a scenario describing what would be expected to happen «but for» actions taken specifically to reduce emissions. As for CDM projects, ship owners (sellers of credits) and buyers would like to get a maximum emission reduction (credit) through the abatement measures taken. Both parties therefore have incentives to overstate baseline emissions in order to inflate the credits. Thus, ensuring that the measures that form the basis for credits are additional, i.e. would not otherwise have been implemented, is crucial.

Preparing for the 6. Conference of the Parties (COP 6) in November 2000, establishing rules and guidelines for the operation of CDM is important. In this process it seem to be generally agreed that baselines should [Ellis and Bosi, 1999]:

- be environmentally credible to prevent fictitious emission reductions
- be transparent and verifiable by a third Party
- be simple and inexpensive to draw up (ensuring low transaction costs), and
- provide a reasonable level of crediting certainty for investors.

There may be several trade-offs between these criteria. If the baseline level (emission path) is set too low to ensure additionality, rather few measures to curb emissions from ships would gain credits. In this case many measures which are truly additional would be ruled out. On the other hand, too lax baselines would allow some measures that would anyway be implemented to gain credits. Thus, the right balance between lax and stringent baselines should be found.

There is another important trade-off between environmental credibility and costs. Baselines are generally costly to set up if they are complex and detailed to ensure credibility. Furthermore, complex baselines will generally not be transparent for 3. parties. Thus some ways of standardisation of guidelines for baseline calculations should be found. This would reduce costs, improve the verification process and make the baseline calculation less cumbersome for project participants. Such guidelines could be easier to establish for abatement measures on ships than for most onshore measures. Some multi-project baselines could be established, for instance for the 4 ship segments oil tankers, bulk carriers, container ships and general cargo ships or sub-groups of these segments. Instead of calculating baselines for each vessel, some common baselines for these groups could be established, for instance through a benchmark in terms of emissions per unit of output, fuel use per output or similar.

Another option is to require some special hull or propeller design etc. to be installed to earn credits. If ship owners for instance were allowed to earn emission reduction credits for exceeding design standards for new constructions as defined above, they could, for example, receive tradable credits to the extent they improve upon the standard set for $CO_2$ emissions. By this approach, standards for new constructions would form the baseline towards which the credits would be decided. On this basis the size of the credits could be calculated rather automatically.

Once a baseline is set for a particular new vessel, this baseline should follow the vessel for its entire lifetime or at least for some years. Otherwise, ship owners will not have sufficient incentive to make the additional investment required to reduce emissions below the baseline. The baseline could for instance be gradually reduced over the years, implying that ship owners will earn a decreasing amount of credits from the original investment. It may be necessary to regularly control the ship to see if it still exceeds the baseline. Baselines for new constructions should be regularly upgraded over time to reflect technical improvements. The prospect of earning credits for exceeding the set baseline can become a valuable driving force in technological advances as regards the fuel efficiency in sea transport. This paves the way for gradually stricter baselines towards new ships.

If improvements to *existing* ships should be allowed to potentially qualify for credits, then there would most probably have to be a screening of each vessel to reveal the emissions reduction potential, in the absence of common baselines for existing vessels. Thus, baseline setting would be more complex, and monitoring and verification more difficult. It could be hard to determine a baseline that could pass «the additionality test». The possibilities of crediting existing vessels should be further investigated.

Incorporating credits earned from emissions reductions in international shipping into the planned international emissions trading system is fully compatible with the fundamental principles of the UNFCCC as well as the stated objectives of the Kyoto Protocol. The central aim of the UNFCCC is to reduce global emissions, of which international shipping forms a part. However, resistance against incorporating credits from shipping should be expected, parallel to the arguments against the use of CDM, JI and emissions trading.

The basis for an IMO credits program would have to be a priori approved by the UNFCCC Conference of the Parties (COP). The IMO will need to convince the COP that its program will contribute real, additional, measurable, long-term emissions reductions. The consequences on world economy and world trade should be demonstrated. The challenge will be to show that the IMO or other responsible international body will have the administrative capacity and commitment to make and enforce strict rules and procedures for baseline setting as well as for emissions monitoring, verification, and certification. It may also be necessary to demonstrate to the COP that credits earned for improving emissions standards in international shipping will not adversely affect the international market in emission reduction units.

## 8.7. How to implement abatement measures

### 8.7.1. Introduction

Implementing policy instruments to limit GHG emissions from international shipping industry should contribute to global, cost-effective emission reductions. Thus, abatement measures in the shipping industry should only be implemented if the marginal costs are equal to or lower than the marginal abatement costs in other sectors.

It is likely that the ratification of the Kyoto Protocol is dependent of the establishing of the flexible mechanisms international emissions trading, JI and CDM. Therefore, there will be an international market for emission allowances and credits, and the price in this market will form the upper limit of what abatement measures that will be cost effective to implement, also in the shipping industry. Therefore, the abatement measure implementation towards international shipping should aim at such cost-effective measures.

When using a bunker fuel charge, a charge equal to the international emission allowance/credit price will automatically ensure global cost effectiveness. Ship owners will implement measures with a marginal cost lower than the current charge. Also emissions trading will ensure cost effective emission reductions from ships. The ship owners will face the international allowance/credit price, which will determine the level of actions they will take to reduce emissions. When technical standards are used as the policy instrument, careful calculations of costs for the different abatement measures will have to be done before the standards are fixed, to ensure the same marginal abatement cost level in the shipping industry as in other sectors.

It is very difficult to predict what the price level in the future emission allowance/credit market will be. A survey of different studies of abatement costs in some key countries and possible prices in future international emission trading markets presented in ECON, 1998, indicate price levels from slightly above zero to almost USD 40/tonne $CO_2$. However, most of the estimates are in the range of USD 5 to USD 13/tonne $CO_2$. This could form a very uncertain indication of what abatement measures in the shipping industry that would be cost effective to implement.

### 8.7.2. Operational measures

These are measures that can be implemented during the operation of ships to reduce GHG emissions. The discussion in chapter 5 shows that operational measures include the following activities:

- *Operation plannning/speed selection*: reduced speed/slow steaming may reduce emissions up to 40%.
- *Weather routing*: 2-4% emissions reduction could be possible

- *Optimising operating parameters*: include measures like steady power (minimum RPM variations), optimal trim and propeller pitch, minimum ballast, and optimal rudder. 1-5% emissions reduction is possible.
- *Reduced time in port*: comprises more efficient cargo handling and more efficient anchoring. 1-7% emission reduction could be obtained.

It can be seen from the list that operational planning/reduced speed (see also conclusions from Chapter 6) and reduced time in port are the measures with the greatest reduction potential.

A *bunker fuel charge* and *emissions trading* based on emissions allowances will give incentives to implement all the operational measures mentioned above. What measures the ship owner may choose to implement, will depend on the level of the fuel charge compared to the marginal costs. Those measures with marginal costs lower than the charge will be implemented, others not.

An important question is whether a bunker charge will result in reduced speed. During the early 1980s, reduced speed is reported to have been common, resulting in energy intensity reductions by 10-20% [OECD, 1997]. This practice was motivated partly by high oil prices and partly by over-capacity in the industry. Melissen et. al. 1993 analyses the economics of specific voyages for different types of bulk carrier (a 4,700 nautical mile voyage for an iron ore carrier and a 11,000 nautical mile voyage for an oil tanker). The possible effects on costs of a hypothetical fuel price increase from USD 85/tonne to USD 170/tonne are evaluated. This shows for these voyages that while the overall costs for older oil tankers are 35% lower than the costs for new vessels with a fuel price at USD 85/tonne, the gap is reduced to about 20% when the fuel price is doubled. The fuel price increase results in 30% lower optimum (minimum cost) operating speed for older vessels, newer vessels minimise their overall costs by operating at maximum speed even at the higher fuel price.

These results indicate possible implications for how a bunker charge might affect GHG emissions from bulk carriers. According to OECD, 1997:

- The remaining steam turbine-powered fleet would be less economical to operate and would probably be operated at lower speeds, resulting in more demand for new vessels with lower energy intensity and higher optimum operating speeds.
- Reduced speed by old vessels and accelerated fleet replacement would lead to reduced energy-intensity.
- Higher transport costs would dampen the growth in demand for maritime transport.

*Technical/emission standards* are in general not very well suited to implement operational measures to reduce emissions, due to limited control possibilities. Exceptions may be standards for maintenance and possibly also standards to reduce time in port. Requiring a certificate showing that required maintenance have been carried out according to specified technical standards or as a part of fulfilling an emission standard could be checked by port authorities. Such standards could therefore be implemented. It should be considered whether it is possible to impose standards on ports and/or ship owners for measures for more effective handling of cargo in ports and/or to set some maximum time for time spent in ports.

*Emissions credit trading* could most likely not be based on operational measures. This view is based on the ongoing discussion on guidelines for the CDM mechanism, where only investments in technical installations where emissions reductions are embedded (for instance fuel switching, investments in more energy efficient equipment etc.) will be accepted. This is due to verification problems for operational measures and a doubt that such measures would be additional i.e. not carried out in the absence of credit trading. A possible exception is maintenance measures that could probably be verified and subject to credit trading. However, the UNFCCC would have to be convinced that these measures would be additional.

### 8.7.3. Technical measures

#### *8.7.3.1. Existing ships*

The discussion in chapter 5 shows that different machinery measures seems to be the only realistic options to reduce GHG emissions from existing ships through technical changes. Such measures are modifications in the fuel injection, efficiency rating, technical changes to use other fuel qualities etc.

All these measures would be considered by the ship owner if a *fuel charge*, *emissions allowance trading* or *credit trading* are imposed. When the latter policy instrument is used, the measures would have to pass the additionality test. If it could be argued that such measures would not otherwise be implemented, among other things of economical reasons, passing this test should be rather straight-forward.

*Technical standards* could also lead to the implementation of such measures. However, it should be carefully concerned whether such measures are cost effective to reduce GHG emissions.

#### *8.7.3.2. New ships*

Chapter 5 shows the following possible technical measures to reduce GHG emissions from new ships:

- *Optimised hull shape*: 5-20% reduction-potential in the short term (i.e. based on existing technology).
- *Choice of propeller*: 5-10% reduction potential in short term.

- *Machine measures*: Additional measures compared to existing marine engines (10-20 years old). Total emission reduction potential 18-24%.

In the long term (20 years) several other measures may according to chapter 5 be feasible. Use of other fuels like other fuel distillates, natural gas and fuel cells may be an option. Technology development in other areas may also be significant.

The policy instruments *fuel charge, emissions allowance trading and credit trading* will spur technology development, and give ship owners incentives to consider all the measures above.

*Technical standards* may also lead to implementation of these measures. However, standards have a disadvantage in the long run compared to the other policy instruments in that they do not spur technology development. If they are not adjusted in the long term, they will gradually lag behind and loose their effect as new technologies are developed and implemented. Therefore, standards should be adjusted in the long term to keep up with technology development.

## 8.8. Policy strategies for IMO

### 8.8.1. Summary

The discussion in this chapter on what policy instruments to pursue to curb GHG emissions reductions could be summarised as follows:

- *Carbon charge* on bunker fuel is not a viable option, due to huge evasion possibilities.
- *A voluntary agreements programme* does not seem to be a very efficient policy tool towards international shipping. However, some reductions may be achieved by local agreements etc. or agreements between Annex I-countries/IMO and ship owners, where Annex I-countries co-ordinate their efforts.
- *Environmental indexing* does not seem to be a very efficient tool to reduce emissions, even if some reductions may be achieved on voluntary basis.
- *Emission allowance trading*, either along with other sectors in Annex I-countries or as a separate system outside the Annex I-countries seems to be a no-viable option, due to severe problems capturing emissions from the shipping industry.
- *Energy or emission efficiency standards* seems to be a promising option, especially for new vessels.
- *Emissions credits sales*, resulting from abatement measures on new ships and possibly also existing ships, is also a very promising option, and could in the long run provide very strong economic incentives for ship owners to reduce emissions through technical measures.

### 8.8.2. Proposed strategy

The survey in chapter 6 of this report shows that there are several technical and operational measures that could be implemented to limit GHG emissions from ships. Reduction of speed is identified as the single measure that results in highest emissions reductions. Implementation of new and improved technology is identified as the second best approach to reduce emissions, in terms of technical emissions reduction potential.

However, our forecasts indicates that total emissions from international shipping will increase even if most of the identified measures are implemented, due to expected growth in the world economy and thus expected increase in demand for international freight services. Taking into account the conclusion of this chapter that there seems to be no feasible effective policy instruments that could lead to reduced speed, it seems inevitable that total emissions from international shipping will increase in the years to come.

This is in line with forecasts for other transport modes. OECD, 1999 indicates a similar development for $CO_2$ emissions from land-based transport and aviation. Our analysis shows that sea transport is the most GHG benign freight transport mode. It is also our understanding that there may be more technical options for GHG emission reductions in international shipping than in most other transport modes. Technical improvements on hull and machinery on new ships could lead to emission reductions, and thus reduce the growth in future emissions.

The different transport modes are closely interlinked, and dependent on each other. Thus, measures to curb GHG emissions should be co-ordinated between the different transport modes, to avoid policies that are not cost effective and only contributes to move transport from one mode to another with no effects on overall, global emissions.

On this background, and in the light of the ongoing ratification process of the Kyoto Protocol, the following strategy for policy implementation for IMO to curb GHG emissions could be feasible:

1. Explore the interests for entering into voluntary agreements or on GHG emission limitations between the IMO and the ship owners, or to use environmental indexing.
2. Start working on how to design emission standards for new and possibly also on existing vessels.
3. Pursue the possibilities of credit trading from additional abatement measures implemented on new and possibly also on existing vessels.

This could be a strategy that could meet several outcomes of the ratification process of the Kyoto Protocol, and in the short term contribute to implementation of some of the cheapest abatement measures on new and existing ships. It will also ensure co-ordination with the use of policy instruments towards other transport modes to curb emissions.

## 8.9. References

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